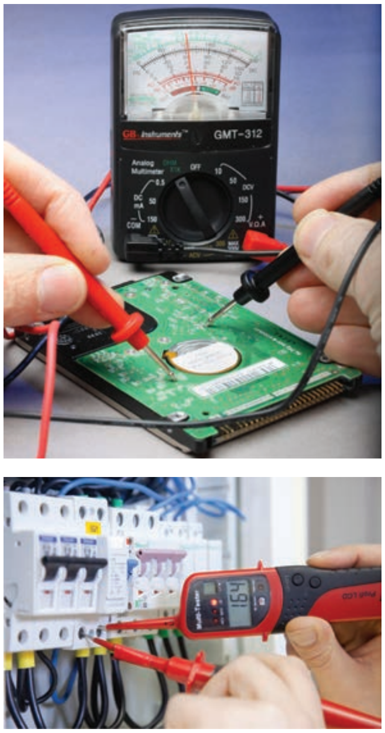


(a) (b)

FIGURE 19–30 (a) An analog multimeter. (b) An electronic digital meter measuring voltage at a circuit breaker.

PHYSICS APPLIED
Ammeters use shunt resistor in parallel

19–8 Ammeters and Voltmeters—Measurement Affects the Quantity Being Measured

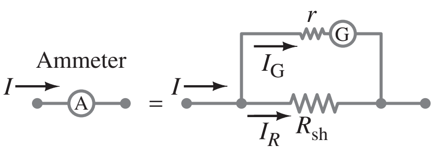
Measurement is a fundamental part of physics, and is not as simple as you might think. Measuring instruments can not be taken for granted; their results are not perfect and often need to be interpreted. As an illustration of measurement "theory" we examine here how electrical quantities are measured using meters. We also examine how meters affect the quantity they attempt to measure.

An **ammeter** measures current, and a **voltmeter** measures potential difference or voltage. Each can be either: (1) an *analog* meter, which displays numerical values by the position of a pointer that can move across a scale (Fig. 19–30a); or (2) a *digital* meter, which displays the numerical value in numbers (Fig. 19–30b). We now examine how analog meters work.

An analog ammeter or voltmeter, in which the reading is by a pointer on a scale (Fig. 19–30a), uses a *galvanometer*. A galvanometer works on the principle of the force between a magnetic field and a current-carrying coil of wire; it is straightforward to understand and will be discussed in Chapter 20. For now, we only need to know that the deflection of the needle of a galvanometer is proportional to the current flowing through it. The *full-scale current sensitivity* of a galvanometer, I_m, is the electric current needed to make the needle deflect full scale, typically about $50\,\mu A$.

A galvanometer whose sensitivity I_m is $50\,\mu A$ can measure currents from about $1\,\mu A$ (currents smaller than this would be hard to read on the scale) up to $50\,\mu A$. To measure larger currents, a resistor is placed in parallel with the galvanometer. An analog **ammeter**, represented by the symbol •–Ⓐ–•, consists of a galvanometer (•–Ⓖ–•) in parallel with a resistor called the **shunt resistor**, as shown in Fig. 19–31. ("Shunt" is a synonym for "in parallel.") The shunt resistance is R_{sh}, and the resistance of the galvanometer coil is r. The value of R_{sh} is chosen according to the full-scale deflection desired; R_{sh} is normally very small—giving an ammeter a very small net resistance—so most of the current passes through R_{sh} and very little ($\lesssim 50\,\mu A$) passes through the galvanometer to deflect the needle.

FIGURE 19–31 An ammeter is a galvanometer in parallel with a (shunt) resistor with low resistance, R_{sh}.



EXAMPLE 19–15 Ammeter design. Design an ammeter to read 1.0 A at full scale using a galvanometer with a full-scale sensitivity of $50\,\mu A$ and a resistance $r = 30\,\Omega$. Check if the scale is linear.

APPROACH Only $50\,\mu A\;(= I_G = 0.000050\text{ A})$ of the 1.0-A current passes through the galvanometer to give full-scale deflection. The rest of the current $(I_R = 0.999950\text{ A})$ passes through the small shunt resistor, R_{sh}, Fig. 19–31. The potential difference across the galvanometer equals that across the shunt resistor (they are in parallel). We apply Ohm's law to find R_{sh}.

SOLUTION Because $I = I_G + I_R$, when $I = 1.0$ A flows into the meter, we want I_R through the shunt resistor to be $I_R = 0.999950$ A. The potential difference across the shunt is the same as across the galvanometer, so

$$I_R R_{sh} = I_G r.$$

Then

$$R_{sh} = \frac{I_G r}{I_R} = \frac{(5.0 \times 10^{-5}\text{ A})(30\,\Omega)}{(0.999950\text{ A})} = 1.5 \times 10^{-3}\,\Omega,$$

or $0.0015\,\Omega$. The shunt resistor must thus have a *very* low resistance and most of the current passes through it.

Because $I_G = I_R(R_{sh}/r)$ and (R_{sh}/r) is constant, we see that the scale is linear (needle deflection is proportional to I_G). If the current $I \approx I_R$ into the meter is half of full scale, 0.50 A, the current to the galvanometer will be $I_G = I_R(R_{sh}/r) = (0.50\text{ A})(1.5 \times 10^{-3}\,\Omega)/(30\,\Omega) = 25\,\mu A$, which would make the needle deflect halfway, as it should.

PHYSICS APPLIED
Voltmeters use series resistor

An analog **voltmeter** (•–Ⓥ–•) consists of a galvanometer and a resistor R_{ser} connected in series, Fig. 19–32. R_{ser} is usually large, giving a voltmeter a high internal resistance.

EXAMPLE 19–16 **Voltmeter design.** Using a galvanometer with internal resistance $r = 30\,\Omega$ and full-scale current sensitivity of $50\,\mu\text{A}$, design a voltmeter that reads from 0 to 15 V. Is the scale linear?

APPROACH When a potential difference of 15 V exists across the terminals of our voltmeter, we want $50\,\mu\text{A}$ to be passing through it so as to give a full-scale deflection.

SOLUTION From Ohm's law, $V = IR$, we have (Fig. 19–32)

$$15\text{ V} = (50\,\mu\text{A})(r + R_{\text{ser}}),$$

so

$$R_{\text{ser}} = (15\text{ V})/(5.0 \times 10^{-5}\text{ A}) - r = 300\text{ k}\Omega - 30\,\Omega \approx 300\text{ k}\Omega.$$

Notice that $r = 30\,\Omega$ is so small compared to the value of R_{ser} that it doesn't influence the calculation significantly. The scale will again be linear: if the voltage to be measured is 6.0 V, the current passing through the voltmeter will be $(6.0\text{ V})/(3.0 \times 10^5\,\Omega) = 2.0 \times 10^{-5}\text{ A}$, or $20\,\mu\text{A}$. This will produce two-fifths of full-scale deflection, as required $(6.0\text{ V}/15.0\text{ V} = 2/5)$.

FIGURE 19–32 A voltmeter is a galvanometer in series with a resistor with high resistance, R_{ser}.

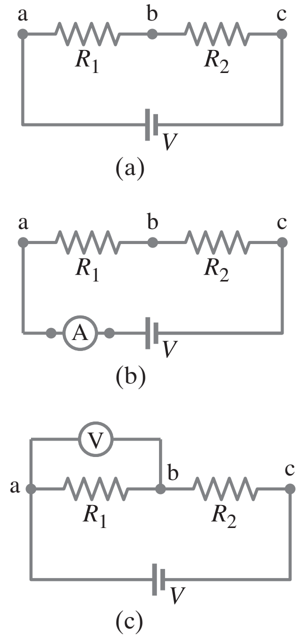
How to Connect Meters

Suppose you wish to determine the current I in the circuit shown in Fig. 19–33a, and the voltage V across the resistor R_1. How exactly are ammeters and voltmeters connected to the circuit being measured?

Because an ammeter is used to measure the current flowing in the circuit, it must be inserted directly into the circuit, in series with the other elements, as shown in Fig. 19–33b. The smaller its internal resistance, the less it affects the circuit.

A voltmeter is connected "externally," in parallel with the circuit element across which the voltage is to be measured. It measures the potential difference between two points. Its two wire leads (connecting wires) are connected to the two points, as shown in Fig. 19–33c, where the voltage across R_1 is being measured. The larger its internal resistance ($R_{\text{ser}} + r$, Fig. 19–32), the less it affects the circuit being measured.

FIGURE 19–33 Measuring current and voltage.



Effects of Meter Resistance

It is important to know the sensitivity of a meter, for in many cases the resistance of the meter can seriously affect your results. Consider the following Example.

PHYSICS APPLIED
Correcting for meter resistance

EXAMPLE 19–17 **Voltage reading vs. true voltage.** An electronic circuit has two 15-kΩ resistors, R_1 and R_2, connected in series, Fig. 19–34a. The battery voltage is 8.0 V and it has negligible internal resistance. A voltmeter has resistance of 50 kΩ on the 5.0-V scale. What voltage does the meter read when connected across R_1, Fig. 19–34b, and what error is caused by the meter's finite resistance?

APPROACH The meter acts as a resistor in parallel with R_1. We use parallel and series resistor analyses and Ohm's law to find currents and voltages.

SOLUTION The voltmeter resistance of 50,000 Ω is in parallel with $R_1 = 15\text{ k}\Omega$, Fig. 19–34b. The net resistance R_{eq} of these two is

$$\frac{1}{R_{\text{eq}}} = \frac{1}{50\text{ k}\Omega} + \frac{1}{15\text{ k}\Omega} = \frac{13}{150\text{ k}\Omega};$$

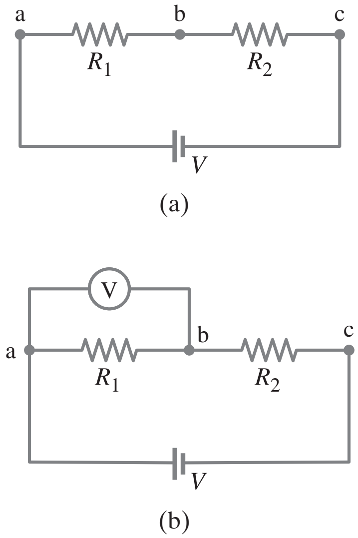
so $R_{\text{eq}} = 11.5\text{ k}\Omega$. This $R_{\text{eq}} = 11.5\text{ k}\Omega$ is in series with $R_2 = 15\text{ k}\Omega$, so the total resistance is now 26.5 kΩ (not the original 30 kΩ). Hence the current from the battery is

$$I = \frac{8.0\text{ V}}{26.5\text{ k}\Omega} = 3.0 \times 10^{-4}\text{ A} = 0.30\text{ mA}.$$

Then the voltage drop across R_1, which is the same as that across the voltmeter, is $(3.0 \times 10^{-4}\text{ A})(11.5 \times 10^3\,\Omega) = 3.5\text{ V}$. [The voltage drop across R_2 is $(3.0 \times 10^{-4}\text{ A})(15 \times 10^3\,\Omega) = 4.5\text{ V}$, for a total of 8.0 V.] If we assume the meter is accurate, it reads 3.5 V. In the original circuit, without the meter, $R_1 = R_2$ so the voltage across R_1 is half that of the battery, or 4.0 V. Thus the voltmeter, because of its internal resistance, gives a low reading. It is off by 0.5 V, or more than 10%.

NOTE Often the **sensitivity** of a voltmeter is specified on its face as, for example, 10,000 Ω/V. Then on a 5.0-V scale, the voltmeter would have a resistance given by $(5.0\text{ V})(10{,}000\,\Omega/\text{V}) = 50{,}000\,\Omega$. The meter's resistance depends on the scale used.

FIGURE 19–34 Example 19–17.



Example 19–17 illustrates how seriously a meter can affect a circuit and give a misleading reading. If the resistance of a voltmeter is much higher than the resistance of the circuit, however, it will have little effect and its readings can be more accurate, at least to the manufactured precision of the meter, which for analog meters is typically 3% to 4% of full-scale deflection. Even an ammeter can interfere with a circuit, but the effect is minimal if its resistance is much less than that of the circuit as a whole. For both voltmeters and ammeters, the more sensitive the galvanometer, the less effect it will have on the circuit. [A 50,000-Ω/V meter is far better than a 1000-Ω/V meter.]

CAUTION
Measurements affect the quantity being measured

Whenever we make a measurement on a circuit, to some degree we affect that circuit (Example 19–17). This is true for other types of measurement as well: when we make a measurement on a system, we affect that system in some way. On a temperature measurement, for example, the thermometer can exchange heat with the system, thus altering the temperature it is measuring. It is important to be able to make needed corrections, as we saw in Example 19–17.

Other Meters

The meters described above are for direct current. A dc meter can be modified to measure ac (alternating current, Section 18–7) with the addition of diodes (Chapter 29), which allow current to flow in one direction only. An ac meter can be calibrated to read rms or peak values.

Voltmeters and ammeters can have several series or shunt resistors to offer a choice of range. **Multimeters** can measure voltage, current, and resistance. Sometimes a multimeter is called a VOM (Volt-Ohm-Meter or Volt-Ohm-Milliammeter).

An **ohmmeter** measures resistance, and must contain a battery of known voltage connected in series to a resistor (R_{ser}) and to an ammeter which contains a shunt R_{sh} (Fig. 19–35). The resistor whose resistance is to be measured completes the circuit, and must not be connected in a circuit containing a voltage source. The needle deflection of the meter is inversely proportional to the resistance. The scale calibration depends on the value of its series resistor, which is changeable in a multimeter. Because an ohmmeter sends a current through the device whose resistance is to be measured, it should not be used on very delicate devices that could be damaged by the current.

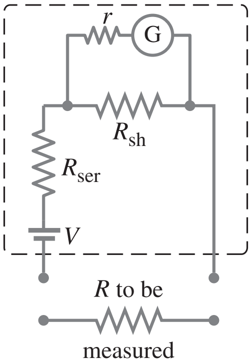


FIGURE 19–35 An ohmmeter.

Digital Meters

Digital meters (see Fig. 19–30b) are used in the same way as analog meters: they are inserted directly into the circuit, in series, to measure current (Fig. 19–33b), and connected "outside," in parallel with the circuit, to measure voltage (Fig. 19–33c).

The internal construction of digital meters is very different from analog meters. First, digital meters do not use a galvanometer, but rather semiconductor devices (Chapter 29). The electronic circuitry and digital readout are more sensitive than a galvanometer, and have less effect on the circuit to be measured. When we measure dc voltages, a digital meter's resistance is very high, commonly on the order of $10\,\mathrm{M}\Omega$ to $100\,\mathrm{M}\Omega$ $(10^7\text{–}10^8\,\Omega)$, and doesn't change significantly when different voltage scales are selected. A 100-MΩ digital meter draws very little current when connected across even a 1-MΩ resistance.

The precision of digital meters is exceptional, often one part in 10^4 $(=\ 0.01\%)$ or better. This precision is not the same as accuracy, however. A precise meter of internal resistance $10^8\,\Omega$ will not give accurate results if used to measure a voltage across a 10^8-Ω resistor—in which case it is necessary to do a calculation like that in Example 19–17.