reduce the input coupling capacitor, since its load has been bootstrapped to high impedance. However, this can generate a peak in the frequency response, in the manner of an active filter (see Section 5.06).

Ideal current-to-voltage converter

Remember that the humble resistor is the simplest I-to-V converter. However, it has the disadvantage of presenting a nonzero impedance to the source of input current; this can be fatal if the device providing the input current has very little compliance or does not produce a constant current as the output voltage changes. A good example is a photovoltaic cell, a fancy name for a sun battery. Even the garden-variety signal diodes you use in circuits have a small photovoltaic effect (there are amusing stories of bizarre circuit behavior finally traced to this effect). Figure **4.16** shows the good way to convert current

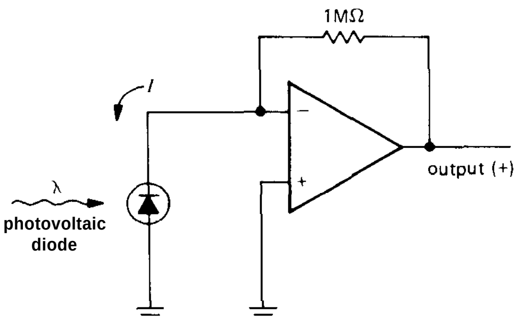

Figure 4.16

to voltage while holding the input strictly at ground. The inverting input is a virtual ground; this is fortunate, since a photovoltaic diode can generate only a few tenths of a volt. This particular circuit has an output of 1 volt per microamp of input current. (With BJT-input op-amps you sometimes see a resistor connected between the noninverting input and ground; its function will be explained shortly in connection with op-amp shortcomings.)

Of course, this transresistance configuration can be used equally well for devices that source their current via some positive excitation voltage, such as V_{CC}. Photomultiplier tubes and phototransistors (both devices that source current from a positive supply when exposed to light) are often used this way (Fig. **4.17).**

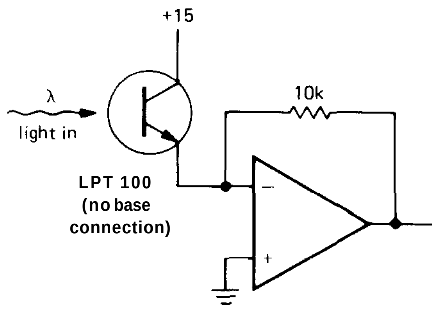

Figure 4.17

EXERCISE 4.4

Use a 411 and a 1mA (full scale) meter to construct a "perfect" current meter (i.e., one with zero input impedance) with 5mA full scale. Design the circuit so that the meter will never be driven more than ±150% full scale. Assume that the 411 output can swing to ±13 volts (±15V supplies) and that the meter has 500 ohms internal resistance.

Differential amplifier

The circuit in Figure 4.18 is a differential amplifier with gain R_2/R_1. As with the current source that used matched resistor ratios, this circuit requires precise resistor matching to achieve high common-mode rejection ratios. The best procedure is to stock up on a bunch of 100k 0.01% resistors next time you have a chance. All your differential amplifiers will have unity gain, but that's easily remedied with further (single-ended) stages of gain. We will treat differential amplifiers in more detail in Chapter 7.

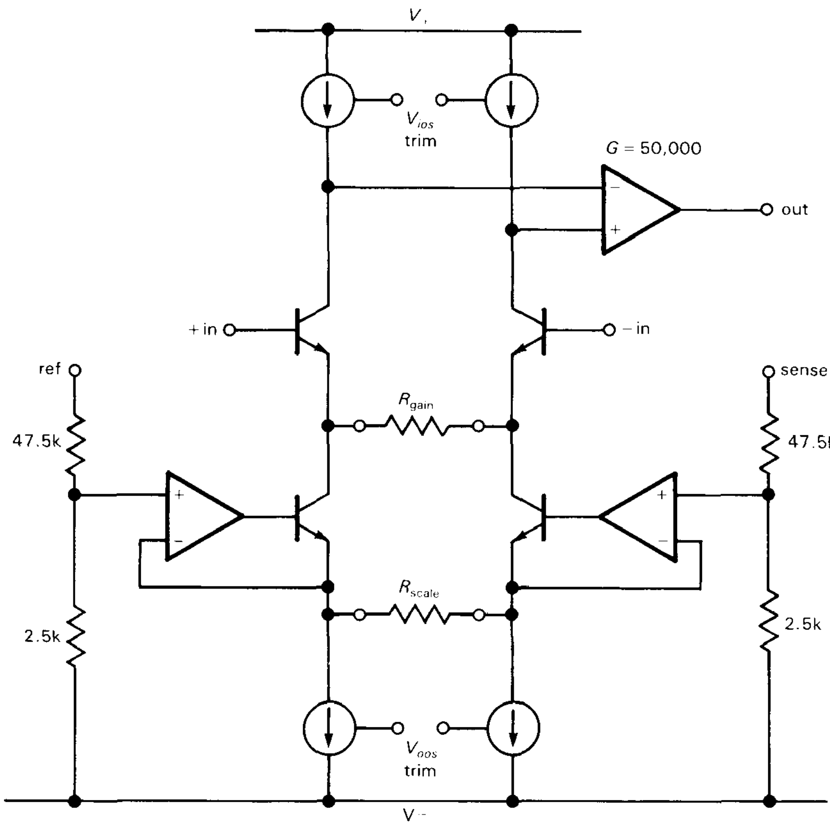

Figure 7.37. Block diagram of the AMP-01 instrumentation amplifier IC.

kinds of noise that afflict electronic circuits. Then we will launch into a discussion of transistor and FET noise, including methods for low-noise design with a given signal source, and will present some design examples. After a short discussion of noise in differential and feedback amplifiers, we will conclude with a section on proper grounding and shielding and the elimination of interference and pickup. See also Section 13.24 (Analog modeling tools).

7.11 Origins and kinds of noise

Since the term **noise** can be applied to anything that obscures a desired signal, noise can itself be another signal ("interference"); most often, however, we use the term to describe "random" noise of a physical (often thermal) origin. Noise can be characterized by its frequency spectrum, its amplitude distribution, and the physical mechanism responsible for its generation. Let's next look at the chief offenders.

Johnson noise

Any old resistor just sitting on the table generates a noise voltage across its terminals known as Johnson noise. It has a flat frequency spectrum, meaning that there is the same noise power in each hertz of frequency (up to some limit, of course). Noise with a flat spectrum is also called "white noise." The actual open-circuit noise voltage generated by a resistance R at temperature T is given by

$$V_{\text{noise}}(\text{rms}) = V_{nR} = (4kTRB)^{\frac{1}{2}}$$

where k is Boltzmann's constant, T is the absolute temperature in degrees Kelvin (°K = °C + 273.16), and B is the bandwidth in hertz. Thus, $V_{\text{noise}}(\text{rms})$ is what you would measure at the output if you drove a perfect noiseless bandpass filter (of bandwidth B) with the voltage generated by a resistor at temperature T. At room temperature (68°F = 20°C = 293°K),

$$4kT = 1.62 \times 10^{-20}\text{V}^2/\text{Hz} - \Omega$$

$$(4kTR)^{\frac{1}{2}} = 1.27 \times 10^{-10} R^{\frac{1}{2}} \qquad \text{V/Hz}^{\frac{1}{2}}$$

$$= 1.27 \times 10^{-4} R^{\frac{1}{2}} \qquad \mu\text{V/Hz}^{\frac{1}{2}}$$

For example, a 10k resistor at room temperature has an open-circuit rms voltage of 1.3μV, measured with a bandwidth of 10kHz (e.g., by placing it across the input of a high-fidelity amplifier and measuring the output with a voltmeter). The source resistance of this noise voltage is just R. Figure 7.38 plots the simple relationship between Johnson-noise voltage density (rms voltage per square root bandwidth) and source resistance.

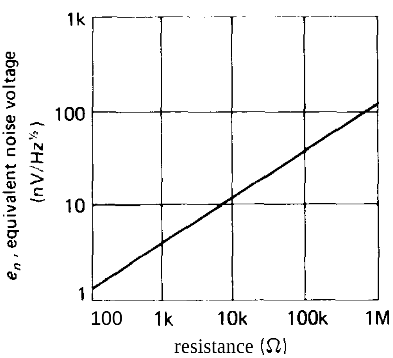

Figure 7.38. Thermal noise voltage versus resistance.

The amplitude of the Johnson-noise voltage at any instant is, in general, unpredictable, but it obeys a Gaussian amplitude distribution (Fig. 7.39),

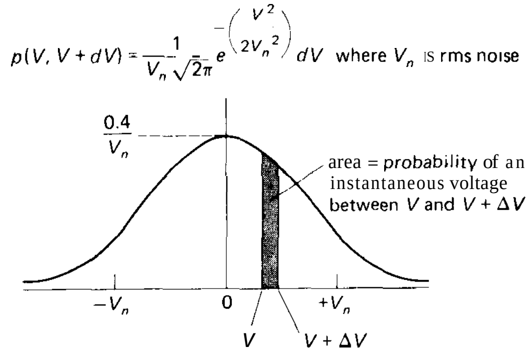

Figure 7.39

where $p(V)dV$ is the probability that the instantaneous voltage lies between V and V + dV, and V_n is the rms noise voltage, given earlier.

The significance of Johnson noise is that it sets a lower limit on the noise voltage in any detector, signal source, or amplifier having resistance. The resistive part of a source impedance generates Johnson noise, as do the bias and load resistors of an amplifier. You will see how it all works out shortly.

It is interesting to note that the physical analog of resistance (any mechanism of energy loss in a physical system, e.g., viscous friction acting on small particles in a liquid) has associated with it fluctuations in the associated physical quantity (in this case, the particles' velocity, manifest as the chaotic Brownian motion). Johnson noise is just a special case of this fluctuation-dissipation phenomenon.

Johnson noise should not be confused with the additional noise voltage created by the effect of resistance fluctuations when an externally applied current flows through a resistor. This "excess noise" has a 1/f spectrum (approximately) and is heavily dependent on the actual construction of the resistor. We will talk about it later.

Shot noise

An electric current is the flow of discrete electric charges, not a smooth fluidlike flow. The finiteness of the charge quantum results in statistical fluctuations of the current. If the charges act independent of each other, the fluctuating current is given by

$$I_{\text{noise}}(\text{rms}) = I_{nR} = (2qI_{dc}B)^{\frac{1}{2}}$$

where q is the electron charge (1.60×10^{-19} coulomb) and B is the measurement bandwidth. For example, a "steady" current of 1 amp actually has an rms fluctuation of 57nA, measured in a 10kHz bandwidth; i.e., it fluctuates by about 0.000006%. The relative fluctuations are larger for smaller currents: A "steady" current of 1μA actually has an rms current noise fluctuation, measured over a 10kHz bandwidth, of 0.006%, i.e., -85dB. At 1pA dc, the rms current fluctuation (same bandwidth) is 56fA, i.e., a 5.6% variation! Shot noise is "rain on a tin roof." This noise, like resistor Johnson noise, is Gaussian and white.

The shot-noise formula given earlier assumes that the charge carriers making up the current act independently. That is indeed the case for charges crossing a barrier, as for example the current in a junction diode, where the charges move by diffusion; but it is not true for the important case of metallic conductors, where there are long-range correlations between charge carriers. Thus, the current in a simple resistive circuit has far less noise than is predicted by the shot-noise formula. Another important exception to the shot-noise formula is provided by our standard transistor current-source circuit (Fig. 2.21), in which negative feedback acts to quiet the shot noise.

EXERCISE 7.4

A resistor is used as the collector load in a low-noise amplifier; the collector current I_C is accompanied by shot noise. Show that the output noise voltage is dominated by shot noise (rather than Johnson noise in the resistor) as long as the quiescent voltage drop across the load resistor is greater than $2kT/q$ (50mV, at room temperature).

1/f noise (flicker noise)

Shot noise and Johnson noise are irreducible forms of noise generated according to physical principles. The most expensive and most carefully made resistor has exactly the same Johnson noise as the cheapest carbon resistor (of the same resistance). Real devices have, in addition, various sources of "excess noise." Real resistors suffer from fluctuations in resistance, generating an additional noise voltage (which adds to the ever-present Johnson noise) proportional to the dc current flowing through them. This noise depends on many factors having to do with the construction of the particular resistor, including the resistive material and especially the end-cap connections. Here is a listing of typical excess noise for various resistor types, given as rms microvolts per volt applied across the resistor, measured over one decade of frequency:

Carbon-composition	0.10μV to 3.0μV
Carbon-film	0.05μV to 0.3μV
Metal-film	0.02μV to 0.2μV
Wire-wound	0.01μV to 0.2μV

This noise has approximately a 1/f spectrum (equal power per decade of frequency) and is sometimes called "pink noise." Other noise-generating mechanisms often produce 1/f noise, examples being base current noise in transistors and cathode current noise in vacuum tubes. Curiously enough, 1/f noise is present in nature in unexpected places, e.g., the speed of ocean currents, the flow of sand in an hourglass, the flow of traffic on Japanese expressways, and the yearly flow of the Nile measured over the last 2000 years. If you plot the loudness of a piece of classical music versus time, you get a 1/f spectrum! No unifying principle has been found for all the 1/f noise that seems to be swirling around us, although particular sources can often be identified in each instance.

Interference

As we mentioned earlier, an interfering signal or stray pickup constitutes a form of noise. Here the spectrum and amplitude characteristics depend on the interfering signal. For example, 60Hz pickup has a sharp spectrum and relatively constant amplitude, whereas car ignition noise, lightning, and other impulsive interferences are broad in spectrum and spiky in amplitude. Other sources of interference are radio and television stations (a particularly serious problem near large cities), nearby electrical equipment, motors and elevators, subways, switching regulators, and television sets. In a slightly different guise you have the same sort of problem generated by anything that puts a signal into the parameter you are measuring. For example, an optical interferometer is susceptible to vibration, and a sensitive radiofrequency measurement (e.g., NMR) can be affected by ambient radiofrequency signals. Many circuits, as well as detectors and even cables, are sensitive to vibration and sound; they are *microphonic*, in the terminology of the trade.

Many of these noise sources can be controlled by careful shielding and filtering, as we will discuss later in the chapter. At other times you are forced to take draconian measures, involving massive stone tables (for vibration isolation), constant-temperature rooms, anechoic chambers, and electrically shielded rooms.

7.12 Signal-to-noise ratio and noise figure

Before getting into the details of amplifier noise and low-noise design, we need to define a few terms that are often used to describe amplifier performance. These involve ratios of noise voltages, measured at the same place in the circuit. It is conventional to refer noise voltages to the input of an amplifier (although the measurements are usually made at the output), i.e., to describe source noise and amplifier noise in terms of microvolts at the input that would generate the observed output noise. This makes sense when you want to think of the relative noise added by the amplifier to a given signal, independent of amplifier gain; it's also realistic, because most of the amplifier noise is usually contributed by the input stage. Unless we state otherwise, noise voltages are referred to the input.

Noise power density and bandwidth

In the preceding examples of Johnson noise and shot noise, the noise voltage you measure depends both on the measurement bandwidth B (i.e., how much noise you see depends on how fast you look) and on the variables (R and I) of the noise source itself. So it's convenient to talk about an rms noise-voltage "density" v_n:

$$V_n(\text{rms}) = v_n B^{\frac{1}{2}} = (4kTR)^{\frac{1}{2}} B^{\frac{1}{2}}$$

where V_n is the rms noise voltage you would measure in a bandwidth B. White-noise sources have a v_n that doesn't depend on frequency, whereas pink noise, for instance, has a v_n that drops off at 3dB/octave. You'll often see v_n^2, too, the mean squared noise density. Since v_n always refers to rms, and v_n^2 always refers to mean square, you can just square v_n to get v_n^2! Sounds simple (and it is), but we want to make sure you don't get confused.

Note that B and the square root of B keep popping up. Thus, for example, for Johnson noise from a resistor R

$$v_{nR}(\text{rms}) = (4kTR)^{\frac{1}{2}} \qquad \text{V/Hz}^{\frac{1}{2}}$$

$$v_{nR}^2 = 4kTR \qquad \text{V}^2/\text{Hz}$$

$$V_n(\text{rms}) = v_{nR} B^{\frac{1}{2}} = (4kTRB)^{\frac{1}{2}} \qquad \text{V}$$

$$V_n^2 = v_{nR}^2 B = 4kTRB \qquad \text{V}^2$$