HOW TO BUILD AND USE ELECTRONIC DEVICES WITHOUT FRUSTRATION, PANIC, MOUNTAINS OF MONEY, OR AN ENGINEERING DEGREE

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Over the years I have seen books dedicated to wives, children, secretaries, and sometimes even students, all of whom played a big part in the writing of the book. However, I haven't seen any books dedicated to Mammon, which is really why most of them are written in the first place. I almost didn't have a dedication at all, except that this seemed a good spot to point out that electronics really is *fun* once you get used to it and stop being afraid. The invention of op-amps played a big part in getting one engineer (SAH) over the transistors-are-too-much-for-me hang-up. So perhaps the book should be dedicated to Harold S. Black, who first recognized that a linear DC amplifier could be used for all sorts of useful things and called it a "negative feedback amplifier."

Contents

Preface

Dear Reader, you are looking at the second edition of this electronics book. The fact that there is a second edition implies that the first edition sold enough copies to justify a second I must have done something right. This in turn suggests that I keep the same approach that worked the last time.

The book is designed to show you how to build circuits in the minimum length of time without the mathematical juggling that fills most books on electronics. The math may be necessary for electrical engineer types, but my observations have convinced me that practicing engineers seldom use it. Most circuits are designed by scratching on the backs of envelopes, building the damn thing, and testing it out. I urge you to read this book with "soldering-iron in hand."

You can start at a particular chapter, learn the material you need to know, and build circuits using what you have learned. In some cases, the designs will be inelegant; in fact, "quick and dirty" is the best descriptive phrase. Engineering often involves settling for the "third best" of anything. "Second best" takes too long, and the "best" design comes only when the whole process is obsolete. One might paraphrase the poet. "Come learn along with me, third best will work – you'll see."

My method of teaching is somewhat unorthodox. It is based on the system used in the Navy during World War II to teach farm boys to be sailors. The system was called "monkey see, monkey do." First, you do something by brute copying; then, when you know how to do it, you ask about how it works. Then they give you a book called Operation of Mark IV Torpedo, and you are on your way to being a Chief Torpedo Mechanic. Why not start with the book first? Well, if you started with the theory first, you would never get to take a torpedo apart; you would be a Seaman II forever.

As a professor or graduate student, you may be insulted by being treated like an 18-year-old. The question is, do you want to learn something fast, or do you want to play games that soothe your ego? If you want to learn, sit down at the laboratory bench and start reading the book!

You might be more justified in asking what I am trying to teach you. First, I am gomg to try to bring you to the point where you can design your own instruments using op-amps. Second, I want to teach you the nomenclature and jargon of the electronics business so that you can steal useful circuits from the manufacturers and the trade magazines. In the Selected Reading List in the Appendixes several good sources for such circuits are listed. Many of these are intended for electrical engineers, but when you have gone halfway through this book, you'll be stealing from them like a veteran. Try to get on the mailing lists of the free magazines such as *Electrical Design News.* Once word gets out that you are in the market for op-amps, you will be deluged with catalogs.

"You realize, of course, that this is grounds for a divorce?"

Some of you may be wondering why I emphasize op-amps so much. Are they any better or different than transistors? The answer is yes! Op-amps *are* different, and by the time Hoenig is done with you, you'll be talking about op-amps in your sleep. For the moment, I will simply state that an *op-amp* is a transistorized linear DC amplifier with high gain and good stability. At least five PhD electrical engineering man-years have gone into designing and testing this gadget. You can expect it to be *better* than anything you could learn to build in the next year. The point is that you don't have to reinvent the wheel, electronically speaking; the product of all this effort is ready for you to use.

You might also be wondering just how good op-amps are for building circuits. To answer that question, I could quote the industry trade reports that say the number of op-amp manufacturers has increased from one in 1946 to 40 in 1978. Believe it or not, most of them are making money. What better proof could there be?

The cooperation of the Burr-Brown Research Corp. (Tucson) and the Motorola Semiconductor Products Division (Phoenix) in providing equipment and supplies is gratefully acknowledged. The cartoons in the text were drawn by Ms. Derith Glover of Tucson. Paul R. Stauffer helped with the corrections and improvements for the second edition.

Before turning you loose on the op-amps, I have one more quote that I hope will help when things don't go right. It is sometimes paraphrased "persistence pays," and is attributed to Calvin Coolidge, 30th president of the United States.

Press On

> Nothing in the world can take the place of persistence. Talent will not; nothing is more common than unsuccessful men with talent. Genius will not; unrewarded genius is almost a proverb. Education alone will not; the world is full of educated derelicts. Persistence and determination alone are omnipotent.

S.A.H.

1 A Little Circuit Theory and an Instrument or Two

Before starting to become op-amp experts, you have to understand a little circuit theory. Even if you flunked Physics 1 and are terrified by the toaster, you will fmd that circuit theory is not an ineffable mystery.

We propose to start at the beginning and teach by our own technique. First we explain in the simplest terms; then you do an experiment to convince yourself that it's all true. Finally - after you have used the device – we explain the theory. It is a little backward, but it seems to work.

In this book you should *not* hesitate to skip over certain dull subjects to get to something interesting. When you get stuck, you can go back and perhaps discover that certain dull topics aren't so dull after all.

You should first arm yourself with a soldering iron, a 45 volt dry-cell battery, a volt-ohmmeter (a Heathkit MM-l is great*), and some carbon resistors (the cheapest kind). This book is written with the assumption that you will read it with soldering iron in hand. Do the experiments as you read the book – *don't wait, do them now!*

RESISTORS

Resistors are marked with colored stripes. The stripes tell the resistance value and tolerance according to the resistor code. The code itself is given in Table 1-1, and you might want to try to memorize it. If you do, there is a mnemonic to help. The colors go black, brown, red, orange, yellow, green, blue, violet, gray, and white. The mnemonic is "**B**etty **B**rown **R**uns **O**ver **Y**ellow **G**rapes **B**ut **V**iolet **G**oes **W**alking." The application of this color code is shown below. These colored bands are grouped toward one end of the resistor body. Starting with that end of the resistor, the first band represents the first digit of the resistive value; the second band represents the second digit; and the third band represents the power of 10 by which the first two digits are multiplied. A fourth band of gold or silver represents a tolerance of ±5% or ±10% respectively. The absence of a fourth band indicates a tolerance of ±20%.

The physical size of a carbon† resistor is related to its wattage rating: its size increases progressively as the wattage rating is increased. The diameters of 1/4, 1/2, 1, and 2 watt resistors are approximately 3/32, 1/8, 1/4, and 5/16 inch respectively. For now, just get the 1/4 watt size – they will do for most of our experiments. If high wattages are needed, we will say so.

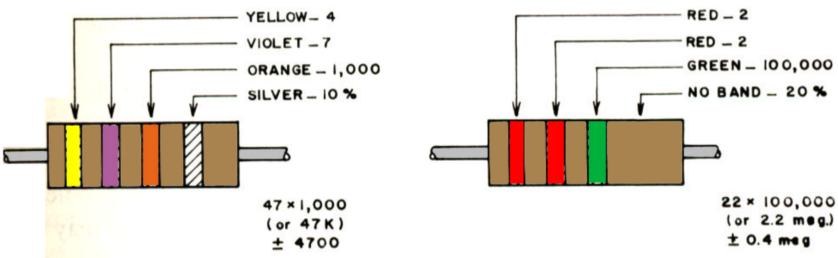

Figure 1-1 Color-coded resistors

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* Now and then you will note that we mention certain commercial products. These are not paid-for advertisements (at least we haven't had any offers yet), but they represent the results of our experience.

† Carbon resistors are the ones most commonly used. For high currents, wire-wound resistors are available. Other special types are listed in the various catalogs. Just remember that carbon resistors are the lowest in cost. Some military type resistors will have extra bands indicating reliability - ignore them. The first three bands are what really count.

Table 1-1. Resistor Color Code

Multiplier Color	First Digit	Second Digit	Multiplier
Black	0	0	0
Brown	1	1	10
Red	2	2	100
Orange	3	3	1000
Yellow	4	4	10,000
Green	5	5	100,000
Blue	6	6	1,000,000
Violet	7	7	Not used
Gray	8	8	Not used
White	9	9	Not used
Gold			.1
Silver			.01
Tolerance Color			**Tolerance**
Gold			±5%
Silver			±10%
No band			±20%

The color code chart (Table 1-1) and examples (Figure 1-1) provide the information required to identify color-coded resistors.

Another thing worth mentioning is the abbreviations used in electrical engineering. Learning them will help you read this book and the associated literature. (In engineering we read the literature to steal cute circuits from one another.)

A	=	ampere or amp		
Å	=	Angstrom unit (10^{-10} m)		
F	=	farad (unit of capacitance, C)		
f	=	frequency		
Hz	=	hertz (unit of frequency of cycles per second)		
I	=	symbol for current		
Ω	=	ohm		
R	=	symbol for resistance		
V	=	volt		
W	=	symbol for energy, watt		
Z	=	impedance		
ρ	=	resistivity = rho		
σ	=	conductivity = sigma		
ω	=	$2\pi f$, angular frequency = omega		
p	=	pico-	= 0.000000000001	= 10^{-12} (pF = picofarad)
n	=	nano-	= 0.000000001	= 10^{-9} (nm = nanometer)
µ	=	micro-	= 0.000001	= 10^{-6} (µV = microvolt)
m	=	milli-	= 0.001	= 10^{-3} (mA = milliamp)
k	=	kilo-	= 1000	= 10^{3} (k = kilohm)
M	=	mega-	= 1000000	= 10^{6} (MHz = megahertz)

Chances are that you probably don’t want to memorize the code anyway, so run down to your friendly radio shop and buy a resistor guide for 25¢.* You should also start getting catalogs from the following companies (the catalogs are free – you will end up paying for them in the stuff you buy):

Allied Electronics
3160 Alfred Street
Santa Clara, CA 95050

Edmund Scientific Co.
101 E. Gloucester Pike
Barrington, NJ 08007

EICO Instrument Co.
283-T Malta Street
Brooklyn, NY 11207

Heath Company
Benton Harbor, MI 49022

Lafayette Radio
111 Jericho Turnpike
Syosett,NY 11791

Newark Electronics
500-T N. Pulaski Road
Chicago, IL 60624

Olson Electronics
260 5. Forge Street
Akron, OH 44308

Poly Paks
P.O. Box 942
South Lynnfield, MA 01940

Each of these companies specializes in some particular line of items. Many other companies will be listed later in the book; these are just some good ones to start out with. Edmund sells primarily optical equipment; Heath sells electronic instruments; Allied and Newark sell new electronic gear. The others sell both new and old parts, as well as reclaimed military or manufacturing surplus. Buying used or surplus stuff can be great – but watch out: there may be little or no operating data and replacement may be impossible. But don't let this warning scare you. Such problems provide part of the fun of electronics. As part of the fun and games, you may want to start reading things like *Popular Electronics*.

Popular Electronics
Ziff-Davis Publishing Co.
1 Park Avenue
New York, NY 10016

You will find all sorts of useful circuits, many of which will be simple enough for beginners, but it's hoped you won't be a beginner very long.

CIRCUIT SYMBOLS

Part of beginning is learning circuit language. We will now introduce you to the most common cfrcuit symbols (Figure 1-2). Some of them you won't see again for many pages, but there are a few of them that we use all the time.

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* Please remember that when we mention prices, they are for the era 1979–1980 and are subject to inflation. However, we think that it will help if you have some “order-of-magnitude” prices to go by.

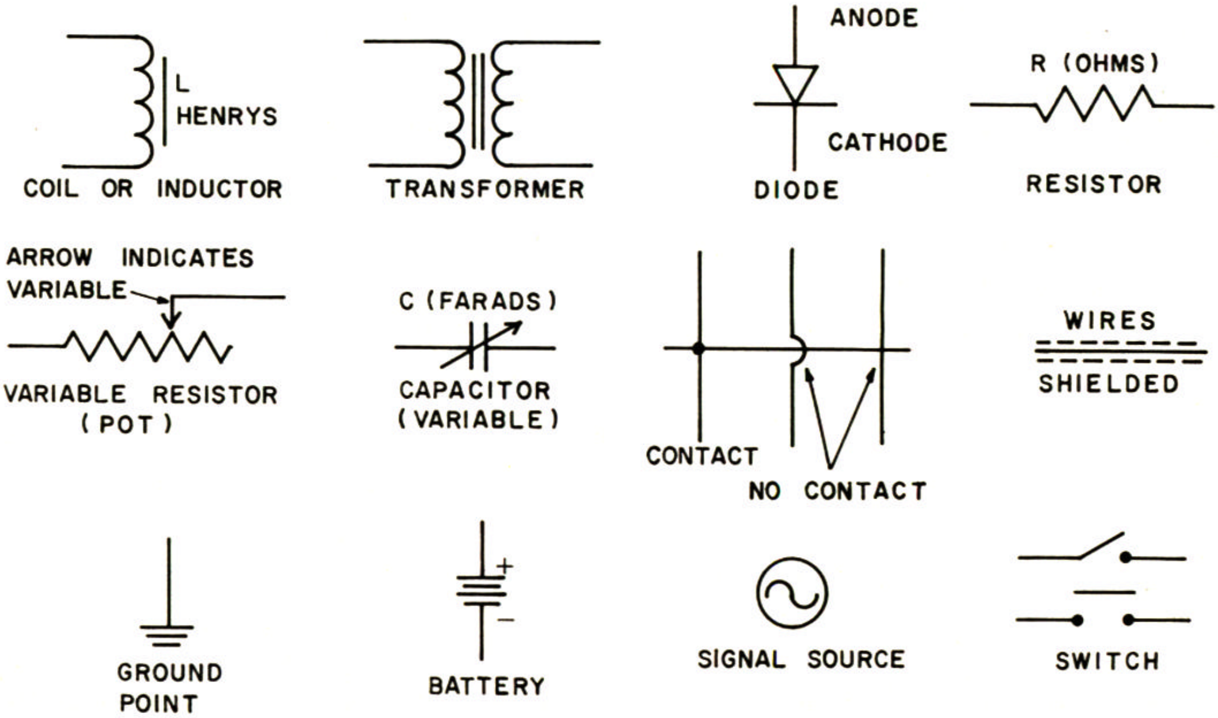

Figure 1-2 Circuit symbols

VOLT-OHMMETERS

The only instrument you will need right now is the volt-ohmmeter (VOM). Later, we will discuss this device in detail, but for now, just look at the meter scales. You

have a series of ranges, usually 0-50 and 0-15. These are voltage ranges. By means of a switch, the 0-50 range can cover 0-5, 0-50, 0-500, and 0-5000 volts. The 0-15 scale can be used for measuring 0-1,5,0-15,0-150, and 0-1500 volts. The meter will read AC or DC voltages depending on your use of input jacks or switches. The "ohms" scale is nonlinear and reads backward (don't worry about why for now). By means of decade switches, you can read 0-2 kΩ, 0-20 kΩ, 0-200 kΩ, and 0-20 MΩ. You get from the ohms to volts scales by means of a switch on the meter. Some VOMs have a series of current scales or use the voltage scales to measure amperage, i.e., 0-150 mA, 0-15 mA, and so on. Again, a switch is used to get on to the current scales.

VOMs are rugged instruments and *almost* student proof: don't use the 0-1.5 volt scale on 110 volts or the ohms scale on any circuit that has current in it. If you have already bought a Heath VOM at this time (as suggested on page 1), *read the instructions*.

POWER RECEPTACLES

At this point we should say a few words about the AC power receptacles found in our homes and laboratories. The old-fashioned, and still very common, type is the two-prong system shown in Figure 1-3A. In this case, one side is "hot," the other is "neutral"; the electricity comes out of the hot side at a "high" electrical pressure (voltage), goes through the appliance or whatever, and returns to the power plant at low pressure via the neutral lead. It is a real mistake to refer to the neutral lead as "ground," and those who do may be setting themselves up for a “shocking surprise” (sorry, we couldn't resist it).

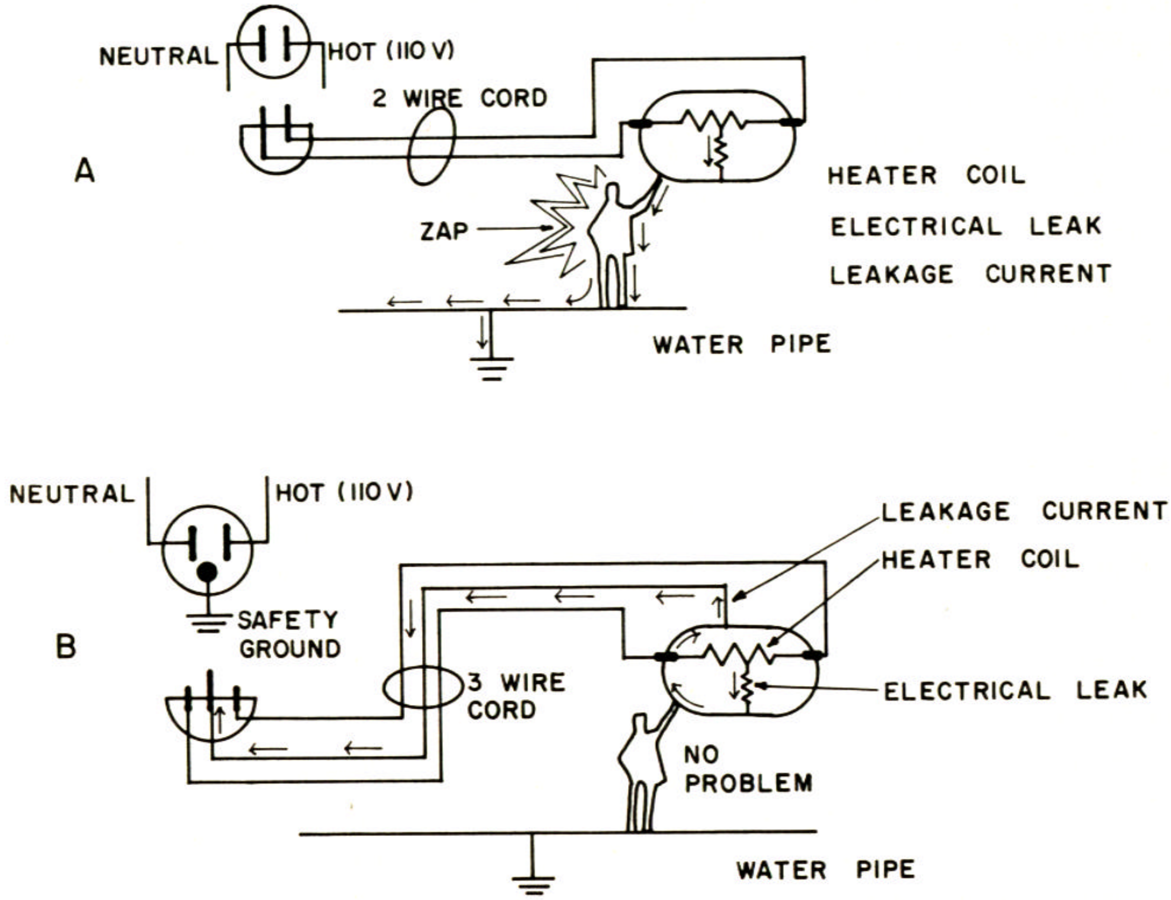

Figure 1-3 Conventional power systems. A. Two-wire system. B. Three-wire system with safety ground.

To appreciate the advantages of the three-wire or grounded system and the dangers of the two-wire system, we show Figure 1-3 where both systems are used with a "defective" appliance. Make sure you understand why in one case (A) the little figure is "shocked." In the other drawing (B) the ground wire carries off the leaking electricity so that it does not go through the person in the circuit.

What do you do if your house or laboratory only has two-wire outlets? This is like the question, how do porcupines make love? To which the answer is, *very carefully*. All we can suggest is (1) be careful, (2) ground every electrical appliance that has a metal case to a water pipe, and (3) keep your fingers dry. (Actually, if you're a college student, you are in more danger from auto accidents than from everything else put together, including the military.) We wifi try to warn you as much as possible, but there is *no substitute for common sense!*

At this point we could consider the matter closed but one of our student readers pointed out that "common sense" is usually the product of experience and that is what students don't have. "Besides," he continued, "I still don't understand why the term 'ground neutral' is ever used." We heard this man ask for help and promptly wrote the expanded discussion which follows. The student in question said that "it helped a lot."

To understand where the term *ground neutral* came from let's start right at the local power plant. The local power company delivers what is called *three-phase power* (Figure 1-4). Note in this figure that there are four wires: A, B, C, and ground. Ground is connected to a big copper plate that is buried in the earth at the power plant and can at this point be correctly called ground. Wires A, B, and C are called hot because they can deliver a painful electrical burn if you are careless. All four wires are carried on power poles throughout the city and countryside. Ground is connected to the earth ground at every pole to reduce the damage from accident lightning strokes.

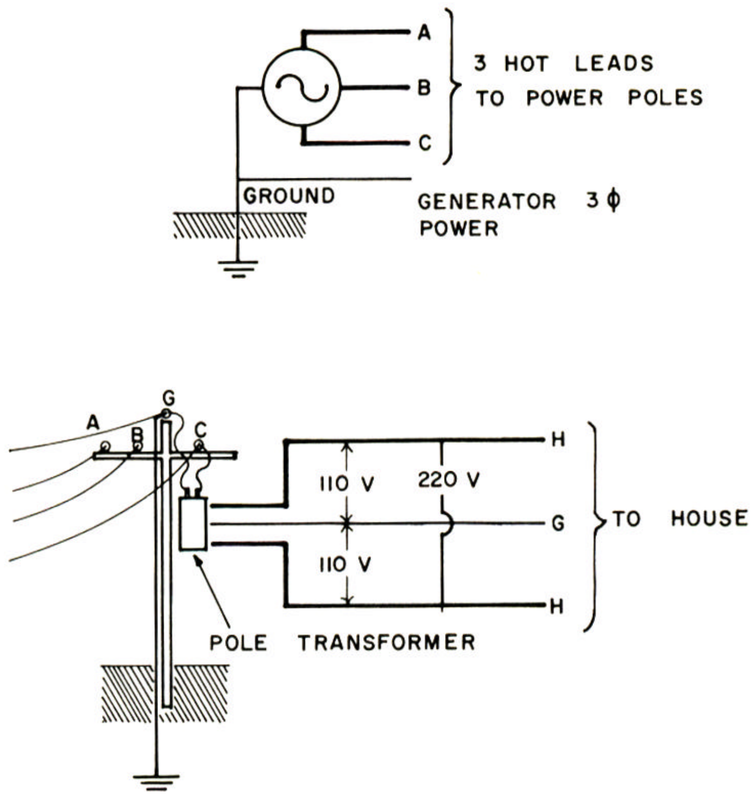

Figure 1-4 Electrical generator and transmission lines

For home service, the high voltages are reduced by transformers. The usable voltages, which are nominally 110 and 220 volts, are delivered to the home or laboratory as shown in Figure 1-5. Notice that now the two "hot leads" and the ground are used to provide power to various areas of the house. The point of this three-wire arrangement should be clear to you. If something goes wrong and the case of an appliance receives some electrical pressure due to leakage, the electricity goes back to the power plant via the ground lead instead of to the body of someone who might be using the device.

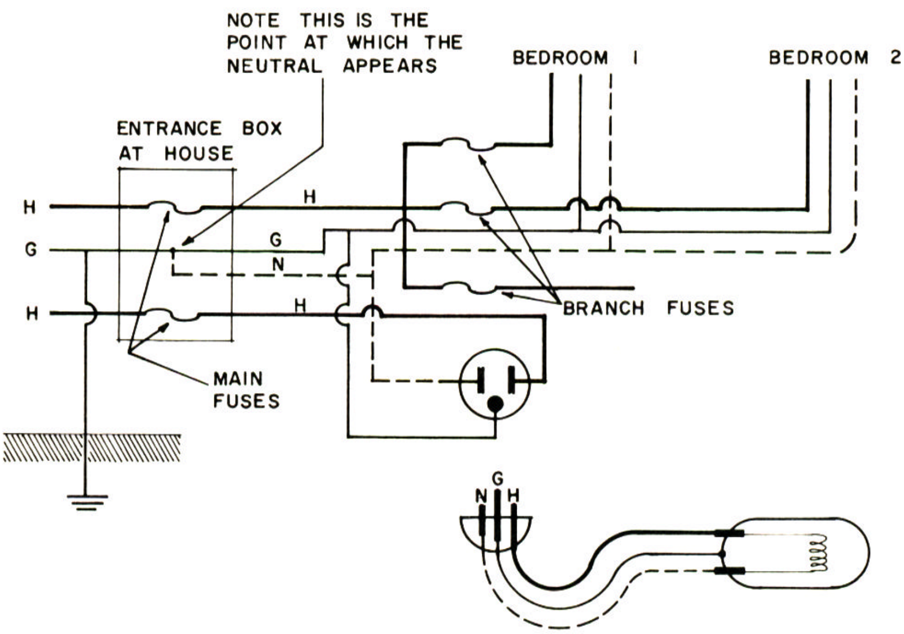

Figure 1-5 House wiring

Looking at Figure 1-5, you can appreciate where the neutral lead appears and that it is only THERE that neutral and ground are the same. Inside the house the neutral lead carries the normal current returning to the power plant while ground serves only as a safety wire in case something goes wrong. Outside the house the neutral lead does not exist.

Returning to the question of neutral versus ground, we leave you with the knowledge that *neutral is not, is not, ground inside a building! Never, Never, Never!!!*

This conchides our discussion of house wiring and how it works. For more details you will have to consult another book or wait until we write one. Our next step will be to take you through some simple circuits and instruments that you will need to make use of op-amps. Some of them you may be familiar with, and in that case skip over the material. However, if you haven't seen something before, read the discussion over carefully. We didn't write it into the book just to take up space.

A VOLTAGE DIVIDER

For our first experiment, let's take the VOM and adjust it for DC volts on a range that is greater than the battery voltage. Now measure the battery voltage. If it reads 45 volts, great! If you have noticed that the VOM goes off scale, the leads are reversed. But this is typical when working with DC; you can expect to do it wrong the first time (the chances are 50-50).

Step two is to make up a voltage divider. Set up a circuit as shown in Figure 1-6. Use 5.1 kΩ and 10 kΩ 1/4 watt resistors.

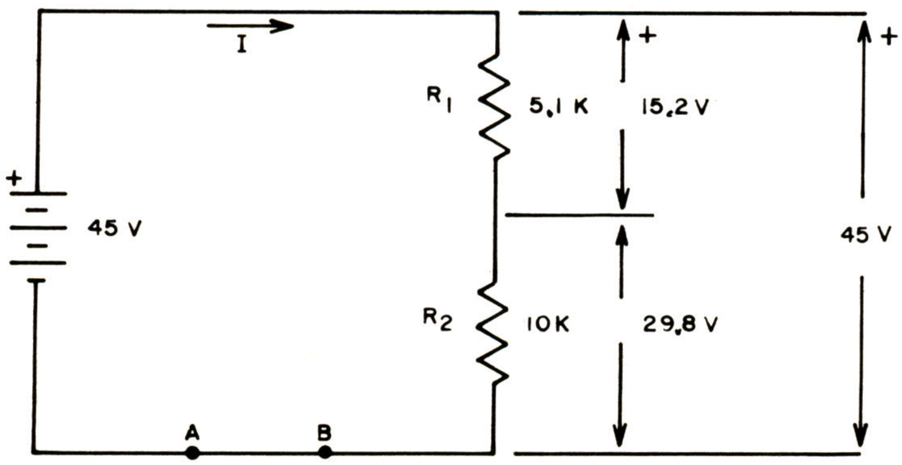

Figure 1-6. Voltage divider.

Ohm's law states – remember Physics 1? If not, see the next section. But do the experiment first! – that *V (volts) = I (amps) × R (ohms)*. In this case

$$I = \frac{V}{R}$$

$$I = \frac{45\text{ volts}}{15.1\text{k}\Omega}$$

$$I = 3 \times 10^{-3}\text{ amps}$$

$$I = 3\text{mA}$$

You can convince yourself of this, if you have any doubts about Ohm's law, by putting the VOM on the milliamp scale (full scale must be more than 3 mA) and connecting it in series with R_1 and R_2 and B and connecting in the VOM. Now the voltage across R_2 (10 kΩ), from Ohm's law, should be

$V_2 = 3 \times 10^{-3}$ amps (10^4 ohms) = 30 volts.

Across R_1 (5.1 kΩ), the voltage should be

$V_1 = 3 \times 10^{-3} (5 \times 10^3) = 15$ volts.

You have built a *voltage divider*. This is a useful gadget for obtaining any voltage between 0 and 45 volts from a 45 volt battery (all calculations are only slide-rule-accurate).

How much power are we dissipating in the resistors? The power dissipation law is

P(watts) = I^2 (amps) × R (ohms).

In the 10kΩ resistor, we dissipate

$P = (3 \times 10^{-3})^2 \times 10^4 = 9 \times 10^{-2}$ watt;

in the 5.1 kΩ resistor, the dissipation, by a similar calculation, is 0.045 watt. The use of 1/4 watt resistors thus provides an adequate margin of safety; besides, they are easily available.

After having performed this simple experiment with the voltage divider, we are now ready to get into some physical concepts of resistance and some of the details of circuit theory, which are not so simple. As we said before, if you want to skip the details of circuit theory, go ahead. You should read the sections on capacitors, inductors, filters, power supplies, and oscilloscopes. Of course, if you want to go on to Chapter 2 now and come back to this chapter as you need it, that is your decision. Who are we to tell you how to learn?

OHM'S LAW AND RESISTIVITY

An important property of all materials is called *conductivity*, i.e., the ability to pass electricity. Suppose we have a bar of length L and cross-sectional area A, and we apply a voltage V between the ends of the bar. If V is in volts and L is in meters, we can define the *voltage gradient*, E, as

E = V/L (volts/meter)

Now if this voltage V forces a current I (in amps) through the bar of area A (meters²), we can define the *current density*, J, as

J = I/A (amps/meter²)

The conductivity, σ, is defined as the current density per unit voltage gradient, so

$$\sigma = \frac{J}{E} = \frac{I/A}{V/L} \left(\frac{\text{amps}}{\text{volts} \times \text{meters}} \right)$$

The nice thing about σ is that it is *independent* of the shape of the conductor.

Sometimes we use $\rho = \frac{1}{\sigma}$ where ρ is called the resistivity. The fact that resistivity (or conductivity) is a natural property of a certain material leads us to Ohm's law. Consider our bar of length L and area A. If it has a resistivity ρ, then its resistance (which *is* shape-dependent) is

R = ρ (L/A)

The resistance R is expressed in *ohms*. Since the resistivity, ρ, is the reciprocal of conductivity, then

$$\rho = \frac{V/L}{I/A}$$

when this is substituted into the equation for R, we obtain

$$R = \frac{V/L}{I/A}\left(\frac{L}{A}\right) = \frac{V}{I}$$

The relation R = V/I (or V = IR) is known as *Ohm's law*.

The fact that we used Ohm's law earlier without deriving it doesn't bother us a bit. *First* we show you how to do something useful; *then* we explain it. (The old Navy system again!)

Ohm's law as stated above assumes that the resistance is *linear*, i.e., if the voltage across the resistance is doubled, the current through it is also doubled. The resistance of materials like carbon, aluminum, copper, silver, gold, and iron is linear These materials are also *bilateral*, that is, a wire made of one of these metals will conduct electricity equally well in either direction. Many devices that conduct electricity, however, are both nonlinear and unilateral. Such devices include rectifiers and transistors. Have patience, we will get to them faster than you think.

While we are on this topic, we should throw in another useful law (though without proof) that we mentioned previously. The current through a resistor R (ohms) is I (amps) when we apply a voltage of V (volts). The heat produced is giver by

$$P\ (\text{watts}) = I^2R = I\,V$$

(this is called Joulean Heating or Joule's law heat because Joule first proposed that $P = I^2R$). Usually P is called *power*, the rate at which heat is produced. The power rating or wattage rating of a resistor tells you how much heat (power) you can dissipate in that resistor without destroying it. For example, a 1000 ohm, 1/4 watt resistor will be at its maximum temperature when a current of about 16 mA (0.016 amp) is passing through it. If you want to pass, say, 40 mA (0.040 amp) through a 1000 ohm resistor, it had better be rated at 1.6 to 2 watts to be safe.

FACTORS AFFECTING RESISTANCE

Some materials are better conductors of electricity than others, and the conductivity varies with temperature. Metals have a *positive coefficient of resistivity*, i.e., their resistance increases with temperature. Table 1-2 shows the effect of temperature on the resistance of some metals. The table lists the ratio R/R_0, which is the ratio of the resistance of a given piece of wire at the given temperature to its resistance at zero degrees Centigrade.

Table 1-2. Variation of Resistance with Temperature

Temp. (°C)	R/R_0 Copper	R/R_0 Silver	R/R_0 Nickel	R/R_0 Iron	R/R_0 Platinum
-200	0.117	0.176	.. . .	. . . .	0.177
-100	0.557	0.596	. . . .	. . .	0.599
0	1.000	1.000	1.000	1.000	1.000
+100	1.431	1.408	1.663	1.650	1.392
+200	1.862	1.827	2.501	2.464	1.773

The point of providing you with Table 1-2 is to impress you with the fact that the resistance of a wire goes up with its temperature. If you're going to be running experiments using high currents in hot environments, you might have to take account of the change in wire resistance. Also, you might note the nice linear change in the resistance of platinum with temperature – Platinum is great for resistance thermometers and is surprisingly low in cost (contact Minco Products, 7300 Commerce Lane, Minneapolis, MN 55432).

A useful relationship between resistance and temperature is:

$$R = R_0 [1 + \alpha(T - T_0)]$$

In this equation, R is the resistance of a material at temperature T, and R_0 is the resistance at some reference temperature, T_0. The coefficient α is almost a constant for some materials like platinum, which allows us to build super-accurate devices called *resistance thermometers*. Their output isn't very high ($\alpha \approx 0.003$ for platinum), but we will show you later how to make big signals out of little ones. Now, on to circuit theory!

KIRCHOFF'S LAWS

An electric circuit must consist of a complete closed loop in order for current to flow. The simplest closed circuit possible is shown in Figure 1-7. The current I flowing in R causes a voltage drop V. According to Ohm's law, V = RI. Knowing V and R, we can solve for I.

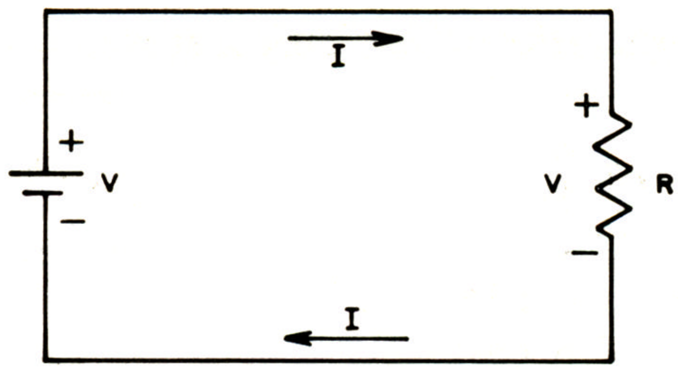

Figure 1-7. Simplest closed-loop circuit.

If there are two resistors in series connected across V as shown in Figure 1-8, then the sum of the two voltage drops, $R_1I + R_2I$, is equal to V. (Note that the current is shown as flowing out of the positive terminal of the battery and into its negative terminal, and that the current enters the positive terminal of the resistor and leaves the negative terminal.* The battery is supplying energy, the resistor is absorbing energy).

KIRCHOFF'S LOOP VOLTAGE LAW

Figure 1-8 illustrates *Kirchoff's loop law*. This law simply states that *the sum of the voltage drops around any closed loop is equal to zero,* a voltage rise being considered as a negative voltage drop. In other words, the voltage drops in any closed loop are equal to the voltage rises in the same loop. Applying this law to Figure 1-8:

$$R_1I + R_2I = V$$

From Kirchoff's loop law, we can deduce a very useful relation showing how voltage divides across two (or more) resistors in series. For the circuit shown in Figure 1-8, Kirchoff's loop law states that

$$V = V_1 + V_2$$

in which V_1 is the voltage across R_1 and V_2 is the voltage across R_2. However,

$$V_1 = R_1I$$

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* Those of you who have had physics know that current really flows from the negative side of the battery. We know it, too, but EEs do it the other way, and we have to teach you their jargon.

and since resistance in series is additive,

$$I = \frac{V}{R_1 + R_2}$$

Substituting for I:

$$V_1 = R_1\left(\frac{V}{R_1 + R_2}\right) = V\left(\frac{R_1}{R_1 + R_2}\right)$$

Similarly,

$$V_2 = V\left(\frac{R_2}{R_1 + R_2}\right)$$

This concept of voltage division in a series circuit is very useful in solving circuit problems; for now, you can take our word for it.

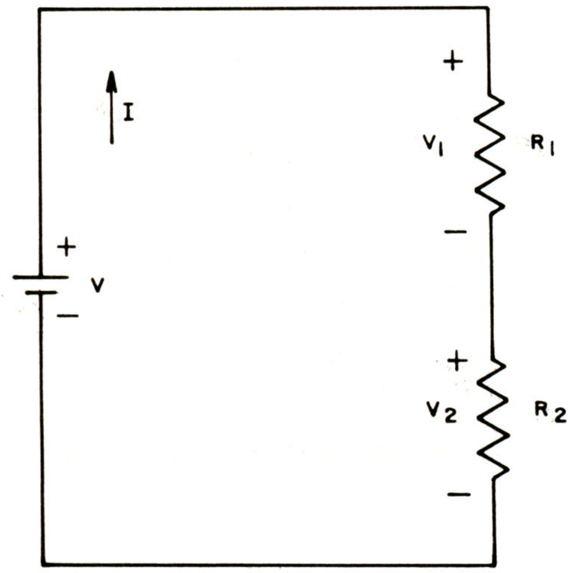

Figure 1-8. Two-resistor series loop.

Kirchoff's loop law applies even though a circuit may consist of many closed loops with many batteries, but care must be taken to consider all currents through any one circuit element. The procedure is to assign a current to each closed loop and then write the voltage drops around each loop realizing that, because of the arbitrary assignment of a current to each loop, more than one of these currents may be flowing in any one resistor. Since in a complicated circuit it is not possible to reason out intuitively the direction of current flow in all parts of the circuit, it is best to assign all currents in a clockwise direction.

KIRCHOFF'S NODE CURRENT LAW

For circuits containing many loops, the above method becomes very laborious, and it may be better to use *Kirchoff's node law*, which states that *the sum of all the currents entering a node is equal to the sum of all the currents leaving that node.*

Consider the simple circuit shown in Figure 1-9.

There are two current loops, so Kirchoff's node law states that:

$$I = I_1 + I_2 \tag{1-1}$$

This is true unless there is a storage of electric charge at point a. From Kirchoff's node law, we can deduce a very useful relationship showing how current divides in two resistors connected in parallel. The voltage drop across R_1 must be equal to the voltage drop across R_2 since the two resistors are connected together at their terminals. From Ohm's law, the voltage drop V_a across R_1 is

$$V_a = R_1 I_1 \qquad (1\text{-}2)$$

in which V_a is the voltage at point a if the voltage at point b is considered to be zero. V_a, then, is the voltage across R_1. Also:

$$V_a = R_2 I_2 \qquad (1\text{-}3)$$

From equations (1-2) and (1-3):

$$R_1 I_1 = R_2 I_2$$

Solving for I_2:

$$I_2 = \left(\frac{R_1}{R_2}\right) I_1$$

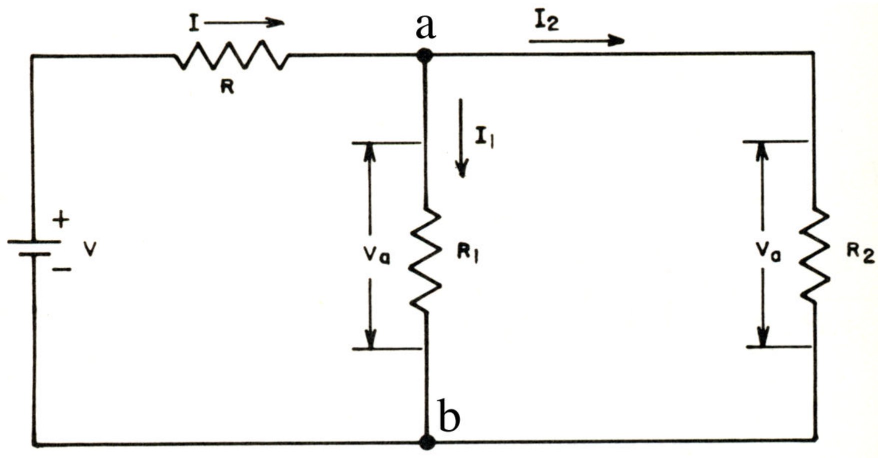

Figure 1-9. Kirchoff's node currents.

Substitution in equation (1-1) yields

$$I = I_1 + \left(\frac{R_1}{R_2}\right) I_1 = I_1\left(1 + \frac{R_1}{R_2}\right) = I_1\left(\frac{R_2 + R_1}{R_2}\right)$$

Thus:

$$I_1 = I\left(\frac{R_2}{R_1 + R_2}\right)$$

And similarly:

$$I_2 = I\left(\frac{R_1}{R_1 + R_2}\right)$$

This is often called the *current divider equation*.

Equations (1-2) and (1-3) can be solved for I_1 and I_2 respectively:

$$I_1 = \frac{V_a}{R_1} \qquad (1\text{-}4)$$

$$I_2 = \frac{V_a}{R_2} \qquad (1\text{-}5)$$

However, there is a complication with regard to writing an expression for I. This complication is that V_a is not the voltage across R; the voltage across R is $V - V_a$. I, then, must be expressed as:

$$\frac{V - V_a}{R} = I \qquad (1\text{-}6)$$

Substituting equations (1-4), (1-5), and (1-6) into equation (1-1) gives

$$\frac{V_a}{R_1} + \frac{V_a}{R_2} = \frac{V - V_a}{R}$$

from which V_a can be determined if V, R, R_1 and R_2 are known. The values of I, I_1 and I2 can be calculated from equations (1-6), (1-4), and (1-5) respectively, and the performance of the circuit shown in Figure 1-9 is completely known.

IDEAL AND REAL DC POWER SOURCES

In DC circuits the sources are batteries. A new battery consists of an *electromotive force* (emf) in series with a very low resistance; for our purposes, emf can be expressed in volts. A new 1.5 volt dry-cell battery, for example, consists of an emf of Approximately 1.55 volts in series with a resistance of approximately 0.01 ohm. As this dry-cell battery ages, its emf remains approximately the same, but its equivalent series resistance increases and may become as high as 100 ohms or more. (Of course, as the battery becomes very old and its chemical reaction ceases, its emf becomes zero.) For this reason, testing a dry-cell battery with a high resistance voltmeter *gives very little information concerning its condition*. The battery must be tested under load. A good test is to measure the voltage across the terminals under no load with a high resistance voltmeter and then measure the terminal voltage when 0.01 amp is being delivered to an external resistance. If the battery terminal voltage decreases appreciably, the battery's internal resistance has increased to the point where it should be replaced.

In solving DC circuit problems, the source is usually separated diagrammatically into its emf and its internal resistance, as shown in Figure 1-10.

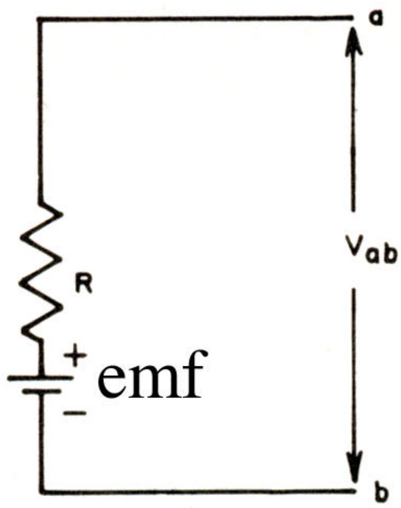

Figure 1-10. A real voltage source.

The terminal voltage V_{ab} is that voltage which is available for the external circuit. If zero current is being drawn from the circuit, this terminal voltage is equal to the emf. If a current I is being drawn from this source, the terminal voltage is the emf minus the drop R I across the internal resistance R. A new battery can usually be considered as an emf with zero internal resistance. As such, it is called an ideal source. If the internal resistance is considered, then it is called a real source. The difference between "ideal" and "real" batteries should explain why a dry cell which reads the full 1.5 volts on a good voltmeter (which draws very little current) won't light your flashlight bulb (which takes about 300 mA.)

AC POWER

Up to this point we have only discussed DC circuits. In electronics, however, AC circuits are more often used. The reasons for this will become apparent as we move into this topic.

A typical DC voltage-versus-time plot is shown in Figure 1-11A and an AC voltage-time plot is shown in Figure 1-11B for comparison.

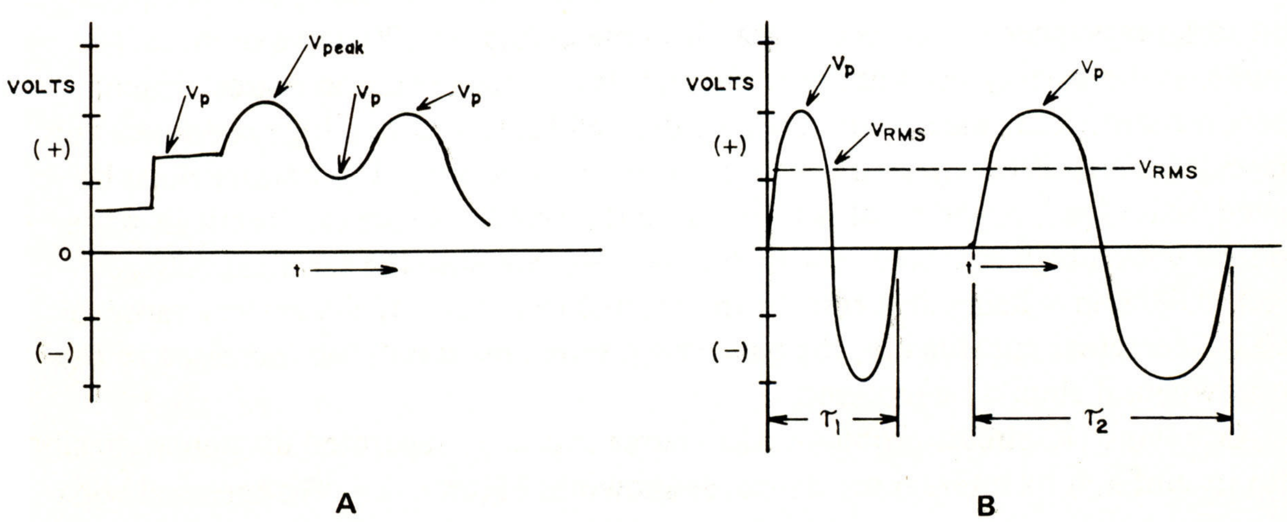

Figure 1-11. A. DC voltage. B. AC voltage.

When dealing with DC signals we use *peak voltage* (V_{peak}), and it is important to realize that it *may* vary with time. With AC we use *root-mean-square* (rms) voltage, where

$$V_{rms} = 0.707\ V_{peak}$$

(in this book all AC signals are pure sine waves).

Whenever we talk about AC voltage, current, or power, *we mean rms unless otherwise specified*. You might wonder why this is done. The answer is that when a current is forced through a resistor, power

$$P = I^2R$$

is dissipated. For DC circuits, there wasn't much doubt about what numbers to put in this equation. We just use the actual current at that instant of time, so for DC the power is $P = (I_{peak})^2R$. For AC circuits, we want to use the same formula ($P = I^2R$) and get the same result whether I is AC or DC amperage. To do this, we use I (root-mean-square) if it is AC and I(peak) if it is DC.

How do we define rms? Well, the AC signal shown in Figure 1-11 is described by a formula of the form

$$V = A \sin 2\pi f t$$

Here f is frequency in cycles per second or hertz, t is time in seconds, and π and A are constants. Given V, we define V_{rms} as

$$V_{rms} = \left[\frac{1}{\tau}\int_0^{\tau} V^2 dt\right]^{\frac{1}{2}} = 0.707\ V_{peak}$$

where τ is the period of time that we integrate over. I_{rms} is defined in a similar manner, *but you don't really have to learn integral calculus to use these definitions*. For now, remember that if we talk about AC voltages and currents, we *always* mean *rms*. If we talk about DC voltages and currents, they are always *peak* unless defined otherrwise.

FILTERS (HOW TO SEPARATE SIGNALS OF DIFFERENT FREQUENCIES)

Having defmed the basic AC terminology, we can do something useful almost immediately and build some filters. In the first part of this section, we will cheat a little bit by leaving out some complex and confusing material in order to provide you with the *concept* of a filter and an idea of why filters act the way they do. (The real EEs who read this book will be screaming, "No! The numbers won't come out right!") If you build filters from the formulas we give, the circuits will *work*, but the numerical values won't quite be correct. We feel, though, that it is more important right now for you to build a filter that *works*, however badly, than to be buried and turned off by a "correct" mathematical analysis. The "correct" analysis is given a later part of this section on page 24. You math freaks who dig complex numbers can start reading that.

BASIC FILTER DESIGN

If we get a little sloppy (in the semantic sense), we can define the resistance of a resistor as a reactance, X_R. Note that X_R is still expressed in ohms, and that for a resistor, it does not vary with frequency, at least not at the frequencies we will be dealing with.

Now let's introduce two other devices: capacitors (which are measured in farads) and inductors (which are measured in henrys). The number of *farads* (or microfarads) is denoted by C and the number of *henrys* (or millihenrys) by L; the abbreviations for farads and henrys are "F" and "H," respectively. The interesting thing about these devices is that their reactance *is* a function of frequency, *f* as shown in the formulas below. For inductors,

$$X_L = 2\pi f L$$

For capacitors,

$$X_C = \frac{1}{2\pi f C}$$

These devices can be used to design circuits that stop certain frequencies and allow signals of other frequencies to pass. A circuit that passes low freqnencies and stops high frequencies is called a *low-pass filter*. Conversely, a filter that passes high frequencies and stops low ones is called a *high-pass filter*. Since you will be needing circuits of these types, we will teach you how to design simple but useful filters as the next step.

Let's assume that you want to measure some DC signal but the measurement is made difficult by some 1000 Hz electrical "noise"* from a local industrial plant. You need a low-pass filter that will pass the DC signal and stop the 1 kHz noise. The 1 kHz signal looks like a sine wave of the form A sin $2\pi f_1 t$, where $f_1 = 1000$ Hz. The DC signal looks like a constant of value B, so the total signal looks like

$$V = A \sin 2\pi f_1 t + B$$

This is shown in Figure 1-12, where we picked A = 1, B = 3.

To design our filter, we assume that we want to pass at least 90% of all signals having a frequency of 10 Hz or less and that we want to stop at least 90% of all signals at the noise frequency of 1 kHz. A simple filter circuit to perform this function is shown in Figure 1-13 – an approximate analysis follows.

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* Electrical noise is simply an unwanted messy signal that makes our desired signal come out messy, too; it's like static on your radio.

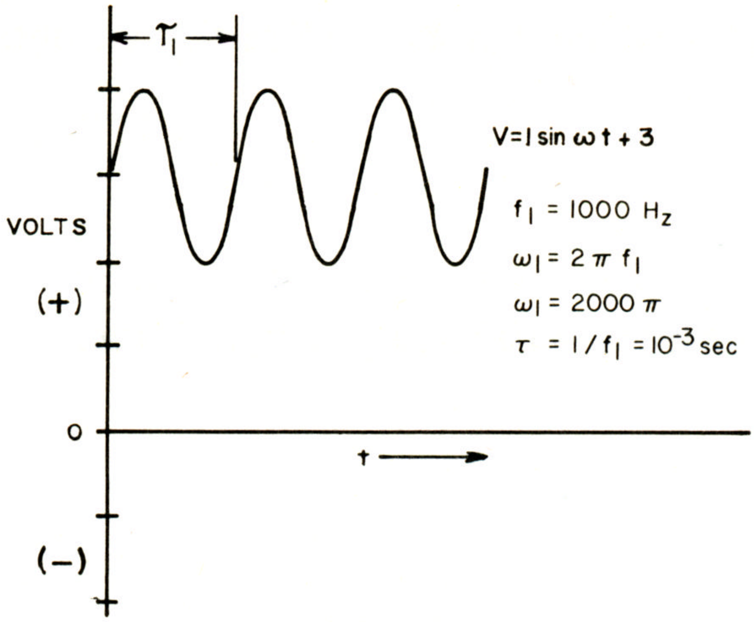


Figure 1-12. AC-plus-DC voltage versus time.

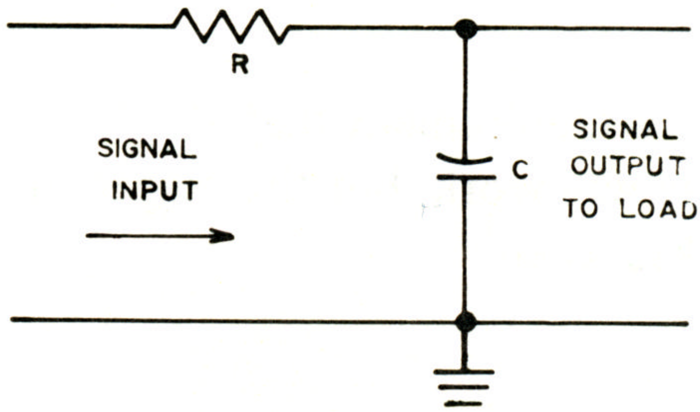


Figure 1-13. Low-pass filter.

In the circuit of Figure 1-13, the signal input voltage V is applied across the series combination of Rand C. The reactance of R is just X_R, and the reactance of C is $X_C = \frac{1}{2\pi f C}$. The current I is determined by the total reactance of R plus C:

$$I = \frac{V}{X_R + X_C}$$

For our filter, we want to pass a 10 Hz signal with only 10% loss (there has to be some loss) to the output. The 1000 Hz signal must lose 90% of its value before it gets to the output. This means that at 10 Hz, the voltage across the capacitor, C, should be 90% of the input value, i.e.,

$$\frac{V_C}{V} = 0.9$$

and at 1000 Hz, this voltage must be

$$\frac{V_C}{V} = 0.1$$

The output signal (if we ignore any current going to the load, which is the usual assumption in designing this type of filter) is the current times the reactance of C.

(Notice that we can use Ohm's law and treat capacitors and inductors just like resistors as long as we use the reactance concept.)

$$V_C(\text{output}) = I\ X_C = \frac{V\ X_C}{X_R + X_C}$$

Rewriting the above and recalling that $X_C = 1/(2\pi f C)$, we obtain

$$\frac{V_C}{V} = \frac{1}{2\pi f RC + 1}$$

Using the values we assumed (f = 10 Hz, $V_C / V = 0.9$), then

$$\frac{1}{20\pi RC + 1} = 0.9$$

So $18\pi RC = 0.1$, or $RC = 0.006/\pi$. At 1000 Hz,

$$\frac{V_C}{V} = \frac{1}{12 + 1} = 0.08$$

which more than satisfies our requirement that $V_C / V = 0.1$ at 1000 Hz. Now to pick R and C. Any RC value will work, but the bigger the R, the bigger our I^2R losses. If we pick R = 100 kΩ, then

$$C = \frac{0.006}{10^5 \pi} = 1.59 \times 10^{-8}\,F = 16\,nF$$

(There is one possible point of confusion here: when we say "the bigger the R is, the bigger the I^2R losses," we have a special situation in mind. Suppose you want to pass a given current I_L to the load. Then the loss $I_L{}^2R$ will go up with R, assuming that the applied voltage is big enough to keep I_L constant.)

At this point we might note that it is *not* possible to write

$$0.9 = \frac{1}{20\pi RC + 1} \quad \text{and} \quad 0.1 = \frac{1}{200\pi RC + 1}$$

and solve the equations simultaneously, or the answer is "over-determined." You have to pick RC to satisfy one equation and check that it more than satisfies the other equation. In this case the equations $18\pi RC + 0.9 = 1$ and $200\pi RC + 0.1 = 1$ require that

$$RC \le \frac{0.1}{18\pi} = 1.77 \times 10^{-3} \quad \text{and} \quad RC \ge \frac{0.9}{200\pi} = 1.43 \times 10^{-3}$$

so

$$1.43 \times 10^{-3} \le RC \le 1.77 \times 10^{-3}$$

Turning back to the design of filters, suppose we interchanged the capacitor and resistor in the circuit shown in Figure 1-13. The current to ground would still be

$$I = \frac{V}{X_R + X_C}$$

But the output voltage would be taken across the resistor and we can assume $X_R = R$, so

$$V_R = IR = \frac{VR}{R + X_C}$$

or

$$\frac{V_R}{V} = \frac{2\pi f CR}{2\pi f CR + 1}$$

Now as f approaches zero, V_R/V approaches zero. However, as f approaches infmity, V_R/V approaches unity. This is a *high-pass filter* and again our analysis is only an approximation.

[At this point, we do have to sound a warning note because of a problem we seen students run into when they try to design a filter network for a hi-fi system. A typical 20 watt amplifier driving a 4 ohm loudspeaker will deliver some 2.24 amps; if you don't believe it, try the formula $W = I^2R$. If you design a filter with 100 ohms of resistance into the circuit, the voltage drop (if the amplifier could produce it) would be 224 volts. Since the usual output voltage is about 10 volts from an amplifier of this type, you don't want to design high-value resistors into the circuit. Inductor capacitor systems waste far less power than systems using resistors. Another point to remember – we never quit – is that the resistance heating of the resistors controls the wattage rating. A 100 ohm resistor carrying 2.24 amps will liberate 500 watts of heat and must be designed accordingly.]

We suggest that you stop right here and build a high-pass and a low-pass filter. To test them, you can skip to the sections on signal generators and oscilloscopes. Hook a signal generator to the input, the oscilloscope to the output, and go to it. If you are chicken, keep reading and do the experiment when you have finished the chapter. You are the best judge of how and when to learn.

You can build even better filters by replacing the resistor shown in the circuit of Figure 1-13 with an *inductor*. You can see why by recalling that $X_L = 2\pi fL$, where L is in henrys. To pick the right inductor, you can replace R with $X_L = 2\pi fL$ in our formula

$$V_C = \frac{VX_C}{R + X_C}$$

and calculate it from there.

We should warn you that inductors are more expensive than resistors, and they are seldom sold with large power-handling capability. You can wind them yourself by winding 100 turns of #28 insulated wire on an iron nail. Use the inductor in a filter with the nail left in; then pull the nail out. You should see a drop in L unless you are using a very high frequency.

To conclude our discussion of filters, we have to introduce two new concepts: *roll-off* and the *Bode plot*. Roll-off is a measure of the ability of a filter to separate the signal frequency you want from the noise signal you don't want. The faster the roll-off, the better you can separate two signals that differ in frequency by only a small number of cycles. A typical roll-off curve is shown in the Bode plot of Figure 1-14. The ratio of output to input voltage is some value V_{out}/V_{in}, The corresponding decibel (dB) value is

$$dB = 20 \log_{10}(V_{out}/V_{in})$$

Decibels are a convenient way of expressing large number ratios, e.g., $l0^5 = 100$ dB; $10^4 = 80$ dB, and so on. However, the decibel is not just a way of handling large ranges of numbers. It has a basic relationship to the way the human eye and ear respond to changes in signal level. If an observer is asked to listen to two signals (I the sarne frequency) whose intensity differs by a factor of 2, we can expect the observer to say that one is louder than the other by a factor of 0.3, which is $\log_{10}(2)$. This is not an exact relationship, but it does demonstrate that the response of the ear is more logarithmic than linear.

Another application of the decibel concept is in characterizing the slope of the V_{out}/V_{in} versus frequency curve. Assume that we are testing a low-pass filter at some frequency f_1 above its cut-off value. We go to some higher frequency $2f_1$ (one octave), and the ratio of the output voltages at the two frequencies defines the decibel per octave value:

$$dB/octave = 20 \log_{10} [V_0(f_2)/V_0(f_1)]$$

It happens that most filters roll off in multiples of 6 decibels per octave (6, 12, 18,... dB/octave). Due to this general characteristic, filters are referred to as second, third, ... order filters. The higher the order, the more nearly the perfect filter is approached. However, more passive elements (resistors and capacitors) are needed to realize higher order filters. In practice, orders higher than 6 or 7 are rarely seen. Actually, first-order filters are often found useful, and second-order filters are used extensively.

In Figure 1-14, output versus input filter characteristics are plotted against frequency in both decibels and powers of 10. The high-pass filter rolls off about 6 decibels per octave below cut-off.

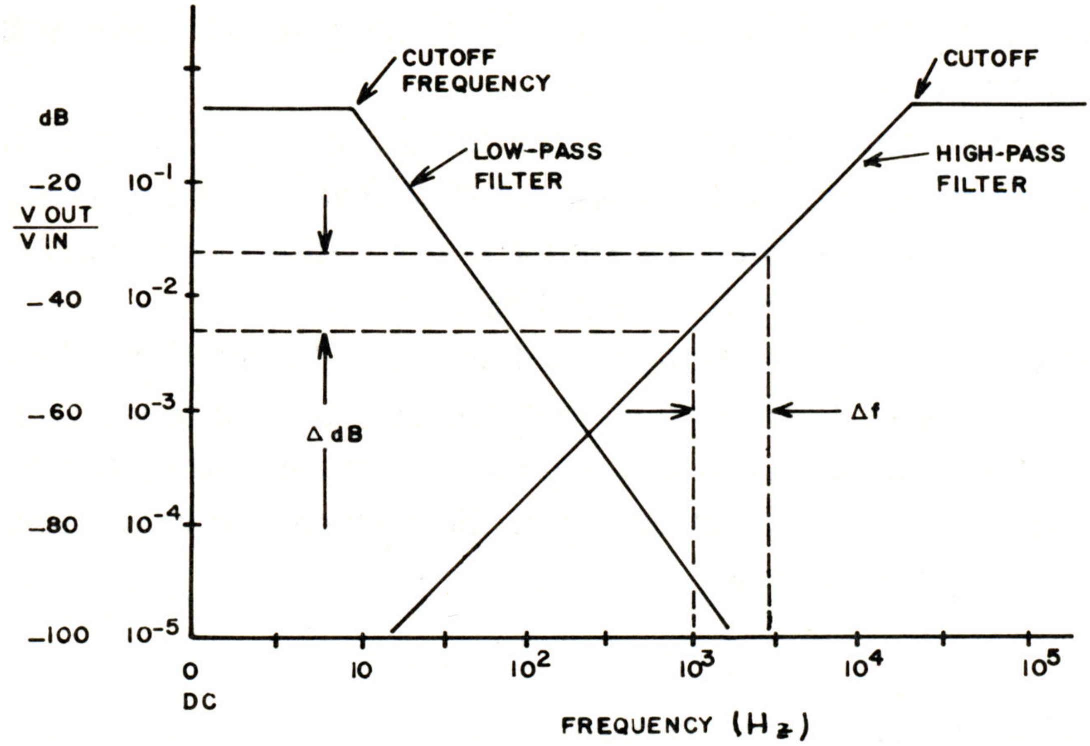


Figure 1-14. Bode plot of filter characteristics.

Figure 1-15 shows circuits for various types of filters. Those adventurous souls who want to build a 60 Hz slot filter can follow the diagram given in Figure 1-15C. The combination of a high-pass and a low-pass filter produces a *band-pass* filter; this is shown in Figure 1-15A. You have to pick the values of L, R and C for the frequency bands that you want to stop or pass, which you can do by using the formulas we have given you.

In case you get more deeply into filter design, the best "simple" reference we know of is by R. P Sallen and E. L. Key, *A Practical Method of Designing R. C. Active Filters*. Another excellent reference is J. L. Hilburn's *Manual of Active Filter Design*. (See the Bibliography for the publisher.)

In the next part of this section, we will give the "correct" mathematical analysis of filter circuits. If you don't need it now, feel free to skip it and start reading about phase shift. We are throwing out this sop to those purists who would object to our rough but handy formulations given above. Be warned: we won't always be so generous in the pages to follow.

MATHEMATICAL ANALYSIS OF FILTER CIRCUITS

The correct analysis of a filter circuit requires that we define

$$Ae^{i\theta} = A(\cos\theta + i\sin\theta)$$

where $i = \sqrt{-1}$ and e = 2.7183. (EEs use lower case "j" instead of the lower case "i" that physicists use. Be warned!) In this system of notation, numbers may have a real part as well as an imaginary part indicated by the "i" factor. Such numbers are called *complex numbers*; the rules for using complex numbers are given in most algebra textbooks. (If you want a correct analysis, we will show no mercy.)

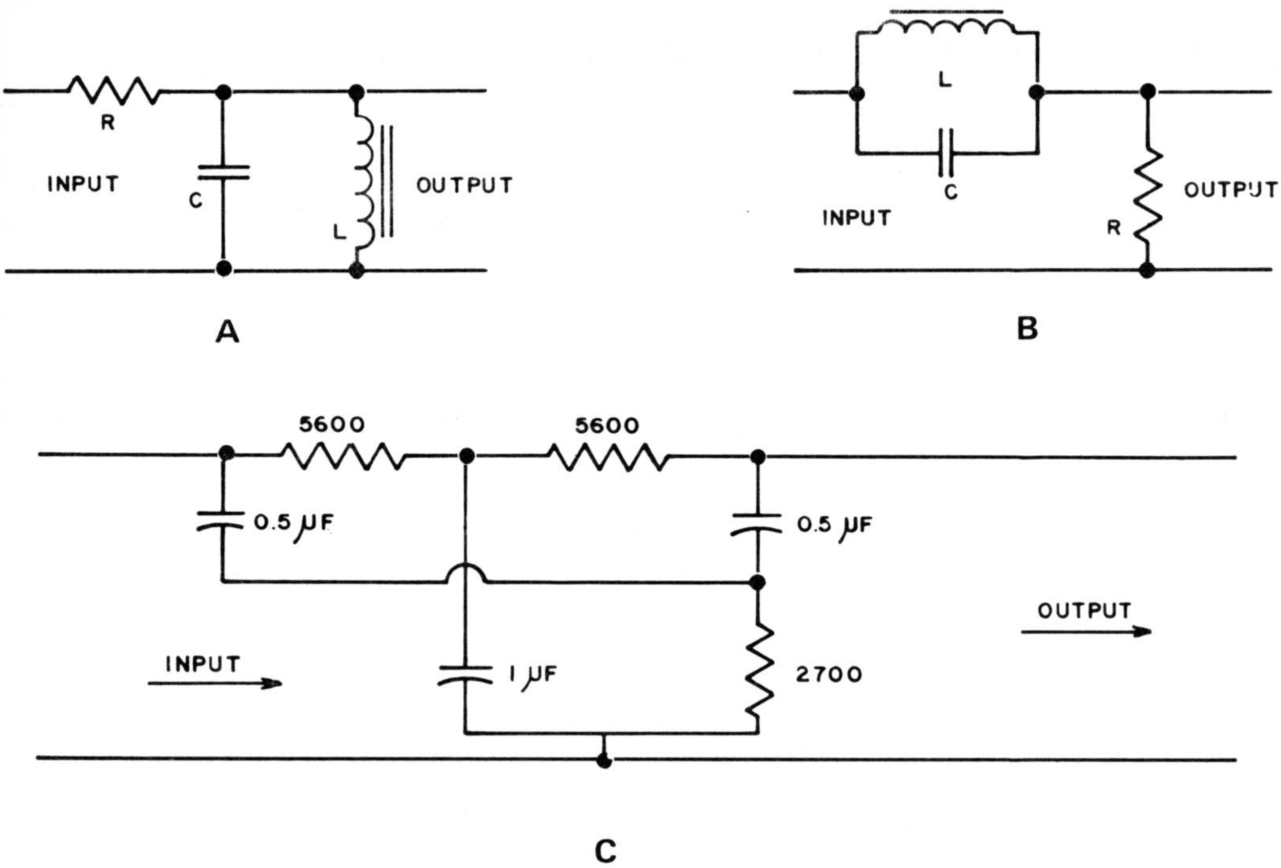


Figure 1-15. Filter circuits. A: Band-pass, second order; B: Band-attenuation, second order; C: 60Hz slot (hum reduction) filter.

The general technique for filter analysis involves recognizing that the presence of reactive components induces phase shifts (see next section) 50 that the voltage peaks for the various circuit elements occur at different times. To take account of this problem, we use the X_C and X_L notation where now

$$X_C = \frac{1}{i\,\omega C} \quad \text{and} \quad X_L = i\,\omega L$$

and $2\pi f = \omega$. To handle these complex numbers, we use exponential notation to write $Z = A + iB$ as

$$Z = Me^{i\theta}$$

where

$$M = \sqrt{A^2 + B^2} \quad \text{and} \quad \theta = \arctan\left(\frac{B}{A}\right)$$

The impedance of a low-pass resistor-capacitor network (Figure 1-13) is

$$Z = R + X_C = R + \frac{1}{i\,\omega C} = R - \frac{1}{\omega C}$$

or

$$Z = \left[\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}\right] e^{i\arctan\left(\frac{-1}{\omega CR}\right)}$$

To apply this to a low-pass filter, we write the input voltage, V, in exponential notation as Ve^{i0}. In this notation, since cos 0 = 1, and sin 0 = 0

$$Ve^{i0} = V(\cos 0 + i\sin 0) = V$$

The current, I, is

$$I = \frac{V}{Z} = \left[\frac{V}{\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}}\right] e^{i\theta}$$

If X_C is written as

$$X_C = \frac{1}{\omega C} e^{i(-\pi/2)}$$

then the input-output voltage ratio is

$$\frac{V_C}{V} = \left[\frac{1}{\sqrt{(R\omega C)^2 + 1}}\right] e^{i[-\pi/2 + \arctan(1/\omega RC)]}$$

This is the correct input-output ratio for a low-pass filter. Note that as $2\pi f = \omega$ increases, the ratio V_C/V goes to zero. As $2\pi f = \omega$ goes to zero (DC), the voltage ratio goes to one.

The high-pass RC filter formula is obtained the same way. The input-output voltage ratio is

$$\frac{V_R}{V} = \frac{R\omega C}{\sqrt{(R\omega C)^2 + 1}} e^{i\theta}$$

where $\theta = \arctan\left(\frac{-1}{R\omega C}\right)$. Here, as ω goes to infinity, the ratio V_R/V goes to one; as ω goes to zero, the voltage ratio goes to zero. This is why it's a high-pass filter.

As a final example, consider a resistor, capacitor, and inductor in series. Now,

$$Z = R + i\left(\omega L - \frac{1}{\omega C}\right) = Me^{i\theta_1}$$

$$M = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \quad \text{and} \quad \theta_1 = \arctan\frac{\left(\omega L - \frac{1}{\omega C}\right)}{R}$$

If the applied voltage is Ve^{i0}, the current is I = V/Z. The voltage across the various elements of the circuit is I times the impedance of that element. For the resistor,

$$V_R = \left(\frac{VR}{M}\right) e^{-i\theta_1}$$

For the capacitor,

$$V_C = \left(\frac{V}{M\omega C}\right) e^{-i[-\pi/2 - \theta_1]}$$

And for the inductor,

$$V_L = \left(\frac{V\omega L}{M}\right)e^{-i[\pi/2-\theta_1]}$$

At resonance, $\omega_1^2 = \frac{1}{LC}$ or $f_1 = \frac{1}{2\pi\sqrt{LC}}$, M = R, and θ_1 = 0. In this case, then, the expressions above take on a simple form:

$$V_R = V \qquad V_C = \left(\frac{-V}{R\omega C}\right)e^{-i\pi/2} \qquad V_L = \left(\frac{V\omega L}{R}\right)e^{i\pi/2}$$

In this condition, the voltage V is *entirely* across the resistor because $V_L + V_C = 0$ when $\omega_1^2 = 1/(LC)$. This is the condition for resonance, and at resonance the resistance of the string of elements is just R. It is interesting to note that at resonance, the voltages V_L and V_C are by no means zero. If you measure them with a good AC voltmeter or oscilloscope, you will find that they can be quite large.

The *quality* of the circuit as a filter, also called its *Q factor*, is defined by

$$Q = \frac{\omega_1 L}{R} = \frac{1}{\omega_1 RC}$$

The greater the voltage across L and C at resonance, the better the "quality" of the device. Don't forget that the voltages V_C and V_L are, at resonance, equal but opposite in sign, so their sum is zero.

The parallel RLC circuit shown in the next section in Figure 1-16 has an impedance Z given by

$$\frac{1}{Z} = \frac{1}{R} + \frac{1}{i\omega L} + i\omega C \quad \text{or} \quad Z = \frac{i\omega LR}{R\left(1-\omega^2 LC\right) + i\omega L}$$

At resonance, Z equals R as before. When ω doesn't equal $1/\sqrt{LC}$, the value of Z will decrease. This makes a parallel circuit useful for picking a particular signal out of a mixture of signals at other frequencies. Measuring the voltage across this RLC network will show that the voltage is greatest when Z has its largest value (assuming that the current is constant). To pick out a fiequency $f_1 = \omega_1$, we set $\omega_1 = 1/\sqrt{LC}$; by doing so, the voltage across the network will be greatest for signals of frequency f_1. For all other signals, the value of Z will be smaller and the voltage across the network, V = IZ, will be smaller (still assuming that I is constant). We call it *tuning the radio* – more discussion on that point later.

PHASE SHIFT

Now let's discuss a new idea: phase shift. To understand this concept, think of a power supply driving a resistor, capacitor, and inductor in parallel as shown in Figure 1-16.

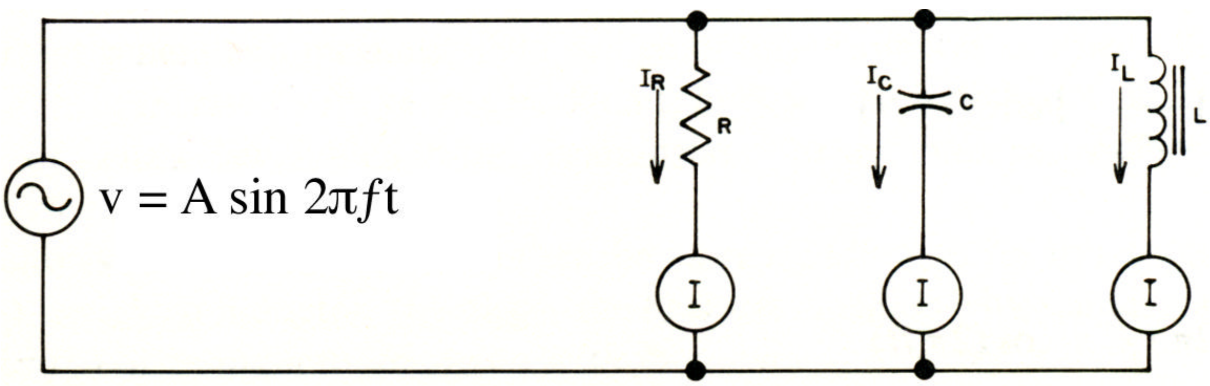


Figure 1-16. Phase-shift circuit.

The voltage is the same to each of the elements ($V = V_R = V_C = V_L$), but what about the currents I_R, I_L, and I_C? Elementary AC circuit theory tells us that

$$I_R = \frac{V}{X_R} = \frac{V_R}{X_R} \qquad I_C = \frac{V}{X_C} = \frac{V_C}{X_C} \quad \text{and} \quad I_L = \frac{V}{X_L} = \frac{V_L}{X_L}$$

What we need now are some formulas relating voltage and current in capacitors and inductors. You may have seen them in elementary physics. For those of you who didn't take physics (or have forgotten it by now), we list the formulas below.

Note: V is the applied voltage. It is called V_C when applied to a capacitor, V_L when applied to an inductor.

$$V_L = L\left(\frac{dI_L}{dt}\right) \qquad I_L = \frac{1}{L}\int V_L dt$$

$$I_C = C\left(\frac{dV_C}{dt}\right) \qquad V_C = \frac{1}{C}\int I_C dt$$

If you didn't take calculus either, don't worry. All you really need to know is *what phase shift is*, not how to derive the formulas.

If our applied voltage is $V = A \sin(2\pi f t)$, by substitution and integration and differentiation in the respective formulas we obtain

$$I_R = \left(\frac{A}{R}\right)\sin(2\pi f t) \qquad -I_L = \left(\frac{A}{2\pi f L}\right)\cos(2\pi f t) \quad \text{and} \quad I_C = 2\pi f C A \cos(2\pi f t)$$

Both I_L and I_C are cosine functions, but the negative sign on I_L tells us that when t = 0, I_C is positive and I_L is negative. This means that I_C and I_L are 180 degrees out of phase with each other and 90 degrees out of phase with V. Since I_C reaches its positive peak before V, we say it *leads* V. Conversely, I_L reaches its positive peak after V, so we say that I_L *lags behind* V. These relationships are illustrated Figure 1-17. The current through the resistor is in phase with the applied voltage and is not shown in Figure 1-17.

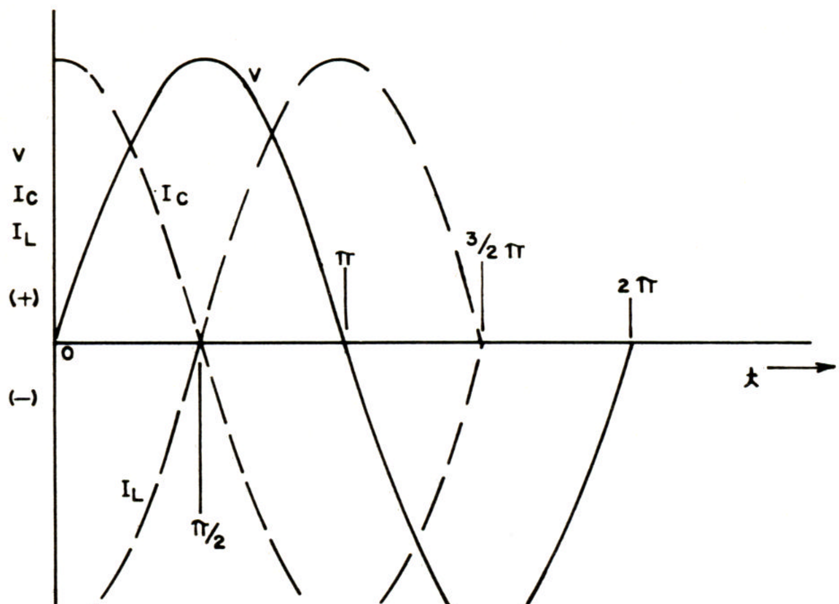


Figure 1-17. Phase-shift relationships.

Now you can impress (or bore) your friends by talking about phase shift in capacitors. To be even more esoteric, we can note that a sine wave repeats itself endlessly with a frequency f. This means that the period or time between cycles is $T = 1/f$. A point going around a circle arrives where it started after 360 degrees, so $T = 360° = 2\pi$ radians. This means that the phase shift between I_C and V_C is $T/4 = 90° = \pi/2$ radians.

INDUCTORS AND TRANSFORMERS

Inductors have interesting properties, one of which is that two inductors can produce a device called a *transformer*. What is a transformer? A transformer is really a pair of coupled inductors that we can use for all sorts of interesting projects.

If you apply a voltage to a coil of wire, you pass a current through that coil. This current generates a magnetic field, which in turn generates another voltage in the coil. This generated voltage, the back-emf, opposes the initial voltage. This is an instance of Lenz's Law, which in turn is an instance of the more general law: *Nature always fights back*.

It follows (take our word for it) that the *more rapidly* you try to change the current through an inductor, the bigger the back-emf. This is why the reactance ($X_L = 2\pi fL$) of an inductor *increases with frequency*.

A current passing through a coil generates a magnetic field. If this magnetic field intercepts another coil, a voltage will be generated in the second coil. This combination of two coils is a *transformer*. The symbol for a transformer is two coils back to back (see Figure 1-2).

In the world of transformers we refer to the coil that you apply the voltage to as the primary coil. The magnetic field generated by this primary coil interacts with the nearby secondary coil and a voltage is generated in the secondary coil. Interestingly enough, this process only works if the primary current is either AC or pulsating DC. You can apply a constant voltage DC signal to a transformer primary coil, and a current will flow in the primary coil, but no signal will appear in the secondary coil. Normally we think of a transformer as an AC device used to raise or lower a voltage (more on that point later).

While we are on the subject of transformers we should remind you that they are inductances having rather low DC resistance and an AC resistance (or reactance) given by the familiar law

$$X_L = 2\pi fL$$

We can put some numbers in this equation by thinking of a 1 henry inductor to which we apply a signal of 1 volt AC at 60 Hz. Using the above formula the current is about 2.7 mA (0.0027A). If we tried a DC signal the only thing limiting the current would be the wire resistance (about 0.0001 ohm) and something would melt rather quickly. This paper experiment might help you remember the difference between AC and DC in an inductor – now back to the transformer.

A transformer, then, is a device to change one AC voltage to a higher or lower voltage. Transformers are useful gadgets but THEY CAN KILL YOU (or at least provide you a shocking experience) if you are careless. The laws of the transformer are given below. N_{pri}, N_{sec} are the number of wire turns in the primary and secondary.

$$\frac{V_{sec}}{V_{pri}} = \frac{N_{sec}}{N_{pri}} \qquad I_{pri}V_{pri} = I_{sec}V_{sec}$$

where all voltages and currents are rms. If you use a transformer to get high secondary voltage, then $(N_{sec}/N_{pri}) >> 1$, and $(I_{sec}/I_{pri}) << 1$. You get out *only* what you put in.

Transformers with many taps are available, but center-tapped transformers are most often used. Their voltage system is shown in Figure 1-18.

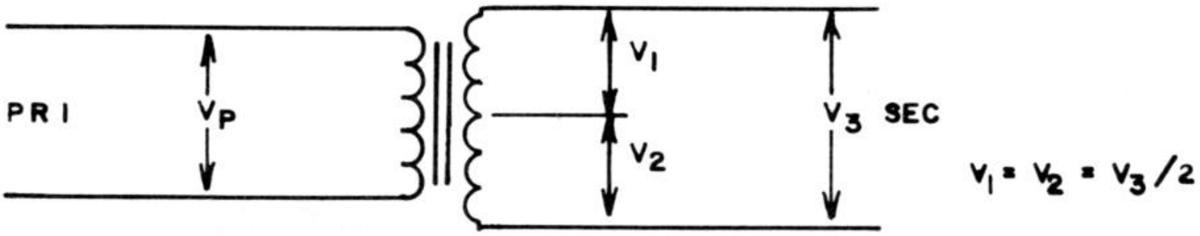


Figure 1-18. Center-tapped transformer

The autotransformer (Variac) is a useful gadget. It can give you any voltage from zero to full line voltage, but you had better know how it works. (There are old EEs and careless EEs, but no old, careless EEs!) An autotransformer system is shown in Figure 1-19. You should note that when the male plug is in with orientation A-A and B-B, the output lead (C) is at 110 volts *regardless of the dial setting or the on/off switch*. If you turn the plug over so it's A-B and A-B, things are okay; output C is "ground" neutral, and D is whatever voltage you set on the dial. The point here is that an autotransformer *does not* isolate you from ground. A regular transformer *does* provide isolation.

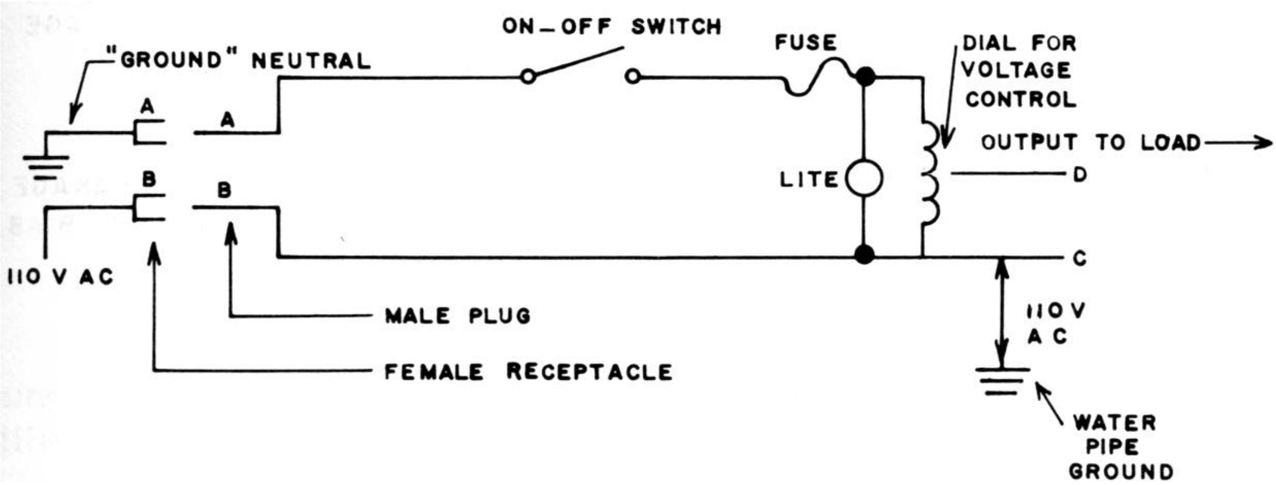


Figure 1-19. Autotransformer (Variac).

In Figure 1-20 we show a typical application where a transformer is used as a voltage step-down device for a DC power supply. You might want to learn how to build a DC battery charger, and that leads us to our next gadget: the diode. (See how we can lead you on from one thing to another?)

DIODES

Diodes are devices with unidirectional current-carrying characteristics. An *ideal* diode would carry current in one direction with no voltage drop, i.e., with zero voltage across its terminals. An attempt to pass current in the opposite direction would be aimost completely futile. This ideal characteristic is shown in the V versus I curve in Figure 1-2IA. The V-I curve of a real diode is shown in Figure 1-2lB.

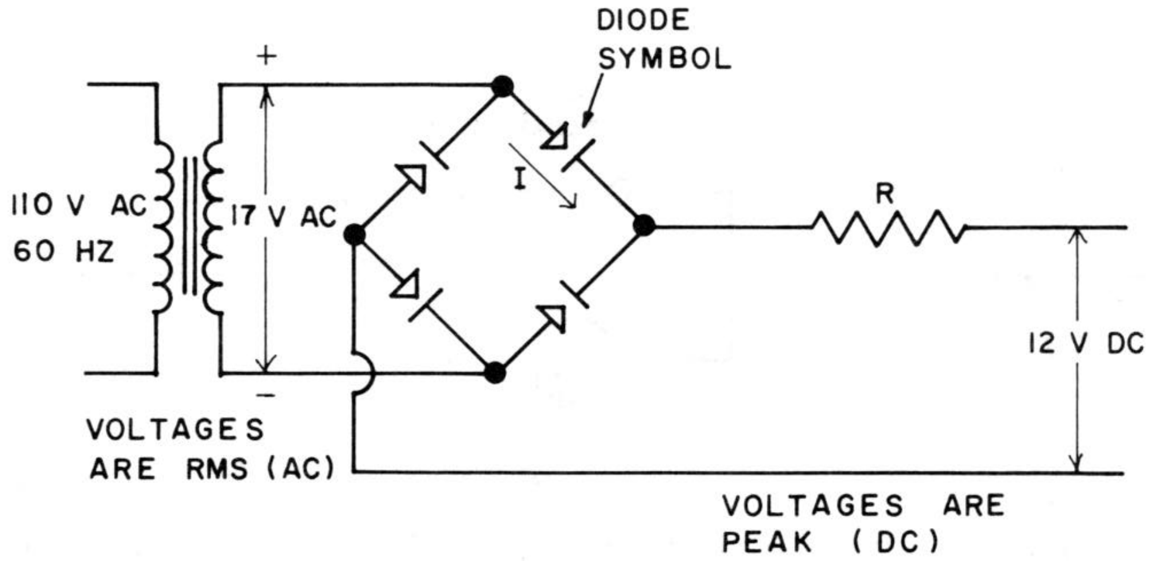


Figure 1-20. Twelve-volt DC power supply.

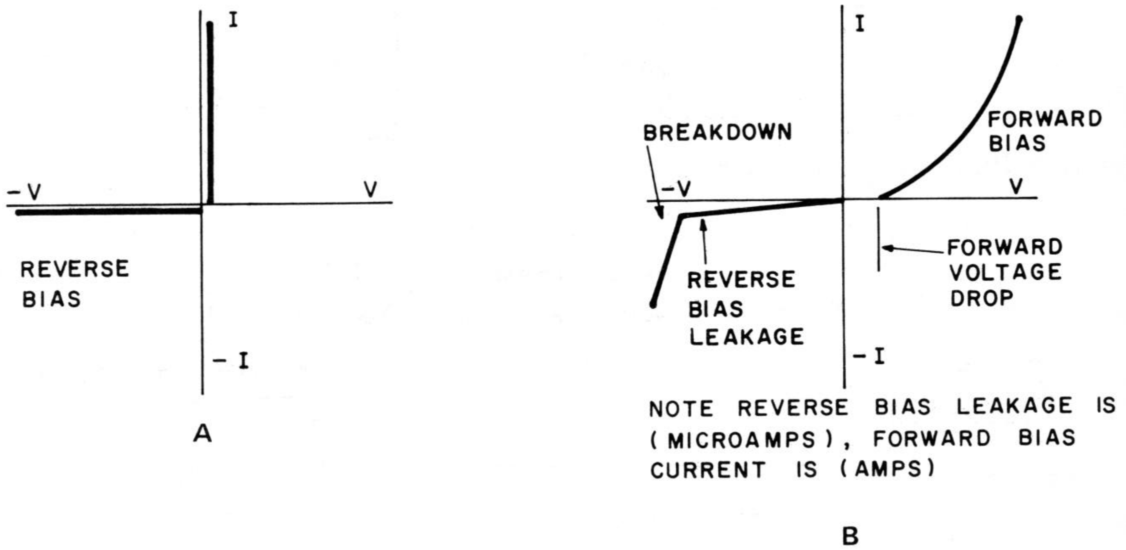


Figure 1-21. Diode characteristics. A: Ideal; B: Real.

The current direction shown is for positive current. Electron or "negative" current is in the opposite direction. The most common use of diodes is to convert AC voltage to DC, i.e., to act as *rectifiers*. Examples of diode rectifiers are shown in Figures 1-22 and 1-23.

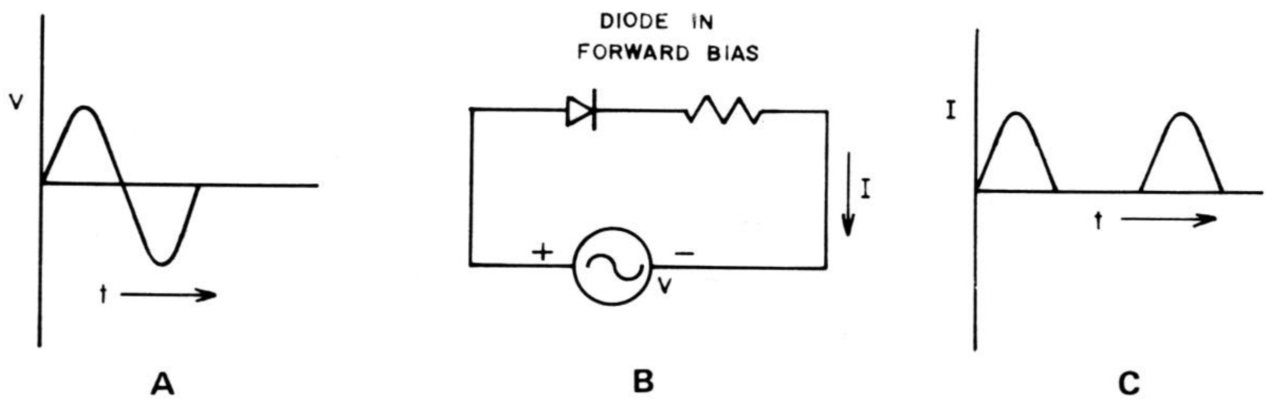


Figure 1-22. Diode operation. A: Input signal; B: Diode circuit; C: Current waveform.

As you can see from the waveforms shown, the output of straight diode rectifiers is not exactly a constant voltage. It is sometimes called *pulsating DC.* With a large capacitor and a transformer, we can obtain a usable DC power supply.

Before you run to your local radio shop to buy parts for a DC power supply, we need to mention the concepts of diode *peak inverse voltage* (PIV) and *current rating.* Diodes are rated simply in terms of current carrying capacity (amps) and the reverse voltage that can be safely applied (peak inverse voltage or PIV). If you want to rectify 15 volts at 10 amps, you should purchase a 20 volt PIV diode with a 12 amp current rating. (A 20% safety factor is part of *every* good ekctronic circuit design; we know that 20% of 15 is 3, but a 20 volt PIV diode may be easier to get than an 18 volt type.)

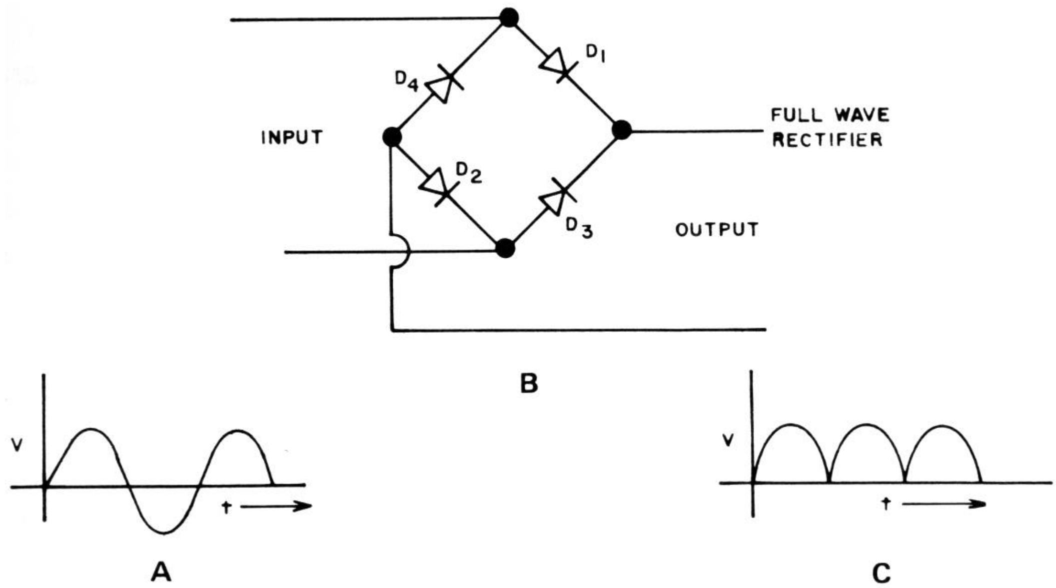


Figure 1-23. Diode rectifier bridge circuit. A: Input waveform; B: Full wave rectifier; C: Output waveform.

Suppose you want to put your new knowledge to work and build a 12 volt, 1 amp battery charger. We look back at Figure 1-20 and choose a 110 volt input, 12 volt output (1 amp) transformer. An Allied 6K94HF (1980 catalog) has a rating of 12.6 volts at 1.2 amps for about $7.70. Remember these are rms voltages: 12.6 volts rms is 17.8 volts peak.

Now we pick a diode, or, if we want to use a bridge rectifier, four diodes. From Allied's catalog, VS148 diodes are rated at 70 volts PIV at 2 amps (for $1.93 each, why look further?). If we put four of them into a bridge, our 17.8 volts peak drops to about 16 volts due to diode resistance. This diode bridge gives us 16 volts DC peak, but suppose we want to charge the battery at 13 volts peak with a 1 amp current. We then add a resistor in series with the diode bridge. Since V = IR, if V = 3 volts and I = 1 amp, R = 3 ohms. At a current of 1 amp, that's 3 watts. Last, but not least, we add a 1.2 amp slow-blow fuse to prevent short-circuits from destroying the diodes, and the job is done. The complete circuit and the charging cycle are shown in Figure 1-24.

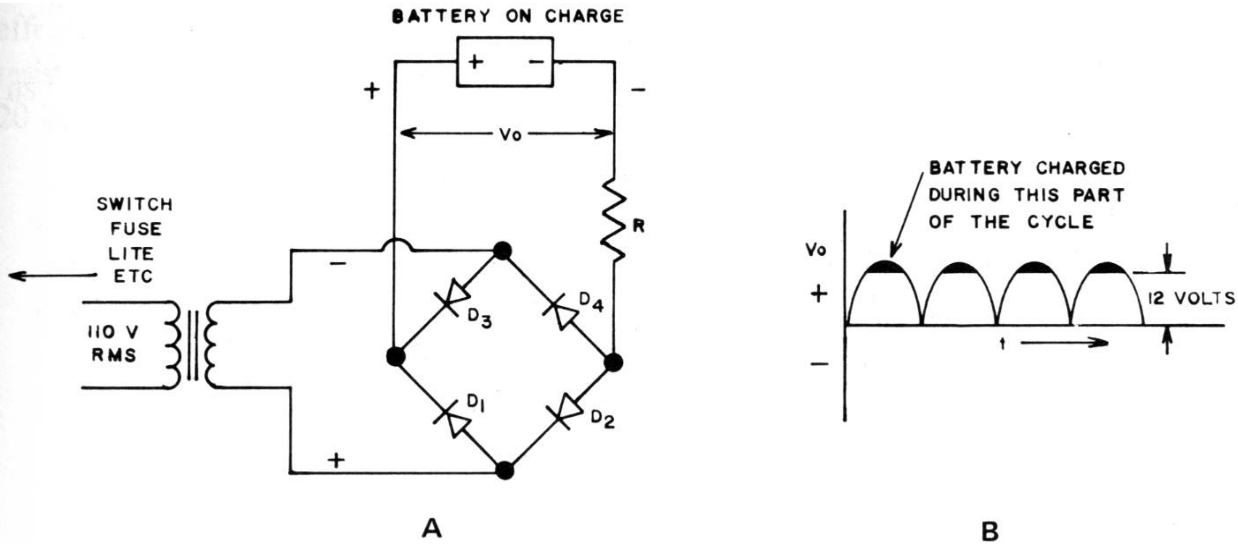


Figure 1-24. Battery charger. A: Circuit; B: Output voltage.

The circuit is completed, but now do you really know how the rectifier bridge works? As the transformer output swings (+) and (–) as shown, diodes D_1 and D_4 carry the current. Diodes D_2 and D_3 are *reverse biased*; therefore they are carrying no current. (You can pretend they aren't there). On the other half-cycle, the situation is the same except that D_2 and D_3 conduct, while D_1 and D_4 are reverse biased. The important thing to note is that in *both cases* the current flows in the *same direction in the load,* i.e., it is DC.

NEON BULBS AS PILOT LIGHTS

This topic should really come in Chapter 7, but since you will want to build circuits right away, we won't delay you. You must have seen the red glow of neon bulb pilot lights on all sorts of apparatus. They are low in cost, last a long time, and take very little power. The only problem is that they don't limit their current: if the current goes up, their resistance goes down, so the current goes up more and zap – it's all over.

To prevent this, we put a resistor in series with the neon bulb before we put it across the 110 volt line. At the instant the voltage comes on, the voltage drop across the resistor is zero (because the current is zero) so the full 110 volts is across the neon bulb and it lights. But then current flows and a voltage drop appears across the resistor. The current, however, is limited to a value that doesn't destroy the neon bulb. Neat, isn't it?

What size resistor is best? A good starting value is 60 kΩ, but note that the lower the resistor value, the *brighter* the light *and* the less the time until it burns out. You can use neon bulbs for all sorts of clever timing, switching, and counting circuits. Go to your local radio shop and buy a copy of the *General Electric Glow Lamp Manual* for about $1.00. Sometimes G.E. even gives away manuals to educational types; try writing to their Lamp Department and see what happens.

FUSES: ELECTRICITY'S SAFETY VALVE

Buying small electronic equipment fuses can be the most irritating business in the world. There are about 20 lengths, three diameters, and God knows how many voltage ratings, to say nothing of fast-blow types, slow-blow types, and so on. It can make you want to blow your brains out.

We have found it best to stick to type 3AG in standard and slow-blow styles. Buy holders for them and stock them in assorted sizes. Newark Electronics sells an assortment in a rack called an "Industrial Fuse Caddy" for about $16.95 and it is worth it. When you install fuses, use the standard type except for cases in which a heavy starting current is drawn. In that case, use slow-blow fuses.

VOLTMETERS AND AMMETERS

USE OF VOLTMETERS

For use in the laboratory or in electric circuits, a voltmeter can be thought of as an ammeter with a series resistance and a scale pointer system that indicates the amount of current flowing. Since the ammeter resistance is low, the current flow is controlled by the series resistance. Since we know the resistor value and can measure the current flow from the scale of the ammeter, we can calculate the applied voltage. In many cases the scale will be marked directly in volts. There are some types of voltmeters whose resistance is so high that in ordinary work they do not disturb the circuit being measured. They are vacuum-tube voltmeters, electrometers, or electrostatic voltmeters and are used much like the conventional units.

Voltmeters are usually marked in ohms per volt, and *if* you know the secret code you can figure out the total effective voltmeter resistance from the ohms-pervolt rating and the meter scale. The full-scale voltage (V_{fs}) across the meter is the drop across the meter resistance R_M *plus* the drop across any resistor R_S in series with the meter. We can write this as $V_{fs} = I_{fs}(R_M + R_S)$. We must note that I_{fs} is a constant of the meter coil itself whereas V_{fs} and R_S are at our choice. The ratio

$$\frac{R_S + R_M}{V_{fs}} = \frac{1}{I_{fs}}$$

is the oms-per-volt constant for that particular meter.

Given I_{fs}, the actual resistance of the voltmeter circuit is therefore a function of the full-scale voltage range of the meter. For example, if $1/I_{fs}$ is 20 kΩ/volt and the V_{fs} of the meter is 1 volt, then $R_S + R_M = 20$ kΩ. If V_{fs} were 100 volts, $R_M + R_S$ would equal 2×10^6 or 2 MΩ. In each case, the sum $R_M + R_S$ is equal to the ohms-per-volt rating times the full-scale voltage reading. Note that in both cases, the meter current was the same: 50μA. This follows from the fact that 1 volt divided by 20 kΩ is the same as 100 volts divided by 2 MΩ. We repeat, the ohms-per-volt rating is the reciprocal of I_{fs} in amps, which agrees with the dimensions of Ohm's law. It may be a screwy way to define things, but that's the way it is. Note that you never do find out what R_M is, but in most cases R_S is many times larger than R_M, so doesn't hurt to assume that $R_S + R_M \approx R_S$.

Realizing that a voltmeter is an "indicating resistance", we can now study the effect of connecting a voltmeter into a circuit to measure the voltage across another resistor. Consider the simple circuit shown in Figure 1-25, which consists of two 20 kΩ resistors connected across a 100 volt power supply or battery. We want to measure the voltage between terminals a-b. It is obvious from the voltage division formula developed earlier (p.8) that it is 50 volts.

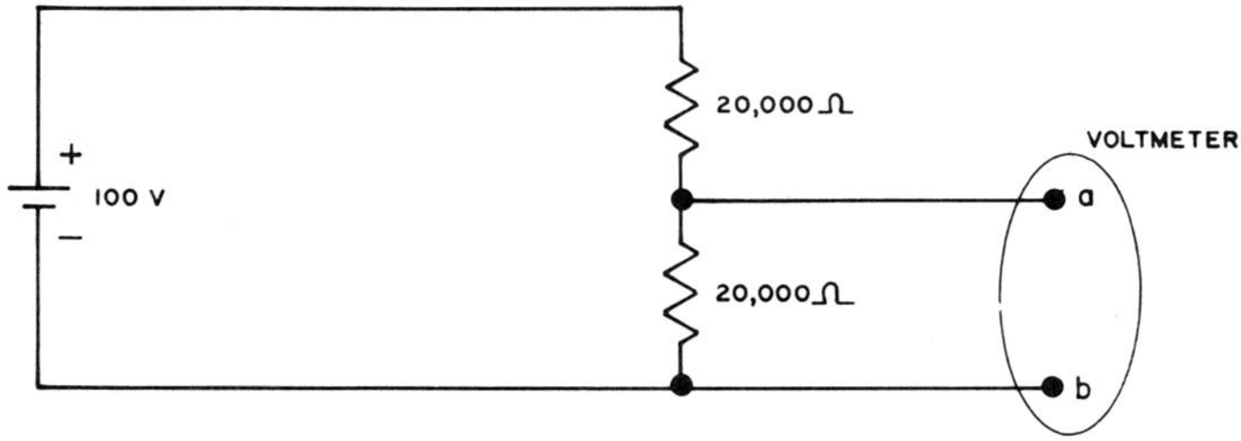


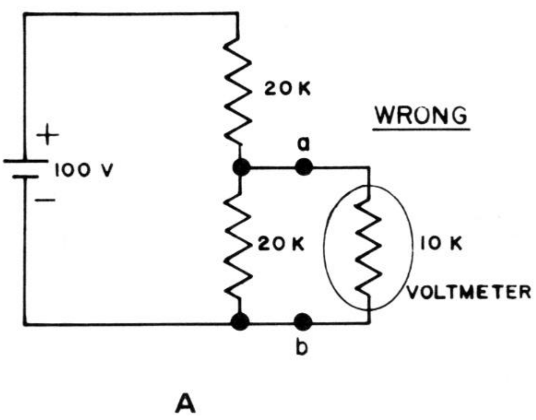
Figure 1-25. Simple series circuit containing a voltmeter: Error induced by voltmeter.

Now let's check this by measuring it with a voltmeter. Assume that two voltmeters are available. Voltmeter A has a full-scale reading of 100 volts and a rating of 100 ohms per volt. Voltmeter B has a full-scale reading of 100 volts and a rating of 1000 ohms per volt. Voltmeter A has a resistance of 10 kΩ. When connected across terminals a-b, the complete circuit is as shown in Figure 1-26A. (The voltmeter is depicted as a resistance within the circle in the diagram.) The voltage appearing across terminals a-b under these conditions can be calculated from the voltage division formula to be

$$V_{ab} = 100 \times \frac{\frac{(10k\Omega)(20k\Omega)}{10k\Omega + 20k\Omega}}{20k\Omega + \frac{(10k\Omega)(20k\Omega)}{10k\Omega + 20k\Omega}} = 25 \text{ volts}$$

Thus, the voltmeter resistance effectively reduces the measured voltage to *one-half* its previous value.

Now let's use voltmeter B. Its resistance is 100 kΩ, and the circuit with the voltmeter connected is shown in Figure 1-26B. Use of the voltage division formula shows that under these conditions, V_{ab} = 45.5 volts.



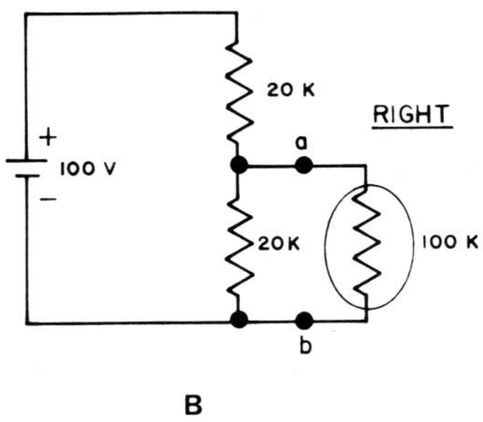


Figure 1-26. Voltage measuring circuits. A: Low voltmeter resistance; B: High voltmeter resistance.

It is obvious that voltmeter B has not disturbed the circuit as much as voltmeter A, but it has still caused an error of 9.1%.

If a voltmeter of infinite resistance were used, V_{ab} would be measured as 50 volts. A voltmeter with a rating of 20 kΩ per volt and a full-scale reading of 100 volts would have a resistance of 2 MΩ, and its effect when connected across terminals a-b in

Figure 1-26A would be negligible. On the other hand, if the circuit shown in Figure 1-26A were made up of two 1 MΩ resistors across the power supply, even the 20 kΩ-per-volt voltmeter would disturb the circuit. From this it is seen that *each case must be considered individually to determine the error caused by the voltmeter.*

The *ideal* voltmeter would be one with infinite resistance. Certain types of voltmeters approach this ideal, but they have other disadvantages. The best rule to w is to use a voltmeter with the highest ohms-per-volt rating available, and then it intelligently, while appreciating that the voltmeter has a finite internal re.nce. Of course, voltmeters with a high ohms-per-volt rating may be more expenthan ones with a low ohms-per-volt rating because of the additional sensitivity uired of the meter movement.

VTVM (vacuum-tube) or FET (field effect transistor) voltmeters have resistances to 20 M~ (depending on the manufacturer) even on low full-scale ranges. They the disadvantages, however, of being slightly more expensive and requiring the of a 115 volt AC power line or batteries. (Recently, the Heath Company has red a battery operated FET-VOM; it is a winner.)

USE OF AMMETERS

Ammeters are connected in series with a circuit to measure the current through that circuit. Figure 1-27 shows the simplest possible circuit containing an ammeter.

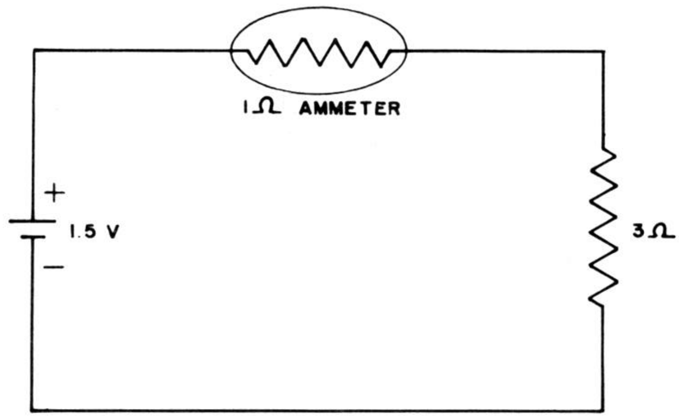


Figure 1-27. Simple circuit containing an ammeter.

Again, the ammeter should be thought of as an indicating resistance, this time indicating the current flowing through it. If the ammeter were not present in the circuit of Figure 1-27, the current would be, by Ohm's law, 0.5 amp. When the ammeter is connected into the circuit, the current drops to 0.375 amp. The ammeter has disturbed the circuit appreciably. If the ammeter had a resistance of 0.01 instead of 1 ohm, the current in the circuit – including the ammeter – would 0.484 amp, so the circuit would not be disturbed so much by the insertion of the meter. From this, it can be concluded that an ideal ammeter is one with zero resistance (compare this with the infinite resistance that was the case for the ideal voltmeter).

In actual practice the ideal ammeter is approached quite closely, much more closely than is the case for voltmeters. The following list shows the resistance of meters of various ratings as advertised by a leading manufacturer:

Full-scale Rating	*Resistance*
50 amps	0.001 Ω
10 amps	0.005 Ω
1 amp	0.050 Ω
100 milliamps	0.5 Ω
1 milliamp	70.0 Ω
0.1 milliamp	1625.0 Ω

These ratings will vary from one manufacturer to another, of course.

Sometimes it is difficult or impossible to connect an ammeter in the circuit where the current is to be measured. Several companies manufacture a clip-on type of milliammeter, for AC only, which is very convenient to use. Every wire carrying an electric current is surrounded by an electric field. The clip-on milliammeter senses this field and interprets it electronically in terms of the current flowing in the wire. Clip-on meters in the ampere range are sold by several manufacturers (you can find them in the Allied Electronics Catalog).

AMMETERS AND SHUNTS

Any single-range DC ammeter can be made into a multi-range ammeter by a system of "shunts," which are resistors connected in *parallel* across the ammeter. The resistance of these shunts can be calculated very simply from the current division formula. Notice that with ammeters, we put the added resistors in *parallel* with the meter. If you will look back at page 35 where we discussed voltmeters, you will see that in that case we put the resistors in *series* with the meter.

Consider an ammeter with a full-scale reading of I_M amps and a resistance of R_M ohms. We want to change the full-scale reading of this ammeter to I amps by connecting a shunt with a resistance of R_1 across its terminals. The circuit is shown in Figure 1-28.

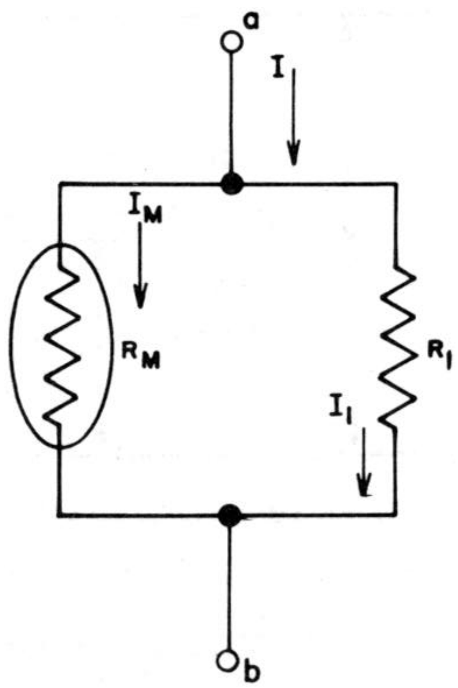


Figure 1-28. Ammeter with shunt.

The terminals a-b are now the terminals of the new ammeter with a full-scale reading of I amps. The full-scale current through the original ammeter will still be I_M and the excess current $I - I_M$ must be shunted around the original ammeter by R_1. By the current division formula (see page 14),

$$I_1 = I\left(\frac{R_M}{R_1 + R_M}\right) \tag{1-7}$$

and by Kirchoff's node law,

$$I = I_1 + I_M$$

or

$$I_1 = I - I_M \tag{1-8}$$

Substitution of equation (1-8) into (1-7) yields

$$I - I_M = I\left(\frac{R_M}{R_1 + R_M}\right)$$

Solving for the value of the shunting resistor R_1 yields

$$R_1 = \frac{R_M I_M}{I - I_M} \tag{1-9}$$

As an example, assume that an ammeter with a full-scale reading of 1 mA and a resistance of 70 ohms is to be made into an ammeter with a full-scale reading of 100 mA. We are to calculate the value of R_1 required. Using equation (1-9),

$$R_1 = \frac{70 \times 0.001}{0.1 - 0.001} = \frac{0.07}{0.099} = 0.707 \text{ ohm}$$

In this new ammeter, 1 mA will still be flowing through the meter movement at full scale, and 99 mA will be flowing through the shunt R_1. The total current flowing into the combination will be 100 mA.

Multi-range ammeters can be homemade by using a new shunt for each new range required. Such multi-range ammeters are readily available on the market, and any single-range ammeter can be readily converted to a multi-range ammeter.

VOLTMETERS AND MULTIPLIERS

Any single-range DC voltmeter can be made into a multi-range voltmeter by a system of resistors connected in *series* with the voltmeter. These series resistors, or *multipliers*, as they are usually called, can be calculated very simply from the voltage. division formula.

Consider a DC voltmeter with a full-scale reading of V_M and a resistance of R_M ohms. We want to increase the range of this voltmeter by means of a series resistance so that it will have a full-scale reading of V volts. The complete circuit is shown in Figure 1-29. In effect, R and R_M must divide the voltage V so that there are only V_M volts across R_M.

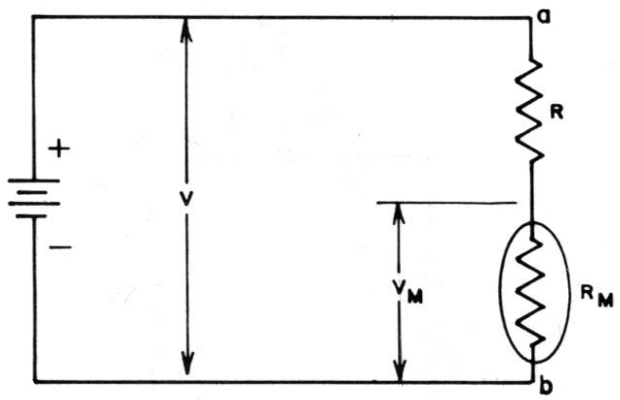


Figure 1-29. Voltmeter with a series resistor.

The required value for R can now be calculated from the voltage division formula as follows:

$$V_M = V\left(\frac{R_M}{R + R_M}\right)$$

Solving this equation for R gives

$$R = \frac{R_M(V - V_M)}{V_M}$$

As an example, assume that a voltmeter with a full-scale reading of 100 volts and a resistance of 100 kΩ (1 kΩ per volt) is available, but a voltage of 300 volts is to be measured. A series resistor, R, can be used, and its value is calculated as

$$R = \frac{100{,}000(300 - 100)}{100} = 200{,}000 \text{ ohms}$$

The terminals *a-b* are now the terminals of the new voltmeter with a full-scale reading of 300 volts. Multi-range voltmeters can be made by using a new series resistor for each new range required. Multi-range voltmeters are readily available on the market, and you can buy one from the Heath Company.

The problem with using voltmeters for precision measurements is that they draw current from the circuit being measured. The need for a device that does not draw current brings us to the potentiometer, which will be discussed in the next section.

POTENTIOMETERS: PRINCIPLE OF OPERATION AND SOME APPLICATIONS

The potentiometer is a device for measuring an unknown emf (or voltage) without drawing *any* current from the source being measured. With thermocouple devices, you *must* use a device of this type or the measurement will be useless. In a sense, the potentiometer can be considered as an infinite resistance voltmeter.

Its principle of operation is illustrated in Figure 1-30. The element enclosed in the box with the three terminals a, *b,* and *c* is called a *potentiometer* because the potential or voltage between terminals *b* and *c* can be varied from zero to some maximum value that is set by V_1. Assuming that *emf* is the unknown potential, we adjust the variable resistor until the ammeter, A, reads zero. (You can also use super-sensitive ammeters, called *galvanometers,* for this measurement.) The point is that when the ammeter reads zero, *no* current is being drawn from the unknown emf. In this case, we know that the voltage from point *b* to ground is the same as that from *d* to ground. At this point, we can close the switch shown in Figure 1-30 and measure the voltage from point *b* to ground. The fact that the battery V_1 has enough output capacity so the current drawn by the voltmeter *can be neglected* makes this complex procedure worthwhile.

Before you go on to the next (and more complex) cfrcuit, we suggest that you sit down and think this one through. We have to measure the output of an unknown source without drawing *any* current. We set up a battery and a variable resistor, making sure that the battery we use will have the necessary current capacity to drive a voltmeter. Then we close switch A and balance off some fraction of the battery voltage against the unknown voltage until the two voltages are equal. Now we only need to open switch A and close switch B to measure the voltage across the variable resistor with our voltmeter. Now we know exactly what the output of the unknown source is *without* having drawn any current from it.

In more complex instruments, such as those that you will find in laboratories, the simple voltmeter just isn't good enough. Instead, we use a *standard cell* and a *linear resistance.* A "'linear resistance" is a fancy term for a long resistance wire that has been carefully constructed so that its resistance is a function of how long the wire is. (You thought all resistance wires did that; well, this one is accurate to four decimal places.) Turning now to Figure 1-31, we have a battery V_W, a linear resistor (so called because it has a linear scale along the wire), some resistors R and R_S and a standard cell V_{std}.

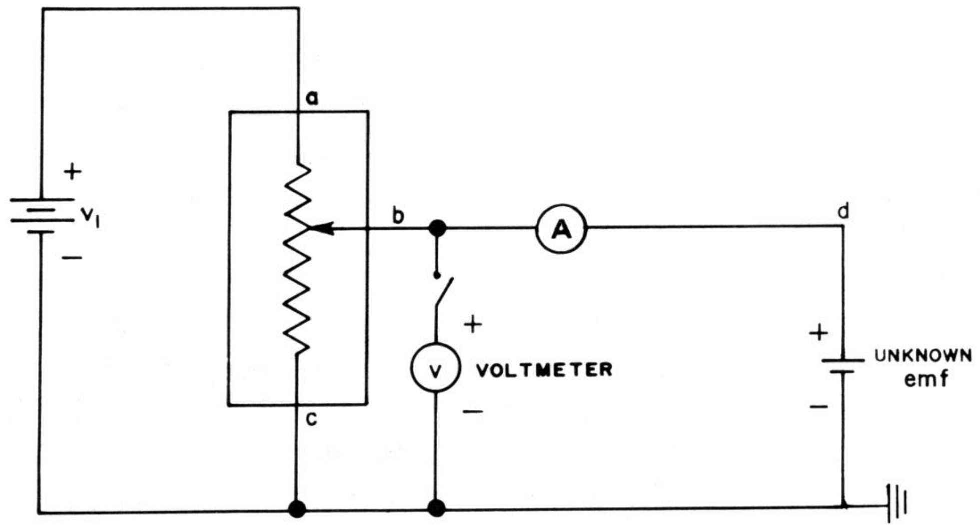


Figure 1-30. Potentiometer: principle of operation.

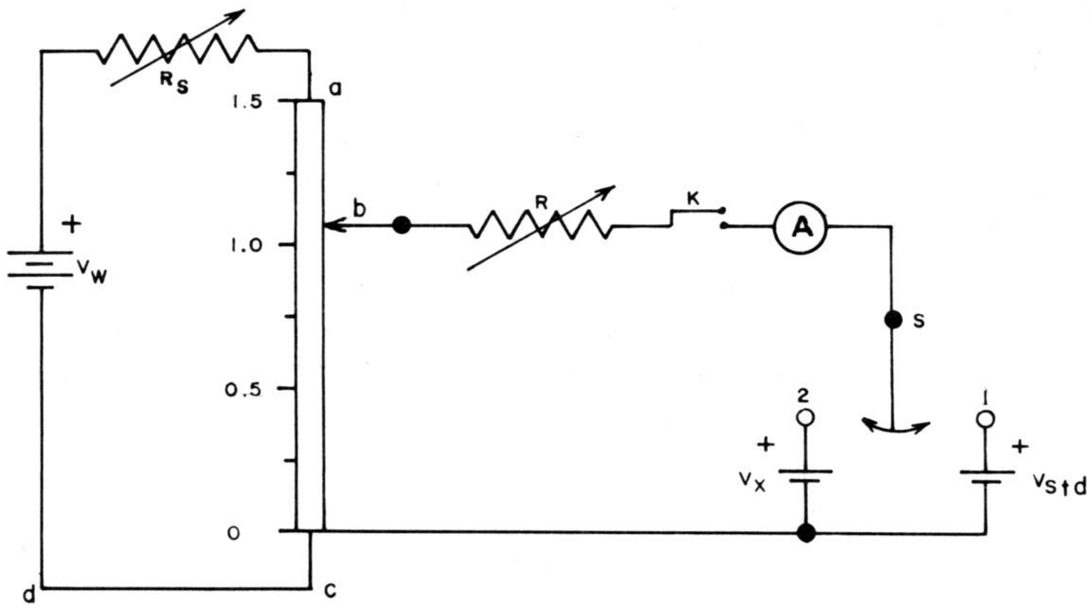


Figure 1-31. Calibrated potentiometer.

In this circuit, the voltage of V_{std} is known to a high degree of accuracy. It is called a *standard cell* or Weston cell and has a voltage of approximately 1.0184 volts (its actual value is usually indicated by a tag attached to the cell). This voltag extremely stable, but it is accurate only if *no* current is being drawn from the cell. Care should be taken to draw the least possible current from the standard cell during the calibration or standardization operation explained later.

The potentiometer in Figure 1-31 is set up for determining the value of the unknown potential V_X by comparing it with the emf of the standard cell. The first step in the use of the potentiometer is to *standardize* it, that is, to adjust the system in such a way that the mechanical position of the pointer on the slide wire reads directly in volts. This is done by putting the switch S in position 1, setting R (the protection resistor) at its maximum resistance value (usually 10 kΩ), and setting the slider to a reading on the slide wire corresponding to the emf of the standard cell. The key switch K is tapped, and R_S is adjusted so that the ammeter reads sero. Now the protective resistance of R is decreased, and the setting of R_S is refined until the ammeter reads zero with R at zero resistance and the tap key K closed. Note the use of a series protective resistor protects not only the ammeter by limiting the current, but also protects the standard cell. If a protective resistor in parallel with the ammeter had been used, this would have protected the ammeter by shunting current around it, but it would not have protected the standard cell.

The potentiometer is now standardized, i.e., the physical position of the wire is a direct reading of the voltage appearing across terminals *b-c*. Now, provided (1) the working battery V_W maintains its voltage, (2) the value of R_S does not change because of excessive current, and (3) the slide wire has been accurately marked by the manufacturer, the slider can be moved to any other place on the slide wire and the voltage between terminals *b-c* can be read directly from the slide wire. Here we assume, of course, that for each measurement of V_X you go through the sequence of tapping the switch (K) and adjusting the slide wire until the ammeter reads zero.

The next step is to put the switch S in position 2, return the protective resistor R to its maximum value, tap the key, and adjust the slider again until the ammeter reads zero with R at its minimum value and the tap key closed. The value of the unknown voltage V_X is now read directly from the slide wire.

Note that the maximum value of V_X that can be measured is determined by the slide wire. This is usually 1.6 volts. Actually, a slide wire potentiometer of this type is primarily for education because of the low precision with which the slide wire can be set and read. laboratory potentiometers usually have fine and coarse adjustments for standardization, and the actual slide wire is only a very small portion of the total resistance between terminals *a-c*. Precision potentiometers have an additional dial enabling the operator to check standardization by merely throwing a double-pole-double-throw switch. This switch selects either the standard cell or the unknown emf, and standardization can be checked just before and just after obtaining a balance with the unknown emf. Such an arrangement is shown in Figure 1-31.

In addition to the feature enabling the standardization to be readily checked, precision potentiometers have an 11-turn slide wire for the fine emf dial. With this, a more accurate balance can be achieved and the position of the slider can be more accurately read.

The potentiometer is in effect a precision voltmeter. It is a device for comparing an unknown emf with the emf of a standard cell that may be known to five significant digits. However, by applying Ohm's law and using precision resistors, the potentiometer can also be used to measure current. Furthermore, by using a precision ammeter and again relying on Ohm's law, the potentiometer can be used to measure resistance.

THE SELF-BALANCING RECORDER

An even more interesting and useful appllcation of the above ideas occurs in the laboratory or commercial recorder. To see how the system works we look back at Figure 1-30 and think about having a motor drive (called a *servo system)* to move the contacter on the resistor. The movement would be controlled by a signal generated by the voltmeter; when the two voltages are balanced, the movement stops. If we have a pen attached to the moving resistor contact arm and a piece of chart paper underneath, we can call this a *recorder*. The whole system is shown in Figure 1-32.

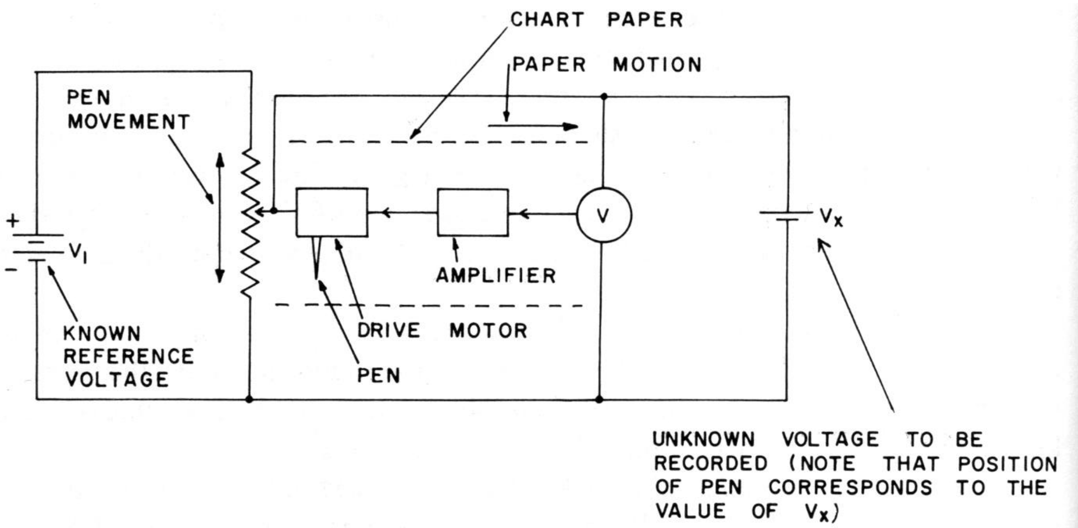


Figure 1-32. Self-balancing potentiometric recorder.

THE WHEATSTONE BRIDGE AND ITS APPLICATION TO RESISTANCE MEASUREMENT

The basic principle of the Wheatstone bridge that makes it so valuable for measurements is that it matches the amplitude of two voltages *without regard to their absolute values.* The ammeter, which is used to detect only the *difference* between the two voltages, can be a very sensitive instrument allowing the resistance values to be matched quite closely. In effect, the circuit of the Wheatstone bridge is that of two voltage dividers connected across a battery with an ammeter that indicates the *difference* between the two divided voltages. When the ammeter indicates zero, the two voltages are equal and the bridge is said to be balanced.

To really appreciate the advantages of the Wheatstone bridge we will think of a simple experiment, measuring an unknown resistance with a known voltage source and an ammeter as shown in Figure 1-33.

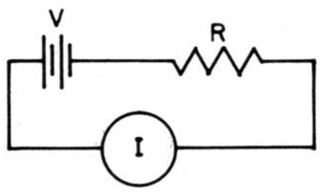


Figure 1-33. Measuring resistance with a voltage source and an ammeter.

This is the system used in the familiar VOM and we shall assume that the battery voltage is 1.5 volts and the resistance is about 1 kΩ. The current is about 1.5 mA, and we shall assume that the ammeter has a range of 0-10 mA with an accuracy of 1% (this is a precision meter). The error in the meter is then 1% of 10 mA or 0.1 mA. Therefore, the error in measuring the resistance is also 1% or 10 ohms. In words the best measurement we can make of this resistance is ±10 ohms. We might get a more accurate meter, but that would be very expensive and there is a limit to how far we can go in that direction. What we need is a way of balancing most of the resistance against a known resistance and then measuring the remainder. If the remainder is 10 ohms we can measure it to ±1% or 0.1 ohm, which is a lot better than the ±10 ohm accuracy we had before. We do this with a Wheatstone bridge, which should indicate to you what a remarkable gadget it really is. The Wheatstone bridge principle has many applications, and you would do well to understand it.

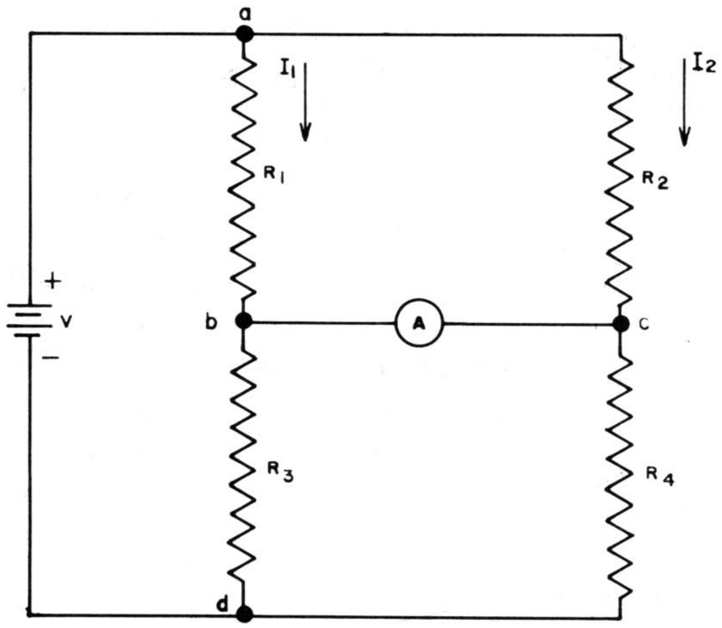


Figure 1-34. Wheatstone bridge

The Wheatstone bridge circuit is shown in Figure 1-34. When the ammeter reads zero, points *b* and *c* are at the same potential. The voltage drop across the resistance R_1 then must be equal to the voltage drop across R_2, and the voltage drop across R_3 must be equal to the voltage drop across R_4. It follows that the current through R_3 must be equal to the current through R_1, which is I_1 (there is no current through the ammeter, so there is no other place for the current to go except through R_3). Likewise, the current through R_4 must be equal to the current through R_2, which is I_2. Applying Ohm's law to the two circuits we adjust R_1 until:

$$R_1 I_1 = R_2 I_2 \tag{1-10}$$

$$R_3 I_1 = R_4 I_2 \tag{1-11}$$

Dividing equation (1-10) by equation (1-11) and cancelling out the current yields

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}$$

This is the basic equation of balance for a bridge circuit. If the bridge is being used to measure an unknown resistance, say R_2,then

$$R_2 = \frac{R_4 R_1}{R_3} \tag{1-12}$$

It is interesting to note that according to equation (1-12), when measuring an unknown resistance, R_2, it is *not* necessary to know the absolute value of R_1 and R_3 but only the *ratio* of R_1 to R_3. For this reason, in commercially available Wheatstone bridges, the ratio of R_1 to R_3 usually appears as a ratio arm or multiplier whose value can be selected by a knob and pointer. These ratios are usually 0.001, 0.01, 0.1, 1, 10, 100, and 1000. R_4 usually appears as a four-knob decade resistor.

In general, voltages from 1.5 volts to 6 volts are used as the driving voltage. Voltages in excess of 6 volts might damage the precision resistors built into the Wheatstone bridge, thus ruining its accuracy.

One more comment before we leave the Wheatstone bridge. The principle involved is at least 5000 years old and is by no means limited to electricity. In fact, what we might call the *mechanical Wheatstone bridge* was invented by the first great traders of the Mediterranean, the Phoenicians. If you think about the problems of accurately weighing something on a typical spring balance (like that in a grocery store) you can see it is comparable to the circuit of Figure 1-33. Its accuracy is limited. In contrast is the beam balance, where the unknown weight is balanced against a known series of weights. The ultimate accuracy may be in the range of 0.25 mg when the weight itself is ≥25 grams (an accuracy of 10^{-3}%). Clever people those Phoenicians.

SIGNAL GENERATORS

The signal generator is a variable frequency source of AC voltage. It is used in testing circuits, for instance, in measuring the frequency response of a filter or amplifier. Most signal generators provide either a sine or a square wave output. The available output frequencies range from 10 Hz to about 0.6 MHz. For frequencies below 10 Hz, ramp generators are used; above 0.6 MHz, we often speak of pulse generators, which are just signal generators by another name.

You should be aware that *most* audio frequency signal generators do not have a low output impedance. It is often 600 ohms; for this reason, short-circuiting the output *usually* does no harm.* In addition they may have three-wire cords and three-output terminals allowing either floating or grounded operation. In this instance, "ground" refers to the *earth ground* provided by the power company. If the supply has a two-wire cord, ground is really only "ground" neutral. While we are on this topic, it wouldn't hurt you to review the material on pp. 6-8 so you can be sure that you understand the difference between neutral, ground, and the abomination of "ground" neutral. The reason this is so important is because of the many different ways that signal generators have their outputs arranged. We can't describe all of them, but we will give a few examples to show you how they go.

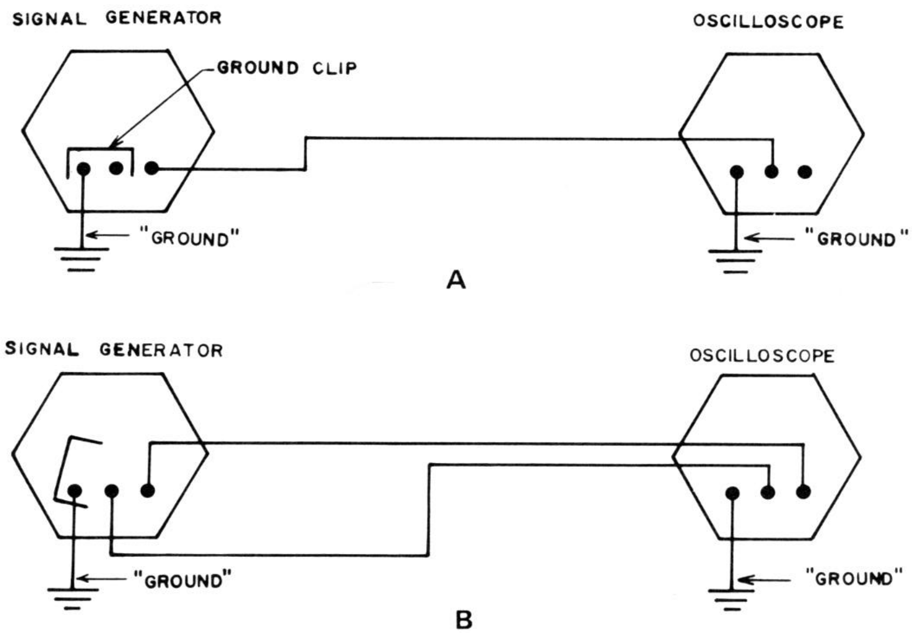


Figure 1-35. Signal generator connections. A. Grounded system. B. Floating system.

A signal generator that has only two outputs may have one of them connected to the case, or both outputs may be floating with respect to the case. If it has a three-wire cord, the case will be connected to the third, or "ground," wire. If it has a two-wire cord, the case will be floating with respect to power ground. Most modern laboratory power

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* The 600 ohm output impedance protects the signal generator by limiting the current if you accidentally short-circuit the output. The only time the 600 ohms can cause you trouble is when you try to drive a low impedance load. For example, suppose you set the signal source for an output voltage of 1 volt and then hooked it up to a 1000 ohm load. What would the voltage across the load be? Before you say "1 volt," draw the circuit and convince yourself that it will really be 0.625 volt.

supplies have a three-wire cord and three-output terminals. In this situation - which is shown in Figure 1-35 - the case and one terminal are counected to power ground. You can operate these sources as either grounded or floating systems, as shown in Figure 1-35.

If you were to use the grounded system (which is generally preferable) and you hooked the output of the signal generator to the grounded input of the oscilloscope, you would be short-circuiting the signal generator. Short-circuits are *bad;* that is why signal generators, at least those for student use, have a 600 ohm internal impedance to keep accidental short-circuits from damaging the equipment.

POWER SUPPLIES

Power supplies are sources of AC or DC electricity, but they differ from signal generators in one significant way: they have a low output impedance with considerable current capabifity, and if you short-circuit them, there may be sparks flying. The better and more expensive supplies have current-limiting circuits or fuses to *protect the supply,* but that will not protect *you* or some other delicate piece of equipment, so be careful. In any case, read the directions *first.*

There are all sorts of power supplies and output configurations, but the first thing to do is look at the cord. If it is a *two-wire cord,* the case (the box it is built in) of the supply will be floating and so will the two output jacks. Be warned that their resistance to the case may be only 10 kΩ or less but it should be something.

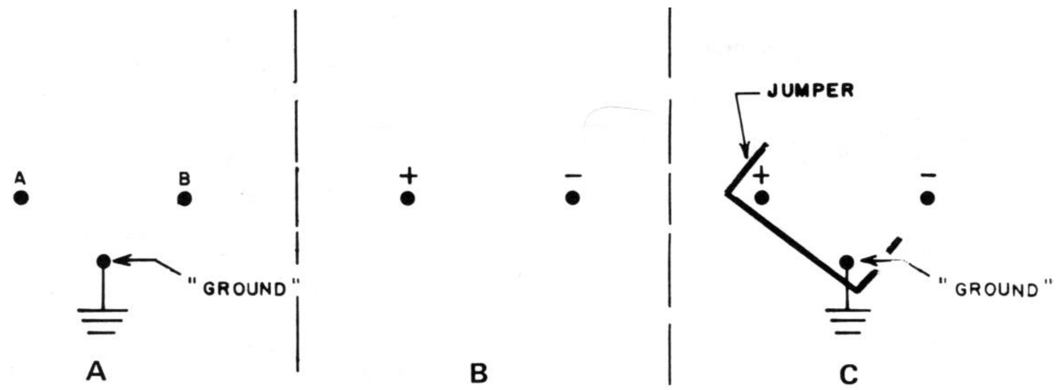

Figure 1-36. Power supply terminals.

That is the problem with two-wire instruments: the case is usually at some potential with respect to the outputs and to ground, but no one can predict what it will be. For power supplies with *three-wire cords,* the case is always at ground potential. Where there is a three-wire cord, there are usually three output jacks: two floating with respect to ground and the third at ground potential. You can use either grounded or floating operation by putting in jumper wires between the terminals shown in Figure 1-36C.

As you get more interested in electronics, you will want to use constant current or constant voltage supplies. A *constant current supply* puts out whatever voltage is necessary to keep the current to the load constant. The *constant voltage system* produces whatever current is necessary while keeping its output at a constant voltage. In Chapter 3, we will discuss how to turn a simple battery charger into a constant voltage or current source.

Other types of power supplies have dual outputs with respect to ground, e.g., ±6, 12, 15, or 24 volts. They are used to power operational amplifiers or other devices requiring two voltages. (We will have more to say about these later.)

If you have specific power supply problems or just want to learn more about them, we suggest you write to the Kepco organization, and ask for their *Power Supply Handbook* (see the Appendix). It is well written, very informative, and free!

CATHODE RAY OSCILLOSCOPE

The cathode ray oscilloscope is the most useful and versatile indicating and measuring device available in the field of instrumentation. It can be used as an AC or DC voltmeter, an ammeter, a frequency meter, and a phase difference meter. However, its greatest usefulness comes from its ability to give a visual display of voltage or current waves, at frequencies from DC to 500 MHz. These waves may be either periodic, in which case there is a constant image on the face of the tube, or transient, in which case a single trace of the phenomenon occurs across the tube and then disappears. In the early days of its development, it was a tool exclusively used by electrical engineers. Today, however, its usefulness, indeed its indispensability, extends far beyond the field of electrical engineering into mechanical engineering, physics, chemistry, physiology, medicine, and other fields too numerous to mention.

The heart of the cathode ray oscilloscope is the *cathode ray tube,* which contains an electron source with a beam-forming arrangement and accelerating and focusing electrodes that serve to form a fme stream of high velocity electrons. The electrons are projected between two sets of plates arranged so that, when charged, one set of plates will deflect the electrons horizontally and the other set will deflect them vertically. A typical cathode ray tube of the electrostatic deflection type is shown in Figure 1-37.

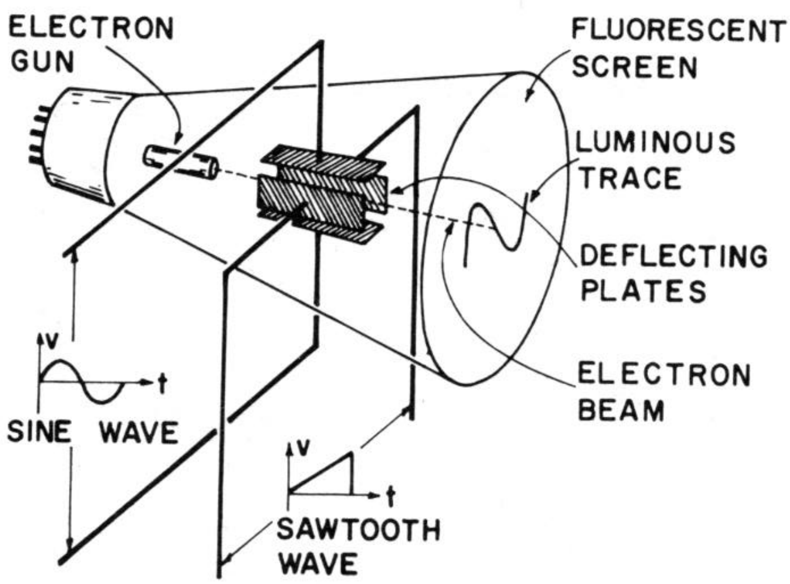

Figure 1-37. Cathode ray tube of the electrostatic deflection type.

A bright spot is formed when the electron beam strikes the fluorescent screen. Because of the very low mass of the electrons, their inertia is extremely low and the beam can be made to follow high frequency variations well into the 500 MHz frequency range. Because of the persistence of the screen and the persistence of vision, the pattern appears stationary on the fluorescent screen. However, it is actually a dynamic pattern formed by a single spot in rapid motion.

Many controls are necessary to make the cathode ray oscilloscope the versatile instrument that it is. Amplifiers are required to increase the deflection sensitivity, and a sweep generator with a trigger circuit is required to form the apparently stationary patterns.* A typical cathode ray oscilloscope is shown in block form in Figure 1-38. To help you understand how this system works, we will discuss it section by section. Figure 1-39 shows the systems that you will find on a typical oscilloscope.

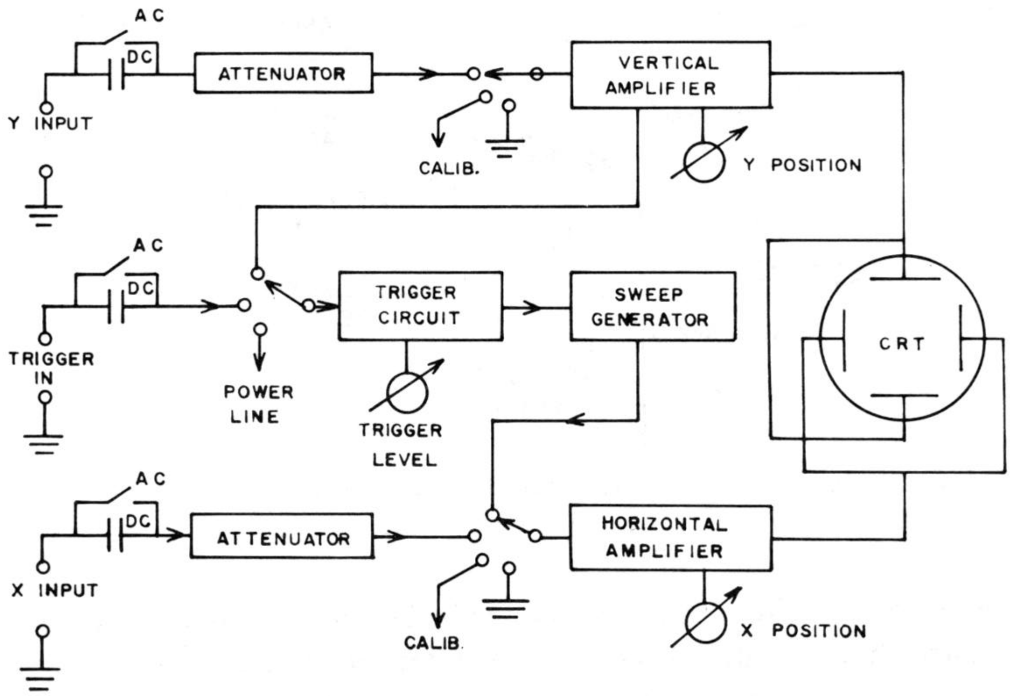

Figure 1-38. Block diagram of cathode ray oscilloscope.

VERTICAL DEFLECTION SECTION

This section consists of three parts: A Y-positioning control to position the spot in the Y direction, an attenuator to take care of high-level input signals, and an amplifier to take care of low-level input signals.

The *Y-positioning control* is a DC control device that sets the undeflected position of the spot in the vertical direction. With this control, the spot can be placed at any position on the face of the tube in the vertical direction, and even off the face of the tube for special applications.

The *attenuator* reduces the sensitivity between the vertical input terminals and the vertical deflection plates so that signals of high amplitude, which would drive the spot off the face of the tube on peaks, may be viewed.

The *amplifier* increases the sensitivity between the vertical input terminals and the vertical deflection plates so that signals of low amplitude, which would not deflect the spot sufficiently, may be viewed. The frequency range of this amplifier allows signals from DC to radio frequencies to be viewed. There is usually provision for shorting a blocking capacitor at the input of this amplifier when DC signals, or signals of very low frequency or with a DC component, are to be viewed. Sometimes it is desirable to block DC from the input of the oscilloscope, sometimes it is immaterial, and at other times it is necessary not to. So the position of this switch may be important.

Some oscilloscopes are calibrated directly in Y volts per centimeter; others are not calibrated. The calibration of this control is always made with DC, so on DC inputs, the peak-to-peak volts per centimeter are indicated by this control. Provision is made in some oscilloscopes to check the Y-deflection calibration against an internal signal in

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* Some of these terms may seem a little strange to you, but stick with us. It will gradually become less confusing as we discuss how the system works.

the oscilloscope itself. This is usually a square wave of known amplitude. The square wave is used, instead of a sine wave, because with square waves there is no question about peak versus root.mean~square values - you just take the top and bottom of the square wave. Other uses for the square waves will be developed in later chapters. They are a great way to test an amplifier for its response to AC and DC signals.

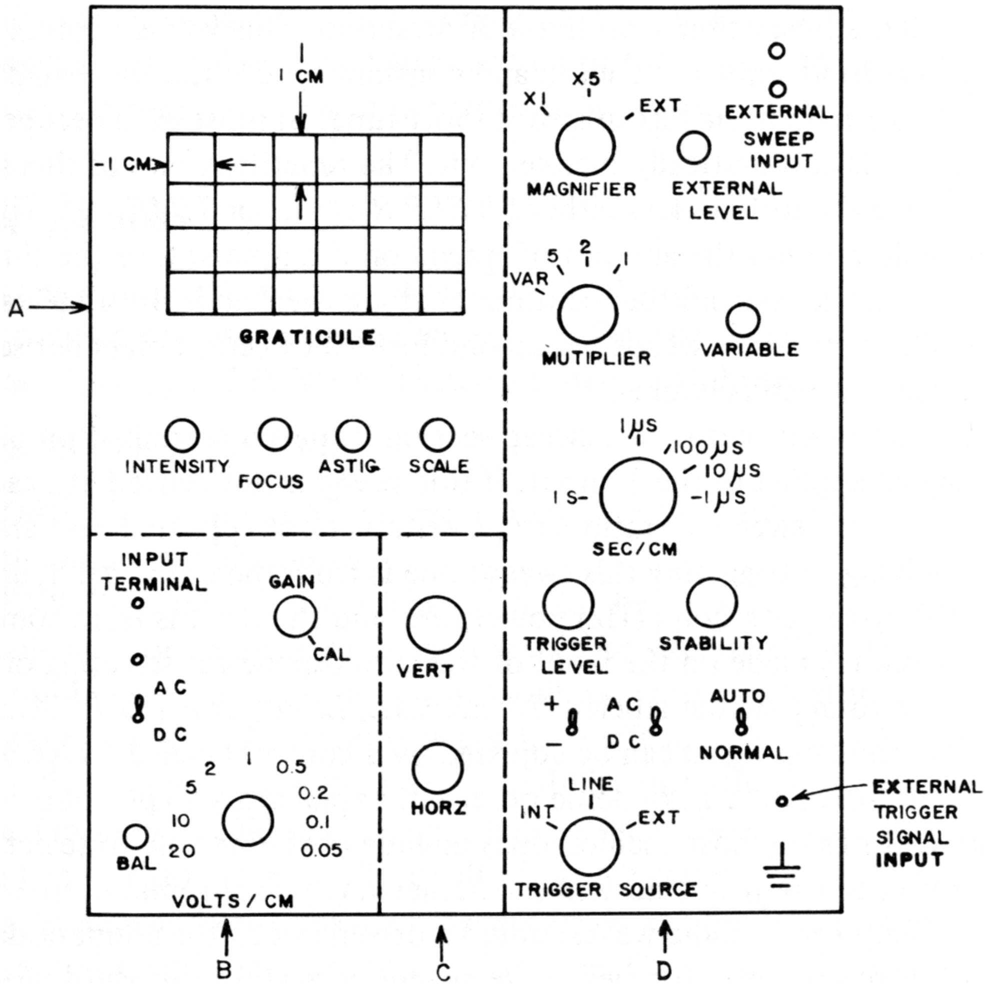

Figure 1-39. Typical oscilloscope controls. A: Cathode ray beam controls; B: Vertical amplifier; C: Positioning; D: Time base.

So far all we have talked about is the vertical deflection circuitry in the oscilloscope. If we stopped here you would be left (in the figurative sense) with a trace that went up and down but did not travel from left to right. This travel from left to right is controlled by the horizontal deflection section. It applies the necessary voltage to sweep the trace across the screen at some prechosen velocity usually rated in centimeters per second or per millisecond. It also provides a means of "stretching out" the trace to permit the experimenter to view only the most "interesting" part.

HORIZONTAL DEFLECTION SECTION

The horizontal deflection section consists of the same three parts as the vertical deflection section: an X-positioning control, an attenuator, and an amplifier. In some oscilloscopes the horizontal amplifier is less sensitive than the vertical amplifier because in most applications, the X-deflection is usually brought about by the sweep or trigger voltage present inside the oscilloscope, and sufficient voltage is present so that a sensitive amplifier is not needed. On the other hand, the signal voltage under investigation is usually applied to the vertical amplifier, and this may be of very low amplitude.

SWEEP OR TRIGGER SECTION

The sweep or trigger voltage consists of a saw-tooth voltage wave that can be applied to the horizontal deflection plates through the horizontal amplifier. This horizontal sweep provides a linear time base in the X direction. This voltage moves the spot from left to right at some pre-chosen and constant speed, and then snaps it back to its original position on the left in a very short time. In most oscilloscopes, this "return trace" is automatically blanked out. The repetition rate of this sweep is adjustable by a control marked either SWEEP RANGE or TIME/CM. The setting of this control determines the amount of spread on the time axis or the time base of the pattern, i.e., the seconds per centimeter along the X axis. In some oscilloscopes this control is marked in sweeps per second instead of centimeters per second. It is usually obvious which is implied.

A very important part of the sweep section is the synchronization of the sweep with the signal applied to the Y input. If this sweep is not started at exactly the right time for each sweep, a stationary pattern will not appear. There are three ways of synchronizing or triggering this sweep: one is from the signal itself, another is from the 60 cycle per second (Hz) power line, and the third is from some external signal. Provision is made on the front of the oscilloscope for selecting one of these methods by a rotary switch labeled INTERNAL, LINE, or EXTERNAL. The level of this synchronizing signal can be adjusted by a control labeled SYNC AMPLITUDE, TRIGGER LEVEL, or some other self-explanatory expression.

Other features on most oscilloscopes include (1) being able to select a single sweep for nonrecurrent or transient phenomena, (2) an automatic, free-running or recurrent sweep for periodic waves, or (3) a driven sweep for nonperiodic waves (but which is often useful for viewing recurrent waves). In this third mode of operation, the input signal triggers the sweep so no pattern is present on the screen in the absence of an input signal at the Y terminals.

INTENSITY AND FOCUS CONTROLS

These two controls are for controlling the intensity of the electron beam and for focusing it down to a small diameter on the fluorescent screen. The least intensity needed (depending on room illumination) should always be used. A low-level beam gives the sharpest focus and prevents burning of the screen. Never leave a small intense spot fixed on the screen for more than a few moments, because this may leave a permanent black spot on the screen.

DISPLAY OF WAVEFORMS: AMPLITUDE VERSUS TIME

When a recurrent waveform is applied to the vertical plates and a saw-tooth waveform is applied to the horizontal plates, a stationary pattern is observed on the screen if the two waveforms are properly synchronized. This type of pattern can be understood by a very simple experiment: move a pencil back and forth on a piece of paper in such a way as to repeatedly trace a straight line about one inch long. Now pull the paper underneath the pencil perpendicularly to the line being traced, and a crude sine wave is traced out by the pencil. The pencil point represents the spot on the screen tracing out a vertical line in the absence of a sweep voltage. The moving of the paper is analogous to sweeping the spot across the screen at the same Lime it is moving up and down. Synchronization of the vertical movement of the pencil and the horizontal motion of the paper produces a sine wave.

OSCILLOSCOPE OPERATION

How do we begin to use the oscilloscope? This stops many students cold. Let's look at a typical oscilloscope as shown in Figure 1-39. We have grouped the controls into four sections: *A, B, C,* and *D*. We will discuss other capabilities on page 56.

A. CATHODE RAY BEAM CONTROLS

1. *ON/OFF* Turns on the AC power. It may be a separate switch or incorporated with another beam control.
2. *INTENSITY:* Controls the brightness of the beam trace or spot. This control should be adjusted for an easily observable trace. An excessively intense beam may burn the cathode ray tube phosphor. Almost all oscilloscopes feature *retrace blanking* This means that after the beam is swept from left to right, the beam intensity is automatically reduced below the level of visibility until the beam is returned to the left side. On some oscilloscopes a spot will be seen when the beam is not being swept from left to right. This spot is usually at a reduced intensity. The intensity control may be adjusted until the spot disappears. When the beam is swept, the intensity will automatically increase to a visible level. On some oscilloscopes the beam spot is completely blanked and will not appear for any setting of the intensity control. These oscilloscopes often have a *FREE RUN* switch setting in the time base controls that always produces a trace.
3. *SCALE ILLUMINATION:* Controls the graticule brightness.
4. *ASTIGMATISM:* Controls spot shape.
5. *FOCUS:* Controls spot size. The astigmatism and focus control should be used together to obtain a sharp trace.

B. VERTICAL AMPLIFIER

1. *INPUT TERMINALS:* The terminals to which the signal to be viewed is attached. Many oscilloscopes have only two terminals, one of which is taken through tile power line ground to earth. Other terminals may be in the form of a coaxial* connector. Some oscilloscopes have three input terminals. The signal may be attached to the ungrounded pair if floating or ungrounded operation is desired. Still others may have a switch that grounds one of a pair of input terminals.

   (**Warning**: Many other types of electronic equipment have a grounded terminal. *Always attach all grounded terminals to a common circuit point;* otherwise, a short-circuit will exist via the power line.)
2. *VOLTS/DIVISION:* This control will adjust the height of the waveform present. There is usually an electric switch with several positions labeled in volts per inch or centimeter.
3. GAIN CONTROL: This is a continuously variable control that may be put in the position marked calibrated. When the gain control is in this position, the VOLTS / DIV control setting is calibrated to a known value. The GAIN CONTROL provides a continuous gain adjustment between the calibrated positions of the VOLTS / DIV switch.
4. AC-DC: A switch that determines whether only AC beam deflection or AC and DC deflection will occur. This is illustrated in Figure 1-40. If the trace or spot is previously adjusted to a zero reference line, the waveforms shown will produce displays sinailar to those shown in Figure 1-40.

* *Coaxial:* A fancy word for a shielded connector consisting of a central wire (that carries the signal) fixed by insulation inside a grounded shield.

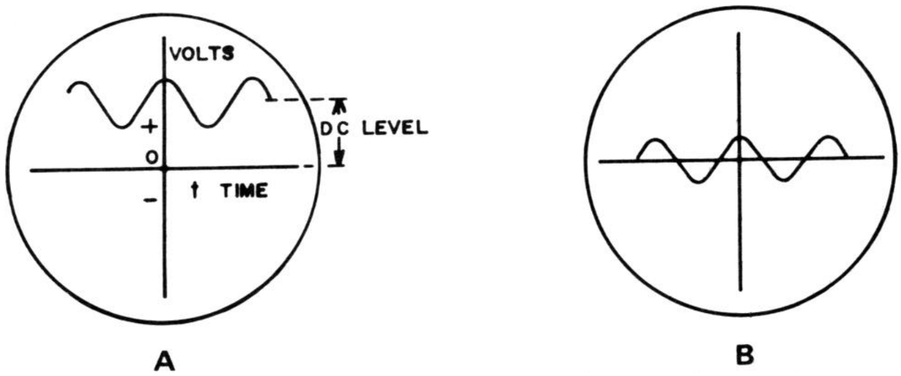

Figure 1-40. Oscilloscope traces. A. DC operation. B. AC operation.

5. BALANCE: This control pertains to operation with the AC-DC switch in the DC position. It should be adjusted to minimize the vertical movement of the trace or spot when the GAIN or VOLTS/DIV controls are moved between their extreme positions. Only one may be affected by the balance control. This, as well as other details, may be determined by consulting the equipment manual or by trial and error (if all else fails, read the directions).

C. POSITIONING

1. VERTICAL: Moves the spot or trace up or down. Internally, this control is a part of the vertical amplifier, but this is often grouped separately from the other vertical amplifier controls.
2. HORIZONTAL: Adjusts the spot or trace left or right.

D. TIME BASE

Time base controls are the most numerous and difficult to understand. Lack of appreciation of their functions can lead to hours of frustration.

1. TIME/DIV: This control is a selector switch with positions marked in microseconds, milliseconds, or seconds per inch or centimeter. Various settings of this control will adjust the sweep speed to various calibrated values, thus controlling the spread of a waveform.
2. MULTIPLIER: This control is a selector switch with positions often marked *variable, 1, 2, ... 5*. In the variable position, a separate control will adjust the sweep time continously between the calibrated times per division of the *TIME/DIV* switch. In the *1, 2,* or 5 position, the sweep is still calibrated, but the time per division indicated by the *TIME/DIV* switch should be multiplied by 1, 2, or 5 respectively. Some oscilloscopes have no multiplier, but have many more positions on the *TIME/DIV* switch.
3. VARIABLE: Continuously adjusts the sweep time when the multiplier is in the variable position.
4. MAGNIFIER: Usually a two-position switch which is marked X 1, X5, or Off and On-X5. In the X5 position the sweep speed is increased by 5; thus, the time per division value must be divided by 5. Magnification actually makes the trace five times longer. As a result you can only see about one-fifth of the trace at a time, and you must adjust the HORIZONTAL POSITION control to view the entire trace.
5. EXTERNAL LEVEL or ATTENUATION Attenuates the sweep signal to obtain the desired sweep length.
6. INTERNAL/EXTERNAL: A switch which, when in the external position, allows the beam to be horizontally swept by an external signal applied to the EXTERNAL SWEEP TERMINALS.

7. TRIGGER SOURCE: Selects either internal, line, or external triggering. The trigger voltage is an AC, DC, or AC + DC signal that starts the horizontal oscillator for each sweep. In the intemal position, the sweep triggers on the signal applied to the vertical amplifier. This is the most frequently used mode. For line triggering, a 60 cycle per second signal from the power line is used. This is convenient when investigating signals synchronized to the power line. In the external position, the sweep may be triggered by an external signal attached to the EXTERNAL TRIGGER TERMINALS.
8. TRIGGER LEVEL: This control adjusts the instantaneous voltage level at which the horizontal sweep is triggered. Thus, using internal triggering, you can have the trace begin at any point on the waveform to be viewed.
9. STABILITY: Allows the stability of the sweep oscillator to be adjusted, which has the effect of controlling the minimum amplitude trigger signal necessary for triggering. Adjusting this control prevents triggering by low level signals. Some oscilloscopes do not have a front panel stability control.
10. MODE SWITCH: Determines that the trace is to be triggered on the positive or negative going portion of the trigger signal.
11. A C/DC MODE SWITCH: In the AC position, sweep triggering occurs at some point that is determined by the setting of the TRIGGER LEVEL and ±CONTROL on the AC portion of the trigger signal. In the DC position, triggering occurs anytime the instantaneous trigger voltage exceeds the value determined by the abovementioned switches.
12. AUTO/NORMAL MODE SWITCH: In the auto position, triggering will occur automatically when the stability control is set properly. The trigger level control will be disabled. In the normal position, the abovementioned controls are operative. The auto mode is less than perfect, and manual control is necessary for complex waveforms.

E. OTHER TYPES

There are as many varieties of oscilloscopes as there are manufacturers and models. Many of them have additional capabilities that are not discussed above. Several are listed here with short explanations.

1. MULTIPLE TRACE: Has the capacity of displaying two or more waveforms simultaneously. Most of these alternate the trace between input signals. A few have dual-beam cathode ray tubes that operate simultaneously.
2. X-Y INPUT: Has an additional amplifier – identical to the vertical amplifier that can be used for calibrated, external, horizontal sweeping.
3. STORAGE: The cathode ray tube has an electron flood source that allows the trace of a nonrepetitive or very slow signal to be displayed for as long as several hours.
4. SAMPLING: Sampling is a technique by which displays of very high frequency, repetitive signals are obtained. Most oscilloscopes have a high frequency limit that is determined by the bandwidth (roll-off) of the vertical amplifier. If the bandwidth is pushed up, a further limitation encountered is the electron transit time from the deflection plates to the screen. As a result, direct trace viewing beyond a few thousand megahertz has been impossible to obtain, which resulted in the development of the sampling scope. This instrument samples the fast signal at various times and displays the result as a sequence of spots that show what the original waveform was like. This system can only be used if a repetitive signal is available.

OSCILLOSCOPE APPLICATIONS

FREQUENCY MEASUREMENTS

When using the oscilloscope as a frequency meter, sine waves are applied to each set of plates. When the two sine waves are of the *same* frequency, an elliptical pattern appears on the screen. When the vertical frequency is *twice* that of the horizontal frequency, a butterfly pattern, or a figure eight on its side, appears on the screen. This pattern has two loops or peaks at the top indicating that the vertical frequency is twice that of the horizontal frequency. If the vertical frequency is *three* times that of the horizontal frequency, there will be three loops or peaks at the top, and so on. These patterns are called *Lissajous figures*. Frequencies may be compared in this way up to a ratio of about 10 to 1. For higher ratios, it becomes difficult to count the peaks unless the two frequencies are extremely stable and very fine frequency adjustment of'one of them can be made.

Another method of comparing two frequencies is to connect both of them, either in series or in parallel, to the vertical deflection terminals and set the sawtooth sweep frequency at a very low rate. When the two frequencies are very close together, the beat* notes can be observed on the screen. Beats with higher harmonics of one of the frequencies can also be observed as stationary patterns.

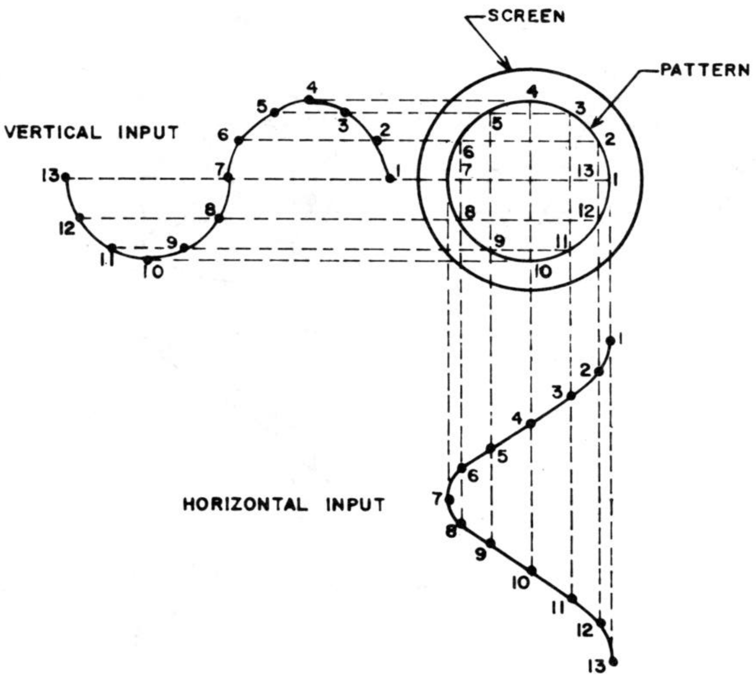

Figure 1-41. Circular Lissajous figure from two sine waves 90 degrees out of phase. (Note that when the phase difference is zero, the circle shrinks to a single line at a 45 degree angle.)

Lissajous figures can be understood from the following explanation. Figure 1-41 shows a circular pattern obtained from two sinusoidal waves 90 degrees out of phase: a sine wave applied to the vertical input and a cosine wave applied to the horizontal input. Equal intervals of time along each wave are marked with numbers from 1 to 13, and each of these numbers is joined by a straight line to the place on the screen where the spot will be at that particular instant in time. The circle swept out by the spot is shown. Figure 1-42 shows a figure eight or butterfly pattern swept out by the spot when a sine

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* The term beat comes from music. When two signals of almost the same frequency are added, certain "sum" and "difference" frequencies appear. The low-frequency difference signals are called beats.

wave of frequency f_1 is applied to the vertical plates and a cosine wave of frequency f_2 is applied to the horizontal plates. Again, equal intervals of time are marked, and the position of the spot is shown at each instant in time. If the frequency ratio were 5 to 1 instead of 2 to 1, five peaks would appear.

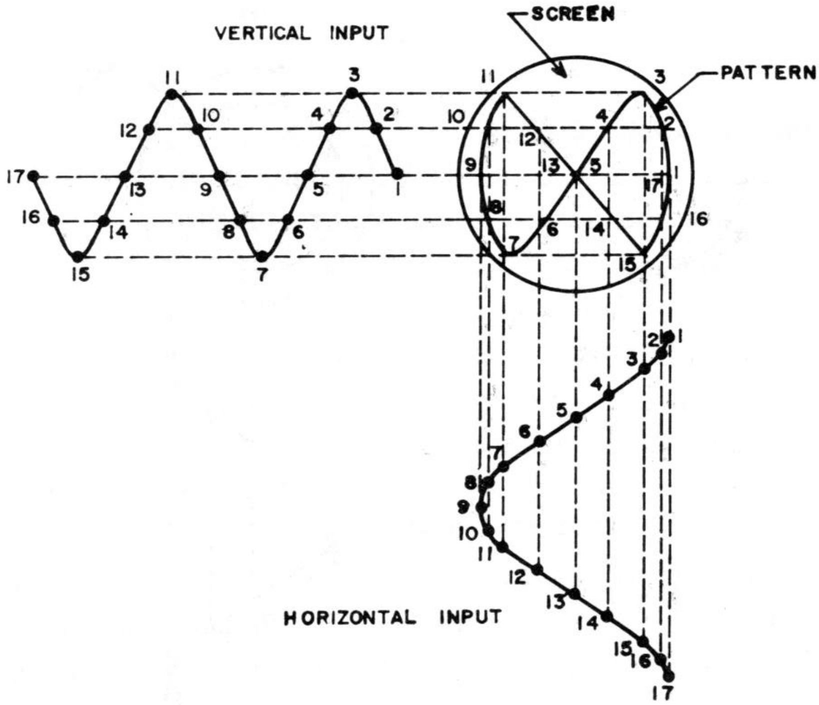

Figure 1-42. Butterfly pattern from two sine waves: the frequency of the vertical input is twice that of the horizontal input.

If the frequency is not a simple ratio such as 5 to 1 or 7 to 1, but, for example, is 9 to 4 or 8 to 3, then the frequency applied to the horizontal plates is to the frequency applied to the vertical plates as the number of loops across the top is to the number of loops along a vertical side.

For a perfectly circular pattern, the two signals must be of the same amplitude.

PHASE MEASUREMENTS

In the previous explanation of the circular Lissajous figure shown in Figure 1-41, the statement was made that when the signals are 90 degrees out of phase, the pattern is a circle. If the signals were in phase, the pattern on the face of the oscilloscope would be a straight line with a slope of 1. This can be shown by making a diagram similar to Figure 1-41, with the two applied voltages equal in amplitude and in phase. As the phase relation between the two signals departs from zero degrees, the straight line "opens up" into an ellipse slanted to the right, and becomes a circle when the phase difference is 90 degrees. When the phase difference exceeds 90 degrees, the circle becomes an ellipse slanted to the left, and this ellipse becomes a straight line with a slope of –1 when the phase difference is 180 degrees.

The phase difference can be calculated from the relationship

$$\theta = \arcsin\left(\frac{Y_{intercept}}{Y_{max}}\right)$$

in which

θ = phase angle between the two signals;

Yintercept = axis point where the ellipse crosses the vertical; and

Ymax = highest vertical point on the ellipse.

When making the above calculation, the two signals must have equal amplitudes. In other words, the ellipse must be contained within a square on the grid on the face of the oscilloscope.

This is a good spot to stop, do an experiment, and learn something about oscilloscopes plus phase shift (Figures 1-16 and 1-17). In Figure 1-17 you will note that the current through capacitor I_C is exactly $I_C = 2\pi f AC \cos 2\pi f t$ or 90 degrees out of phase with the applied voltage. To make use of this fact, we set up the circuit shown in Figure 1-43.

In Figure 1-43 a signal generator drives a resistor and a resistor-capacitor circuit.

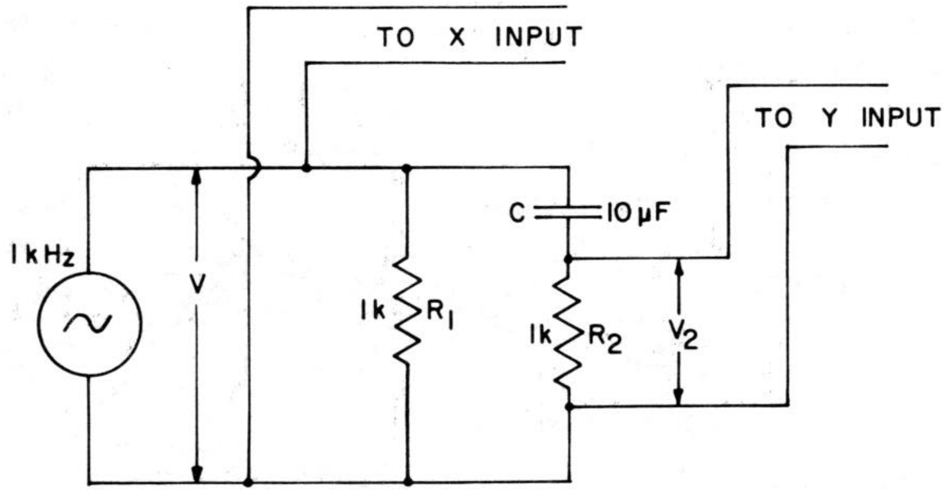

Figure 1-43. Phase shift demonstration circuit.

The current through the resistor is out of phase with V so the voltage across R_2 is out of phase with V too. If you put V into the X axis of the scope and use the V_2 signal to drive the Y axis or sweep (read the manual if necessary), you will be looking at two signals that are exactly 90 degrees out of phase. The Lissajous signal should be a circle.

Try the effect of changing the frequency of V (Should it affect the Lissajous figure?) Try changing C and R_2 to larger or smaller values. For very small values of C, i.e., 10 pF and R = 106 ohms, you may find the phase shift is less than 90 degrees. (Why?) (Answer: Think ofwhat happens as C becomes a short-circuit so that we have zero phase shift. When the phase shift is zero, V and V_2 are "in phase," and the trace on the oscilloscope will be a straight line.)

THE SELF-BALANCING POTENTIOMETRIC RECORDER

The operating principles of this system were discussed earlier in the text associated with Figure 1-32. Here we will go through some of the how4o-use4t details. We might begin by noting that the word *potentiometric* implies that at balance the unit does not draw current from the signal source. Actually, the "infinite" input impedance does not really exist, but units like the Heath Company IR-18M come pretty close (i.e., above 5 MΩ at balance and 500,000 ohms when off balance). Another point of interest is that the "reference voltage" is obtained from a Zener diode rather than a mercury cell (the mercury cells have a nasty habit of going dead just when you need them).

These instruments, though somewhat expensive, $229.95 (1980 dollars), are very useful and no lab is really complete without one. They are essentially voltage sensitive, but current signals are easily converted to voltage for recording. Typical sensitivities are zero to 10 mV with ability to cover any voltage up to zero to 250 mV. Beyond that you have to use external voltage dividers (you do remember them, we hope). To see how recorders work, we refer to Figure 1-44 showing a typical unit. Note that it takes standard ink pens, soft-tip pen, or even a soft pencil; this avoids having to buy special pens at "special cost."

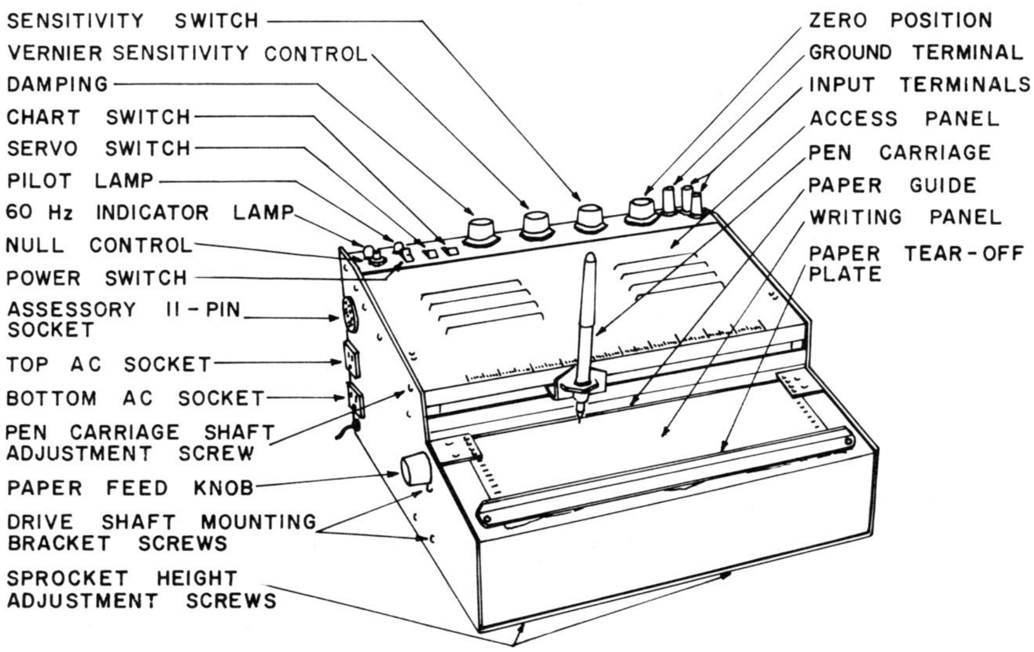

Figure 1-44. Typical pen recorder.

Looking at the controls on top, from left to right, the three rocker switches provide (1) power-on for warm-up and standby conditions; (2) servo-on to allow adjustment for zero and sensitivity; (3) chart-on so that you can actually record the data.

The damping control allows the operator to control the speed of response and oscillation of the pen-servo system. The best setting is one where the pen is just at the threshold of oscillation. The sensitivity control consists of two units – a decade switch for basic range control (i.e., zero to 10 mV, zero to 100 mV, etc.) and a vernier pot which allows intermediate adjustments.

The zero position control allows the operator to set the pen at zero on the chart or at some other position if necessary. This is convenient when both (+) and (–) signals are to be recorded.

There are three input terminals marked (+), (–), and ground. In most cases the (–) terminal is grounded, but for "floating operation" (see the material on page 47 for a discussion of "floating") the (–) terminal is not to be grounded. Usually the "high" side of the signal source (the ungrounded wire) is connected to the (+) terminal. In some cases this wire may have to be shielded (with the shield connected to ground) to avoid AC pickup.

You should practice hooking up something like a signal source (a sine or square wave generator will be great) to the recorder and playing (yes, we said "play") with the damping control, the gain, etc. How else can you learn?

MODES OF RECORDING

In general, recorders fall into two large classifications: (1) direct writing and (2) photographic. The charts that these types make fall into three general classifications: strip chart (Z-fold), circular chart, and X-Y charts.

DIRECT-WRITING RECORDERS

There are five recording methods in general use in direct-writing oscillographs. These are (1) ink pen on hard-surface paper, (2) heated stylus on temperature-sensitive paper,

(3) sharp stylus tracing on carbon-coated paper, (4) metal stylus on electro-sensitive paper, and (5) the chopper bar-typewriter ribbon method on hard surface paper. All of these have advantages, disadvantages, and limitations which will now be considered in turn.

The *ink pen* method makes a very neat record under laboratory conditions, but it is definitely limited in usefulness if the recorder is in a vehicle subject to acceleration. The ink will either flow too freely or not freely enough if the acceleration is in line with the direction of the pen. Also, this method is inconvenient if the recorder is to be used intermittently since the ink might dry in the pen and clog. However, under continuous use, very neat records can be obtained and the width of the line is not so dependent on the speed at which the recording pen moves as it is in certain other methods. Trace widths of from 0.015 to 0.005 inch are available. The pen is of the trussed capillary type with one end of the capillary tube riding below the surface of the ink in an inkwell and the other end riding lightly on the chart paper. Provision is usually made to prevent spillage of the ink and for priming the system to start the flow of ink. Once started, however, the inking system will work over long periods of time without attention.

Some recorders, such as those made by the Heath Company, use low-cost tip-wick pens. This makes it easy to change the colors of the ink. It is also much easier to put in a new pen than to clean a capillary inkwell system.

The *heated stylus on temperature-sensitive paper* method is very convenient for eitlier continuous or intermittent use. The stylus consists of a piece of nichrome ribbon or wire that is arranged to ride on the surface of a temperature-sensitive paper as it is pulled over a relatively sharp edge. The general arrangement is shown in Figure 1-45. The temperature of the nichrome ribbon is adjustable and should be set for the best trace. The main disadvantage to this system is that the density and width of the trace depend upon the speed with which the moving arm is deflected.

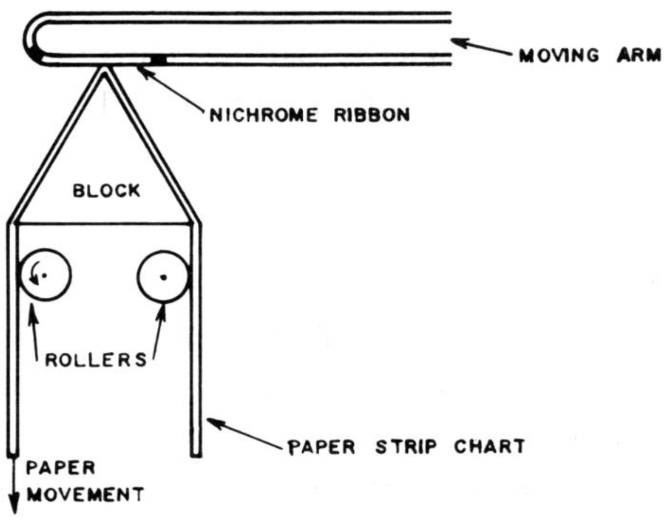

Figure 1-45. Heated stylus on temperature-sensitive paper.

The baseline that is drawn when the arm is not moving is usually much heavier than the line drawn when the arm is moving. However, this system is very convenient for intermittent service because it is ready immediately for service after a short or long period of inactivity. This is not to imply that this system is unsuitable for continuous use; it is very good for continuous use. The temperature of the stylus is adjust~ able while a recording is being made. This makes it possible to adjust the trace for the best resolution of any part of the trace of a periodic function.

The method of a *sharp stylus tracing on carbon-coated paper* is essentially a method of scribing or dotting a trace on blackened or pressure-sensitive paper. This method is also suitable for either constant or intermittent service. The continuous trace type is subject to various errors, and it is thus limited to relatively high current recorders. The dotted-trace type makes a dotted line instead of a continuous line. This is accomplished by intermittently clamping the stylus arm and automatically tapping on the stylus to make a dot on the pressure-sensitive paper. Between dots, the stylus arm is free to swing to a new location, where it is again clamped and tapped to make another dot.

The *metal stylus on electrosensitive paper* is a method in which the circuit between the moving stylus above the paper and the metal platen below the paper is completed by the paper itself, which is electroconductive. This action essentially "burns" a trace into the paper. This method is quite sensitive to the "burning cur-rent": excessive current causes sparking and smoke, and too little current causes an intermittent and weak trace.

The *chopper bar and typewriter* method consists of an oscillating hammer that records a dotted line on a piece of paper in much the same way that a typewriter records letters on a piece of paper. Standard typewriter ribbon is used, and is fed through guides across the strip chart just above a metal writing table. A stylus, activated by the basic current-sensitive element and intermittently tapped, imparts blows on the ribbon, thus making a record on the chart below the ribbon. The records appear to be continuous at most standard chart speeds. For fast chart speeds or rapid deflections of the stylus, the record will be lighter and will consist of a series of dots. This system is very economical, but it is limited to relatively low current, slow speed applications.

More expensive recorders often use paper that is folded (Z-fold) rather than stored on a roll. The only advantage is that the charts tend to lie flat instead of curling up. At this writing, 1980, Z-fold paper is about four times as expensive as regular rolled chart paper.

PHOTOGRAPHIC RECORDERS

Photographic methods are in general of two types: one uses a standard camera mounted to photograph the screen of a cathode ray oscifiograph; the other employs an internal light source and an optical system that focuses the filament of this light source on a photographic strip chart. The position of this image depends upon the position of a small plane mirror attached to a galvanometer, which is a very sensitive ammeter. One great advantage to this latter method is its multi-channel possibilities: only one light source and optical system is required for many channels, and the light beams can cross each other without interference to give overlapping tracings on high amplitude peaks. However, the photographic paper must be loaded, developed, and fixed in a photographic dark room, and the records are not available until after the photographic processing has been completed. With mechanical methods of recording, on the other hand, the records are available immediately.

MULTI-ELEMENT OSCILLOGRAPHS

These instruments are of the photographic type and are available with up to 24 simultaneous recording channels. On most units the paper width is approximately 10 inches, and this paper must be developed by usual photographic techniques. High sensitivity ammeters or galvanometers are usually used with a single-turn coil or even a coil consisting of a single filament of flattened metal with a mirror cemented to it. The frequency response of these galvanometers extends up to 10,000 cycles per second (10kHz), and these units are extensively employed in strain gauge and geophysical exploration work. A single light source is used, and an image of its filament is focused on the photographic paper. There is usually a provision for viewing the trace by means of a many-sided rotating mirror. Only periodic phenomena can be viewed by this rotating mirror system, but transient phenomena as well as periodic phenomena can be recorded.

The principal advantage of multi-element recording oscillographs is the large number of channels that can be viewed simultaneously. This feature is very important in geophysical exploration work in which the delay between the various reflected waves is of significance.

Multi-element recording oscillographs are widely used in the flight testing of aircraft, and special 50-channel units have been developed for this use. Each galvanometer in this unit records the imbalance of a strain-gauge bridge.

X-Y RECORDERS

All of the recording devices described thus far record voltage or current as a function of time. Very often it is desirable to record current as a function of some other parameter. An obvious example is in power supply testing when it is essential to know the output voltage as a function of the current supplied to a load. A device for doing this is called an *X-Y recorder,* and, in the above example, the X quantity would be the current to the load and the Y quantity would be the voltage across the load. These instruments usually employ an ink pen and graph paper 8.5 by 11 inches or 11 by 16.5 inches in size. Some can be converted to Y-t (that is, Y as a function of time) recorders by driving the pen mechanism horizontally with a synchronous motor.

These recorders are actually instruments intermediate between manual data plotting and complex computers. In this respect, the X-Y recorder is a combined data taker and plotter that is very slow compared with oscilloscopes but very fast compared with manual methods. It plots a complex curve in less than 1 minute, and provides a permanent record. Other independent or Y variables may be used to draw a family of curves on a single sheet. Human errors due to interpolation and plotting are eliminated, as is the age-old question of how many points determine a curve – a continuous curve is plotted.

X-Y recorders are usually of the self-balancing potentiometer type with a flat recording surface. Sensitivities of one millivolt per inch for either the X deflection or the Y deflection and writing speeds up to 40 inches per second are available.

Broad fields of application for the X-Y recorder include the recording of strain as a function of stress, pressure as a function of temperature, voltage as a function of current or vice versa, and torque as a function of speed.

CATHODE RAY OSCILLOGRAPH

The cathode ray oscilloscope was described in detail earlier. It is being mentioned again here because of its possible use as a recorder. Recordings are made by photographing the face of the cathode ray tube. This is very often done by mounting a 35 mm roll-film still camera on the front of the oscilloscope, using a light-tight tube. Many oscilloscopes carry a bezel around the tube opening for this use. An-other method is to use a direct.developing Polaroid Land camera. These are available commercially for oscillographic use. Film speeds up to 10,000 ASA are available for these units, and the actual picture is available a few seconds after the exposure has been made.

POSTSCRIPT

At this point we have decided to stop delaying you and launch you into the next chapter, which is all about (you guessed it) op-amps. This doesn't mean there aren't other topics to discuss regarding circuits and instruments – see any FE text for proof of that: But we want you to get some experience with op-amps before you get bored. You will be making mistakes at first, but once you get interested you will find it easier to pick up what you need regarding circuit theory and instrumentation.

There isn't any book, *Circuit Theory Without Pain* (not yet anyway, but give us time). However, the books listed below will be interesting to you when you get to Chapter 3 in our book:

Diefenderfer, A. J. *Basic Techniques in Electronic Instrumentation.*
Philadelphia: W. B. Saunders, 1972.

Smith, R. J. *Electronics: Circuits and Devices.*
New York: John Wiley, 1973.

TEST YOURSELF PROBLEMS AND SUGGESTED EXPERIMENTS

TEST YOURSELF PROBLEMS

1. You have a 90 volt battery, but you really need two voltages of 50 and 40 volts for an experiment. Draw the circuit and show how you would provide these voltages. Note that total current taken from the battery cannot exceed 100 mA.

Answer: The total resistance cannot be less than 900 ohms. The individual resistors have values of 400 and 500 ohms.

2. You have a 0 to 10 mA meter with an internal resistance of 0.01 ohm and you want to be able to read currents from zero to 10 amps. Draw the circuit and calculate the necessary shunt resistor.

Answer: Shunt resistance 10^{-5} ohms.

3. A 2 volt signal source is in series with a resistance of some $l0^4$ ohms. You want to measure this voltage with an error of no more than 1%. How much current can your voltmeter draw from the circuit? What will its internal resistance be?

Answer: Maximum current is 2×10^{-6} amps. Ohmmeter resistance must be 990kΩ.

4. A transformer has a turns ratio (primary to secondary) of 1 to 100. If the input voltage and current are 10 volts at 2 amps, what are the output current and voltage?

Answer: 1000 volts at 20 mA.

What is the wattage input?

Answer: 20 watts.

5. In your own words, discuss the concept of isolation via a transformer and explain why a Variac does not provide isolation.

6. A given meter has an ohms-per-volt rating of 50,000. How much current is required to deflect the meter "full scale"?

Answer: 20 microamps.

If the same meter has a full scale voltage of 100 volts what is the internal resistance?

Answer: 5 M ohms.

7. Discuss, in your own words, how a potentiometer can measure a voltage without drawing any current from the circuit.

8. Discuss, in your own words, the similarities and differences between power supplies and signal generators. What is meant by the phrase "signal generators do not have a low output impedance?" Why would you have units of this type in an introductory student laboratory? What might happen to a low output impedance power supply if you short-circuited it?

9. Suppose you are in charge of a construction project where men are working while standing on wet ground. The engineer in charge asks, "Is it worth paying the extra money to run in three-wire grounded power versus the two-wire system we have now?" Note that a "yes" answer is not enough. He wants to know why.

10. We noted in the text that decibels are a convenient way of handling large numbers. You might convince yourself of this by taking the numbers 10, 100, and 1000 and calculating the decibel values. Even 10^6 is only 120 dB.

11. Design a simple high-pass filter that will stop at least 90% of the signals at 10 Hz and pass at least 90% of the signals at 1000 Hz.

Answer: We can solve for RC from either of two equations

$$0.1 = \frac{20\pi RC}{20\pi RC + 1} \quad \text{yields } RC = 1.77 \times 10^{-3}$$

$$0.1 = \frac{2000\pi RC}{2000\pi RC + 1} \quad \text{yields } RC = 1.43 \times 10^{-3}$$

If we chose 1.77×10^{-3}, the first equation is satisfied and the second yields an even better result.

$$\frac{20\pi 1.77 \times 10^{-3}}{20\pi 1.77 \times 10^{-3} + 1} = 0.916$$

If we use *RC* = 1 .43(10)-~, the first equation yields

$$\frac{20\pi 1.43 \times 10^{-3}}{20\pi 1.43 \times 10^{-3} + 1} = 0.082$$

more than satisfying the 0.1 requirement. If RC = 1.77×10^{-3}, we can choose R = 1000 and C = 1.77×10^{-6} F.

SUGGESTED EXPERIMENTS

Rules of the Lab:

1. *Always check device dial settings before turning on.*
2. *Always turn off all devices before making circuit changes.*

A. VOLTAGE DIVIDER

Using a VOM, two 10 kΩ resistors, and a DC power supply:

1. Draw a voltage divider circuit diagram.
2. Write down circuit equation.
3. Solve equation for the resistor values you are using.
4. Check solution with experimental values.

B. OSCILLOSCOPE

Draw a schematic of the following circuit, then construct it.

1. Connect a diode in *series* with a 10k ohm resistor. Now connect that pair to the function generator set for about 3 volt peak to peak output. The *cathode* of the diode should be connected to the positive terminal of the function generator. Place the scope probe and scope ground across the 10 k ohm resistor.
2. Draw the schematic
3. Which is your choice?

	Scope	Function generator
Ground	____	____
Earth ground	____	____
Chassis ground	____	____
Neutral	____	____
Floating ground	____	____

4. Indicate, on the schematic, how the scope is connected.

C. TIME BASE SELECTOR

Set the oscilloscope trigger mode to INTERNAL AUTOMATIC. Set the function selector, on the function generator, to SINE WAVE. Adjust the frequency on the sine wave to 1 kHz.

1. If the frequency is about 1 kHz, where should the time selector be to see the waveform conveniently on the screen? **(Remember:** Time Base = seconds/cm and 1 kHz = 1000 cycles/sec. Or if you wanted to see 1 sine wave cycle per centimeter,

   1 sine wave cycle/cm = [1000 cycles/sec] [10^{-3} sec/cmj

   Input frequency Time base

2. You should be ready to turn everything ON now. (Remember Rule #1!)
3. At about what setting, on the time base selector, does only 1 cycle fit on the oscilloscope screen?

D. TRIGGERING

There are three modes of triggering: Internal Normal Mode; Internal Automatic Mode; and External Mode.

1. Normal Mode: Set the trigger mode to the "normal" mode. Set the slope of the input waveform, on which triggering is to occur, to POSITIVE (may not be available on your scope). Now adjust the TRIGGER LEVEL until a stable waveform is obtained.

   The scope is~ now triggering on a (1)_______________ (positively or negatively) sloping portion of the input waveform. (Note: The scope triggers on the voltage that first appears at the left hand edge of the screen.) The voltage at the triggering point is (2)________________ (positive or negative).

   Now switch the direction of the diode. (Remember Rule #2!) Adjust the "trigger level" until a stable waveform is obtained. The scope is now triggering on a (1)_________________ (positively or negatively) sloping portion of the input waveform. The voltage at the triggering point is (2)_______ (positive or negative).

2. External Mode: Repeat the above exercise for normal mode except use the external mode selection and external input. The answers are (1)________________ (positively or negatively) (2) (postitive or negative).

   Where was your scope external input connected in the test circuit'? Now connect the scope external input to a different spot on the test circuit (either at the function generator positive terminal or between the diode and resistor). Vary the TRIGGER LEVEL adjustment and note changes. What is the advantage of external mode over other modes'?

E. SIMPLE DC POWER SUPPLY

Construct the following circuit:

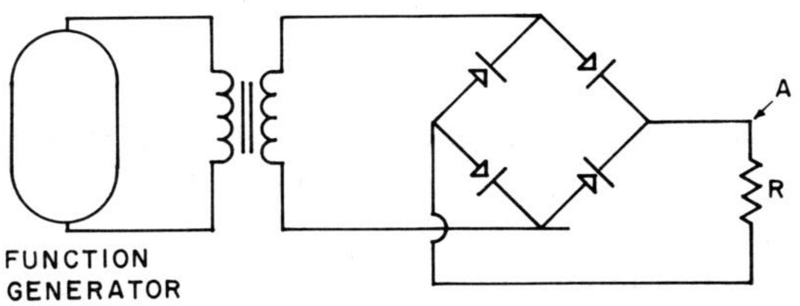

Figure 1-46.

R = 10kΩ

Label the polarities of the transformer output and at point A. Draw a of the output of the transformer (sine wave input).

Draw a sketch of the waveform at point A.

Now place a 0.05μF capacitor in *series* withR. (Remember Rule #1!)

Draw a sketch of the waveform at point A.

Repeat with the capacitor in *parallel* with the resistor *R*.

Insert a 100 kΩ resistor in place of the 10 kΩ and sketch point A. What's happening and why'??

F. TRANSFORMERS

Observe how many inputs and outputs there are; then draw a schematic labelling primary and secondary lines. Using your function generator as an input to the transformer, determine the values of N for each output.

Remember: $N = \frac{V_{secondary}}{V_{primary}}$

BASIC TYPES OF COMMERCIAL OP-AMPS

In Figure 2-1, you are looking at a typical op-amp. An op-amp is a black box or a small can with anywhere from 6 to 14 pins or lead wires.* To find out which pin is which you must first realize that op-amp manufacturers are *not* consistent about how they mark their products. We will start with a variation of the old Burr-Brown system† because I think it is easier to learn. At the same time, we will use the newer system that most manufacturers seem to be using. Manufacturers of op-amps give out instructions with their products, so you can easily identify the proper terminals and correlate our instructions with whatever op-amp you happen to have.

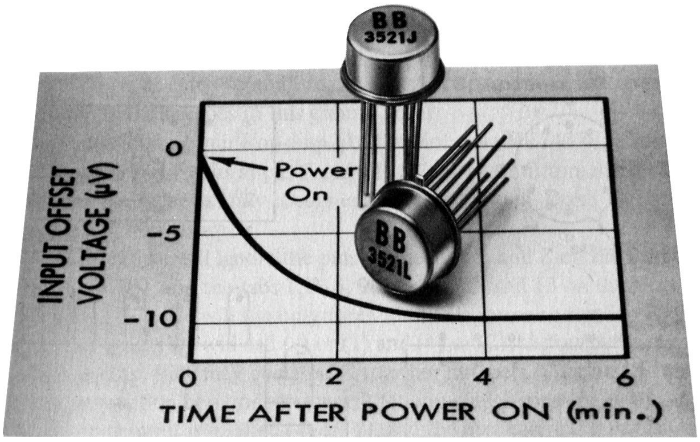

Figure 2-1. A typical op-amp: the Burr-Brown model 3521L. (Courtesy of Burr-Brown Research Corporation, Tucson, AZ)

"First tell me what you can afford, and we'll have a good laugh and go on from there."

---

* I assume that you can find or borrow some op-amps in whatever organization you are connected with. If this is not the case, you may as well torn to the section on “How To Buy Op-Amps” (pages 95-96).

† Burr-Brown Research Corporation, P.O. Box 11400, Tucson, AZ 85734

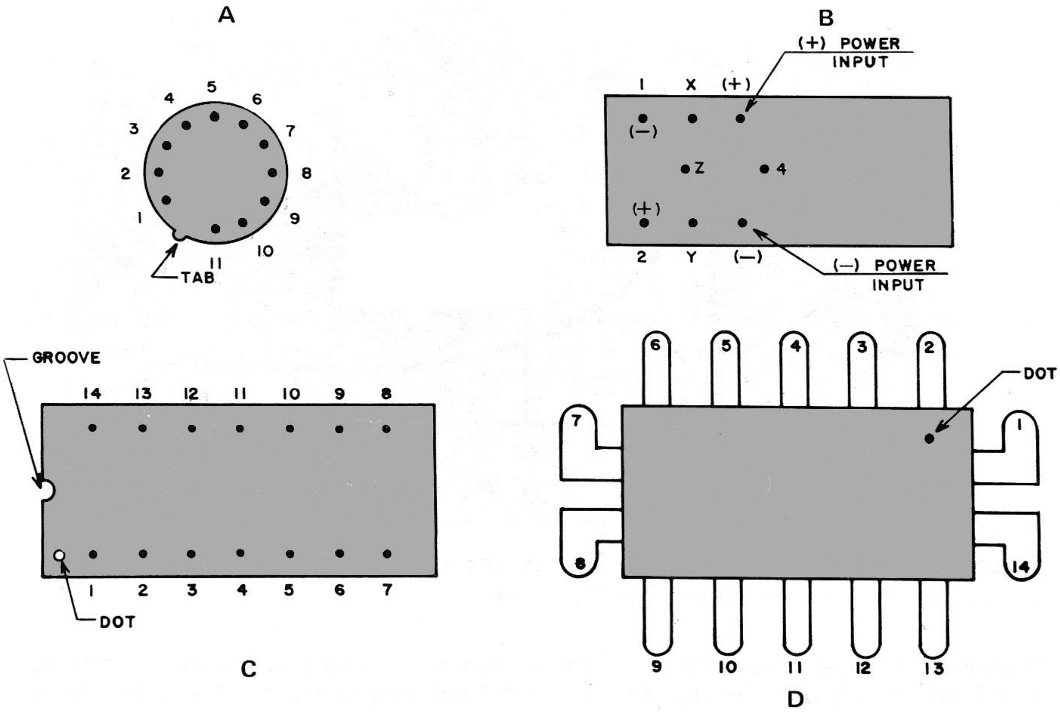

Figure 2-2. Op-amp packages. A: Op-amp can, bottom view; B: Op-amp module, bottom view; C: Dual in line package, top view; D: Flat pack.

There are four basic types of op-amp packages: cans, flat packs, dual inlines, and modules. Figure 2-2 shows the four types and how to identify the terminals. You *should not* – repeat, *should not* – be frightened by the large number of pins. The system is simple once you know the secret code. A few examples will make this clear.

Consider the Burr-Brown 4008/40 module op-amp. The module is shown in Figure 2-2B. The first thing you do is hook up the power supply. Hook up some batteries as shown in Figure 2-3 (batteries are much cheaper; power supply circuits will be discussed later). Numbers 1, 2, and 4 are Burr-Brown's old system. The plus and minus signs on pins 1 and 2 are the more universal notation that we mentioned before. Note that the center tap to ground *could* be run to earth through a water pipe but for now "ground" can be any one point on your circuit breadboard. It doesn't *have* to be connected to anything: it is just your ground point. *Every* connection marked "ground" goes to this ground point.

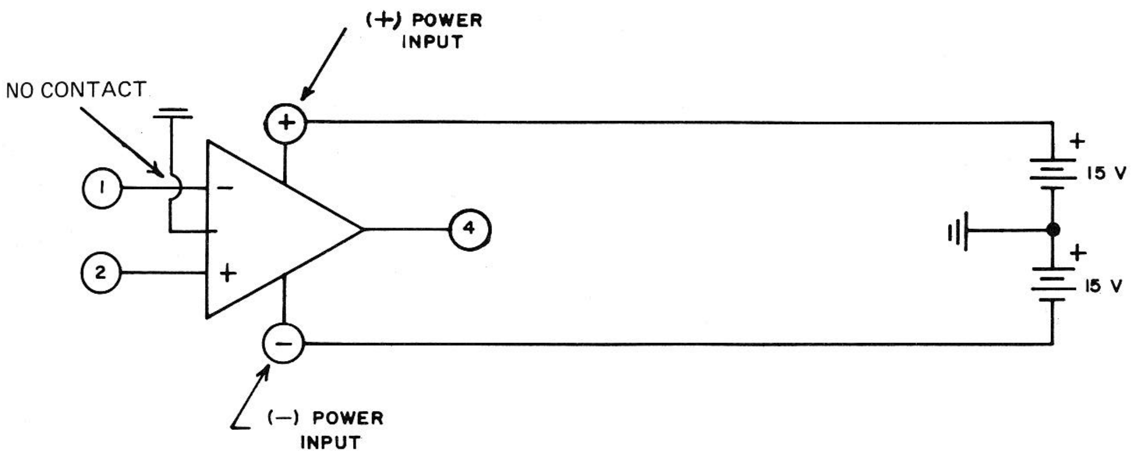

Figure 2-3. Power supply connections for an op-amp.

If you are using a dual inline op-amp like the Motorola MC1437P (Figure 2-2C), the power inputs are –15 volts at pin 7 and +15 at pin 14. In future discussions *we will* *assume* that the power supply is connected to the op-amp. Don't be afraid: count the pins and hook it up.*

For the moment we will ignore the pins marked X, *Y*, and *Z* on the Burr-Brown module (Figure 2-2B), and the tabs 1, 3, 4, 9, 10, 11, 12, and 13 on the Motorola package (Figure 2-2C). We will use only three terminals for now: two inputs and one output. The inputs we will call (–) or (1) and (+) or (2); the output is obviously (4). On your op-amp, they may correspond to other numbers or letters. A look at your op-amp instruction book or catalog will tell you which pins are inputs and outputs. The *inverting* input is marked (–) or (1), and the *noninverting* input is (+) or (2). The other pins and the meaning of inverting and nomnverting will be explained later.

A WORD OF CAUTION: we will assume that you have read and worked through Chapter 1 *or* that you know how to use VOMs, diodes, resistors, inductors, capacitors, signal generators, and oscilloscopes. If you don't, *please* go back to Chapter 1. You can't build bricks without straw. If you are at least vaguely familiar with the above instruments and devices, great! Proceed with vigor, and if you get stuck on a device or an instrument, go back to Chapter 1 and read up on it.

SOME ELEMENTARY OP-AMP CIRCUITS

Having hooked up the power supply, the next thing to do is learn how to draw an op-amp circuit and how to hook one up. Figure 2- 4A shows a symbolic op-amp in which the inputs are designated by (–) and (+) or (1) and (2). The output is numbered (4). We have *assumed* that a power supply has been attached to the proper terminals and that the op-amp is ready to go. The *(-) or (1) input* means that *if a voltage that is positive with respect to the (+) or (2) input were applied, the output would go negative.* **Please note that the (+), (-) notation does *not* mean (+) voltages go in one terminal and (-) at another; it means that the (-) terminal inverts and the (+) one does not.**

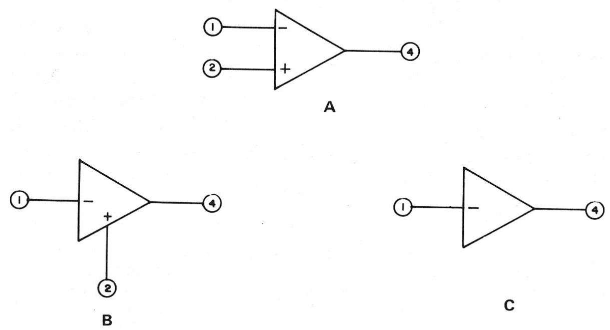

Figure 2-4. Different systems of op-amp notation.

Other and still worse forms of notation are shown in Figure 2-4B and C. In Figure 2-4C the *only* input terminal shown is the (–) or number (1) input. You are supposed to *know* that number (2), the (+) terminal, is connected to ground (which isn't shown either). In this book we will use the notation of Figure 2-4A, but be on your guard when venturing into strange territory.

* When we wrote the first edition of this book, most op-amps required + and –15 volts from the power supply, and in many circuits you will see that a -15 and +15 supply has been drawn in. Before you say, "I can't find that much voltage in my application," you should be aware that in early 1979 two manufacturers announced op-amps that operated on –1.1 and +1.1 volt power supplies. Such is progress: for details see G. Mhatre, Low-voltage op-amps due from two vendors. *Electronic Engineering Times*, Feb. 5, 1979, P.24.

OPEN LOOP AMPLIFIER CIRCUIT

The first and simplest op-amp circuit is what we call an *open loop amplifier,* which is shown in Figure 2-5. The *ratio* of the output to imput voltage, *Vo/Va,* is called *ipen loop gain.** The gain of a good op-amp is large, sometimes as much as 10^5. This is great, but if our trusty op-amp has a maximum output voltage of, say, 10 volts, and if $V_0/V_a = 10^5$, an input of $V_a = 10^{-4}$ volt will drive the op-amp to saturation.† Stray voltages of 10^{-4} volt are all too common, and open loop circuits are used *only* for switches that are ON or OFF.

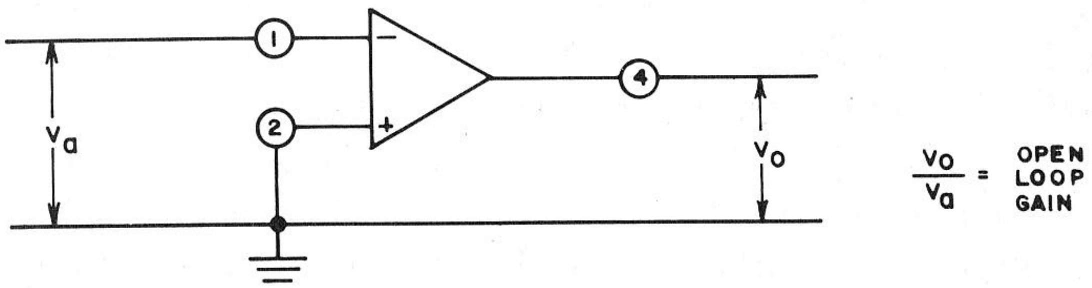

Figure 2-5. Open-loop amplifier circuit.

We would like to have a *linear amplifier,* so that *if the input is a sine wave, the output looks like a bigger sine wave.* A linear amplifier is shown in the circuit of Figure 2-6, which can be considered our first practical op-amp circut, i.e., one you might really use. Notice that a resistor R_0 has been connected between the output and the input: this is called a *feedback resistor* because it feeds back some of the output signal to the input. This improves the amplifier in several different ways, as we shall see below. For the moment, the important point is the *new* relation between V_0 and V_1, to wit, $V_0/V_1 = -R_0/R_1$. Now the gain of the op-amp is *controlled* by the external resistors. More importantly, if R_0 and R_1 are *variable* resistors, we have an amplifier that can be controlled quite easily. We shall refer to the ratio V_0/V_1 as the *closed loop gain* because we have closed the feedback loop by connecting R_0 between the output and the inverting input. Note that the closed loop gain is a function *only* ofR_1 and R_0: it is *not* dependent upon the characteristics of the op-amp. That is the big difference between open loop gain and closed loop gain.

You should set this circuit up and play with it yes, I said *play!* If you can't have fun with electronics, why bother learning about it? So have fun and gain confidence; op-amps are almost indestructible. Use a signal generator to produce V_1 (1 volt peak to peak is about right). If R_0/R_1 is about 5, the output will be about 5 volts peak to peak. Notice that this circuit inverts the sign of any signal you apply to it.

Try varying V_1 from 10 Hz to 10 kHz while holding the peak-to-peak amplitude constant and, at the same time, watch the amplitude of V_0 with an oscilloscope or a voltmeter (remember most meters read rms voltage, not peak-to-peak voltage). You will observe that V_0/V_1 drops off as the input frequency goes up above 10 Hz: this is called *amplifier roll-off.* This decrease in gain with frequency is a characteristic of all amplifiers. (You have to know the habits of an animal in order to catch and tame it.)

---

* This definition of *gain* as output over input is a most important one and we urge you to remember it. It will be used extensively throughout Chapters 2, 3, and 4.

† Saturation means that the op-amp output goes to its maximum value (about 12 volts either plus or minus) and stays there. This isn't necessarily bad for the op-amp but it isn't very useful, so we try to avoid it if possible.

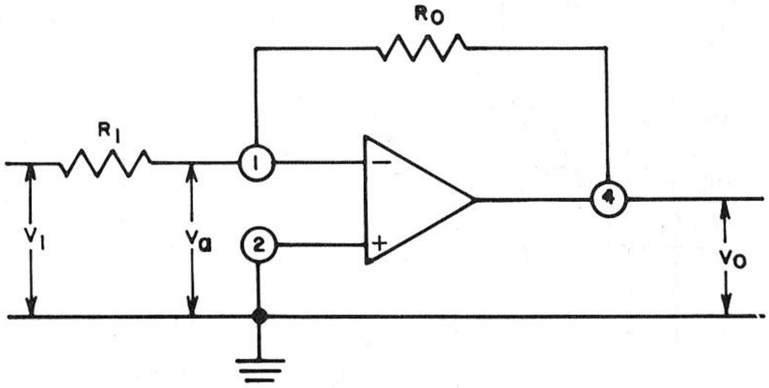

Figure 2-6. Inverting amplifier circuit.

Gain versus input frequency data is presented in what EFs call a *Bode plot.* A typical Bode plot is shown in Figure 2-7. Notice that in Figure 2-7, gain is expressed in *decibels* (dB). We defined the decibel in Chapter 1, and we use it here as a convenient way to handle large numbers. The dB (gain in decibels) = $20\log_{10}(V_0/V_1)$. It is convenient to remember that a gain of 10^5 is 100 dB, 10^4 = 80dB, 10^3 = 60dB, 10^2 = 40 dB, 10 = 20 dB, and 1 is 0 dB. The decibel scale is confusing at first, but it has its virtues.

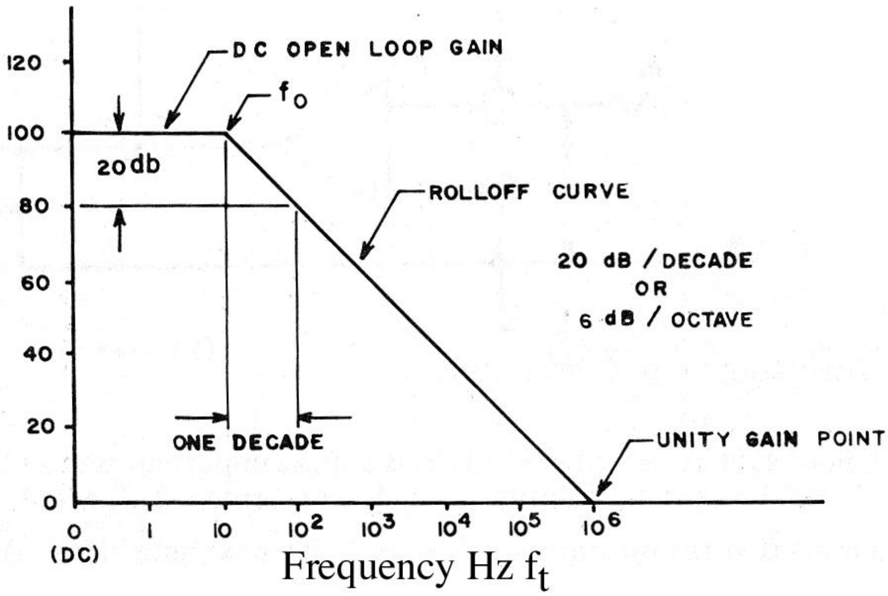

Figure 2-7. A typical Bode plot.

Looking back at Figure 2-7, we see that for this op-amp the gain is constant (and very large) up to 10 Hz. The gain drops off linearly, on a logarithmic plot, until at 1 MHz (10^6 cycles per second) there is *no* gain. It is important to note the frequency at which the gain begins to fall off (often called f_0) and the frequency at which the gain falls to zero dB or *unity gain* (called f_t). The slope is 20 dB per decade or 6 dB per octave. This means that if we double the frequency of the input signal (from, say, 100 Hz to 200 Hz), the gain drops from 80 dB to 74 dB, or a drop of 6 dB. If we go from 100 Hz to 1000 Hz, the gain drops to 60 dB, a loss of 20 dB. This notation may seem complex (and it is), but it is also useful in evaluating amplifiers.

To see what roll-off* means in an actual circuit, let's consider a circuit operating at a gain of 20 dB (V_0/V_1 = 10). The gain stays constant up to 0.1 MHz, so the cuit can be expected to operate without problems from DC to 0~l MHz. If a gain 1000 is needed, the

* Recall – or review – the discussion of roll-off in connection with filters in Chapter 1 (page 22).

gain begins to fall off at 1 kHz. This is called the *gain × bandwidth product,* and, roughly speaking, *the product of the gain and bandwidth is a constant.* High gain means low bandwidth (remember that concept).

Op-amp manufacturers try to get the highest gain-bandwidth product, but of course every improvement adds its factor of increased cost. The fight for increased gain-bandwidth has led to another problem, namely, a change in the slope of the roll-off curve with ftequency. We will come back to this problem later. For now, don't expect both high gain and high frequency response at the same time.

NONINVERTING AMPLIFIER CIRCUIT

Having put together an op-amp circuit, seen it work, and observed its gain-bandwidth behavior, we are ready for our next circuit: the *noninverting amplifier* (Figure 2-8). This circuit has several interesting features: first, the gain is given by

$$V_0/V_2 = (R_0 + R_1)/R_1;$$

second, we note that now the output and input are of the *same sign* – the amplifier does *not* invert the input signal. The gain of this amplifier can be ontrolled by varying either R_1 or R_0, but our gain equation indicates that varying R_0 is more effective (R_1 also occurs in the denominator). For best sensitivity, R_0 should be greater than R_1.

Once again, *you should set up this op-amp circuit, play with it, and test its response to signals of different frequencies.* The gain-bandwidth effect shown previously with the inverting op-amp circuit is easily observed with the noninverting circuit. You may wonder about the resistor R_3: this is something you *might* have to put in if you use certain types of signal generators. The reasons for this will be discussed in more detail in Chapter 6. For now, consider R_3 as something you put in *if* the op-amp fails to work or saturates. Of course, with R_3 in place, the input impedance is no longer infinite but R_3. (Life is like that!)

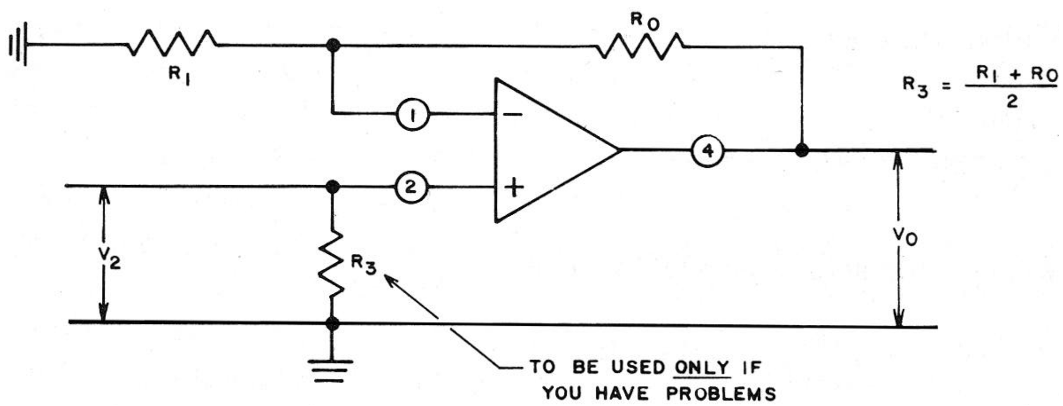

Figure 2-8. Noninverting amplifier circuit.

As long as we are talking about problems, we must prepare you for that old devil: *oscillation.* Op-amp circuits go into oscillation sometimes, and then the output, V_0, looks like a messed-up sine wave no matter what you do to the input. Don't worry about it. We will discuss this problem and its complete cure later. For now, put a capacitor of about 100 pF (1 picofarad is 10^{-12} F) across R_0 and the problem should go away (if 100 pF doesn't work use 10 pF). This will work on either the inverting or noninverting amplifier; it will cut your high-frequency gain but the DC gain will not change.

Returning to the op-amp system, we must introduce some new concepts if you are to use the capability built into every op-amp by the manufacturer. One of these concepts is the notion of *impedance.* When we speak of op-amp impedance, we are talking about *how much* electrical resistance we find at the input terminals. This resistance in turn defines how much current the op-amp will take from a voltage source. For example, if a hypothetical op-amp has an imput impedance (resistance) of 10,000 ohms, how much current will it draw from a 1 volt source? The answer is provided by Ohm's law; since V = IR, I = $1/10^4$ = 0.0001 amp. A 1 MΩ resistance will draw only 1 µA, and so on. This is important to us because some voltage sources have *very little* current capability. A thermocouple, for example, might require a 5 kΩ minimum load impedance; a pH meter will yield a poor or negligible reading when attached to a voltmeter with less than 1 MΩ of impedance.

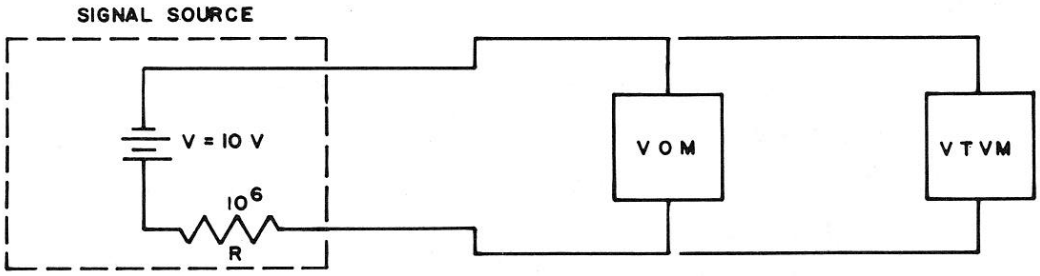

Figure 2-9. Measuring the voltage of a high impedance source.

The concept of impedance is important enough – and confusing enough – to warrant some further discussion. Suppose that our signal source is a 10 volt battery in series with a 1 MΩ resistor (this might well be a certain type of pH meter), as shown in Figure 2-9. A VOM and a VTVM* are used to measure the source voltage. The VOM has an internal resistance of, say, 20 kΩ, and the VTVM has an internal resistance of 10 MΩ. The VOM will draw a current I of

$$I = \frac{10}{10^6 + \left(2 \times 10^4\right)} = 9.8 \times 10^{-6} \text{ amps}$$

The VTVM will draw

$$I = \frac{10}{11 \times 10^6} = 9.1 \times 10^{-7} \text{ amp}$$

The voltage drop across the VOM will be

$$\left(2 \times 10^4\right)\left(9.8 \times 10^{-6}\right) = 0.196 \text{ volt}$$

The remaining 9.8 volts is *across* the internal resistance of the signal source. Our VOM reading is in error by a factor of

$$\frac{10 - 0.196}{10} \times 100 = 98\%$$

With the VTVM, the voltage drop is (9.1×10^{-7}) (10^7) = 9.1 volts: the remaining voltage is dropped inside the signal source. The error is now

$$\frac{10 - 9.1}{10} \times 100 = 9\%$$

This extreme example demonstrates the importance of impedance control and the matching of source output and detector input resistances. The term *matching* is used here to mean that a device with a high output impedance should be monitored by a detector with a still higher input impedance; in this sense, they are matched.

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* Look up VOMs and VTVMs in Chapter 1 if you have forgotten them.

The next question might be: What is the input impedance of an op-amp? Here we must introduce a bit of philosophy. You probably didn't know EEs were philosophers: indeed they are and they work very hard at it (of course, most of them don't realize that some of these ideas are over 2000 years old). Plato introduced the idea of the "ideal" in the sense that there existed, apart from the various imperfect particular instances that we see in the world, an ideal chair, table, man, and so on. The properties of this ideal form could be defined and understood better than those of individual instances. It followed that the more our "real" chair, table, etc., became like the ideal, the more perfect it would be. The ideal need not "really" exist except in one's mind, but the definition of the general properties of the ideal can be useful in our acquiring knowledge of the real world. In electrical engineering we use term *models* instead of ideals, but Plato would feel quite at home with an up-todate book on the theory of modeling in electrical engineering. ("The more things change, the more they remain the same.") We will define the ideal op-amp and use the concept to analyze circuits; then in Chapter 6 we will see how real op-amps and circuits differ from the ideal. We can come far closer to the ideal op-amp than any man has ever come to Plato's ideal man, which might or might not be of some significance. The solution of that question is left as an exercise for the reader.

IDEAL OP-AMPS

The ideal op amp has infinite input impedance and draws zero current from a voltage source. The ideal op-amp has *infinite gain, zero offset voltage, zero phase shift, and zero output impedance*. To see what these strange terms mean, let's return to our first useful circuit, the inverting op-amp.

In Figure 2-10, op-amp inputs (1) and (2) are summing points.* Point (2) is at ground potential and may be considered to have zero voltage.

The input voltage V_1 is applied as shown in Figure 2-10. If the op-amp has zero input current, any input current through R_1 *must* flow out through R_0. The ideal op-amp has infinite impedance, so *no* current flows into the op-amp at terminal (1).

Let's see what we can deduce from these exciting facts. First, the current I_1 is *entirely* controlled by V_1 and R_1, so $I_1 = V_1/R_1$. No current flows into the op-amp, so $I_1 = I_0$. Second, since $I_0 = I_1$, then V_0 must be large enough to push a current I_0 through R_0. Hence, $V_0 = I_0R_0 = I_1R_0 = V_1R_0/R_1$. This leads us to the relationship between V_0 (the output voltage) and V_1 (the input voltage):

$$\frac{V_0}{V_1} = -\frac{R_0}{R_1}$$

The minus sign, which appeared without warning, comes from the fact that this is an *inverting* amplifier: if V_1 is (+), then V_0 is (–). The thing to remember is $V_0/V_1 = -R_0/R_1$. This is an important relationship and you will be seeing it again and again.

To make sure that you really appreciate these great ideas, we will go through this analysis again in a slightly different way. Applying our current conservation rule to junction 1, we write:

$$I_0 = I_1$$

* A summing point is any point where we apply the current conservation law: *The sum of all currents in and out of a summing point must be zero.* In this case, at point (1) we have $I_1 - I_0 = 0$. A summing point is sometimes called a *nodal point*.

Assume for the moment that the op-amp input (1) is at some voltage, V_a (we don't really need to know how much). The current through resistor R_1 is, according to Ohm's law,

$$I_1 = \frac{V}{R_1} = \frac{V_1 - V_a}{R_1}$$

Similarly, the current in resistor R_0 is

$$I_0 = \frac{V_a - V_0}{R_0}$$

Since $I_1 = I_0$,

$$\frac{V_1 - V_a}{R_1} = \frac{V_a - V_0}{R_0}$$

If $V_a = 0$, we would have $V_1 / R_1 = -V_0 / R_0$, or $V_0 / V_1 = R_0 / R_1$, the *gain law* for this circuit. The next problem is to convince ourselves that V_a – the voltage at point (1) with respect to ground – is zero. Recall from our discussion of an open loop amplifier (Figure 2-5) that the gain, which we will now call A, was defined as V_0 / V_a. It follows that $V_0 / A = V_a$. If A, however, is infinite, then $V_a = 0$. And one of the properties of our ideal op-amp is that it has infinite gain. This was what we needed to prove that $V_0 / V_1 = -R_0 / R_1$.

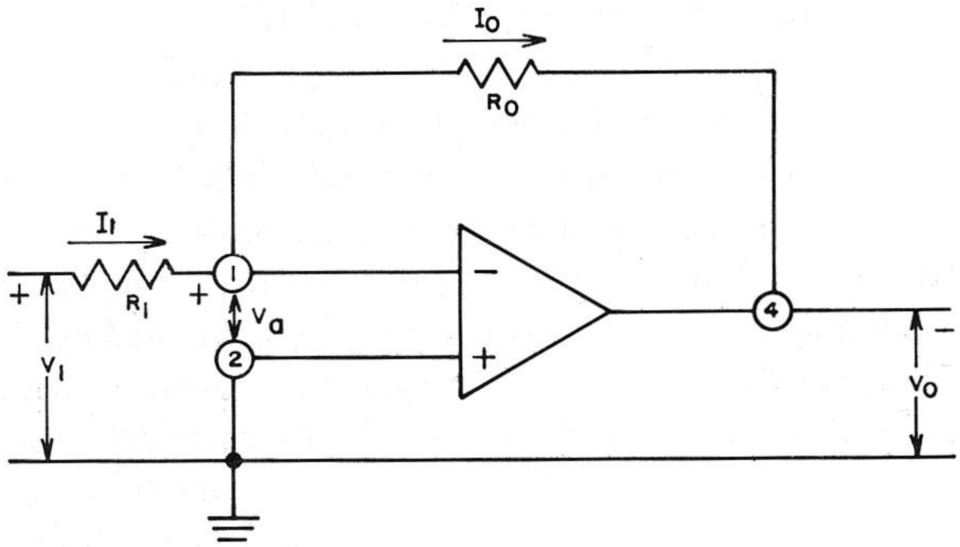

Figure 2-10. Inverting amplifier circuit showing current relationships.

One question. that frequently bothers students is "why" the voltage V_a is zero when a feedback resistor has been connected in the circuit. The answer is simple when you think about it. If V_a is (+) with respect to ground, the voltage fed back from the output is negative – it drives V_a to zero. In fact, the feedback voltage is just large enough to keep $V_a = 0$: the bigger V_a, the bigger the feedback voltage and vice versa.

At this point you probably feel that you have been had, and in a sense you have. However, the trick was played for a good cause: you should be convinced that if A (the gain) is large and there is feedback, the *voltage between points (1) and (2) is vanishingly smalL* This is important since it allows us to assume that for our ideal op-amp, points (1) and (2) are at the *same voltage*. There is an important and subtle point here: the op-amp input impedance is is infinite, but if *any* feedback exists from (4) to (1), then inputs (1) and (2) are at the *same* voltage. This means that the effective resistance between points (1) and (2) is zero, and the op-amp circuit impedance is controlled by R_1 *only*.

If we connect a 1 volt battery as V_1 and if R_1 = 10 MΩ, then I_1 = 0.1 µA. This current does not really flow into (1) and out of (2): rather, it flows in through R_1 and out through R_0, but the effect of the circuit is as though (1) and (2) were connected together.

This inverting op-amp circuit allows us to match the output impedance of any device by choosing R_1 properly. However, we *must avoid* making the common beginner's mistake that is shown in Figure 2-11. Here the source has an impedance of 100 kΩ, and the student matches it with a resistance of R_1 = 100 kΩ. The current is I = 1 volt/200 kΩ = 5 µA, and the voltage drop across the internal resistance is IR = 0.5 volt. So the best op-amp in the world still would give us a 50% error. Why? The answer is we *drew* current from the voltage source.

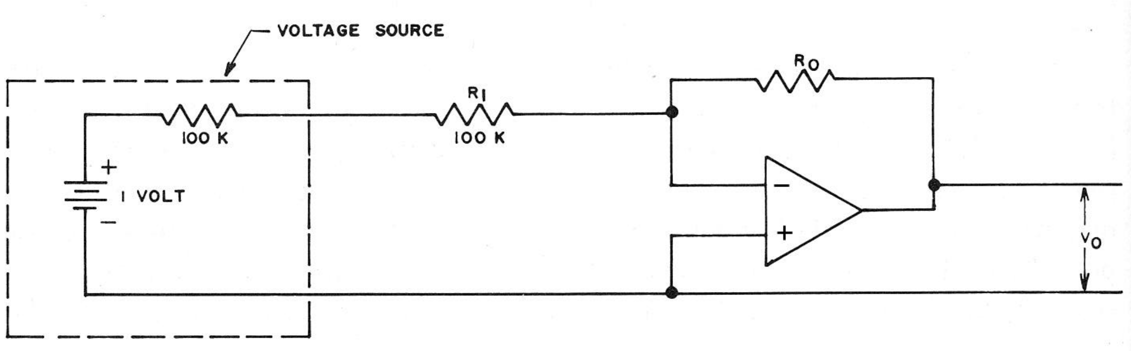

Figure 2-11. How *not* to measure the output voltage of a high impedance source.

To get away from this problem we have to use another op-amp circuit, which will be presented in due course. At this point, we urge you to remember that the input impedance of the op-amp is *infinite.* However, when we look (in the electrical sense) into the inverting amplifier circuit, we see an impedance of R_1 ohms, not infinity. The reason is simple: point (1), the (–) terminal, is at ground potential because V_a = 0. This means that the input impedance is R_1, the external resistance in the input circuit. It follows that the current take is controlled by both R_1 and the source resistance in the voltage source.

This is a point that causes much confusi6n for beginners in the "art of op-amps." The op-amp has certain properties of its own, i.e., infinite input impedance. However, when we hang resistors, capacitors, etc., across the op-amp, its characteristics change. An analogy might be the familiar auto engine. It has certain torque/speed characteristics, but we can put various transmissions and differentials in the system that provide a variety of properties. An example might be the 6 cylinder engine: its behavior in a Chevie truck and a Datsun 280 Z are very different.

There is another point that we must emphasize: if there is feedback from the output to the (–) input, the voltage V_a between the (–) and (+) inputs is zero. This does *not* mean that the (–) and (+) inputs are short-circuited inside the black box: rather, it is a property of the feedback circuit we have built.

Remember that the *effective* input impedance of this circuit is R_1, and that we can match the output of any device by simply adjusting the value of R_1. Those of you who have tried to match a high-fidelity amplifier with a high-output impedance to a loudspeaker with an 8 ohm coil will understand how useful this property of op-amps can be. Of course, a simple op-amp won't drive an 8 ohm speaker by itself, but we will show you how to handle that problem later in Chapter 3. While we are on the question of impedance matching, we should discuss two *separate and distinct* uses of that word.

The first application is *measuring a voltage.* In this case we want a very high input impedance so that essentially *all* the source voltage will be across the measuring device. We saw, in the example of measuring a signal source with a VTVM (Figure 2-9), that 10 MΩ was not really enough when the source impedance was 1 MΩ.

The second case of interest is when we wish to transfer *maximum power to the load.* Every electrical engineering text goes through a derivation that proves that maximum power transfer occurs when the load impedance is *equal* to that of the source. This is illustrated in Figure 2-12.

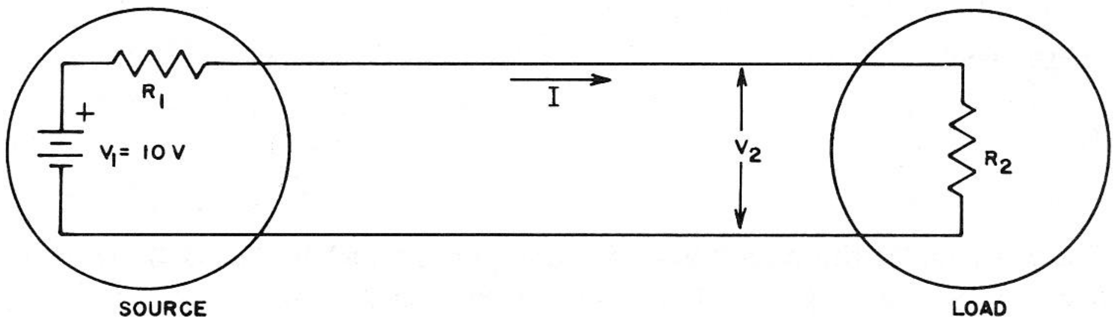

Figure 2-12. Power transfer relation between source and load.

In Figure 2-12,

$$I = \frac{V_1}{R_1 + R_2}$$

and

$$V_2 = IR_2 = \frac{V_1 R_2}{R_1 + R_2}$$

Therefore, if $R_1 = R_2$, then $V_2 = V_1/2$; that is, only *half the* source voltage appears across the load. This is a good matching system for the *best delivery of power* to the load. Once again, however, we repeat that it would be a *very bad* system if you wanted to measure the source voltage V_1.

Another point that sometimes causes confusion is the *current* that an op-amp delivers to a load. With normal inverting or noninverting circuits, we control V_0 by means of resistors, i.e.,

$$\frac{V_0}{V_1} = -\frac{R_0}{R_1} \quad \text{or} \quad \frac{V_0}{V_1} = \frac{R_0 + R_1}{R_1}$$

The current through the load is set by V_0 and the *load resistance,* R_L If V_0 = 8 volts and R_L = 10 kΩ, then

$$I_L = \frac{8}{10^4} = 0.8\text{mA}$$

This is entirely *independent* of the input current I_1; it *only* depends upon V_1, R_1, and R_0. In this case the op-amp acts as a *constant voltage generator.*

However, op-amps can also act as *constant current generators* or current sources. A typical constant current circuit is shown in Figure 2-13.* Here V_1 delivers a constant current through R_1 that *must* flow through R_0. Now if R_0 varies, the current through R_0 *remains constant* because V_1 and R_1 are constant. So if R_0 is our load, the current in

* A "neat" application of this circuit is shown in Figure 3-6, where you will discover how to make a cheap ammeter act like one that costs a lot more.

the load is constant *regardless* of how the load resistance changes with time. The op-amp has become a *constant current source.*

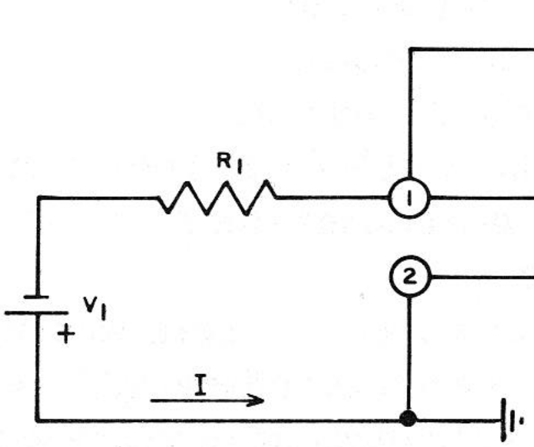

Figure 2-13. Constant-current circuit.

Flushed with these victories, we can resume analyzing the noninverting op-amp circuit of Figure 2-8 in the light of what we have learned from studying ideal op-amps. Redrawing Figure 2-8 as Figure 2-14, we put in current arrows and the hypothetical (but useful) voltage V_a between op-amp inputs (1) and (2).

Since *no* current enters the ideal op-amp at point (1), we know that $I_0 = I_1$. From Ohm's law,

$$I_1 = \frac{V_2 + V_a}{R_1} \quad \text{and} \quad I_0 = \frac{V_0 - (V_2 + V_a)}{R_0}$$

hence,

$$\frac{V_2 + V_a}{R_1} = \frac{V_0 - (V_2 + V_a)}{R_0}$$

If we now assume that $V_a = 0$ (which we can do since this is an ideal op-amp) and some algebraic tricks, we can show that

$$\frac{V_0}{V_2} = \frac{R_0 + R_1}{R_1}$$

This was the gain law that was given earlier for this circuit. This is a *very* important equation. We suggest you not merely learn it, but actually understand where it omes from.

Now we might ask, what is the input impedance of *this* circuit? The answer is infinity: *no current* flows into the ideal op-amp at point (2). For commercial opamps, however, the actual input impedance ranges from perhaps 300 kΩ for cheap ($2) devices to l0^7 MΩ for expensive op-amps. In actual practice there are a few to make the op-amp act as though the input impedance were almost infinite. We will tell you about those tricks in Chapter 6.

By the way, if you put this op-amp circuit on the voltage source of Figure 2-11, the current drain would be *zero.* The voltage drop across the internal resistance would be zero, and the op-amp would measure the *correct* 1 volt output voltage.

Another important op -amp circuit is the *voltage follower.* A typical voltage follower circuit, shown in Figure 2-15, is often used to match high-output-impedance devices to low-input-impedance recorders. The voltage follower does *not* produce any gain, but it is extremely stable and effective as an impedance matching circuit.

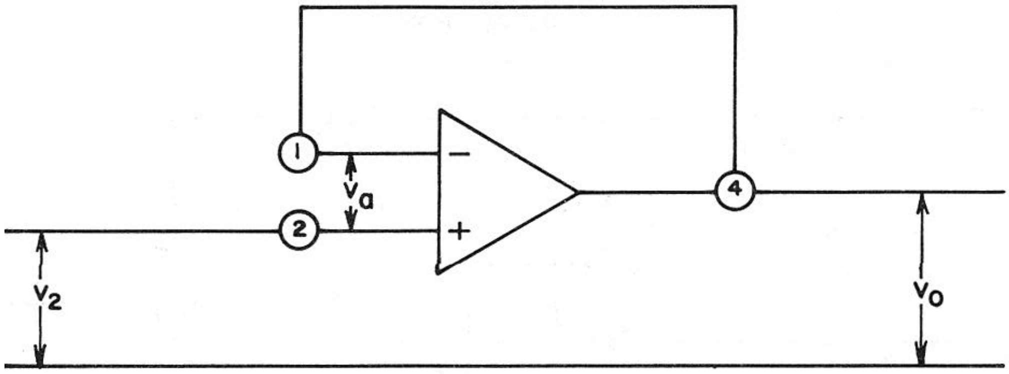

Figure 2-15. Voltage follower circuit.

The analysis of the voltage follower circuit is quite simple: since $V_2 + V_a = V_0$ and $V_a = 0$ (being an ideal op-amp), then $V_0 = V_2$. This is a *unity gain* circuit with *infinite input impedance* and *zero output impedance.* Circuits of this type are frequently used for "signal conditioning" if signals are to be sent over long wires.

The concept of signal conditioning is worth some added discussion. Suppose you are in a copper refining plant where a pH meter is measuring the acidity of a leaching solution. The man in the control center wants to know what the pH is on a continuous basis, but somehow you suspect that a conventional pH meter circuit will not pass current through the two miles of wire between the leach tank and the control center. What to do? You put in an op-amp circuit as shown in Figure 2-15. The input impedance is very high (infinite for an ideal op-amp) so the current taken from the pH meter is very low. Great! The output impedance of the op-amp is very low so it easily drives the necessary current through the two miles of wire – presto, the problem is solved. Industrial operations make use of many, many op-amps.

Here again we emphasize that you should be building op -amp circuits while reading this book. Just reading will never get you to the point of being confident in the use of electronics. ("Be ye doers of the word and not hearers only.")

SOME IMPORTANT OP-AMP CONCEPTS

COMMON MODE VERSUS DIFFERENTIAL MODE

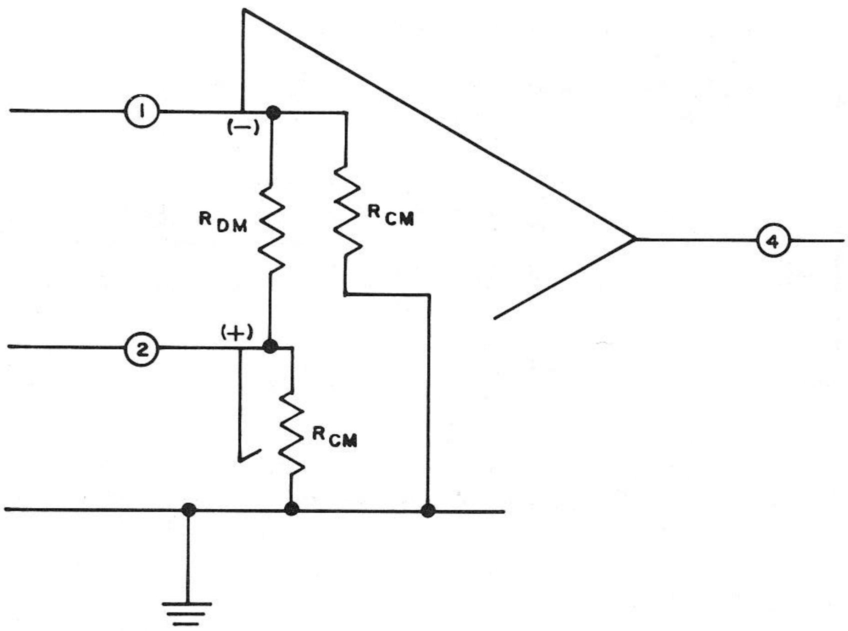

Figure 2-16. Op-amp input impedances.

At this point we must clarify a sometimes confusing definition relating to the input impedance and characteristics of real op-amps: namely, *common mode* versus *differential mode*. The meaning of these terms is illustrated in Figure 2-16. In this diagram there is a resistance R_{DM} between inputs (1) and (2), and a resistance R_{CM} from (1) and (2) to ground. You should note that all these resistors are *inside* the op-amp; you *cannot* change them. The manufacturer will give a *common mode impedance* in the specification sheet. This is the resistance R_{CM}. If we connect input points (1) and (2) together and apply a voltage V, the current to ground will be $I = 2(V/R_{CM})$ because the R_{CM} resistors are in parallel.

If we apply a voltage difference *between* inputs (1) and (2), this is called *differential input*. The impedance in differential input, R_{DM}, is usually smaller than R_{CM} for common mode input. If it is 5 MΩ, the current drain due to a 1 volt difference between (1) and (2) is 0.2 µA.

An important characteristic of op -amps is called the *common mode rejection* (CMR). This simply means that if the voltages applied to inputs (1) and (2) are equal in both sign and magnitude, the output of the ideal op-amp is *zero.* This is easy to see if we note that terminal (1) is the inverting input, whereas (2) is the noninverting input. Suppose V_1 is a positive signal: it thus produces a negative output at (4). However, if $V_2 = V_1$, then V_2 produces a positive output at (4), and the net output is zero. This is illustrated in Figure 2-17. Note in Figure 2-17 the ground connection between V_1 and V_2 is not needed in a real circuit. We use it here as an analytical convenience.

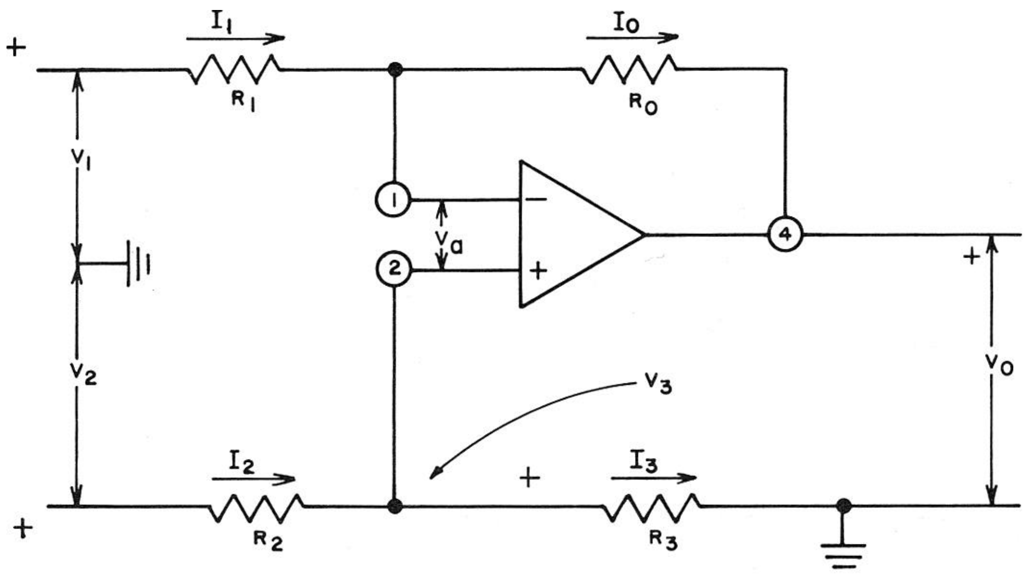

Figure 2-17. Common mode input.

In Figure 2-17, $I_1 = I_0$ and $I_2 = I_3$, because no current can flow into the op-amp. Now V_a is zero so

$$I_1 = \frac{V_1 - V_3}{R_1} \quad \text{and} \quad I_0 = \frac{V_3 - V_0}{R_0}$$

but, since $I_1 = I_0$,

$$V_0 = V_3\left(1 + \frac{R_0}{R_1}\right) - V_1\left(\frac{R_0}{R_1}\right)$$

(Remember that *Va is* zero.)

In the lower part of the circuit, $I_2 - I_3 = 0$, and

$$I_2 = \frac{V_2}{R_2 + R_3}$$

So since $V_3 = I_3R_3$ and $I_2 = I_3$,

$$V_3 = V_2\left(\frac{R_3}{R_2 + R_3}\right)$$

This can be substituted into the above equation for V_0 to yield

$$V_0 = V_2\left(\frac{R_3}{R_1}\right)\left(\frac{R_1 + R_0}{R_2 + R_3}\right) - V_1\left(\frac{R_0}{R_1}\right)$$

Now if $R_2 = R_1$ and $R_3 = R_0$, this reduces to

$$V_0 = \left(\frac{R_0}{R_1}\right)(V_2 - V_1)$$

and therefore if $V_1 = V_2$, *the output is zero.*

The common mode rejection capability of an op-amp is rated in terms of a standardized test. Assume that we apply a 1 volt signal to both the (+) and (–) inputs *after* connecting them together. The output voltage is some value B volts, because the op-amp common mode rejection is not perfect. Now we apply a voltage of C volts *between* the (+) and (–) inputs until the output again reaches B volts. The common mode rejection of the op-amp is the ratio 1/C. Since C is usually about 10^{-5} the common mode rejection ratio is anywhere from 80 to 100 dB. There will be all sorts of applications of this concept in Chapter 3 so we urge you to learn it now!

To demonstrate how the common mode rejection of an op-amp is used, we will do an example. This is a problem you might well encounter in actual practice. In Figure 2-18 we show a signal source that we want to run through wires to an opamp. Let's assume that the signal is a 1 Hz square wave from a grounded signal source. At one part of the cycle, point A is (+); at some time later, point A is (–). This is our signal. To this signal, we add 60 Hz noise from lights and motors. Thus, if the signal is 1 volt peak to peak and the noise is 0.5 volt peak to peak, the result is a mess. If we use an op-amp amplifier in the usual mode (Figure 2-18), it amplifies everything, both *signal and noise*.

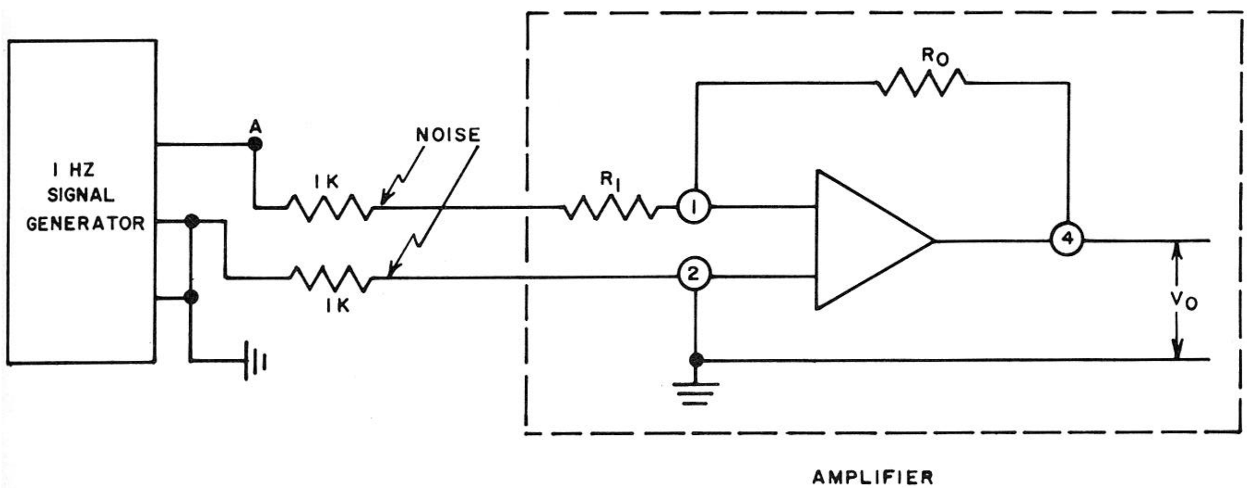

Figure 2-18. Difference circuit.

However, if we use a differential input mode as shown in Figure 2-17, the 60 Hz noise disappears: it is rejected as being common to both inputs. The 1 Hz square wave comes through just great. To make sure you appreciate this achievement, we have designed a laboratory demonstration, which is shown in Figure 2-19.

In Figure 2-19, signal source X is the "good guy" signal going to the op-amp in the differential mode. Note that X is ungrounded – this is an important point. Of course, this requires a signal source with *a floating output* (recall that from Chapter 1, Figure 1-35). Signal source Y is the bad guy, the *noise.* Notice that it is delivered to *both* leads at the same time. Now look at the op-amp output and notice that the X signals are *amplified* and the Y signals are *rejected.* This demonstrates the ability of the differential op-amp circuit to reject common mode signals.

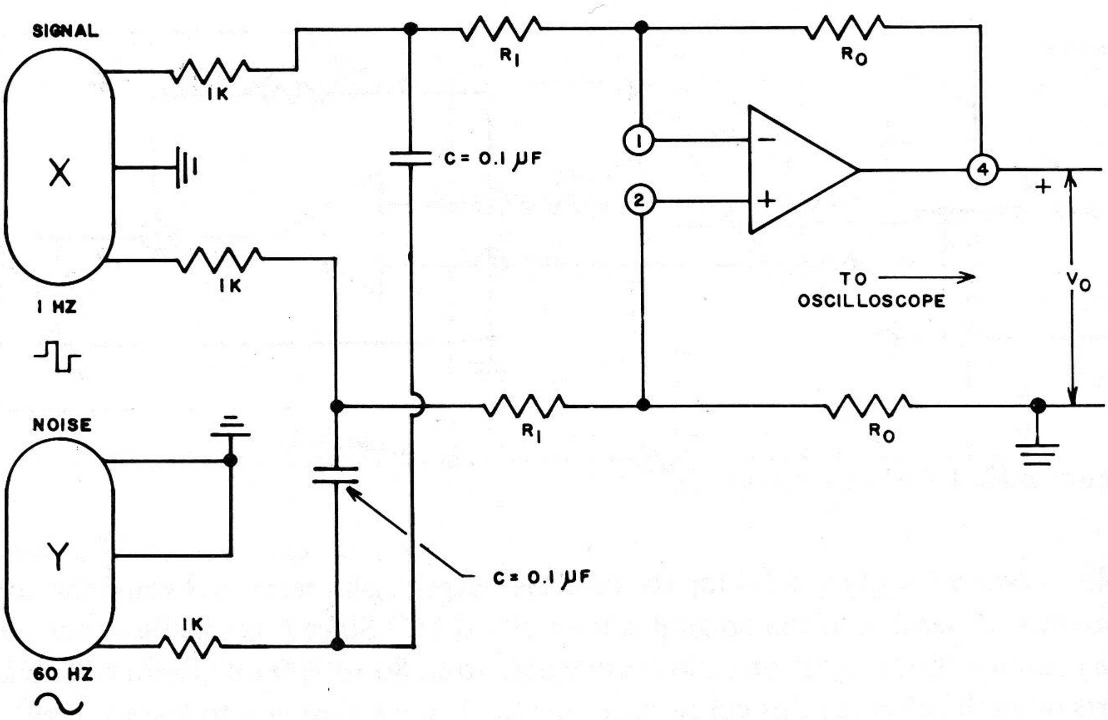

Figure 2-19. Experimental differential input system. (Note that the lower resistor R_0 is needed to balance the R_0 feedback resistor.)

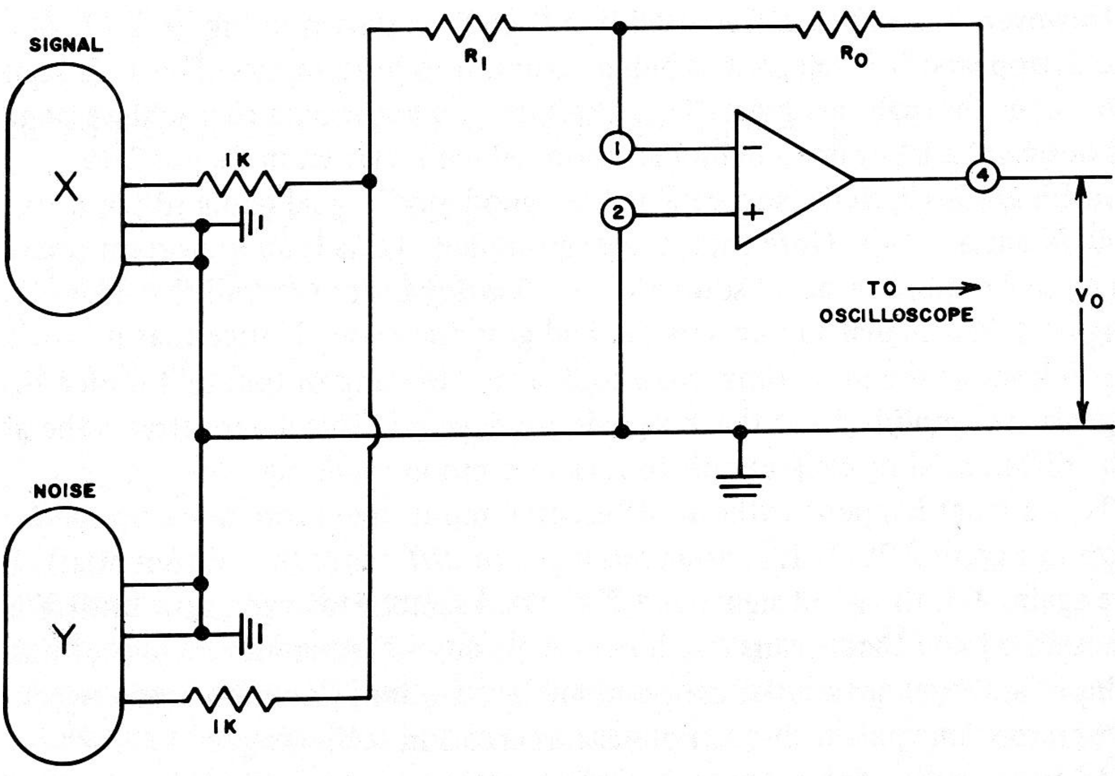

Figure 2-20. Experimental difference (not differential) input circuit.

To see what happens without differential input operation, hook up the circuit shown in Figure 2-20. It is a grounded input or *difference (not* differential) circuit. Once again, X is the good signal and Y the bad signal. However, now both X and Y are amplified and that means trouble. So you should remember the use of differential input and the meaning of common mode rejection. Common mode rejection is a *most important* part of industrial instrumentation technology.

As an example of the common mode rejection we might consider the application to thermocouples. In Figure 2-21 we show a typical copper-constantan thermocouple pair (constantan is an alloy having specific thermocouple properties). The voltage developed is a function of the difference of temperature $T_h - T_c$ and a constant K as $V = K(T_h - T_c)$. In an "electrical" sense we have a voltage source with a "high" 5000 ohm internal resistance. (Thermocouples are *not* current devices.)

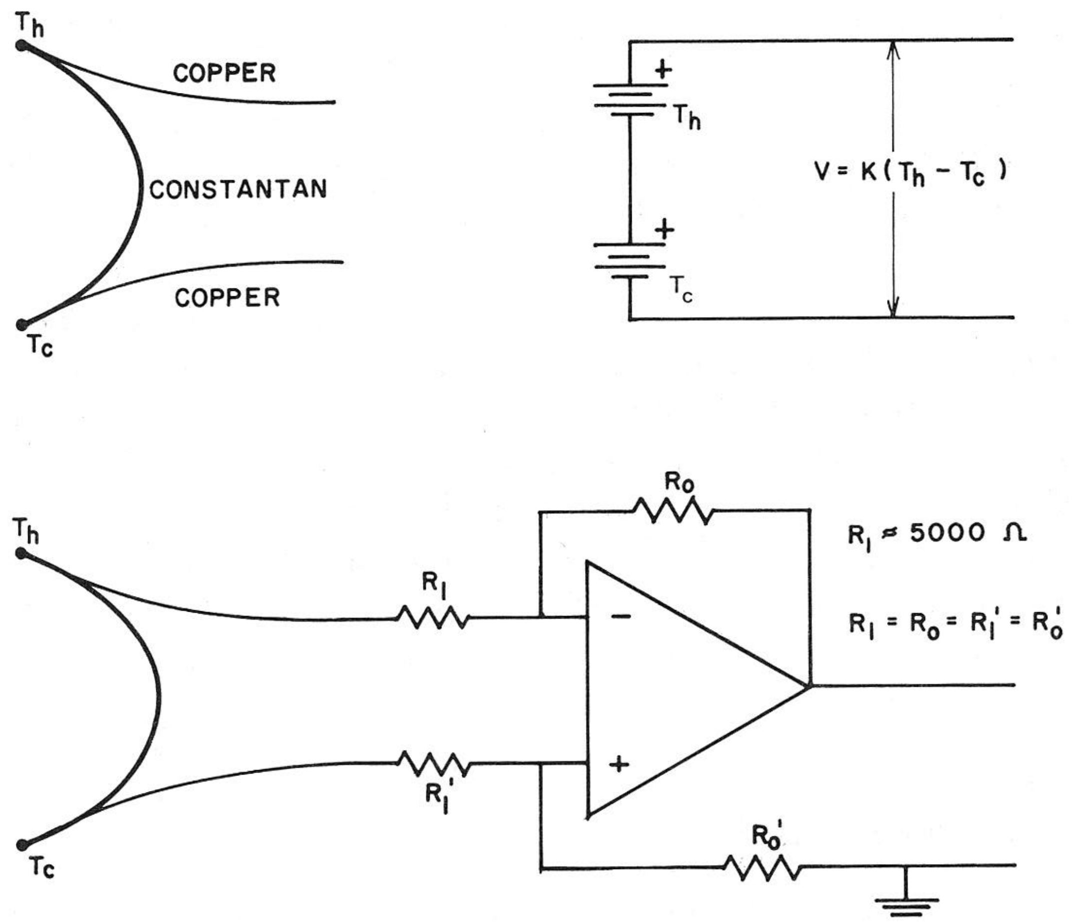

Figure 2-21. Thermocouple connected to an op-amp in differential mode.

In Figure 2-21 we also show the thermocouple connected to a differential op-amp circuit. (A circuit of this type is used in Arizona for the control of air conditioning and evaporative cooler systems. The evaporative cooler works fine as long the air is dry; when the summer monsoons come, you have to switch to the much more expensive air conditioning. The thermocouple circuit is used to sense the relative humidity by having one junction "dry" and the other inside a "wet" sock. At low relative humidity, the temperature difference is large and the signal turns on the evaporative cooler and turns off the air conditioner. When the air is moist, the temperature difference decreases and the system turns the cooler OFF and the air conditioner ON. The unit sells commercially for $65 and you can build one for $10.)

Notice in Figure 2-21 that resistors R_1 and R_0 are about 5000 ohms and R_1' and R_0' are also 5000 ohms. This is done so that the resistance to ground will be the same for both the T_h and T_c leads.

In most circuits the.signal source "knows" where ground is (for example, Figure 2.18), but with thermocouples it is poor practice to ground either of the junctions. So you insure proper grounding as shown in Figure 2-21. Note that T_h "sees" ground at the (–) input via a total of 10,000 ohms plus the load resistance, which is usually rather low. To make everything balance we have to ensure that the "cold" junction T_c has the same resistance to ground; this is done by making R_1' and R_0' equal to 5000 ohms each. The reason for all this fuss is that there will always be some current drawn by any real op-amp and that current has to come from the power supply via the "ground" connection. Another trick that might be used if we don't have the CMR circuit shown in Figure 2-21 involves connecting 2 MΩ resistors from each of the thermocouple connections T_h and T_c to ground. The 2MΩ resistors will not draw enough current to upset the op-amp or the thermocouple reading.

Returning for the moment to the topic of difference versus differential circuits we might note that there is a confusing problem of nomenclature. Correctly speaking, the circuit of Figure 2-17 should be called a *common mode noise rejection* or *differential input circuit.* A circuit like those shown in Figure 2-18 or 2-20, where the signal input is with respect to *ground,* ought to be called a *difference circuit.* Unfortunately, there is no consistency in this matter, either in the industry or in the literature. You just have to look at the circuit and figure it out for yourself. We have tried to be consistent with our notation in this book, but we *do* have to show you how things are done in the real world.

THE INSTRUMENTATION AMPLIFIER

The previous section should have convinced you of the advantages of differential input for common mode noise rejection. In fact the advantages of this circuit are so great that a whole spectrum of specialized op -amps with very high CMR have sprung up. They are called *instrumentation amplifiers,* and a word or two on their properties might be in order.

We begin by noting that with a regular op-amp the gain is under your control, you simply change the feedback resistors. However, the design of the unit is such that it is hard to get high gain and good CMR at the same time. The situation is even worse if the two input resistors (Figure 2-21) are not identical in value. (This can happen in industrial or medical applications and is obviously a problem.) Another difficulty with the usual op-amp circuit, with CMR, is living with relatively low input impedance and obtaining a good CMR at the same time.

The solution is – you guessed it an instrumentation amplifier. It is a high-impedance, high-gain device with excellent CMR. One thing you have to give up is control over the gain. It is usually fixed or adjustable only within narrow limits. This is really no problem; you can always follow it with a standard op-amp amplifier.

To appreciate how this is done, we look at Figure 2-22, which shows the input as two op-amps in the buffer mode. The input impedance is high, and this makes for good CMR. The buffers are followed by a regular differential input op-amp that provides gain. All of these goodies are built into a single package to spare you the problem of having to hook up and balance the circuits.

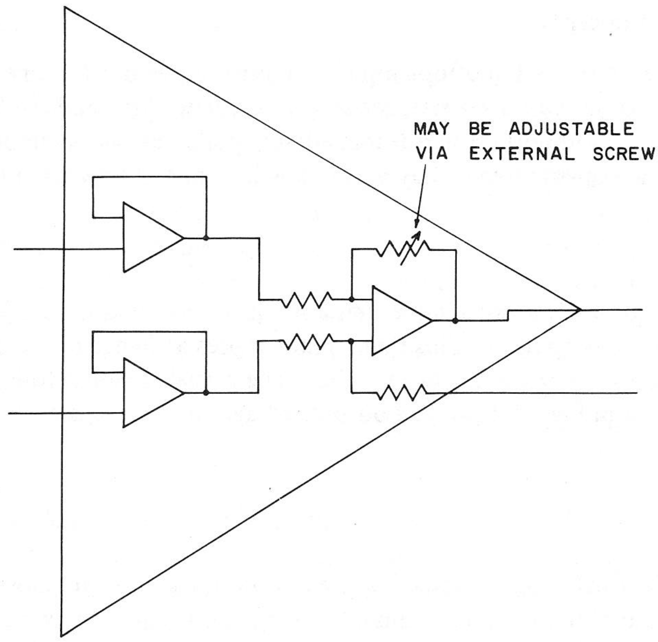

Figure 2-22. The instrumentation amplifier.

For further details on instrumentation amplifiers we refer you to our friends at Burr-Brown Research, or the book by J. Graeme, *Applications of Operational Amplifiers – Third Generation Techniques.* New York: McGraw-Hill, 1973. One comment on the use of these devices with thermocouples or signal sources that have no ground connection – you do have to provide some information about ground to op-amp input, and we show a typical setup in Figure 2-23. The 1 MΩ resistors reduce the input impedance of the circuit from the value set by the instrumentation op-amp (10^{11} Ω in some cases) and if that is a problem you might try 5 MΩ nste ad. If that doesn't work you will just have to look at another book (such as Graeme’s).

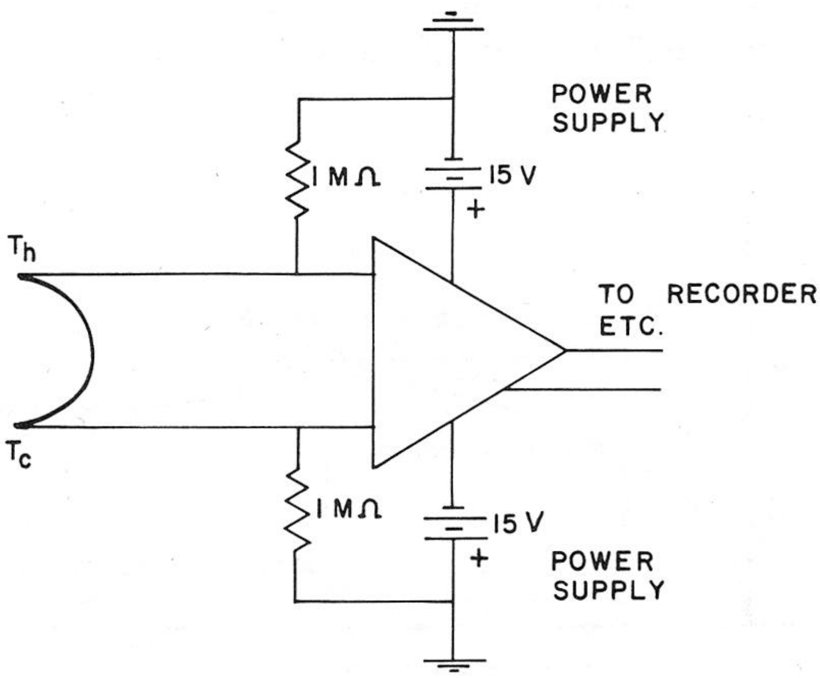

Figure 2-23. The instrumentation amplifier connected to a thermocouple pair.

OTHER USEFUL CONCEPTS

To complete our discussion of op -amp characteristics, we must define a few other terms like *response time, slew rate, settling time, phase shift,* and *feedback factor.* These are not very important in our immediate application of op-amps, but you might be buying op-amps some day and you will want to know what the words mean.

RESPONSE TIME

To define *response time,* we assume that a small voltage (about 50 mV) has been applied to the op-amp input. This signal input causes a change in the output voltage, but this change does *not* occur in zero time. The actual response follows a curve like that shown in Figure 2-24.

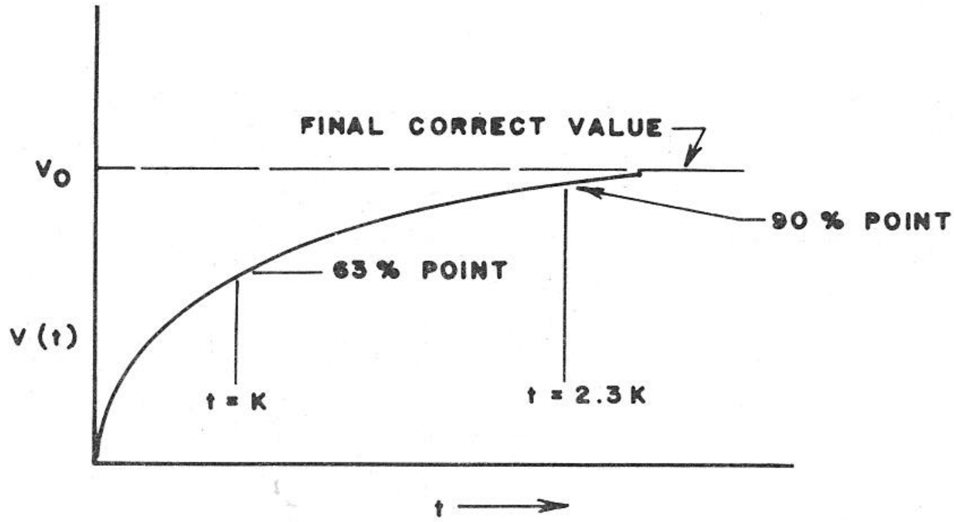

Figure 2-24. Definition of op-amp response time.

The output voltage time curve is given by the equation

$$V(t) = V_0\left(1 - e^{-t/k}\right)$$

Here V_0 is the final "correct value," k is a constant, t is time in seconds, and e = 2.718 (the base of natural logarithms). Looking at our equation, we see that when t = k the output voltage is

$$V(t) = V_0\left(1 - \frac{1}{2.72}\right) \approx 0.63V_0$$

or about two-thirds of its final value. This 63% point (or time) is often called the *eith time* because the difference between the actual and final voltages has been reduced by the factor 1/e. The eith time gives us a measure of how fast things are going. The important point is that some manufacturers refer to the eith time as the *response time.*

Another term that you will see is the *90% time.* This is the time for V(t) to equal 0.90 V_0. Attaining this value requires a time equal, not to k, but to t = 2.3 k. So a device that has an advertised eith response time of 1 second is no better or worse than one having a 90% time of 2.3 seconds.

SLEW RATE AND SETTLING TIME

To define *slew rate* and *settling time,* we assume that an infinite step voltage has been applied to the op-amp input. An *infinite step* means that it goes from, say, 1 volt to 2 volts in zero time; it does *not* mean that the voltage becomes infinite. If the voltage stays at 2 volts, we call it a *1 volt step function.* The rate of change of the output due to this step function input is called the *slew rate.* In general, the higher the slew rate (in volts per microsecond), the better. However, every rose has thorns, and a high slew rate means that the output may overshoot the correct value and have to settle down to the proper level. This takes time: the *settling time.* (Be on guard: various manufacturers may have their own definition for this.) In Figure 2-25, we illustrate our definition of these terms. Here, by *final value* we mean a value within some tolerance that suits our purpose at the time.

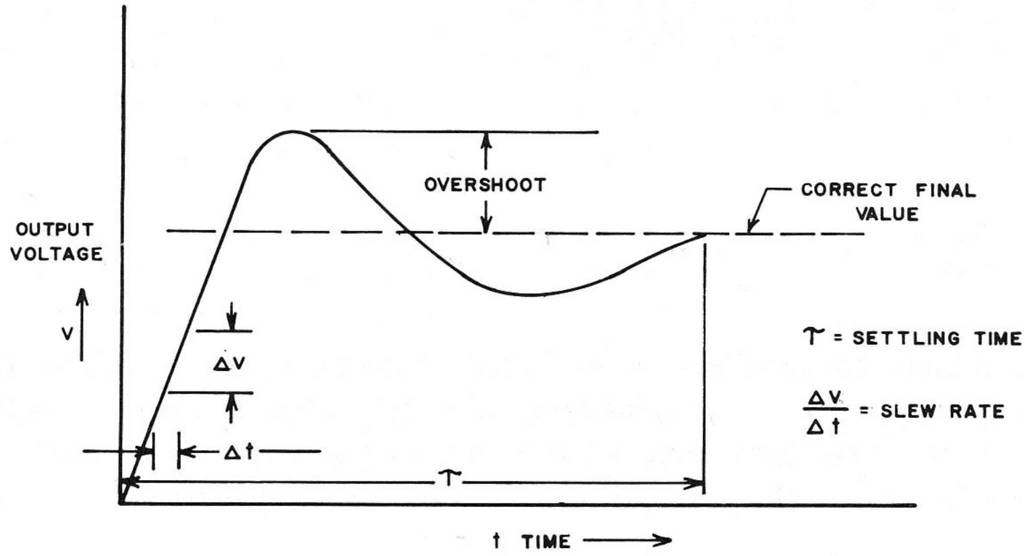

Figure 2-25. Response of an op-amp to a step input.

PHASE SHIFT

The concept of *phase shift,* which was introduced in Chapter 1 (see Figure 1-16), requires a little mathematics. A little mathematics won't hurt you; at least we haven't heard of anyone dying from it yet. You can even skip this section without missing much.

Assume that we have a black box whose input is a signal $V_1 = A\cos 2\pi ft$, where f is the frequency in hertz. The output is also a cosine wave (we hope), and takes the form of $V_0 = B\cos(2\pi ft + \varphi)$. Now B/A is the gain, but the important term here is φ, the *phase shift*. Notice that V_1 is zero when $2\pi ft = \pi/2$ whereas V_0 is zero when $(2\pi ft + \varphi) = \pi/2$. So if φ is not zero, V_1 and V_0 are *out of phase:* there is phase shift in the black box.

If our black box is an op-amp, we know that when input (1) is (+), output (4) is (–). This is a phase shift of 180 degrees. However, it is *customary* to ignore that and to refer to an op-amp that has only a 180 degree phase shift as having "zero" phase shift. If the 180 degree phase shift (which is built into the op-amp) *changes* with frequency or signal amplitude, *then* EEs refer to it as "phase shift." This is just one of the ways we confuse the uninitiated.

Why does phase shift cause problems? To begin with, a good op-amp has zero phase shift at low frequencies, but the phase shift increases as higher input frequencies are used. If the input signal has a number of frequencies, some of them may be shifted more than others because the phase shift is frequency-dependent. This can cause distortion, so the output signal doesn't look like the input. If the phase shift is large enough to produce positive feedback, there may be oscillation. For now though, don't fret about it; we will discuss compensation techniques for this problem in Chapter 6.

FEEDBACK FACTOR

Feedback factor is a term we haven't used yet in discussing op-amps but you often see it in the literature, so it might be well for us at least to define it for you. The general feedback equation (for all types of amplifiers) is

$$A_F = \frac{A_O}{1 + A_O\beta}$$

Here A_F is the closed loop gain and A_O is the open loop gain. The symbol β stands for the *feedback factor*, which is a way of measuring the fraction of the output voltage V_0 that is fed back to the input.

Referring back to Figure 2-8, the current through R_0 and R_1 is

$$I = \frac{V_0}{R_1 + R_0}$$

The fraction of V_0 applied to input (1) is

$$IR_1 = \frac{V_0 R_1}{R_1 + R_0} = V_0 \left(\frac{R_1}{R_1 + R_0} \right) = \beta V_0$$

so

$$\beta = \frac{R_1}{R_1 + R_0}$$

That is all there is to feedback factor. For an ideal op-amp, A_O is infinite, whereas $A_F = (R_0 + R_1)/R_1$ for the noninverting op-amp and $A_F = R_0/R_1$ for the inverting circuit. If you insert these terms in the feedback equation above, it reduces to an identity. Feedback factory analysis is used in circuit stability studies.

HOW TO BUY OP-AMPS – OR A FOOL AND HIS MONEY ARE SOON PARTED

this time you must be thinking of buying op-amps and will have obtained catalogs from people like Burr-Brown, Teledyne, Philbrick, and Analog Devices. The problem is they have so many devices available, with such a bewildering variety of specifications, that you don't know what to buy.

The first thing to do, if you are in a university, is to write some begging letters asking for free op-amps. As one of my students put it, "There is nothing cheaper than free." If something along the line of our sample begging letter (Chapter 8) doesn't move them, you might just have to pay cash. In that sad event, we suggest that you order the cheapest op-amps that are available and use them to learn on. Yes, we know there are people who say “buy something good and you will have it for a lifetime.” Those are the people who, when their darling son says he wants to learn the saxophone, go out and buy a $400 instrument. After 2 weeks of lessons, the ingrate takes up girls instead of music and they have the saxophone sitting around for a lifetime. Go ahead and buy the cheapest op-amps, learn how to use em, and by the time you are really limited by their characteristics, we hope you will have the money for a few good units. Then your students can play with the cheap ones.

While we are on this subject, you may be wondering about all the ads you see for modules to accomplish some specific purpose. There are thermocouple modules that allow you to put on 1/4 mile of extension wire, weighing modules, counting modules, and so on. The only limit is the ingenuity of the human mind and some company's idea of what will sell.

Should you buy these things instead of making them yourself? The answer is probably "yes" in the cases of circuits to multiply, divide, do square roots, or take logarithms. It would take you a long time to learn how to build things like that. Regarding other types of modules, it is a case of your own ratio of money to time. Buying modules is a fast way to get in a position to do something. In industry, time is expensive, so you tend to buy. At universities, time may well be cheap; some university administrations seem to think that faculty time is free and can therefore be wasted in unlimited paperwork. You just have to play this game by your own rules.

Another point of interest is that you can save many dollars by purchasing or leasing used instruments – voltmeters, power supplies, oscilloscopes, gas chromatographs, and so forth – from a variety of second-hand dealers. The instruments are usually in fine condition, and most dealers will guarantee their equipment. A few dealers' names and addresses are listed in the where-to-buy-it section at the back of the book. If you watch the ads in magazines like *Science* or *Industrial Research*, you will see all sorts of equipment available second hand. After a while you may feel like Fanny Brice singing "Second-hand Rose," but you can comfort yourself with the thought that "when you're poor you have to be a little smart."

To sum things up, by now you should be convinced that op-amps are the greatest things since sliced bread. If you are not convinced, throw this book away! Don't try to get your money back, we have already spent it.

In the next chapter, we will discuss the application of op-amps in a variety of circuits. In Chapter 6, we will show you how to compensate for imperfections in real op-amps. We hope that you will stay with us; if not, please recycle the paper on which this book is printed.

TEST YOURSELF PROBLEMS AND SUGGESTED EXPERIMENTS

TEST YOURSELF PROBLEMS

1. What must the internal resistance of the voltmeter V be in order to read the voltage with 1% accuracy?

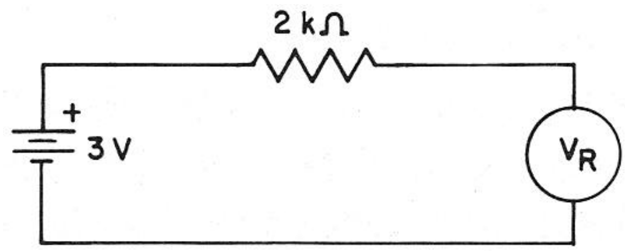

Figure 2-26.

Answer: $V_R \geq 200$ kΩ.

2. What is the gain of this circuit? What is the input impedance (z)?

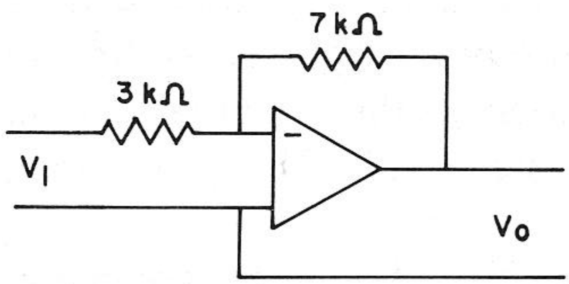

Figure 2-27.

Answer: Gain = 2.33, Z input = 3 kΩ.

3. Draw a common mode rejection circuit and in your own words discuss the way CMR works.

4. Draw a voltage follower circuit.

   What is its input impedance?

   What is its output impedance?

   What might it be used for?

5. Given the following

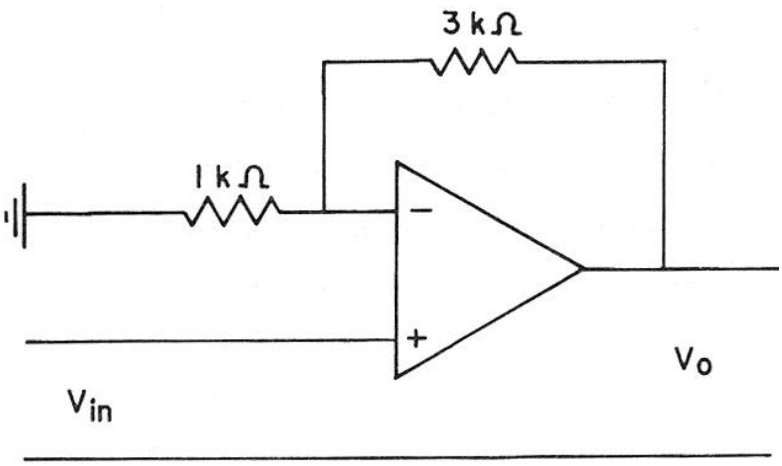

Figure 2-28.

For V_{in} = 10 cos ωt

What is V_{out}? (Answer: V_0 = 40 cos ωt)

What is the input impedance of this circuit? (Answer: ∞)

6. In your own words, what is roll-off? What does gain-bandwidth limit mean?
7. Draw an op-amp circuit to "buffer" a high-impedance signal source. What is the gain of a buffer circuit?
8. Under what conditions does a source transfer maximum power to a load?
9. Draw a simple constant current op-amp circuit. Why is the current through the load constant?
10. What do we mean by Rom, Rcm, and *common mode relection?*
11. What is meant by the terms *slew rate, settling time,* and *overshoot?*
12. What do the terms *response time, eith* (63% point), and *90% time* mean?
13. Discuss the difference between "difference" and "differential" circuits.
14. What are the characteristics of an ideal op-amp?
15. In an ideal op-amp, with negative feedback, there is no voltage between the (+) and (–) inputs. Why?
16. What is the input impedance of an inverting op-amp circuit? (Answer: the impedance is controlled by whatever input resistor is used)
17. What is the input impedance of a noninverting op-amp circuit? (Answer: for an ideal op-amp, the impedance is infinite)
18. What is the output impedance of an op-amp? How would you use an op-amp to couple a high impedance source to a low impedance load?
19. Draw a simple constant current op-amp circuit and show why the current remains constant as the feedback resistance changes.

20. Draw a common mode rejection circuit and indicate what types of noise are rejected. What types of noise will not be rejected?

SUGGESTED EXPERIMENTS

Rules of the Lab:

1. *Always check device dial settings before turning on.*
2. *Always turn off all devices before making circuit changes.*
3. *If you are not familiar with the particular opamp or device that will be used, you should have or try to find the appropriate company manual for more information.*

   (Most large electronic stores – not Radio Shack – will have copies that you can look at. If that doesn't work, you will have to look in *Thomas' Register of American Manufacturers* for the address of Motorola, or whichever company is involved, and write to them for technical information.)

A. OP-AMPS

Never do this:

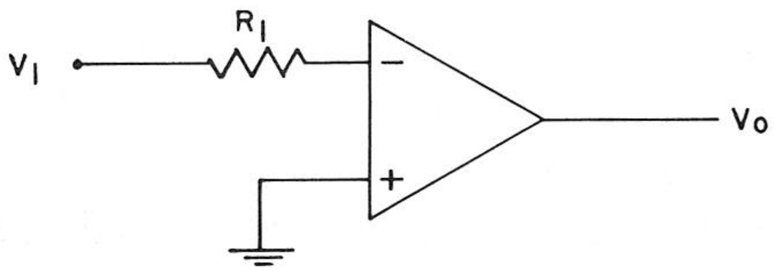

Figure 2-29.

Why?

B. INVERTING AMP

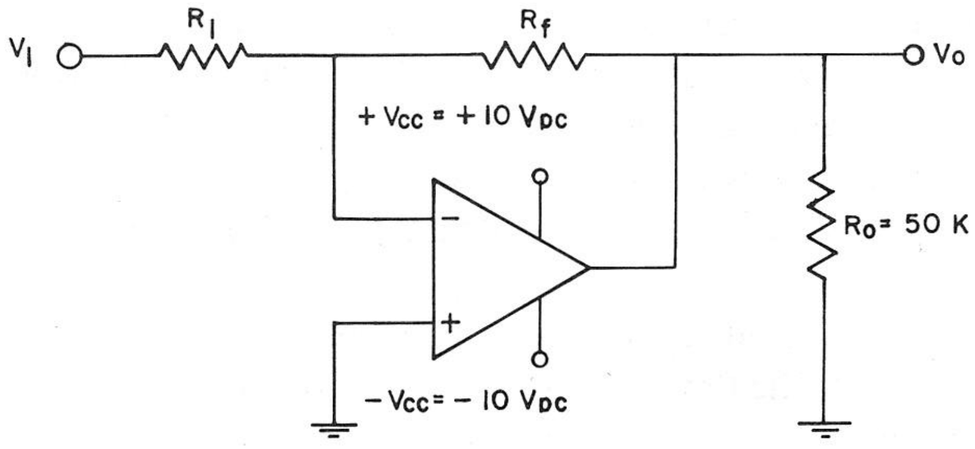

Figure 2-30.

1. What is the maximum voltage that V_1 can be if: $R_1 = R_f$ __________,
   $R_f = 2R_1$ __________, $R_f = 10R_1$ __________, $R_f = 0.5R_1$ __________.
2. What is the equation for V_0 in terms of V_1?
3. How are you going to get ±10 volts DC? (Draw the diagram).
4. Why does the op-amp have offset input controls?

5. How are you going to correct any DC offset that your op-amp might have?
6. Construct the circuit of Figure 2-30 with R_1 = 10 kΩ and R_f = a decade box.* Draw the schematic and *label* the pin numbers on the op-amp.
7. Connect the function generator to V_1 and set R_f = 2 kΩ. What is the gain?

   Theoretically _________. Experimentally _________.
8. Vary the ftequency of the input to the op-amp. Is there any change in the gain?
9. What is the input impedance of this circuit?

   Theoretically _________. Experimentally _________.
10. Use two 10 kΩ resistors to form the folowing circuit; set the function generator to produce a 1 V and DC output.

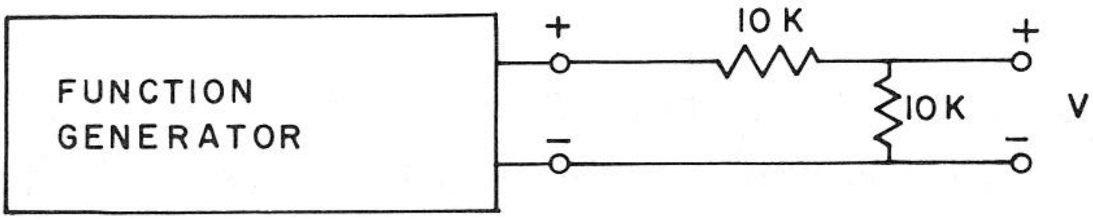

Figure 2-31.

Experimentally, what is the voltage (V)?

Now connect the function generator to the op-amp input (it is now called V_1) and measure voltage V again.

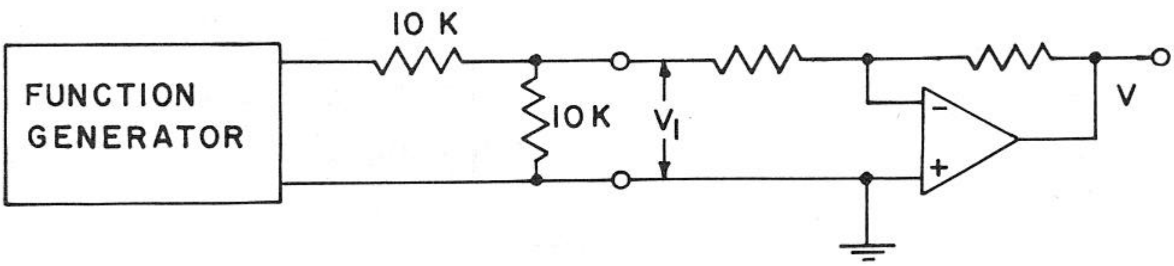

Figure 2-32.

What is it? Why?

C. NONINVERTING AMPLIFIER

If you have the following circuit:

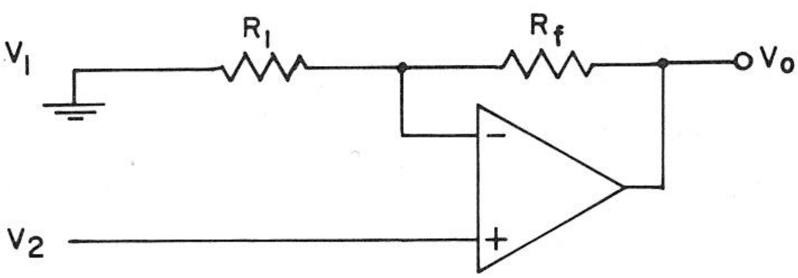

Figure 2-33.

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* A decade box is a metal box containing an assortment of resistors, connectors, and switches that can provide a wide range of resistance values for experimental purposes.

1. What is the gain

   If $R_1 = R_f$? __________.

   If $R_f = 2R_1$? __________.

2. Construct the above circuit with R_1 = 10 kΩ and R_f = 10 kΩ = decade box.
3. Draw the circuit diagram, labeling the op-amp pins.
4. Connect the function generator and see if there is any variation in gain as the frequency is changed.
5. What is the input impedance of this circuit?

   Use two 10 kΩ resistors to form the circuit:

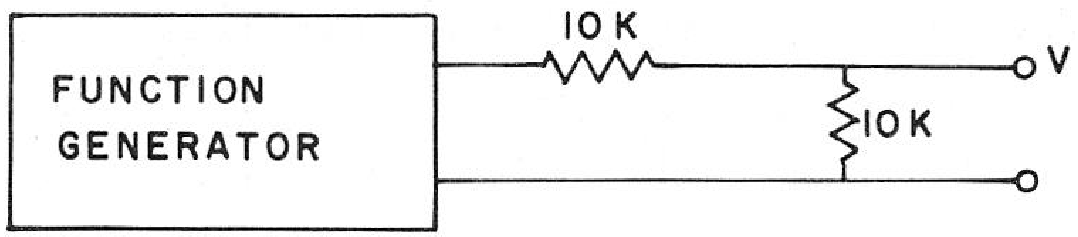

Figure 2-34.

What is the voltage V experimentally?

Now connect V to the amplifier input (V_1) and measure V again.

1. What is it? ______________
2. Why?
3. Can you see any advantage of this circuit over the inverting amplifier?

D. CONSTANT CURRENT SOURCE

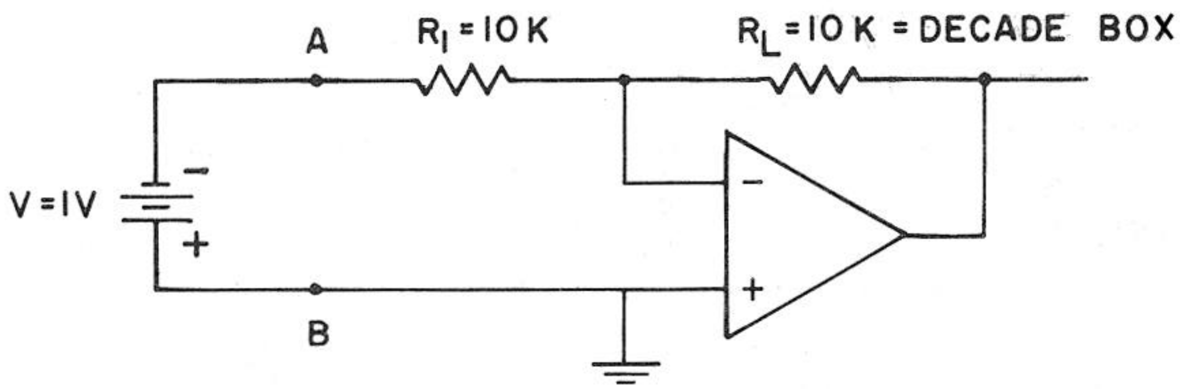

Figure 2.35.

Draw the diagram, labeling all points.

1. Is point A earth, ground, or neutral? _____________
2. Is point B earth, ground, or neutral? _____________
3. What is the current through R_L?
4. Change R_L to 40 kΩ. What is the current through R_L?
5. Change R_L to 20 kΩ. What is the current through R_L?

E. DIFFERENCE AND DIFFERENTIAL AMPS

Using the MC 1437 *dual* op-amp, construct a unity gain difference amp and a unity gain differential amp. Use 10 kΩ resistors for the differential amp and 22 kΩ resistors for the difference amp.

1 Draw circuit diagrams for the difference amp and for the differential amp.

2. Connect the function generator and, using the oscilloscope, test both circuits (ckt) to assure yourself that they are working properly.

Theoretically:	*Differential ckt*	*Difference ckt*
What is the input impedance?	______________	______________
What is the gain?	______________	______________
What is the output impedance?	______________	______________

What is the voltage at the inverting terminal, of the difference amp, for any reasonable input to the circuit? ______________

3. Connect a long wire pair (15-20 feet) from the output of the function generator to the input of the differential amp. Stretch the excess wire out on the floor as far away from the circuit as possible.

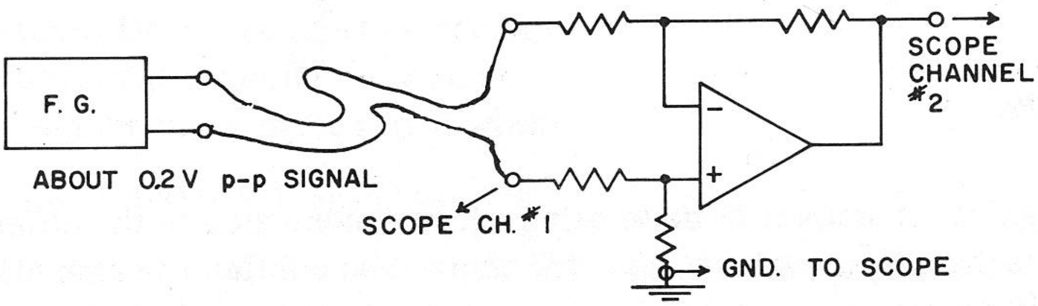

Figure 2-36.

Using the scope, observe the input and output simultaneously *(do not* put an earth ground directly on the function generator terminals).

4. Is there a significant amount of noise or is it being rejected?

Disconnect the long wire from the input of the differential amp and connect it to the difference amp as shown:

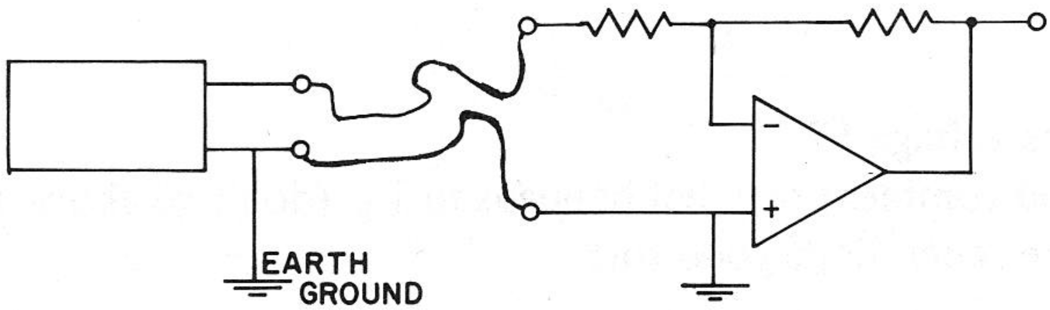

Figure 2-37.

5. Is there a signlficant amount of noise and is it being rejected?

Use a 1/2 inch drill to induce noise onto the long line (plug it into a bench across the room from yours). Keep the drill as far away from the circuit as possible but close enough to the long line to induce noise.

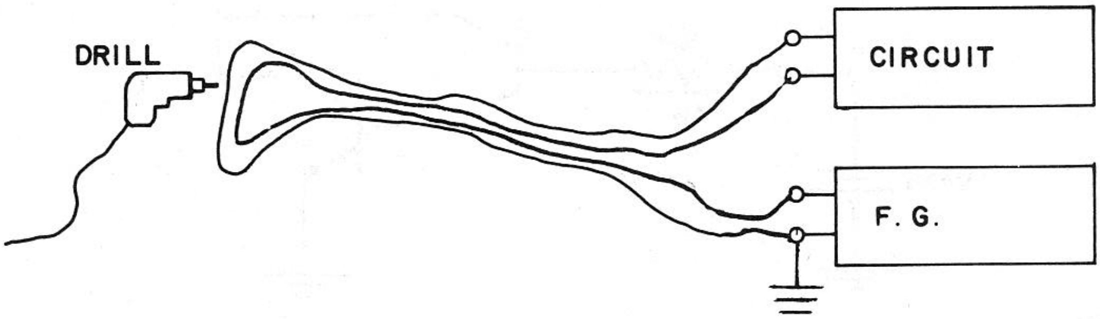

Figure 2-38.

6. Is the noise being rejected?

   Switch the long line to the differential amp and repeat the drill exercise.

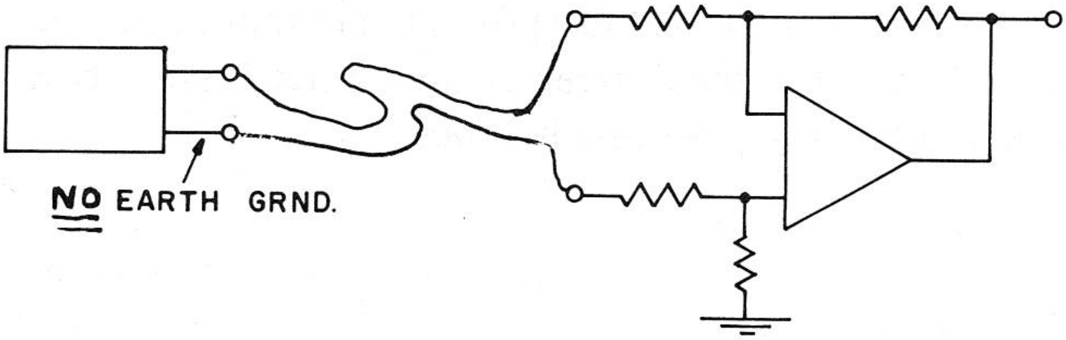

Figure 2-39.

7. Is a significant amount of noise being rejected, compared to the difference amp?
8. What is the difference between a differential and a difference amp, based on your findings?

F. ZENER DIODES

Construct the following circuit:

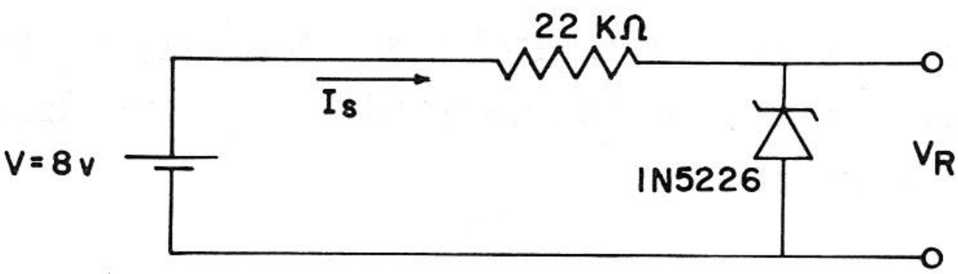

Figure 2-40.

1. What is the voltage V_R?
2. Vary Vand comment on what happens to V_R (don't go above 15 volts).
3. What is the zener diode good for?

G. DARLINGTON CIRCUIT

Construct the following circuit (using 2N4265 NPN, 2N3702 PNP):

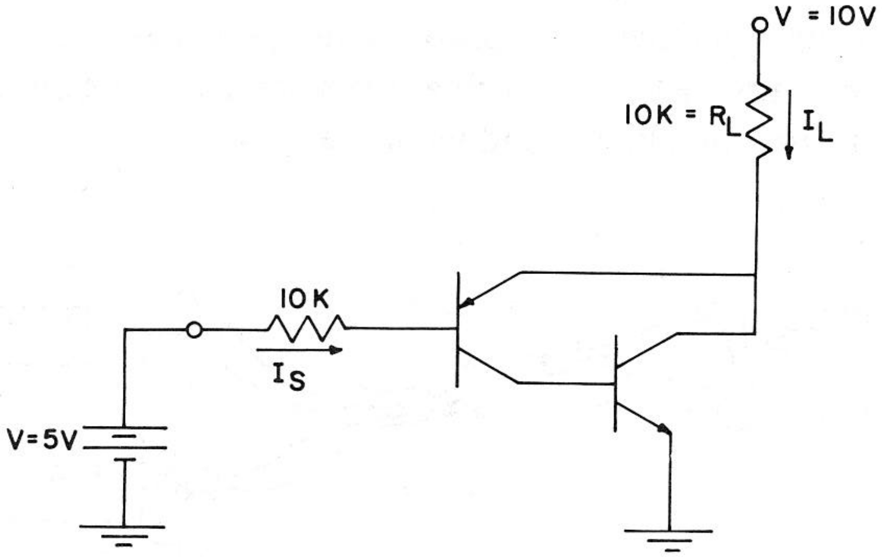

Figure 2-41.

1. What is the input current I_S?
2. What is the output load current I_L?
3. Raise voltage V to 8 volts and repeat measurements: I_S __________ I_L __________

   Try with the function generator as an input.

   What is the Darlington circuit good for?

H. WIRING OP-AMPS FROM SCRATCH

Using the book, page 84, construct a unity gain follower for general appilcations. Draw a complete schematic.

1. What does compensation do for you?
2. Check your circuit to make sure it works.

I. RISE TIME, OVERSHOOT, SETTLING TIME

Using the same circuit you made in Experiment H (unity gain follower), input a 1 kHz, 4 volt peak-to-peak, square-wave signal. Adjust your scope until you can observe the rise time.

1. Draw a picture of the input and output waveforms.
2. Approximately:

   What is the rise time? _______________

   What is the overshoot? ________________

   What is the settling time? ________________
3. Indicate how these were measured.