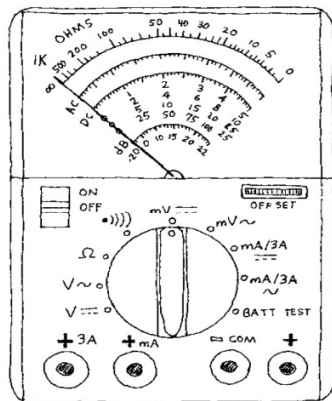


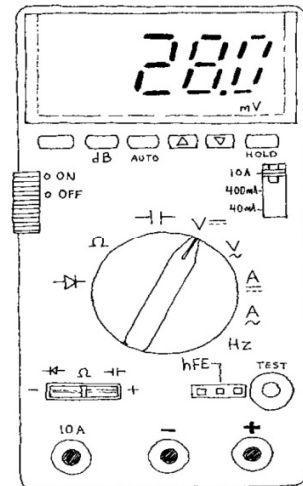
## How do a Multi-meter and an Oscilloscope Work?

### 14.3 Multimeters

A *multimeter*, or VOM (volt-ohm-milliammeter), is an instrument that is used to measure current, voltage, and resistance. The two most common types of multimeters include the analog VOM and the digital VOM, as shown in Fig. 14.11.



Analog multimeter



Digital multimeter

FIGURE 14.11

The obvious difference between the two types of VOMs is that an analog VOM uses a moving-pointer mechanism that swings along a calibrated scale, while the digital VOM uses some complex digital circuitry to convert input measurements into a digitally displayed reading. Technically speaking, analog VOMs are somewhat less accurate than digital VOMs (they typically have a 3 percent higher error in reading than a digital VOM), and they are a harder to read. Also, the resolution (displayable accuracy) for an analog VOM is roughly 1 part in 100, as compared with a 1 part in 1000 resolution for a digital VOM. Despite these limitations, analog VOMs are superior to digital VOM when it comes to testing circuits that contain considerable electrical noise. Unlike digital VOMs, which may go blank when noise is present, analog VOMs are relatively immune to such disturbances.

#### 14.3.1 Basic Operation

##### Measuring Voltages

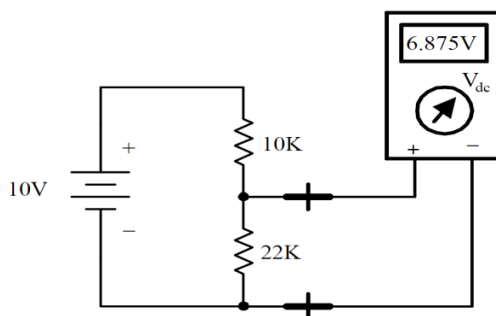


FIGURE 14.12

The trick to measuring voltages with a VOM is to turn the selector knob to the voltage setting. If you want to measure a dc voltage, the knob is turned to the appropriate dc voltage-level setting. If you wish to measure an ac voltage, the knob is turned to the ac voltage setting ( $V_{ac}$ , or  $V_{rms}$ ). Note that the displayed voltage in the  $V_{ac}$  setting is the rms voltage ( $V_{rms} = 0.707 V_{peak-to-peak}$ ). Once the VOM is set correctly, the voltage between two points in a circuit can be measured by touching the VOM's probes to these points (the VOM is placed in parallel). For example, Fig. 14.12 shows the procedure used to measure the voltage drop across a resistor.

### Measuring Currents

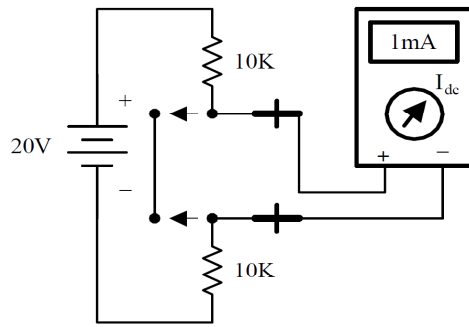


FIGURE 14.13

Measuring currents with a VOM is almost as easy as measuring voltages. The only difference (besides changing the setting) is that you must break the test circuit at the location where you wish to make a current reading. Once the circuit is open, the two probes of the VOM are placed across the break to complete the circuit (VOM is placed in series). Figure 14.13 shows how this is done. When measuring ac currents, the VOM must be set to the rms current setting.

### Measuring Resistances

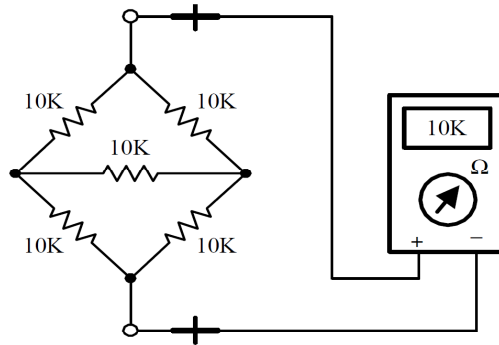


FIGURE 14.14

Measuring resistances with a VOM is simple enough—remove the power to the resistive section of interest, and then place the VOM's probes across this section. Of course, make sure to turn the VOM selector knob to the ohms setting beforehand.

## 14.3.2 How Analog VOMs Work

An analog VOM contains an ammeter, voltmeter, and ohmmeter all in one. In principle, understanding how each one of these meters works individually will help to explain how an analog VOM works as a whole.

### Ammeter

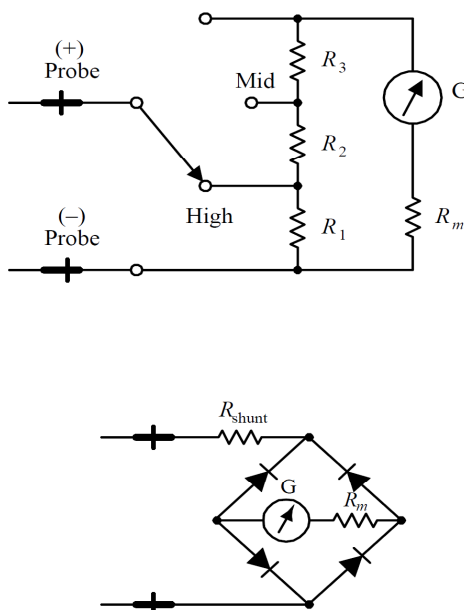


FIGURE 14.15

An ammeter uses a D-Arsonval galvanometer that consists of a current-controlled electromagnetic that imparts a torque on a spring-loaded rotatable needle. The amount of deflection of the needle is proportional to the current flow through the electromagnet. The electromagnetic coil has some resistance built in, which means you have to throw  $R_m$  into the circuit, as shown in Fig. 14.15. ( $R_m$  is typically around 2 k or so). Now, a galvanometer alone could be used to measure currents directly; however, if the input current is excessively large, it will force the needle beyond the viewable scale. To avoid this effect, a number of *shunt resistors* placed in parallel with the galvanometer make up a current divider capable of diverting some of the “needle bending” current away from the galvanometer. The current value read from the display must be read from the appropriate ruler marking on the display that correspond to the shunt resistance chosen. To make this device capable of measuring ac currents,

a bridge rectifier can be incorporated into the design so as to provide a dc current to the galvanometer (see lower circuit). The dc current will produce a needle swing that is proportional to the alternating voltage measured. A typical ammeter has about a 2-k input resistance. Ideally, an ammeter should have zero input resistance.

### Voltmeter

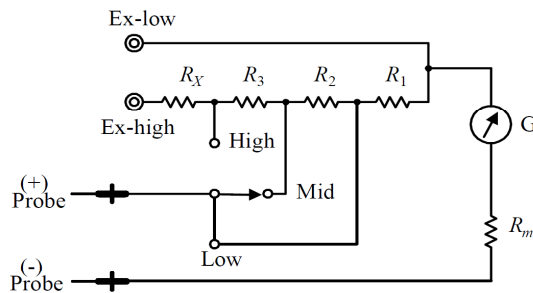


FIGURE 14.16

An analog voltmeter, like the ammeter, also uses a D-Arsonval galvanometer. Again, the galvanometer has some internal resistance ( $R_m$ ). When the voltmeter's leads are placed across a voltage difference, a current will flow from the higher potential to lower potential, going through the galvanometer in the process. The current flow and the needle deflection are proportional to the voltage difference. Again, like the ammeter, shunt resistors are used to calibrate and control the amount of needle deflection. To make ac voltage measurements, a bridge rectifier, like the one shown in the last example, can be incorporated into the meter's design. A typical voltmeter has an input resistance of 100 k. An ideal voltmeter should have infinite input resistance.

### Ohmmeter

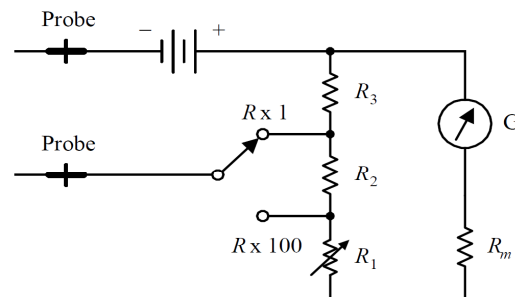


FIGURE 14.17

To measure resistance, an ohmmeter uses an internal battery to supply a current through the measured load and through a galvanometer (the load and galvanometer are in series). If the tested load is small, a large current will flow through the galvanometer, and a large deflection will occur. However, if the tested load resistance is large, the current flow and the deflection will be small. (In a VOM, the ohmmeter calibration markings are backwards—0  $\Omega$  is set to the right of the scale.) The amount of current flow through the galvanometer is proportional to the load resistance. The ohmmeter is first calibrated by shorting the probe leads together and then zeroing the needle. Like the other meters, an ohmmeter uses a number of shunt resistors to control and calibrate the needle deflections. A typical ohmmeter has an input resistance of about 50  $\Omega$ . An ideal ohmmeter should have zero input resistance.

## 14.3.3 How Digital Multimeters Work

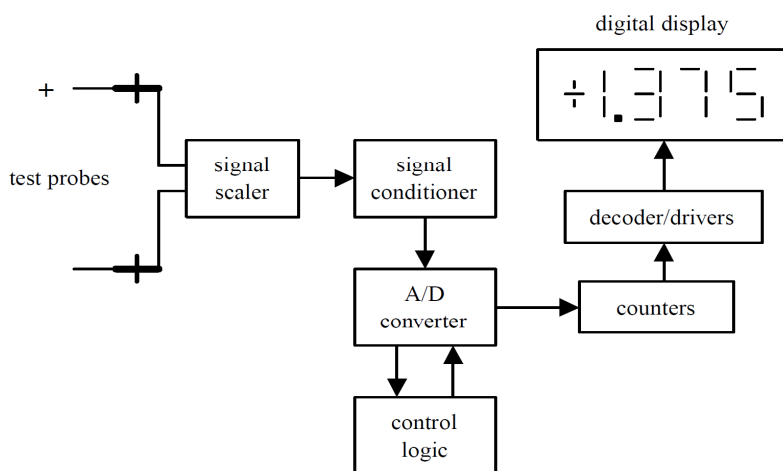


FIGURE 14.18

A digital multimeter is composed of a number of functional groups, as shown in the block diagram. The signal scaler is an attenuator amplifier that acts as a range selector. The signal conditioner converts the scaled input signal to a dc voltage within the range of the analog-to-digital converter (A/D converter). In the case of ac voltage measurements, the ac voltage is converted into a dc voltage via a precision rectifier-filter combination. The gain of the active filter is set to provide a dc level equal to the rms value of the ac input voltage or current. The signal conditioner also contains circuits to convert current and/or resistance into proportional dc voltages. The A/D converter converts the dc analog input voltage into a digital output voltage. The digital display provides a digital readout of the measured input. Control logic is used to synchronize the operation of the A/D converter and digital display.

### 14.3.4 A Note on Measurement Errors

When measuring the current through (or voltage/resistance across) a load, the reading obtained from the VOM will always be different when compared with the true value present before the meter was connected. This error comes from the internal resistance of the VOM. For each setting (ammeter, voltmeter, ohmmeter), there will be a different internal resistance. A real ammeter typically will have a small input resistance of around 2 k, while a voltmeter may have an internal resistance of 100 k or more. For an ohmmeter, the internal resistance is usually around 50  $\Omega$ . It is crucial to know these internal resistances in order to make accurate measurements. The following examples show how large the percentage error in readings can be for meters with corresponding input resistances.

#### Current-Measurement Error

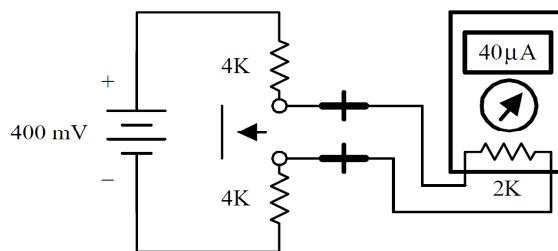


FIGURE 14.19

If an ammeter has an input resistance of 2 k, calculate the percentage error in reading for the circuit shown here.

$$I_{\text{true}} = \frac{400 \text{ mV}}{4 \text{ k} + 4 \text{ k}} = 50 \mu\text{A}$$

$$I_{\text{measured}} = \frac{400 \text{ mV}}{4 \text{ k} + 4 \text{ k} + 2 \text{ k}} = 40 \mu\text{A}$$

$$\% \text{ error} = \frac{50 \mu\text{A} - 40 \mu\text{A}}{50 \mu\text{A}} \times 100\% = 20\%$$

#### Voltage-Measurement Error

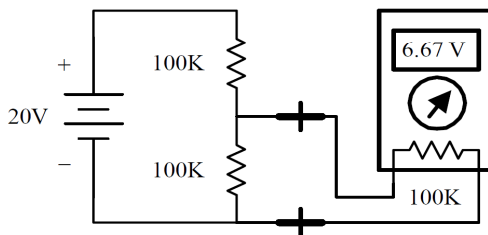


FIGURE 14.20

If a voltmeter has an input resistance of 100 k, calculate the percentage error in reading for the circuit shown here.

$$V_{\text{true}} = \frac{100 \text{ k}}{100 \text{ k} + 100 \text{ k}} (20 \text{ V}) = 10 \text{ V}$$

$$V_{\text{measured}} = \frac{100 \text{ k}}{100 \text{ k} + (100 \text{ k} \times 100 \text{ k}) / (100 \text{ k} + 100 \text{ k})} = 6.67 \text{ V}$$

$$\% \text{ error} = \frac{10 \text{ V} - 6.67 \text{ V}}{10 \text{ V}} \times 100\% = 33\%$$

#### Resistance-Measurement Error

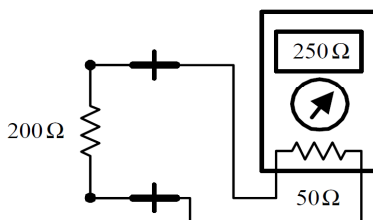


FIGURE 14.21

If an ohmmeter has an input resistance of 50  $\Omega$ , calculate the percentage error in reading for the circuit shown here.

$$R_{\text{true}} = 200 \Omega$$

$$R_{\text{measured}} = 200 \Omega + 50 \Omega = 250 \Omega$$

$$\% \text{ error} = \left| \frac{200 \Omega - 250 \Omega}{200 \Omega} \right| \times 100\% = 25\%$$

To minimize the percentage error, an ammeter's input resistance should be less than the Thevenin resistance of the original circuit by 20 times or more. Conversely, a voltmeter should have an input resistance that is larger than the Thevenin resistance of the original circuit by 20 times or more. The same goes for the ohmmeter; it should have an input resistance that is at least 20 times the Thevenin resistance of the original circuit. By following these simple rules, it is possible to reduce the error to below 5 percent. Another approach (perhaps a bit more tedious) is to look up the internal resis-



tances of your VOM, make your measurements, and then add or subtract the internal resistances afterwards.

## 14.4 Oscilloscopes

Oscilloscopes measure voltages, not currents and not resistances, just voltages—an important point to get straight from the start. An oscilloscope is an extremely fast xy plotter capable of plotting an input signal versus time or versus another input signal. The screen of an oscilloscope looks a lot like the screen of a television. As a signal is supplied to the input of a scope, a luminous spot appears on the screen. As changes in the input voltage occur, the luminous spot responds by moving up or down, left or right. In most applications, the oscilloscope's vertical-axis (y-axis) input receives the voltage part of an incoming signal and then moves the spot up or down depending on the value of the voltage at a particular instant in time. The horizontal axis (x axis) is usually used as a time axis, where an internally generated linear ramp voltage is used to move the spot across the screen from left to right at a rate that can be controlled by the operator. If the signal is repetitive, such as a sinusoidal wave, the oscilloscope can make the sinusoidal pattern appears to stand still. This makes a scope a useful tool for analyzing time-varying voltages.

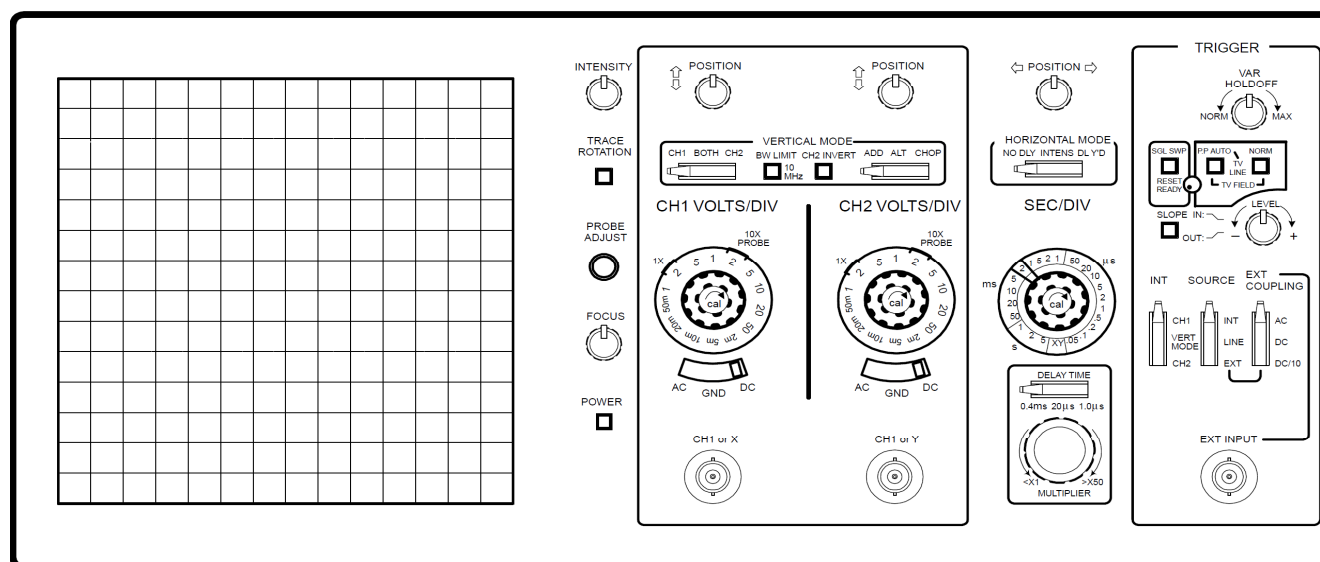


FIGURE 14.22

Even though oscilloscopes only measure voltage, it is possible to convert quantities such as current, strain, acceleration, pressure, etc., into voltages that the scope can use. To convert a current into a voltage, a resistor of known resistance is used; the current is measured indirectly by measuring the voltage drop across the resistor and then applying Ohm's law. To convert strain, movement, etc. into voltage requires the use of transducers (electromechanical devices). By applying some calibrating tricks, the magnitude of, say, a pressure applied to a pressure transducer can be measured accurately.

### 14.4.1 How Scopes Work

An oscilloscope is built around a cathode-ray tube. All the circuits inside the scope are designed to take an input signal and modify it into a set of electrical instructions

that supply the tube's electron gun with aiming instructions (location where to focus the beam). Most of the knobs and switches on the face of a scope that are connected to the interior circuitry are designed to help modify the instructions sent to the cathode-ray tube. For example, these controls set voltage scale, time scale, intensity of beam, focus of beam, channels selection, triggering, etc.

### Cathode-Ray Tube

A cathode-ray tube consists of an electron gun (filament, cathode, control grid, and anode), a second anode, vertical deflection plates, horizontal deflection plates, and a phosphor-coated screen. When current flows through the filament, the filament heats the cathode to a point where electrons are emitted. The control grid controls the amount of electrons that flow through the electron gun and thus controls the intensity of the beam. If this grid is made more negative in voltage, more electrons will be repelled away from the grid, thus reducing the electron flow. The electron beam is focused into a sharp pointlike beam by applying a controlling voltage or focus voltage to anode 1. The second anode is supplied with a large voltage that is used to give the electrons within the beam the additional momentum needed to cause a photon emission once they collide with the phosphor screen. The beam-focusing section of the tube is referred to as the *electron gun*. There are two sets of electrostatic deflection plates (vertical and horizontal) that are set between the second anode and the inner face of the phosphor screen. One set of plates is used to deflect the electron beam vertically; the other set is used to deflect the beam horizontally. For example, when one of the plates of a pair of plates is made more negative in charge than the other, the electron beam will bend away from the negative plate and veer toward the more positive plate. (The electrons in the beam are usually moving with sufficient forward velocity that they never actually come in contact with the plates.) When a sawtooth voltage is applied to the horizontal plates, the gradually rising potential across the plates pulls the electron beam from the negative plate to the positive plate, causing the beam to scan across the phosphor screen. The vertical plates cause the electron beam to move up and down.

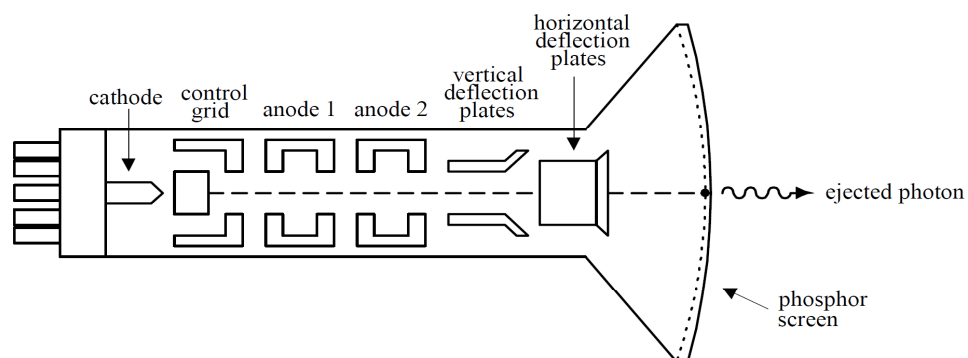


FIGURE 14.23

The next step in understanding how an oscilloscope works is understanding how an incoming signal is converted into a set of electrical signals or applied voltages that control the beam-aiming mechanisms of the cathode-ray tube. This is where the interior circuitry comes in.

## Interior Circuitry of a Scope

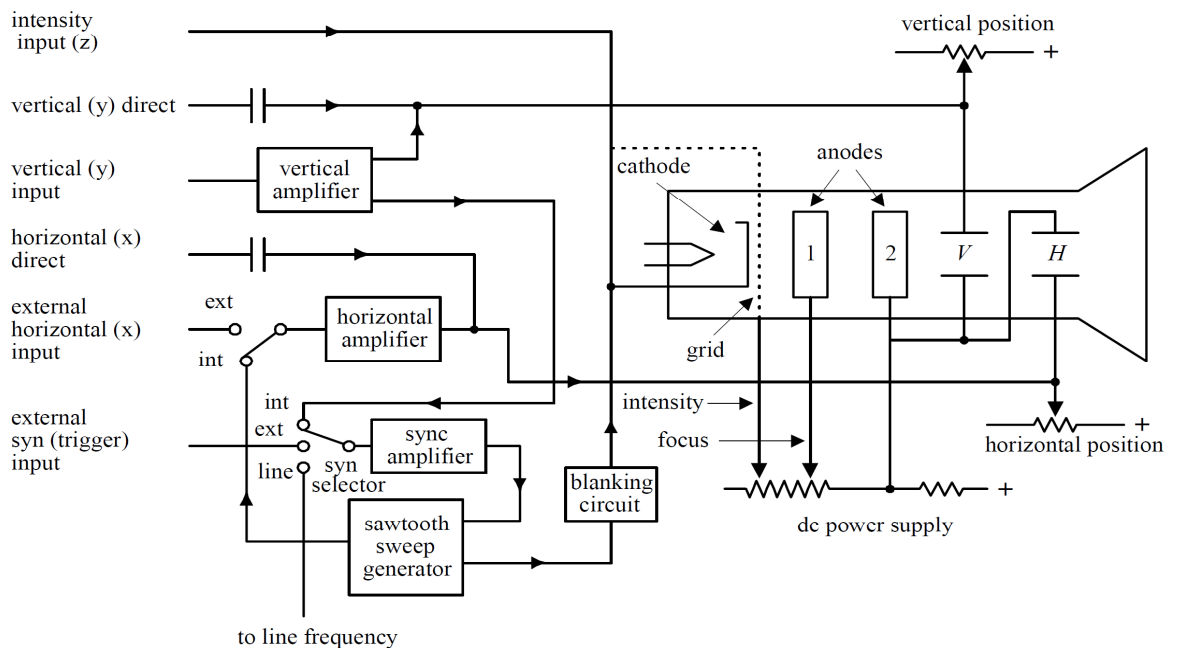


FIGURE 14.24

Let's take a sinusoidal signal and see how the interior circuits of a scope convert it into something you can see on a display. The first thing you do is apply the sinusoidal signal to the vertical input. From the vertical input, the sinusoidal signal is sent to a vertical amplifier, where it is amplified so that it can supply enough voltage to deflect the electron beam. The vertical amplifier then sends a signal to the sweep selector. When the sweep selector is switched to the internal position (the other positions will be explained later), the signal from the vertical amplifier will enter the sync amplifier. The sync amplifier is used to synchronize the horizontal sweep (sawtooth in this case) with the signal under test. Without the sync amplifier, the display pattern would drift across the screen in a random fashion. The sync amplifier then sends a signal to the sawtooth sweep generator, telling it to start a cycle. The sawtooth sweep generator then sends a sawtooth signal to a horizontal amplifier (when horizontal input is set to internal). At the same time, a signal is sent from the sawtooth sweep generator to the blanking circuit. The blanking circuit creates a high negative voltage on the control grid (or high positive voltage on the cathode-ray tube cathode), which turns off the beam as it snaps back to the starting point. Finally, voltages from the vertical and horizontal amplifiers (sawtooth) are sent to the vertical and horizontal plates in a synchronized fashion; the final result is a sinusoidal pattern displayed on the scope's screen.

The other features—such as vertical direct and horizontal direct inputs, external horizontal input, external trigger, line frequency, xy mode, etc.—are described later in this chapter. It is important to note that the scope does not always use a sawtooth voltage applied to the horizontal plates. You can change the knobs and inputs and use another input signal for the horizontal axis. Controls such as intensity, focus, and horizontal and vertical position of the beam can be understood by looking at the oscilloscope circuit diagram.

### 14.4.3 Aiming the Beam

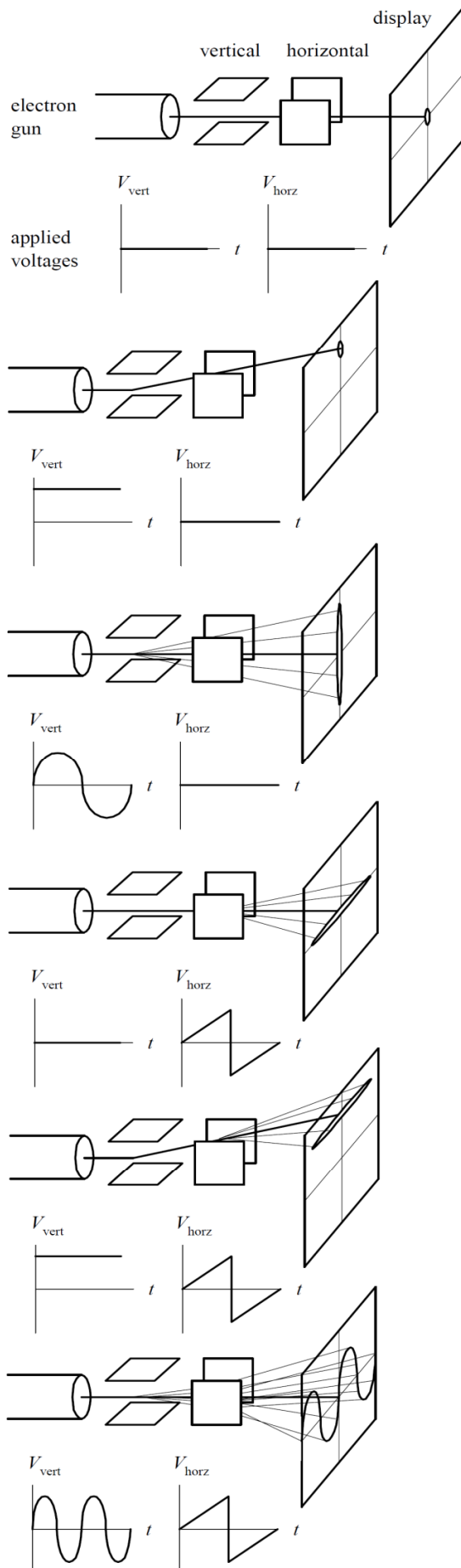


FIGURE 14.25

When no voltages are applied to the horizontal and vertical plates, the electron beam is focused at the center of the scope's display.

When a dc voltage is applied to the vertical plates, while no voltage is applied to the horizontal plates, the electron beam shifts up or down depending on the sign of the applied voltage.

When a sinusoidal voltage is applied to the vertical plates, while no voltage is applied to the horizontal plates, a vertical line is traced on the y axis.

When a sawtooth voltage is applied to the horizontal plates, while no voltage is applied to the vertical plate, the electron beam traces a horizontal line from left to right. After each sawtooth, the beam jumps back to the left and repeats its left-to-right sweep.

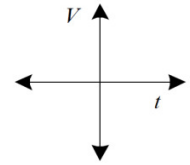
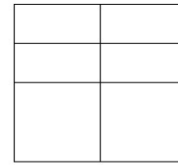
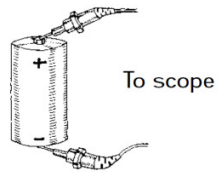
When a dc voltage is applied to the vertical plates, while a sawtooth voltage is applied to the horizontal plates, a horizontal line is created that is shifted up or down depending on the sign of the dc vertical plate voltage (+ or -).

When a sinusoidal voltage is applied to the vertical plates and a sawtooth voltage is applied to the horizontal plates, the electron beam moves up as the signal voltage increases and at the same time moves to the left as the sawtooth voltage is applied to the horizontal plates. The display gives a sinusoidal graph. If the applied sinusoidal frequency is twice that of the sawtooth frequency, two cycles appear on the display.

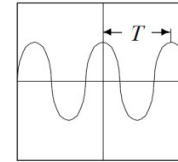
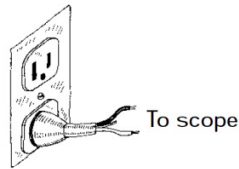


## 14.4.4 Scope Applications

### DC Voltmeter



### AC Voltmeter/ AC Frequency Meter



$$T = \text{period}$$

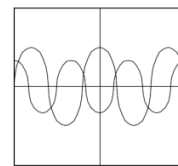
$$f = \text{frequency}$$

$$f = 1/T$$

$$V_{\text{rms}} = \frac{1}{\sqrt{2}} V_{\text{max}}$$

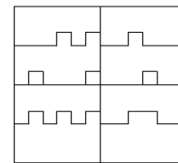
### Phase Relationships Between Two Signals

source 1 → chan 1  
source 2 → chan 2



The scope can be used to compare two source signals (e.g., measure phase shifts, voltage and frequency differences, etc.).

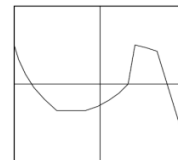
### Digital Measurements



A scope can be used to create timing diagrams for digital circuits.

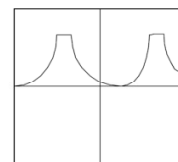
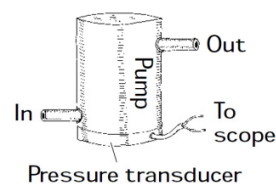
### xy Graphics (xy Mode)

chan 1 input → x-axis  
chan 2 input → y-axis



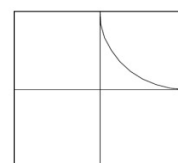
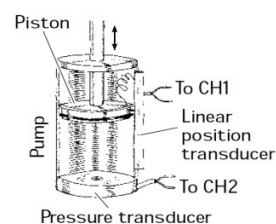
The scope no longer uses the x axis as the time axis but uses signal voltage from another external source.

### Measurements Using Transducers



By using transducers to convert an input quantity, such as pressure, into a voltage, the scope can be transformed into a pressure meter.

y axis → pressure  
x axis → time



Here, a scope is used in xy mode, where  
y axis → pressure  
x axis → piston

FIGURE 14.26