

# TEMPERATURE SENSOR

*Tutorial*



# Temperature Sensor Tutorial

Temperature sensors surround us. They are in our buildings and homes measuring temperature for HVAC systems, refrigerators, freezers, and computers. Industrial applications such as motor controls, assembly lines, processing, and manufacturing all require constant monitoring and control of temperature.

Consequently, many different types of temperature sensors exist to accommodate this wide variety of temperature sensing needs and applications. Some sensors are designed for measuring ambient air temperature in buildings for climate control, while others are designed for use in harsh environments measuring the temperature of liquids like coolants used in automobiles.

This tutorial covers the different types of temperature sensors, their advantages and disadvantages, and the important considerations in selecting a temperature sensor. We will investigate and explore the types of sensors best suited for various applications. Finally, we'll touch on recent advances that are pushing state-of-the-art improvements to develop even better temperature sensors.

## Types of Temperature Sensors Thermocouples, RTDs, Thermistors and Local Temperature Sensor ICs

The availability of temperature sensors in different forms and with various functions make them suitable for specific applications. Within modern electronics, there are five types of temperature sensors that are most commonly used: thermocouples, resistance temperature detectors (RTDs), thermistors, local temperature sensor ICs, and remote thermal diode temperature sensor ICs.

Thermocouples, RTDs, and thermistors are sensing elements that respond to temperature in a measurable way. They are normally connected to circuits that convert the sensor signal into a usable analog or digital value. The circuits are commonly built from analog-to-digital converters (ADCs), amplifiers, voltage references, and other active and passive components, or they can be dedicated sensor signal conditioner ICs.

Local temperature sensor ICs utilize the physical properties of transistors on the die as the sensing element. Additional circuitry, such as an ADC, gain stages, and level shifters, are used to create a sensor with an analog or digital interface. Remote thermal diode temperature sensors employ an external bipolar transistor as the sensing element and include all the signal conditioning circuitry necessary to measure temperature using one or more external transistors. In this tutorial, we will consider both local and remote thermal diode sensors, how they read temperature, and in what applications they are best used.

## Thermocouples

Thermocouples are used extensively in a variety of industrial, automotive, and consumer equipment. They are self-powered, requiring no excitation, and operate over a much wider temperature range (up to +2000°C) than other common sensors. Bare thermocouple junctions can have quick response times, allowing measurements to be done without significant delays in system operation.

Thermocouples sense temperature using the Seebeck effect, which occurs when there is a temperature differential between junctions of dissimilar metals. The temperature

differential between the heated area and the cooler portion causes a voltage difference between the two junctions. This voltage difference can be used to calculate temperature. Thermocouples are made by joining two wires of dissimilar metals. The resulting output voltage is small (about 40µV per °C for a K type), and requires moderately complex signal conditioning (including cold-junction compensation and amplification). There are several thermocouple types, which are designated by letters. The most widely used is the K type. **Table 1** summarizes the characteristics of a few common thermocouple types. Note that the sensitivities and usable temperature ranges differ among the various types.

**Table 1. Characteristics of Some Thermocouple Types**

Type	Temperature Range (°C) (Short Term)	Sensitivity (µV/°C)	Conductor Alloys
K	-180 to +1300	41	Chromel (90% Ni, 10% Cr)
			Alumel (95% Ni, 2% Mn, 2% Al, and 1% Si)
J	-180 to +800	55	100% Fe
			Constantan (55% Cu, 45% Ni)
N	-270 to +1300	39	Nicrosil (84.1% Ni, 14.4% Cr, 1.4% Si, 0.1% Mg)
			Nisil (95.6% Ni, 4.4% Si)
R	-50 to +1700	10	87% Pt, 13% Rh
			100% Pt
S	-50 to +1750	10	90% Pt, 10% Rh
			100% Pt
B	0 to +1820	10	70% Pt, 30% Rh
			94% Pt, 6% Rh
T	-250 to +400	43	100% Cu
			Constantan
E	-40 to +900	68	Chromel
			Constantan

Despite the obvious benefits of thermocouples, measuring temperature with them can be challenging due to their small output voltage, which requires precise amplification. Their susceptibility to external noise, especially when long wires are used between the thermocouple and the measuring circuit, also poses a challenge. Another complication arises from additional thermocouples that are created at the point of contact where the thermocouple wires meet the copper wires (or traces). The copper wires connect to the signal conditioning circuitry, creating another thermocouple. This point is called the cold junction, as shown in *Figure 1*. The junction between metal A and metal B is the main thermocouple junction (also called the “hot junction,” although its temperature can be lower than that of the cold junction).

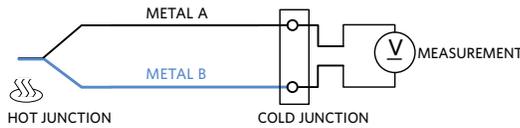


Figure 1. Thermocouple Circuit

The net effect is that the output voltage of this circuit appears to be the voltage due to the thermocouple minus the voltage of a similar thermocouple at the cold junction temperature.

For example; if the thermocouple is at +525°C and the cold junction is at +25°C,  $V_{OUT}$  will indicate +500°C. To compensate for the effect of the cold junction, measure the cold junction temperature and add the thermocouple voltage that would be produced by that temperature to the value indicated by  $V_{OUT}$ :

$$V_{OUT} = V_{TC} - V_{CJ}$$

$$V_{TC} = V_{OUT} + V_{CJ}$$

Cold junction compensation is done by placing a temperature sensor at the cold junction location and using the measured temperature to compensate for the cold junction temperature. A complete thermocouple-to-digital circuit<sup>1</sup> including cold-junction sensing might look like the block diagram shown in *Figure 2*. Precision op amp and resistors provide gain to the thermocouple output signal, which is generally in the millivolt range. A temperature sensor at the cold junction location monitors that value and an ADC provides output data at the required resolution. In general, calibration is necessary

to correct for amplifier offset voltage, as well as resistor, temperature sensor, voltage reference errors, and linearization. This must be performed to correct for the effect of the thermocouple’s nonlinear temperature-voltage relationship.

Dedicated integrated circuits such as the **MAX31855** and **MAX31856** ease the process of designing thermocouple signal conditioning circuits by incorporating a low-noise precision gain stage, a cold junction compensation sensor, and a high-resolution ADC. The MAX31856, shown in *Figure 3*, also includes input protection and linearization for eight popular thermocouple types.

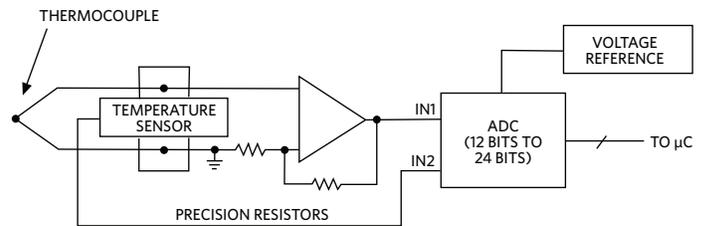


Figure 2. Thermocouple-to-Digital Compensation Circuit

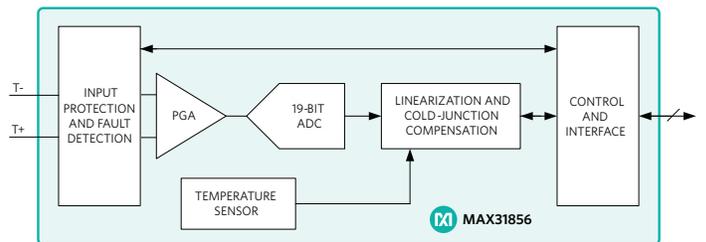


Figure 3. MAX31856 Simple Block Diagram

## RTD (Resistance Temperature Detector)

The electrical resistivity of any metal varies with temperature. RTDs are temperature sensors that are based on this behavior. They are effectively resistors with well-defined resistance vs. temperature characteristics. Platinum is the most common and accurate wire material used in RTDs because of its chemical stability and relatively linear response to temperature changes. Platinum RTDs are also referred to as PRTDs and are often available with 100Ω and 1kΩ resistances (at 0°C), which are referred to as PT100 and PT1000. Nickel, copper, and other metals may also be used to make RTDs. Characteristics of platinum RTDs include wide temperature range (up to 750°C or higher), excellent accuracy and repeatability, and reasonable linearity. Because of their accuracy, stability, and wide temperature range, RTDs are used in a variety of precision applications including instruments and process control.

The resistance vs. temperature curve is reasonably linear, but has some curvature, as described by the Callendar-Van Dusen equation:

$$R(T) = R_0(1 + aT + bT^2 + c(T - 100)T^3)$$

Where:

T = temperature (°C)

R(T) = resistance at T

R<sub>0</sub> = resistance at T = 0°C

IEC 751 specifies the following Callendar-Van Dusen coefficient values:

$$a = 3.90830 \times 10^{-3}$$

$$b = -5.77500 \times 10^{-7}$$

$$c = -4.18301 \times 10^{-12} \text{ for } -200^\circ\text{C} \leq T \leq 0^\circ\text{C}, 0 \text{ for } 0^\circ\text{C} \leq T \leq +850^\circ\text{C}$$

Bare RTD elements generally have higher thermal mass than bare thermocouples, and so will respond more slowly to changes in temperature. RTDs and thermocouples are often encased in protective stainless-steel sheaths. In which case, the mass of the entire probe will be similar for both types of sensors, resulting in similar response times.

Signal conditioning plays an important role in RTD temperature measurement. An excitation current flows through the RTD, and the voltage across the RTD is measured. If the excitation current is known (or can be derived), the RTD's resistance can be calculated. Configurations may be two-/three-/four-wire, as shown below in *Figure 4*. A two-wire configuration, as shown in *Figure 4a*, is useful for cases where the lead length is short enough that wire resistance doesn't significantly affect measurement accuracy. In a three-wire

configuration, shown in *Figure 4b*, a third wire connects to the RTD probe and carries the excitation current. This provides a way to cancel the effect of wire resistance, provided the wire resistances are equal. A four-wire Kelvin configuration, as shown in *Figure 4c*, is the most accurate, as its separate force and sense leads eliminate the effect of wire resistance.

Various circuit architectures implement RTD temperature measurement. Most implementations require two excitation current sources and a high-resolution analog-input signal chain. Many high-resolution ADCs feature current sources and multiple analog inputs that are appropriate for use in RTD or other temperature measurement circuits. The **MAX11410**, shown in *Figure 5*, is an example of a high-resolution ADC that can source a selectable current value from any analog input pin, providing the excitation current for any RTD configuration.

The MAX31865 is an example of a dedicated RTD signal-conditioning circuit. As seen in *Figure 6*, the MAX31865 provides a completely integrated excitation and measurement circuit, allowing for two-/three-/four-wire configurations with 15-bit resolution. The chip accommodates both PT100 and PT1000 RTDs and features protection against overvoltage faults on the input lines. A product like the MAX31865 greatly accelerates design time when implementing an RTD solution.

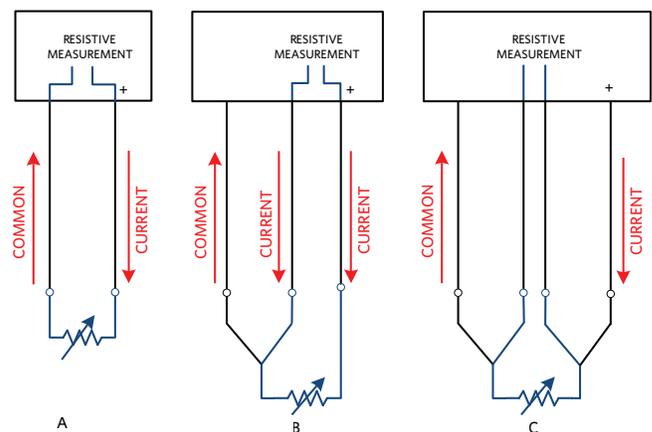


Figure 4. Two-Wire, Three-Wire, and Four-Wire RTD

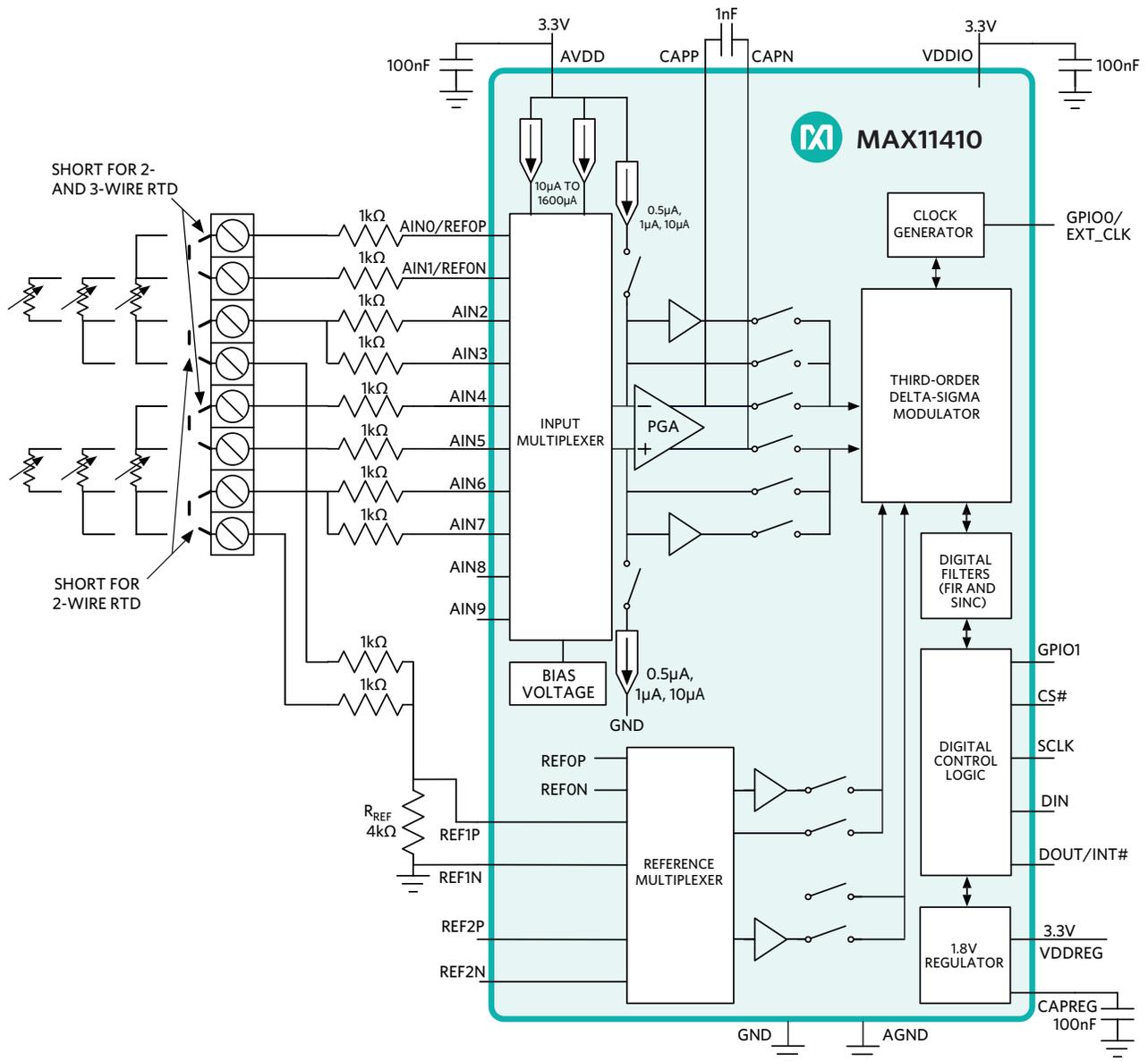
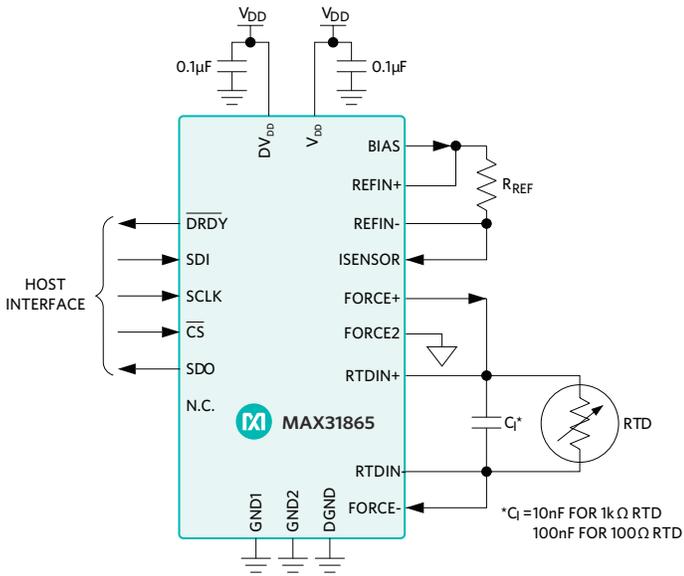
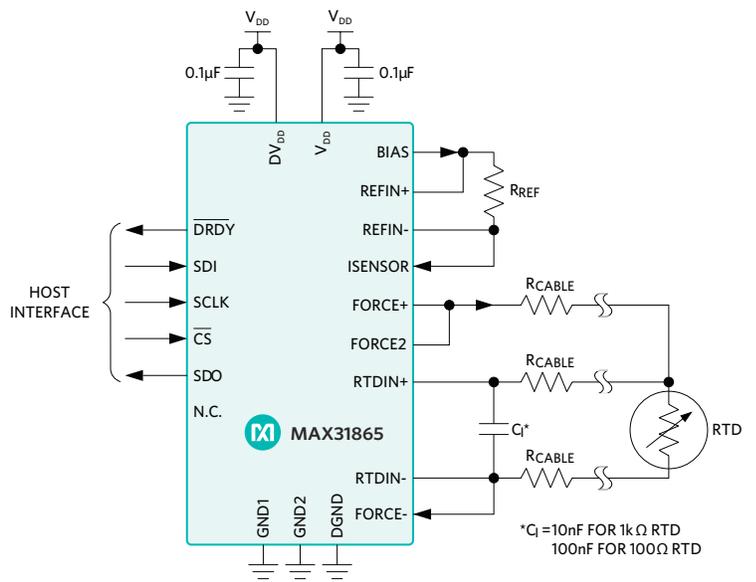


Figure 5. Dual RTD Measurement Circuit

2-WIRE SENSOR CONNECTION



3-WIRE SENSOR CONNECTION



4-WIRE SENSOR CONNECTION

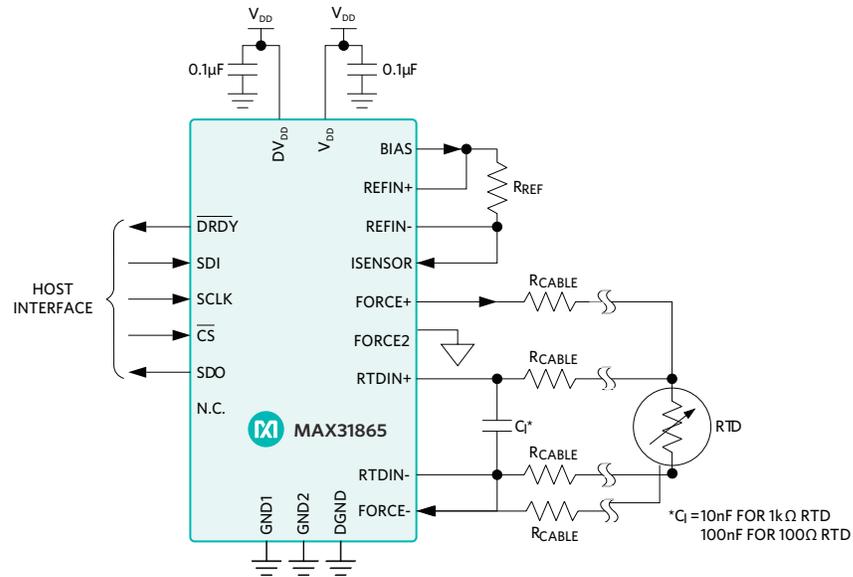


Figure 6. MAX31865 in Two-/Three-/Four-Wire Configurations

## Thermistors

Thermistors, like RTDs, change resistance in response to temperature changes. While RTDs usually consist of a pure metal, thermistors are generally made from a polymer or ceramic material. In general, thermistors are less expensive and less accurate than RTDs, but there are exceptions. Most thermistors are available in a two-wire configuration, like the RTD shown in Figure 4a. Negative Temperature Coefficient (NTC) thermistors are commonly used for measurement applications. As the name suggests, an NTC thermistor’s resistance decreases as temperature increases. A typical temperature range for a thermistor is -90°C to +130°C—much lower than thermocouples and RTDs—although wider range thermistors are available.

Thermistors have very nonlinear temperature-resistance relationships, and therefore, require significant linearity correction. The Steinhart-Hart equation describes the resistance of a thermistor as a function of temperature and is used to approximate individual thermistor curves.

The equation is:

$$\frac{1}{T} = A + B \ln(R) + C [\ln(R)]^3$$

R is the thermistor resistance.

T is temperature in Kelvin.

A, B, and C are curve-fitting constants determined through a calibration process for a given thermistor material and,

ln is the natural log function (log to the base e).

Most thermistor manufacturers provide the A, B, and C coefficients for a typical temperature range. A common approach to using a thermistor for temperature measurement is shown in Figure 7, where a thermistor and fixed-value resistor form a voltage-divider with an output that is digitized by an ADC.

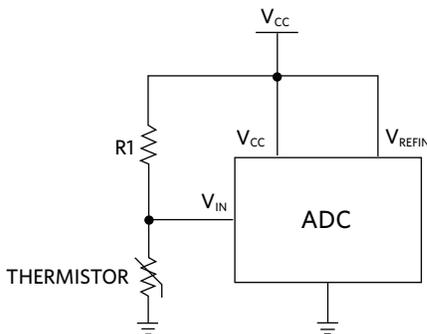


Figure 7. Thermistor-to-ADC Interface

The MAX31740 fan controller, in Figure 8, uses an NTC thermistor input to sense temperature. The IC then generates a PWM output for fan-speed control. This simple fan-speed controller provides low-cost system cooling independent of software.

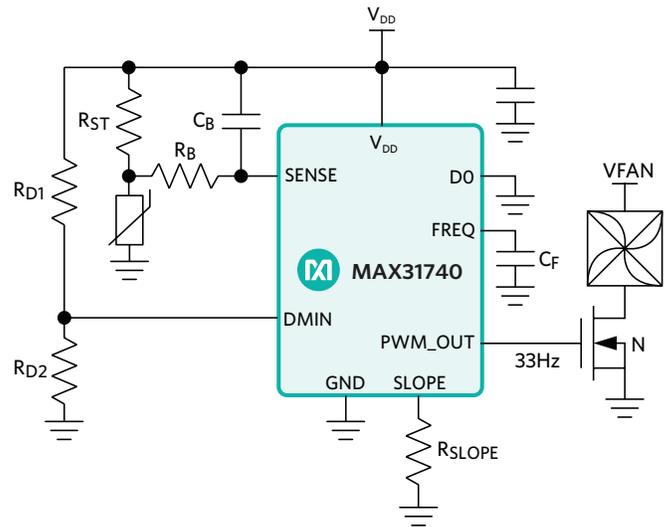


Figure 8. Two-Wire Fan-Speed Controller

## Temperature Sensor ICs

### Local and Remote Thermal Diode Sensors

A local temperature sensor is the common name for an integrated circuit that measures its own die temperature using the physical properties of bipolar transistors. Some local temperature sensors have analog outputs (either voltage or current), while others include an internal ADC and produce a digital output in one of several formats as seen in Figure 9. I<sup>2</sup>C, SMBus, 1-Wire®, and SPI are the most common, but PWM and other output formats are available as well.

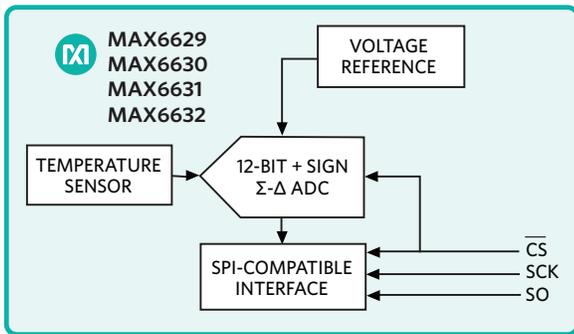


Figure 9. Local Temperature Sensor with an Internal ADC

Local temperature sensors are useful in a variety of applications. Frequently, they sense the temperature of a printed circuit board (PCB) or the ambient air around it. From PCs to industrial control systems to routers to consumer equipment, temperature sensing and control plays a critical role in system performance.

Newer local temperature sensors expand applications by providing tremendous flexibility in implementation. The **MAX31875** features a 0.84mm x 0.84mm x 0.35mm wafer-level package (WLP) that allows the IC to fit in just about any space. The average power-supply current depends on resolution and conversion rate, but is well below 10µA in many configurations. This means the MAX31875 works in a variety of battery-powered applications. Accuracy is ±0.6°C typical from -10°C to +100°C.

A remote digital temperature sensor, also called a remote sensor or a thermal diode sensor, falls into a different category as it measures the temperature of an external transistor—either a discrete transistor or one that is integrated on the die of another IC. Even though the discrete transistor is located away from the temperature sensor chip, the mechanism of sensing temperature is similar to local temperature sensors. Some microprocessors, FPGAs, and ASICs often include one or more bipolar sensing transistors (usually called “thermal diodes”) as seen in *Figure 10*. These thermal diodes allow the die temperature of the target IC to be accurately measured.

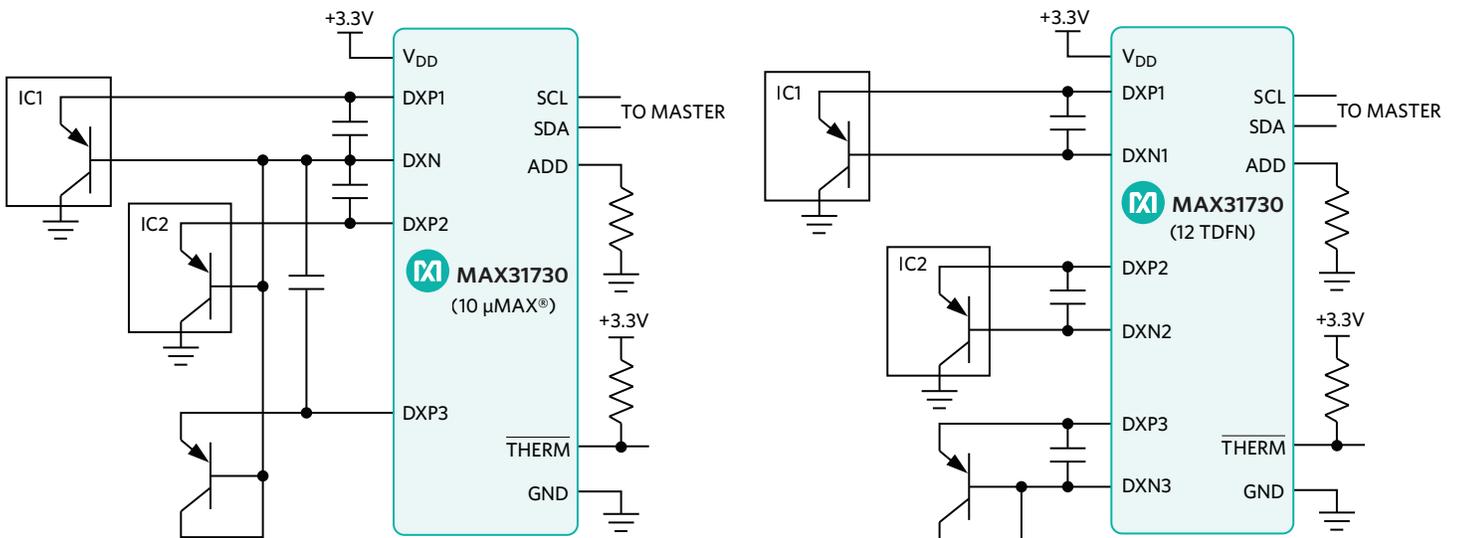


Figure 10. Remote Temperature Sensor Monitoring the Temperature of a Sensing Transistor (or Thermal Diode) on the Die of an External IC

## Conclusion

While the science and art of temperature sensor development is robust and well understood, each design has different requirements and challenges. Undoubtedly, temperature sensing will continue to be necessary and beneficial with the continued development of new manufacturing processes and the advent of various IoT applications. In addition, more solution options will become available, such as those highly accurate temperature sensors featured in Maxim's Thermal Management Handbook.

Thermocouples, RTDs, thermistors, and temperature sensor ICs are the main temperature sensor categories. Thermocouples are inexpensive, durable, self-powering, and measure a wide range of temperatures. Platinum RTDs also measure a wide range of temperatures, although not quite as wide as most thermocouples. They can also provide very accurate and repeatable measurements. Thermistors are generally durable and small. Temperature sensor ICs have tremendous flexibility in implementation. Although they do not share the wide operating temperature range of RTDs and thermocouples, they are easy to use and available in very small packages.

When looking for temperature sensing solutions, consider the many available options to find the one that best matches the requirements of your design. The sensor types covered in this tutorial meet the needs and requirements for almost every application.

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## References

1. K. Lacanette, "Tutorial 4679: Thermal Management Handbook," Maxim Integrated.  
<https://www.maximintegrated.com/en/app-notes/index.mvp/id/4679>

## Temperature Sensor Resources

[Temperature Sensor ICs](#)

[Thermal Management Handbook](#)

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