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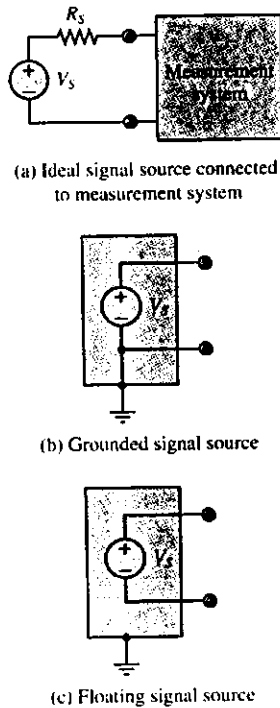
## **15.2 WIRING, GROUNDING, AND NOISE**

The importance of proper circuit connections cannot be overemphasized. Unfortunately, this is a subject that is rarely taught in introductory electrical engineering courses. The present section summarizes some important considerations regarding signal source connections, various types of input configurations, noise sources and coupling mechanisms, and means of minimizing the influence of noise on a measurement.

### **Signal Sources and Measurement System Configurations**

Before proper connection and wiring techniques can be presented, we must examine the difference between **grounded** and **floating signal sources**. Every sensor can be thought of as some kind of signal source; a general representation of the connection of a sensor to a measurement system is shown in Figure 15.7(a). The sensor is modeled as an ideal voltage source in series with a source resistance. Although this representation does not necessarily apply to all sensors, it will be adequate for the purposes of the present section. Figures 15.7(b) and (c) show two types of signal sources: grounded and floating. A grounded signal source is one

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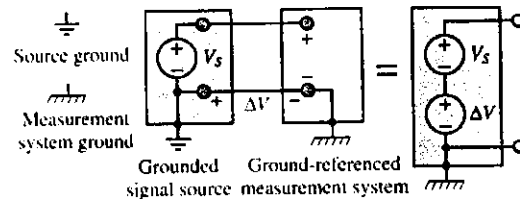


**Figure 15.7** Measurement system and types of signal sources

in which a ground reference is established—for example, by connecting the *signal low* lead to a case or housing. A floating signal source is one in which neither signal lead is connected to ground; since ground potential is arbitrary, the signal source voltage levels (*signal low* and *signal high*) are at an unknown potential relative to the case ground. Thus, the signal is said to be *floating*. Whether a sensor can be characterized as a grounded or a floating signal source ultimately depends on the connection of the sensor to its case, but the choice of connection may depend on the nature of the source. For example, the thermocouple described in Section 15.1 is *intrinsically* a floating signal source, since the signal of interest is a difference between two voltages. The same thermocouple *could* become a grounded signal source if one of its two leads were directly connected to ground, but this is usually not a desirable arrangement for this particular sensor.

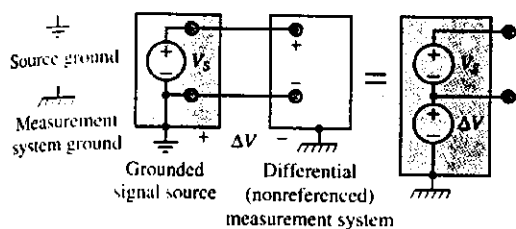
In analogy with a signal source, a measurement system can be either **ground-referenced** or **differential**. In a ground-referenced system, the signal low connection is tied to the instrument case ground; in a differential system, neither of the two signal connections is tied to ground. Thus, a differential measurement system is well suited to measuring the difference between two signal levels (such as the output of an ungrounded thermocouple).

One of the potential dangers in dealing with grounded signal sources is the introduction of **ground loops**. A ground loop is an undesired current path caused by the connection of two reference voltages to each other. This is illustrated in Figure 15.8, where a grounded signal source is shown connected to a ground-referenced measurement system. Notice that we have purposely denoted the signal source ground and the measurement system ground by two distinct symbols, to emphasize that these are not necessarily at the same potential—as also indicated by the voltage difference  $\Delta V$ . Now, one might be tempted to tie the two grounds to each other, but this would only result in a current flowing from one ground to the other, through the small (but nonzero) resistance of the wire connecting the two. The net effect of this ground loop would be that the voltage measured by the instrument would include the unknown ground voltage difference  $\Delta V$ , as shown in Figure 15.8. Since this latter voltage is unpredictable, you can see that ground loops can cause substantial errors in measuring systems. In addition, ground loops are the primary cause of conducted noise, as explained later in this section.

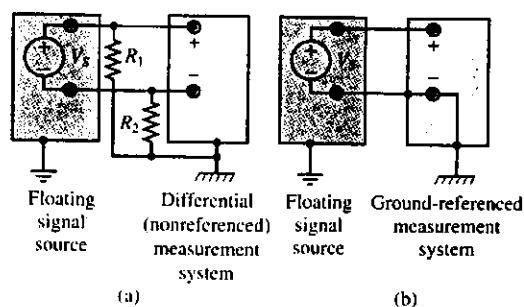


**Figure 15.8** Ground loop in ground-referenced measurement system

A differential measurement system is often a way to avoid ground loop problems, because the signal source and measurement system grounds are not connected to each other, and especially because the signal low input of the measuring instrument is not connected to either instrument case ground. The connection of a grounded signal source and a differential measurement system is depicted in Figure 15.9.



**Figure 15.9** Differential (nonreferenced) measurement system



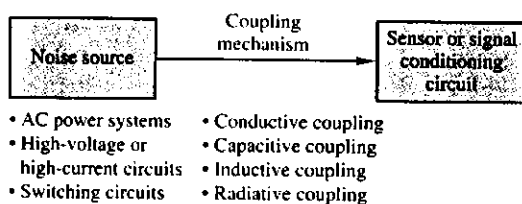
**Figure 15.10** Measuring signals from a floating source: (a) differential input; (b) single-ended input

If the signal source connected to the differential measurement system is floating, as shown in Figure 15.10, it is often a recommended procedure to reference the signal to the instrument ground by means of two identical resistors that can provide a return path to ground for any currents present at the instrument. An example of such input currents would be the input bias currents inevitably present at the input of an operational or instrumentation amplifier.

The simple concepts illustrated in the preceding paragraphs and figures can assist the user and designer of instrumentation systems in making the best possible wiring connections for a given measurement.

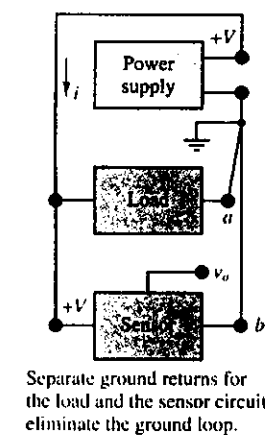
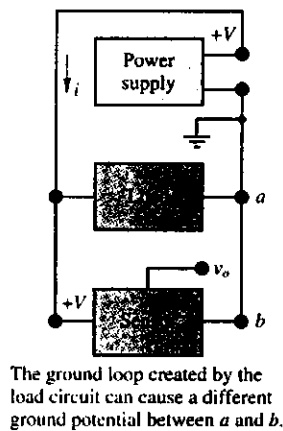
## Noise Sources and Coupling Mechanisms

Noise—meaning any undesirable signal interfering with a measurement—is an unavoidable element of all measurements. Figure 15.11 depicts a block diagram of the three essential stages of a noisy measurement: a **noise source**, a **noise coupling mechanism**, and a sensor or associated signal-conditioning circuit. Noise sources are always present, and are often impossible to eliminate completely; typical sources of noise in practical measurements are the electromagnetic fields caused by fluorescent light fixtures, video monitors, power supplies, switching circuits, and high-voltage (or current) circuits. Many other sources exist, of course, but often the simple sources in our everyday environment are the most difficult to defeat.

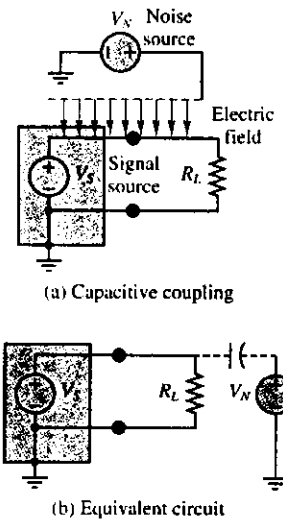


**Figure 15.11** Noise sources and coupling mechanisms

Figure 15.11 also indicates that various coupling mechanisms can exist between a noise source and an instrument. Noise coupling can be conductive; that



**Figure 15.12** Conductive coupling: ground loop and separate ground returns



**Figure 15.13** Capacitive coupling and equivalent-circuit representation

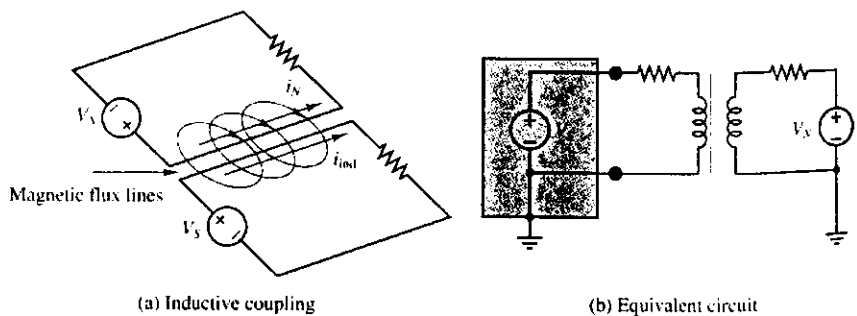
is, noise currents may actually be conducted from the noise source to the instrument by physical wires. Noise can also be coupled capacitively, inductively, and radiatively.

Figure 15.12 illustrates how interference can be **conductively coupled** by way of a ground loop. In the figure, a power supply is connected to both a load and a sensor. We shall assume that the load may be switched on and off, and that it carries substantial currents. The top circuit contains a ground loop: the current *i* from the supply divides between the load and sensor; since the wire resistance is nonzero, a large current flowing through the load may cause the ground potential at point *a* to differ from the potential at point *b*. In this case, the measured sensor output is no longer  $v_o$ , but it is now equal to  $v_o + v_{ba}$ , where  $v_{ba}$  is the potential difference from point *b* to point *a*. Now, if the load is switched on and off and its current is therefore subject to large, abrupt changes, these changes will be manifested in the voltage  $v_{ba}$  and will appear as noise on the sensor output.

This problem can be cured simply and effectively by providing separate *ground returns* for the load and sensor, thus eliminating the ground loop.

The mechanism of **capacitive coupling** is rooted in electric fields that may be caused by sources of interference. The detailed electromagnetic analysis can be quite complex, but to understand the principle, refer to Figure 15.13(a), where a noise source is shown to generate an electric field. If a noise source conductor is sufficiently close to a conductor that is part of the measurement system, the two conductors (separated by air, a dielectric) will form a capacitor, through which any time-varying currents can flow. Figure 15.13(b) depicts an equivalent circuit in which the noise voltage  $V_N$  couples to the measurement circuit through an imaginary capacitor, representing the actual capacitance of the noise path.

The dual of capacitive coupling is **inductive coupling**. This form of noise coupling is due to the magnetic field generated by current flowing through a conductor. If the current is large, the magnetic fields can be significant, and the **mutual inductance** (see Chapters 5 and 16) between the noise source and the measurement circuit causes the noise to couple to the measurement circuit. Thus, inductive coupling, as shown in Figure 15.14, results when undesired (unplanned) magnetic coupling ties the noise source to the measurement circuit.

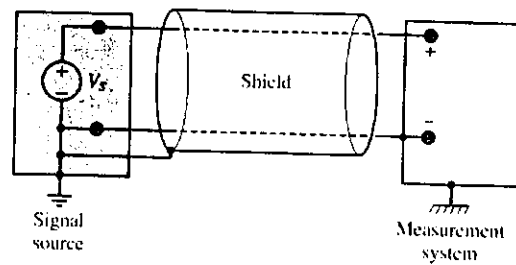


**Figure 15.14** Inductive coupling and equivalent-circuit representation

**Noise Reduction**

Various techniques exist for minimizing the effect of undesired interference, in addition to proper wiring and grounding procedures. The two most common methods are **shielding** and the use of **twisted-pair wire**. A shielded cable is

shown in Figure 15.15. The shield is made of a copper braid or of foil and is usually grounded at the source end *but not at the instrument end*, because this would result in a ground loop. The shield can protect the signal from a significant amount of electromagnetic interference, especially at lower frequencies. Shielded cables with various numbers of conductors are available commercially. However, shielding cannot prevent inductive coupling. The simplest method for minimizing inductive coupling is the use of twisted-pair wire; the reason for using twisted pair is that untwisted wire can offer large loops that can couple a substantial amount of electromagnetic radiation (see Section 16.1). Twisting drastically reduces the loop area, and with it the interference. Twisted pair is available commercially.



**Figure 15.15** Shielding