Temperature Measurement–Circuits and Components

JOSEPH J. CARR

It's easy to put together a temperature-measuring circuit if you know a little basic electronics. Here are several ideas to get you started.

WE'VE BEEN ABLE TO MEASURE TEMPERATURE electronically for many years but only recently have the circuits to do that been readily available. In this article, we will discuss some of the more common temperature-sensitive transducers, the circuits needed to make them work, and will introduce you to several integrated circuit temperature-transducer/amplifier combinations. Several semiconductor manufacturers now make two-terminal temperature devices that are very easy to use.

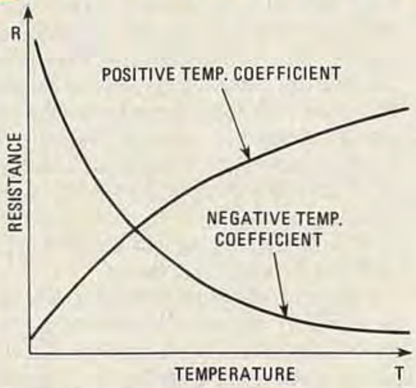
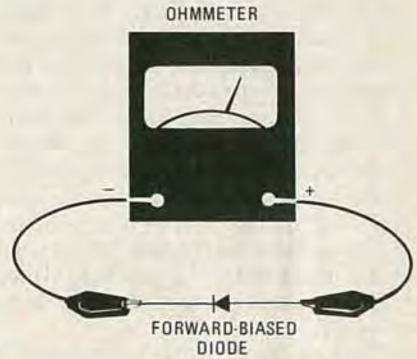


FIG. 2—AS THE TEMPERATURE goes up, the resistance of a positive temperature-coefficient thermistor also rises. The resistance of a negative temperature-coefficient thermistor drops with rising temperature.

FIG. 3—THE CURRENT through a pn junction is dependent on temperature. To demonstrate that, connect an ohmmeter across a diode as shown, grasp the diode in your hand, and note the change in resistance.



Temperature transducers

There are several different types of transducers that will convert a temperature to either a voltage or a current. Once the conversion is made, we can use amplifiers and voltmeters to process and display the result.

One of the earliest forms of temperature transducer was the *thermocouple*. If we form a junction of two wires of different metals as shown in Fig. 1, we will note a very interesting phenomenon called *Seebeck effect*. When the junction is heated, a voltage proportional to the temperature of the junction is developed across the two wires. That voltage can be measured and used to determine the temperature of the junction.

The voltage produced in a thermocouple is created by the different *work functions* of the two metals. Over the years, certain standard sets of metals have been defined for use in thermocouples and each standard set has its own temperature characteristics and applications.

Another very popular form of temperature transducer is the *thermistor*, or *THERMal* res*ISTOR*. That device has a resistance that is a function of temperature (Fig. 2). There are *positive temperature-coefficient* thermistors, with a resistance that rises with temperature, and *negative temperature-coefficient* thermistors, with a resistance that decreases with temperature. The temperature-resistance curves for most thermistors are not linear (i.e., straight-line). That makes it difficult to use thermistors for accurate temperature measurement unless we use them only over the narrow range in which they are linear, or use an external-resistor *linearizing network* to make the curve straighter.

A typical thermistor electronic thermometer uses a Wheatstone bridge, with a thermistor as one of the bridge legs. The output voltage will be zero under a null condition—usually 0° C — and is approximately proportional to the temperature at other points. A differential op-amp can be used to amplify the small output-voltage, and to scale the voltage to some level that is easy to display on an analog or digital voltmeter, such as 10 mV/°K (Kelvin).

In recent years, semiconductor temperature-transducers have become increasingly important. We know that the voltage across a pn diode-junction, and the current flow through the junction, is strongly affected by temperature. (That property is what causes drift in solid-state amplifiers.) We can demonstrate this with an ordinary silicon diode, say one of the 1N4000 series.

Connect an ohmmeter across the diode (Fig. 3) so that the diode is forward biased. That means connecting the positive terminal of the ohmmeter to the anode of the diode, and the negative terminal of the ohmmeter to the cathode. In case of doubt, the correct connection is the one that shows the lowest resistance on the ×1, ×10, or ×100 scale of the ohmmeter. Note the ohmmeter reading, then apply heat (body heat is sufficient—grab hold of the diode and squeeze it in your palm) and watch the resistance change!

Although diodes are often used as temperature transducers, they are not always the best choice. In many cases, an ordinary bipolar transistor will make a better transducer, especially if it is diode-connected. (The collector and the base are shorted together to form one

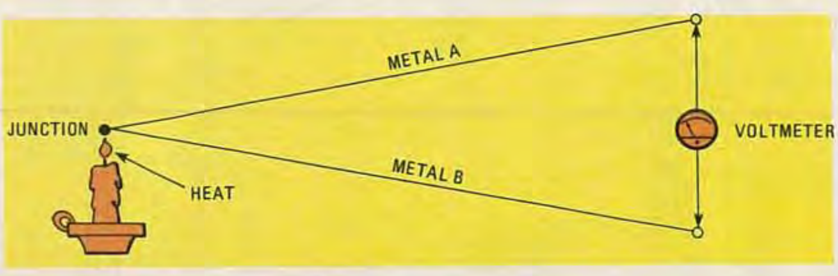


FIG. 1—WHEN A JUNCTION of two dissimilar metals is heated, a voltage that is proportional to the temperature of the junction is created.

terminal of the "diode;" the emitter is the other.)

The base-emitter voltage of a transistor (V_{BE}) is dependent on both the *collector current* and the *temperature*. (If you're interested in the math you can find the formula in any good text on transistors.) Because of that, a transistor can be used to make a very linear temperature transducer that works over a range of approximately −55° C to +125° C.

Transistor temperature transducers

Almost any transistor can be used to make rough measurements of temperature because of the relationship between the base-emitter voltage and temperature, when the collector current is held constant. But, some transistors are better temperature transducers than others. It seems that transistors in metal can-type cases (TO-5 and especially the smaller TO-18) have a better response than most epoxy or plastic-cased transistors. In addition, some transistors have a more linear V_{BE} vs. I_C curve than others.

Figure 4 shows a simple temperature transducer that uses NPN bipolar transistors. In this circuit, a dual transistor (two NPN silicon transistors in a single case) such as a MAT-01 (made by Precision Monolithics, Inc.) is used. The emitters are fed from 1- and 2-mA constant-current sources (it is important to keep the emitter currents *different* for Q1 and Q2) and the output voltage is approximately 59 μV/°K.

A differential op-amp is needed to amplify and scale the output voltage to a usable level. It is particularly convenient to scale the voltage to 10 mV/°K so that a simple voltmeter can be used. To do that for this transducer, the differential op-amp must have a gain of 167. When the output voltage is 10 mV/°K, any 3½-digit DVM can be used to measure temperature.

A solid-state thermometer

The electronic thermometer project shown in Fig. 5 uses a simple op-amp inverting follower circuit and a single—common—transistor such as a metal-case 2N2222. The transistor is used as a temperature probe and needs a suitable enclosure such as an old voltmeter probe grip, a short piece of metal tubing, etc. If the circuit is used to measure the temperature inside some piece of equipment, it can be mounted permanently and does not need a separate enclosure. However used, thermal contact with what is being measured is important. In the case of small-diameter metal tubing, the transistor case should be press-fit inside the tubing to insure that heat is conducted to the transistor's base-collector junction. If the fit is loose, or the enclosure not metal, you should use silicone "heat transfer" grease for the best results.

Two DC reference voltages are needed: plus and minus 6.2 volts. Diode D1 provides the positive 6.2-volts DC reference, while diode D2 provides the negative 6.2-volt DC reference. The +6.2 source is connected to the collector-base terminal of the temperature sensor (Q1). That means that the emitter current of transistor Q1 will be proportional only to the temperature (the collector voltage is *constant*). That current is amplified by an operational amplifier (IC1) and scaled to produce an output potential of 100 mV/°K. Potentiometer R1 is adjusted during calibration to provide the proper scale factor.

Again, an ordinary 3½-digit DVM can be used to measure temperature, but the reading will be in degrees Kelvin. To convert the reading to degrees Celsius, it is important to note that the Kelvin and Celsius scales are the same, but offset by 273 degrees (0° C = 273° K). To read temperature in degrees Celsius, an offset adjustment is needed.

Potentiometer R3 converts the temperature range of the basic circuit from Kelvin to Celsius by summing a countercurrent from the −6.2-volt DC supply with the current from the transistor. The potentiometer is adjusted to produce zero output from amplifier IC1 when the temperature is exactly 0° C.

Calibration

Once the circuit is built it will have to be calibrated. Set R1 and R3 to about the middle of their respective ranges. Turn the circuit on, and wait about 10 minutes for things to stabilize at room temperature. While you're waiting, prepare an "ice-point bath." The ice-point of water is 0° C; (the temperature where ice and water can exist in the same container). Use a regular thermometer to verify that the temperature is 0° C (or 32° F). When the circuit has stabilized and the bath is ready, put the transistor into the water and wait about 30 seconds. When the output voltage of the operational amplifier has stopped changing, adjust potentiometer R3 for 0.00 volts output. Let the transistor stay in the bath for a few more minutes, while monitoring the bath's temperature with a thermometer (*not* the one you're calibrating) to make sure that it doesn't change. When you are satisfied that the output voltage is reasonably stable (some drift will occur), remove the transistor from the bath and allow it and the thermometer to come to room temperature.

Once both have reached room temperature (indicated by the fact that both the thermometer's reading and the circuit's output voltage no longer change), the last step in calibrating the circuit can be done. Adjust potentiometer R3 so that the reading on the DVM is the same as the reading on the mercury thermometer (ignoring the decimal point and trailing zeros on the DVM). When this is

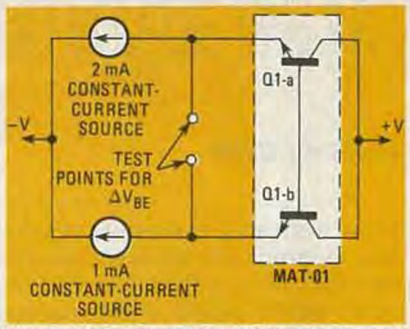


FIG. 4—WHEN THE OUTPUT VOLTAGE of this circuit is scaled by a differential op-amp, an ordinary DVM can be used to read the temperature.

PARTS LIST—FIG. 5

Resistors ¼ watt, 1% unless otherwise noted

R1—100,000 ohms, potentiometer
R2—100,000 ohms
R3—20,000 ohms, potentiometer
R4—2200 ohms
R5, R6—10,000 ohms, 5%

Semiconductors

D1, D2—LM113 (National) 6.2-volt Zener voltage-reference diode or equivalent
Q1—2N2222 or equivalent, metal case
IC1—CA3140 MOSFET op-amp or equivalent

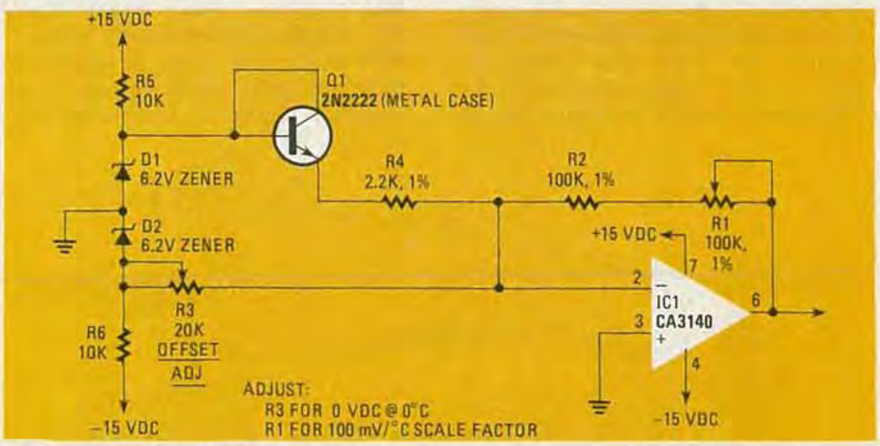


FIG. 5—THIS ELECTRONIC THERMOMETER PROJECT is easy to build and align. A parts list is included in this article for those of you that would like to try it.

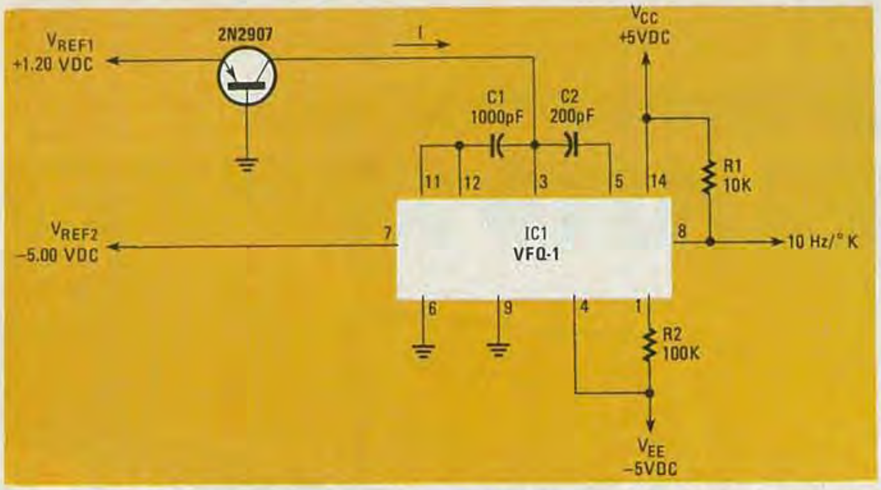


FIG. 6—THE HEART of this temperature-to-frequency converter circuit is a Datel VFQ-1 current-to-frequency converter IC. The 2N2907 is used as the temperature probe.

FAHRENHEIT, KELVIN, CELSIUS AND CENTIGRADE

There are three scales in common use for measuring temperature: Fahrenheit, Celsius (centigrade) and Kelvin.

The Fahrenheit scale, now used only in the United States and a few other English-speaking countries, is based on the freezing and boiling points of water at sea level—32° and 212°, respectively. The zero-point on this scale was probably established by using a mixture of ice and salt—materials commonly used to achieve low temperatures in laboratories at the time the scale was developed.

The Celsius scale, also known as the centigrade scale (it's not capitalized because, while the other three scales bear the names of their inventors—Gabriel Daniel Fahrenheit, Anders Celcius and Lord Kelvin—the term "centigrade" refers to the fact that the scale is divided into a hundred divisions), is used outside the U.S., wherever the metric system is found. On it, the freezing point of water is 0° and the boiling point 100°.

The Kelvin scale is also known as the *absolute* scale because its zero point is *absolute zero*, (−273.16° C or −459.69° F), the point at which all molecular motion ceases and there is—literally—no temperature.

One degree in the Kelvin scale is the same size as one degree in the Celsius scale; therefore water freezes at 273.16° K and boils at 373.16° K. The Kelvin scale is used primarily in applications such as solid-state physics and astronomy.

Incidentally, conversion from Fahrenheit to Celsius, and vice versa, is easier than you may think. To convert from degrees F to degrees C, just subtract 32 from the Fahrenheit temperature and divide the result by 1.8. Going from Celsius to Fahrenheit is even easier—double the temperature, subtract 10%, and add 32.

done, a 0-volts DC output will equal 0° C, a 3.00-volts DC output will equal 30° C, and so on. This happens, of course, because of the 100 mV/°C scaling factor. Alternately, a warm-water bath can be used for this part of the calibration procedure. Prepare the warm-water bath by mixing hot and cold water, and follow the steps that were outlined above for calibrating the thermometer circuit at room temperature.

The precision, and amount of drift, of this electronic thermometer depend on the quality of components used. The resistors, except for possibly R5 and R6, should be 1% precision-types with a low temperature-coefficient of resistance. The Zener diodes should be temperature-compensated reference types, such as National Semiconductor LM113's. The op-amp should also be a low-drift type, although acceptable performance can be obtained with an RCA CA3140, especially if it is heat-sinked. An ordinary TO-5 heatsink (the kind made of thin metal) will work nicely.

Other devices

There are a number of IC voltage-to-frequency (or current-to-frequency) converters on the market. An example of an IC that does both is the Datel VFQ-1. That IC is shown in a temperature-to-frequency converter circuit in Fig. 6. In the circuit, we are using the VFQ-1 as a current-to-frequency converter; the current is supplied by the collector of a PNP transistor that is used as a temperature transducer.

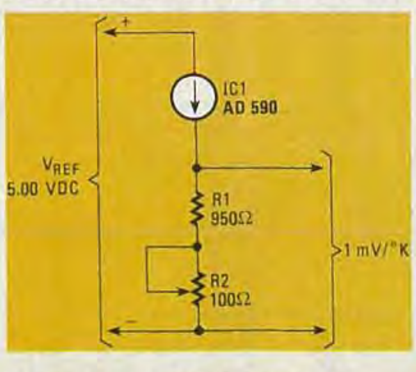


FIG. 7—A TEMPERATURE-SENSITIVE current source, the AD590, is used to measure temperature in this simple circuit.

This circuit's output frequency will have a scaling factor of 10 Hz/°K. We can, therefore, expect an output frequency of 2730 Hz at the freezing point of water (273° K, or 0° C), and a frequency of 3730 Hz at the boiling point of water (373° K or 100° C). This type of circuit can be used to record the temperature data from an experiment on magnetic tape, or to transmit the temperature via radio telemetry from an amateur rocket or model aircraft. Unfortunately, the Datel IC is still a little expensive (although it is one of the lowest cost converters on the market) and is not generally available through hobbyist outlets.

Another special temperature-measurement semiconductor device is the AD590 (Analog Devices, Inc.) It is a two-terminal IC that is available at low cost in either a TO-18 case or a special two-terminal flat-pack. The device is a temperature-sensitive current source and is scaled to approximately 1 μA/°K. If we pass the current from the AD590 through a 1000-ohm resistor, the result (using Ohm's law) is a voltage change of 1 mV/°K.

There are several ways that we can use the AD590 device. One is simply to connect it as shown in Fig. 7, in series with approximatley 100 ohms of resistance. This configuration is called a *one-temperature*, or *one-point*, circuit. We adjust potentiometer R2 so that the output voltage agrees with a mercury thermometer at some specific temperature. Slight nonlinearities in the device, as in all semiconductor devices, will cause some error at points far removed from the calibration point.

Another method is to connect the AD590 directly between a +5.00-volt DC precision reference source and the inverting input of an op-amp. The scale factor of the thermometer can be set by the feedback resistor (R_F) using the formula: $V_O = (1\ \mu A/°K)(R_F)(T)$.

We can also use the AD590 in a *two trim-point* circuit that uses an op-amp as described above. An offset current is summed with the AD590 current at the inverting input of the op-amp. We can then use *two* potentiometers, one for offset and one for gain, to adjust the circuit at two different temperatures, thereby reducing the error.

Electronic thermometer projects are easy to build and calibrate, and they can be put together by anyone who knows Ohm's law and the basic principles of op-amp circuits. Just remember to use precision components that don't drift with—you guessed it—temperature! **R-E**