Thermal Management Handbook

maxim integrated™

Introduction: Thermal Management in Electronic Systems

Thermal management in electronic systems is done for one or more of the three purposes outlined below.

1. **Control** Temperature data is an input to a large number of control systems. The control system may be as simple as an on/off thermostatic controller for room temperature, which activates a heater whenever the temperature drops below a specific threshold. Or it may be a complex fan speed control system that uses measured temperature to adjust the speeds of several fans to ensure adequate cooling of system components, while changing fan speeds in such a way as to minimize the audibility of the changes.

2. **Calibration** Temperature data is used to correct temperature-dependent errors in a component. Calibration functions can be implemented simply using an analog temperature sensor with an operational amplifier circuit, or they may be much more complex with a lookup table that provides a 12-bit correction factor every 5°C for a data acquisition system. For example, a TCXO uses temperature to adjust the operating parameters of a crystal oscillator to compensate for the shift in the crystal's resonant frequency over temperature. Signal conditioners for sensors such as pressure transducers use temperature data to correct for thermally induced drift in the transducers' characteristics.

3. **Protection** Many components in electronic systems can be exposed to temperature extremes—from ambient conditions, power dissipation in nearby components, or their own power dissipation—that can damage them. Thermal management components can be deployed to detect, and in some cases eliminate, potentially dangerous thermal conditions before they can cause damage. Again, these solutions can be as simple as an over-/undertemperature detector to protect circuit board components from damage, or as complex as a cooling system that uses temperature data from multiple locations to ensure proper operating temperature under a variety of external conditions.

This handbook provides an introduction to thermal management devices and illustrates some of the ways in which they may be used.

Temperature-Sensing Technologies

Thermal management begins with the measurement of temperature. Maxim manufactures a wide variety of temperature-sensing ICs for such measurement. In addition to the various types of IC sensors, there are several other technologies that enable temperature to be measured by electronic systems. Some of the more widely used approaches are discussed in this section. Application circuit examples can be found later in this handbook, in the section titled "Using Thermal Management Components—Principles and Circuits."

Thermistors

Thermistors are temperature-dependent resistors, usually made from conductive materials such as metal-oxide ceramics or polymers. The most common thermistors have a negative temperature coefficient (NTC) of resistance and, therefore, are often referred to as NTCs. Positive temperature coefficient thermistors, known as PTCs, are also available.

Characteristics include moderate temperature range (generally up to +150°C, though some are capable of much higher temperatures), low-to-moderate cost (depending on accuracy), poor but predictable linearity, and some signal conditioning required. Thermistors are available in probes, in surface-mount packages, with bare leads, and in a variety of specialized packages. Maxim manufactures ICs that convert thermistor resistance to a digital format.

A common approach to using a thermistor for temperature measurement in shown in **Figure 1**, where a thermistor and fixed-value resistor form a voltage divider whose output is digitized by an analog-to-digital converter (ADC).
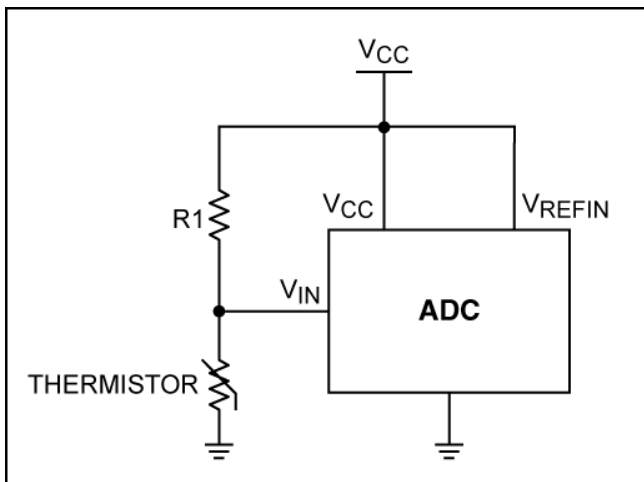
Figure 1. This basic circuit shows how a thermistor can interface to an ADC. Resistor R1 and the thermistor form a voltage divider with a temperature-dependent output voltage.

NTC Thermistors

NTCs are the most commonly used thermistors for measurement applications. Usually molded from metal-oxide semiconductor materials, they have a large negative temperature coefficient. The relationship between resistance and temperature for a common NTC is shown in **Figure 2**. Note the nonlinearity of the resistance vs. temperature curve.
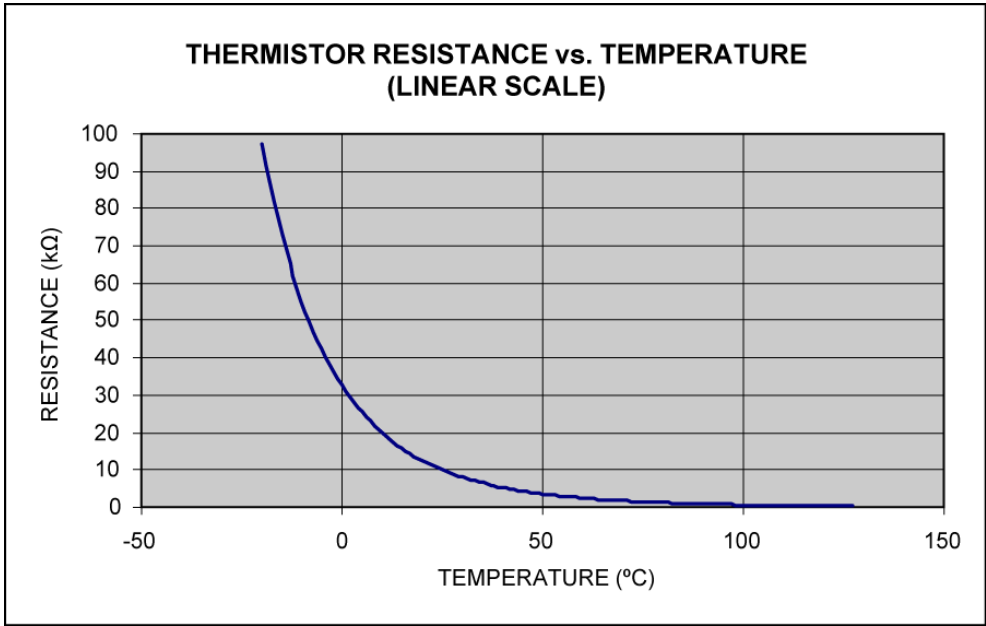
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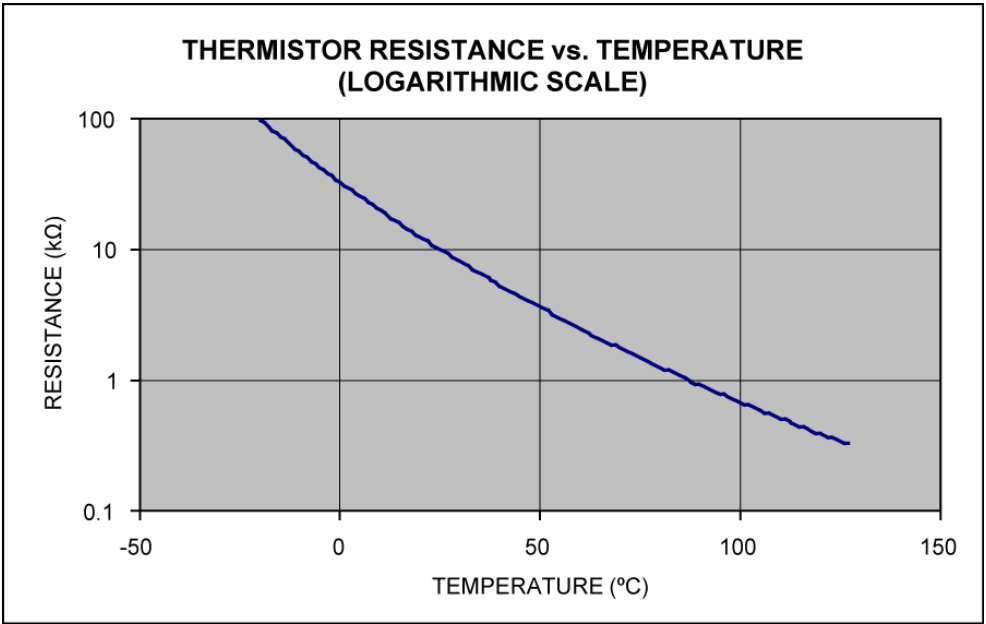
(b)

Figure 2. Resistance vs. temperature curves for a standard NTC. Nominal resistance is 10kΩ at +25°C. Note the nonlinearity and large relative temperature coefficient of curve (a). Curve (b) is based on a logarithmic scale and also exhibits significant nonlinearity.

Note that the nonlinearity of NTCs introduces a difficulty when a wide range of temperatures must be measured. Because the slope of the curves in Figure 2 decreases significantly at temperature extremes, the effective temperature resolution of any ADC used with the NTC will be degraded at those extremes. This may require the use of a higher resolution ADC if a wide range of temperatures must be measured

Combining an NTC with a fixed resistor in a voltage-divider circuit like the one in Figure 1 provides some linearization, as shown in **Figure 3**. By selecting an appropriate value for the fixed resistor, the temperature range for which the curve is most linear can be shifted to meet the needs of the application.
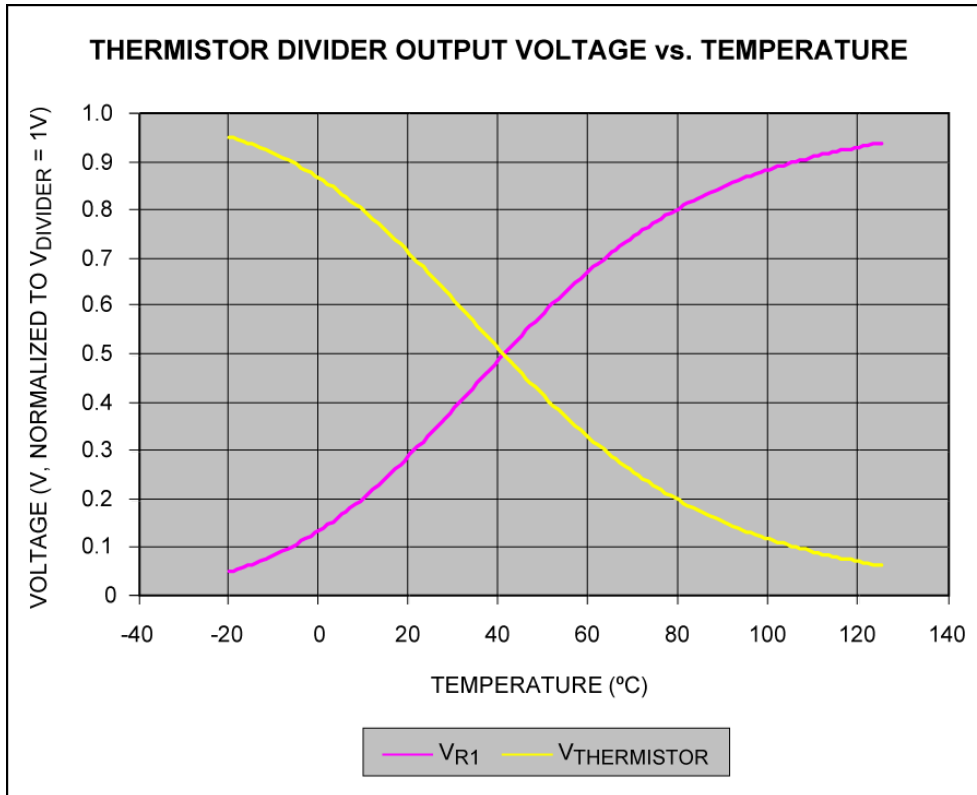
Figure 3. Making an NTC voltage-divider, as in Figure 1, helps to linearize the NTC's resistance curve over a limited temperature range. The voltages on the NTC and the external resistor, R1, are shown as a function of temperature. Note that the voltage is roughly linear from 0°C to +70°C.

The accuracy specifications for NTCs vary significantly. At one end of the spectrum are very low-cost thermistors that are guaranteed only at a single temperature. The components are capable of giving a rough indication of temperature—within a few degrees of the actual value at the guaranteed temperature—and no guarantee at other temperatures. At the other end are significantly more expensive, interchangeable thermistors that are guaranteed to a fraction of a degree accuracy over a wide range of temperature.

RTDs

Resistance temperature detectors (RTDs) are resistors whose resistance varies with temperature. Platinum is the most common, most accurate wire material; platinum RTDs are referred to as Pt-RTDs. Nickel, copper, and other metals may also be used to make RTDs. Characteristics include a wide temperature range (up to +750°C), excellent accuracy and repeatability, reasonable linearity, and the necessity for signal conditioning.

Because of their accuracy, stability, and wide temperature range, RTDs are used in a variety of precision applications, including instruments, process control, and automotive systems.

For Pt-RTDs, the most common values for nominal resistance at 0°C are 100Ω and 1kΩ, though other values are available. The average slope between 0°C and +100°C is called alpha (α). This value depends on the impurities and their concentrations in the platinum. The two most widely used values for alpha are 0.00385 and 0.00392, corresponding to the IEC 751 (Pt100) and SAMA standards.

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_0 = resistance at T = 0°C

IEC 751 specifies α = 0.00385055 and the following Callendar-Van Dusen coefficient values:
$a = 3.90830 \times 10^{-3}$
$b = -5.77500 \times 10^{-7}$
$c = -4.18301 \times 10^{-12}$ for -200°C $\leq$ T $\leq$ 0°C, 0 for 0°C $\leq$ T $\leq$ +850°C

Figure 4 shows the curve of resistance vs. temperature for a Pt100 RTD with a straight-line approximation using α. Note that the straight-line approximation is accurate to better than ±0.4°C from -20°C to +120°C. **Figure 5** shows the error (in degrees) between the actual resistance and the value calculated from the straight-line approximation.
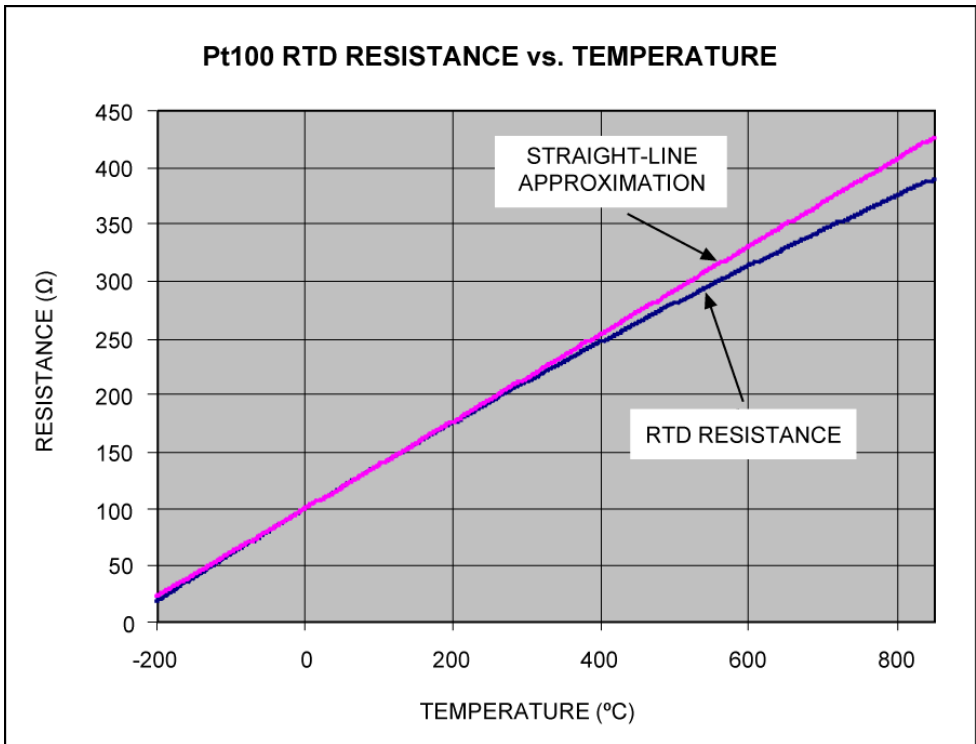
Figure 4. Pt100 RTD resistance vs. temperature. Also shown is the straight-line approximation for 0°C to +100°C.
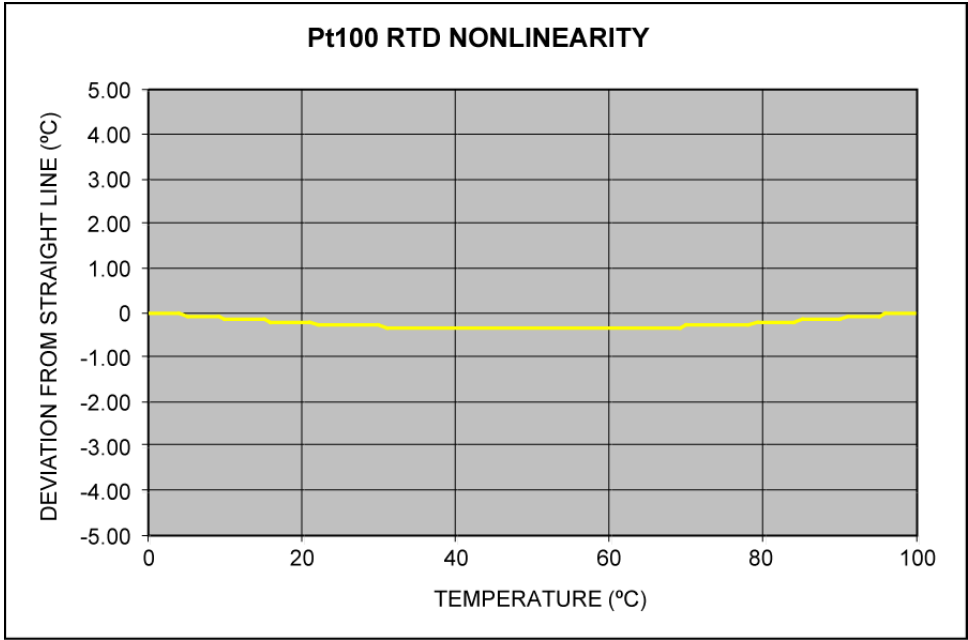
Figure 5. Pt100 nonlinearity compared to linear approximation based on the slope from 0°C to +100°C.

Signal conditioning for an RTD usually consists of a precision current source, a voltage reference, and a high-resolution ADC. An example of an RTD signal-conditioning circuit is shown in **Figure 6**. Several variations are possible. Linearization may be done using a lookup table or external linear circuits. The current source may be replaced by an external precision resistor.

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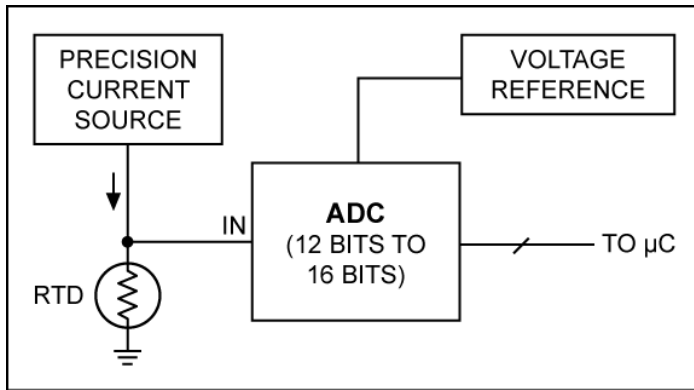
Figure 6. Simplified RTD signal-conditioning circuit.

RTD cost can be high, depending on accuracy and package options. RTDs are available in probes, in surface-mount packages, and with bare leads.

Thermocouples

Thermocouples are made by joining two wires of dissimilar metals. The point of contact between the wires generates a voltage that is approximately proportional to temperature. Characteristics include wide temperature range (up to +1800°C), low-cost (depending on package), very low output voltage (about 40µV per °C for a K type), reasonable linearity, and moderately complex signal conditioning (cold-junction compensation and amplification). There are several thermocouple types, which are designated by letters. The most popular is the K type.

Figure 7 shows the output voltage vs. temperature for a type K thermocouple. The curve is reasonably linear, although it clearly has significant deviations from absolute linearity. **Figure 8** shows the deviation from a straight-line approximation, assuming a linear output from 0°C to +1000°C for an average sensitivity of 41.28µV/°C. In practice, linearity correction can be done by calculating the actual value or by using a lookup table.
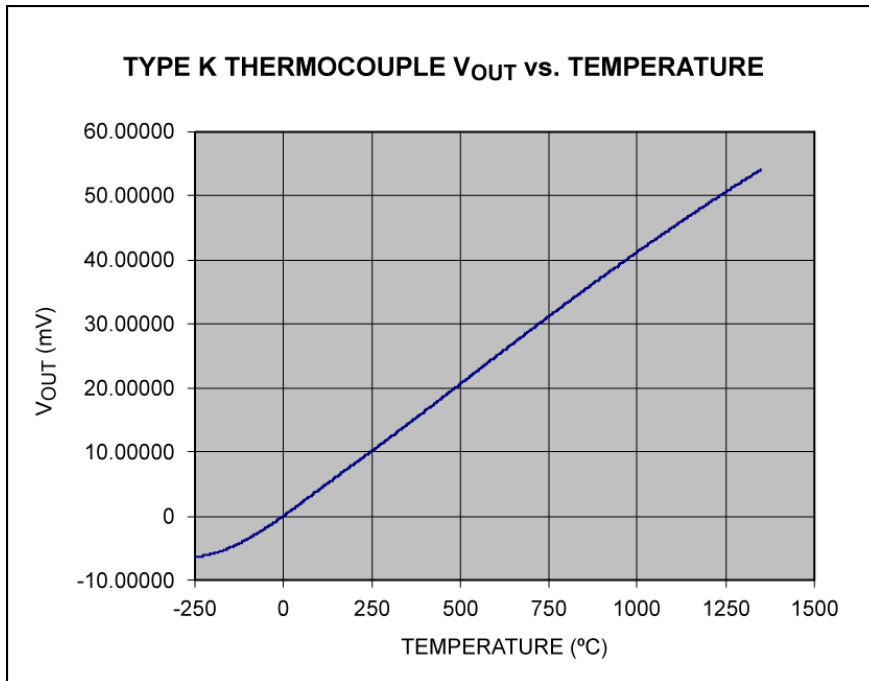
Figure 7. Type K thermocouple output voltage vs. temperature.
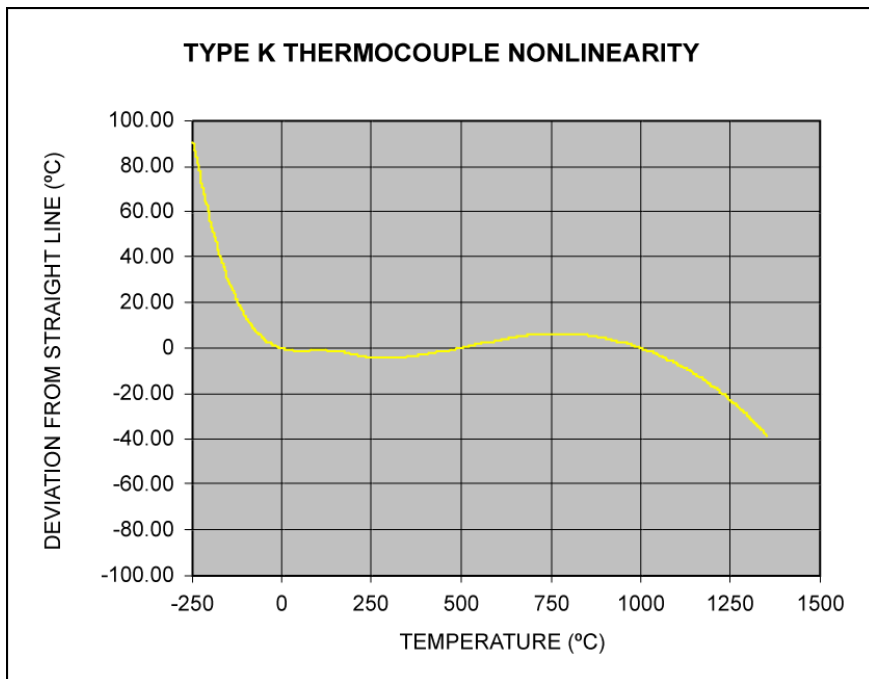
Figure 8. Type K thermocouple deviation from a straight-line approximation.

Measuring temperature with a thermocouple is somewhat difficult because the output of the thermocouple is low. It is also complicated because additional thermocouples are created at the point where the thermocouple wires make contact with the copper wires (or traces) that connect to the signal conditioning circuitry. This point is called the cold junction (see **Figure 9**).

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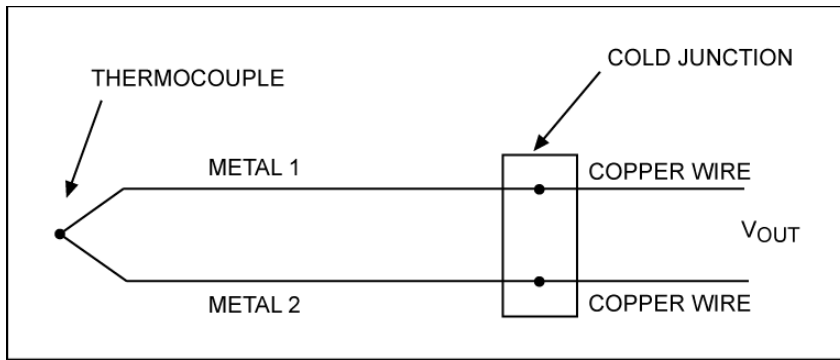
Figure 9. Simple thermocouple circuit. The junction between metal 1 and metal 2 is the main thermocouple junction. Other thermocouples are present where the metal 1 and metal 2 wires join with the measuring device's copper wires or PCB traces.

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. Therefore, if the thermocouple is at +525°C and the cold junction is at +25°C, V_{OUT} will indicate +500°C. To correct for this error, you must measure the cold junction temperature and add that temperature to the value indicated by V_{OUT}:

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

This 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 might look like the one in **Figure 10**. A precision op amp and precision resistors provide gain to the thermocouple output signal. A temperature sensor at the cold junction location is monitored to correct for cold junction temperature, and an ADC provides output data at the resolution required. In general, calibration is necessary to correct for amplifier offset voltage, as well as resistor, temperature sensor, and voltage reference errors.
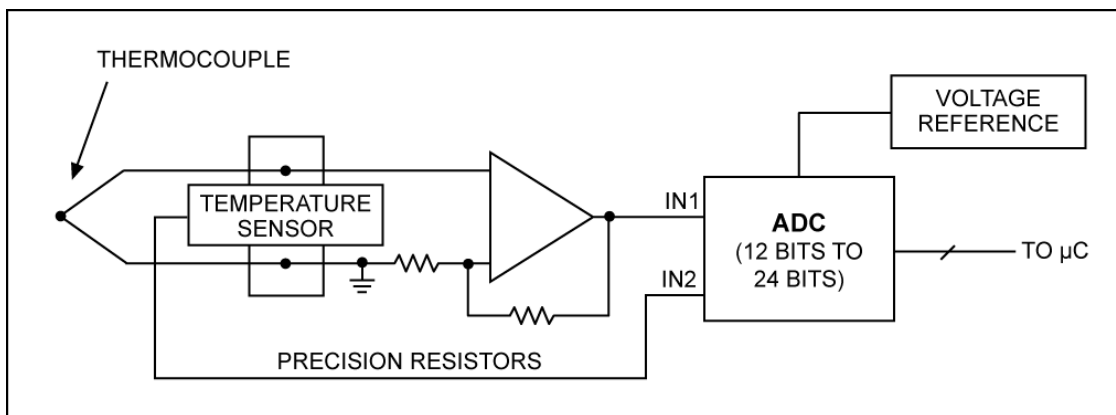
Figure 10. Example of a thermocouple signal-conditioning circuit.

Maxim manufactures ICs (the MAX6674 and MAX6675) that perform the signal conditioning functions for type K thermocouples, thus simplifying the design task and significantly reducing the number of components required to amplify, cold-junction compensate, and digitize the thermocouple's output. Thermocouples are available in probes and with bare leads.

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Temperature Sensor ICs

Temperature sensor ICs take advantage of the predictable thermal characteristics of silicon PN junctions. Because they are active circuits built using conventional semiconductor processes, they can take a variety of forms and include a variety of features (such as digital interfaces, ADC inputs, and fan-control functions) not available in other technologies. The operating temperature range for temperature sensor ICs extends as low as -55°C and as high as +125°C, with a few products operating to an upper limit of around +150°C. Descriptions of common types of temperature sensor ICs follow.

Analog Temperature Sensor ICs

Analog temperature sensor ICs convert temperature to voltage or, in some cases, to current. The simplest analog temperature sensors have just three active connections: for ground, power supply voltage input, and output. Other analog sensors with enhanced features may have additional inputs or outputs—for example, comparator or voltage reference outputs.

Analog temperature sensor ICs use the thermal characteristics of bipolar transistors to develop an output voltage proportional to temperature. A conceptual circuit is shown in **Figure 11**. Practical ICs are designed differently, but this circuit illustrates how active circuits can be made to measure temperature. Two matched transistors on the same die are connected as diodes and biased with currents I1 and I2. The base-emitter voltage (V_{BE}) for each transistor depends on its temperature and collector current. If the transistors are located near each other on the die and there are no significant thermal gradients in their vicinity, their temperatures will be the same. If they are well matched and their collector currents are matched, their V_{BE} values will also match. If the currents are different, the V_{BE} values will follow this equation:

$$V_{BE2} - V_{BE1} = n(kT/q)\ln(I_{C2}/I_{C1})$$

Where:

n = the ideality factor (also called "nonideality factor") of the transistor junction; depends on process and device design and is generally very close to 1.01
k = Boltzmann's constant = $1.3806503 \times 10^{-23}$ m^2 kg s^{-2} K^{-1}
q = the electron charge = $1.60217646 \times 10^{-19}$ coulombs
T = temperature in °K (temperature in °C + 273.15)
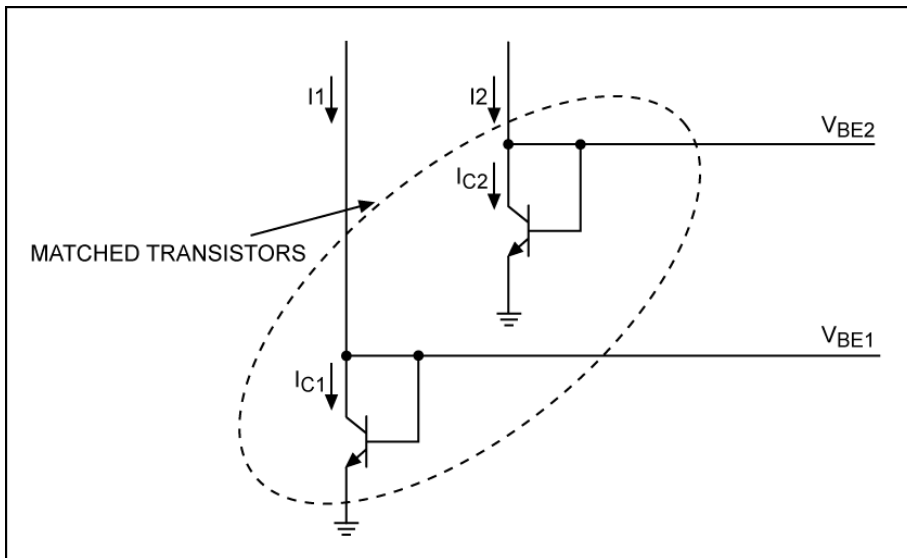
Figure 11. Conceptual circuit showing how two matched transistors can sense temperature.

Practical designs include trim capabilities and compensation for nonideal behavior of the circuit elements.

Figure 12 shows a curve of output voltage vs. temperature for a typical analog temperature sensor, the MAX6605. Note that the curve is quite linear. **Figure 13** shows the deviation from a straight line for this sensor. From 0°C to +85°C, the linearity is within about ±0.2°C, which is quite good compared to thermistors, RTDs, and thermocouples.
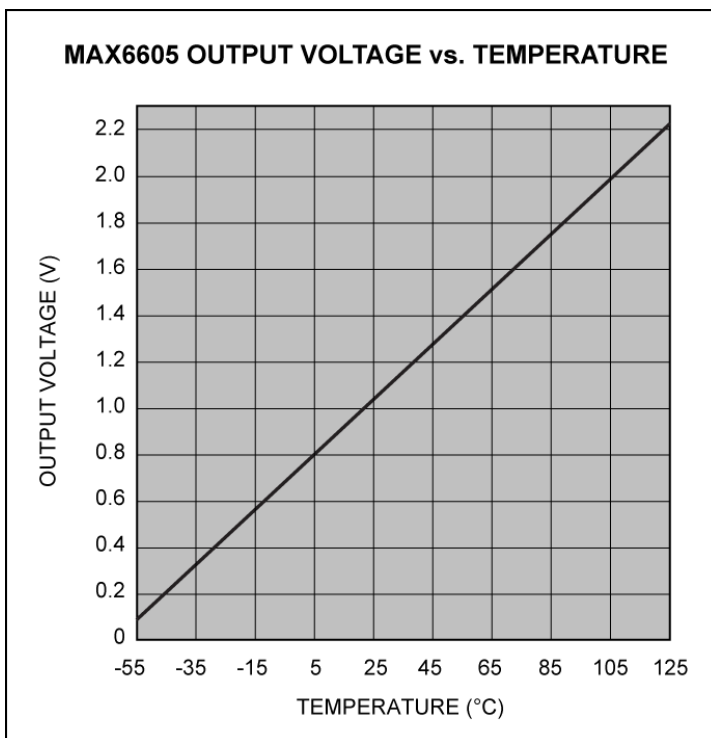
Figure 12. Output voltage vs. temperature for the MAX6605 analog temperature-sensor IC.

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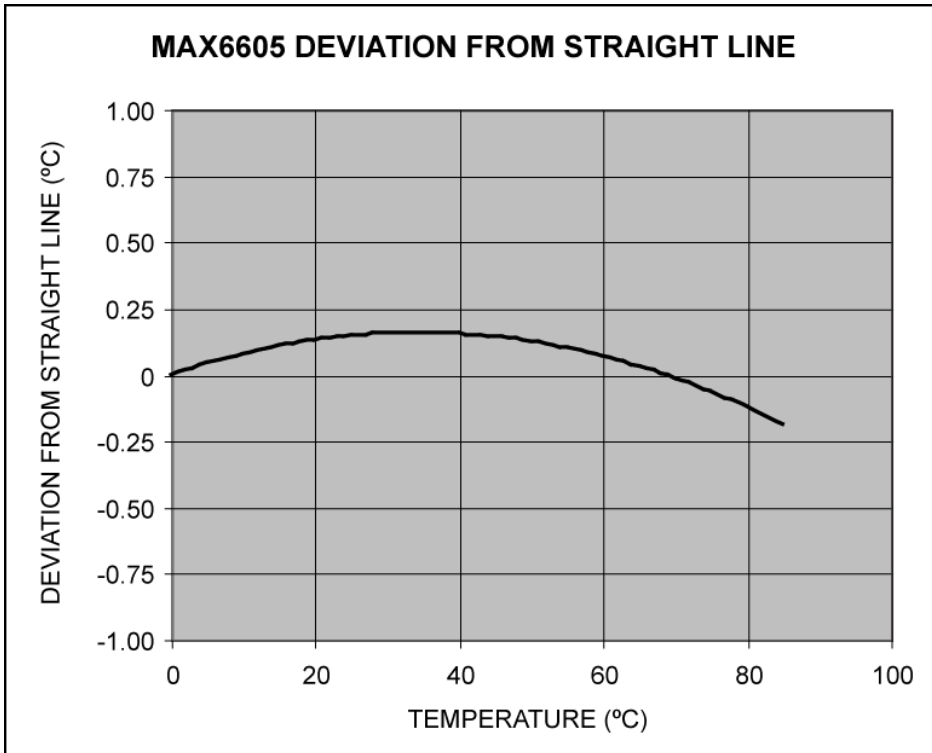
Figure 13. The MAX6605 output voltage deviation from a straight line. Linearity from 0°C to +85°C is approximately ±0.2°C.

Analog temperature sensors can have excellent accuracy. For example, the DS600 has a guaranteed accuracy of ±0.5°C from -20°C to +100°C, as seen in **Table 1**. Other analog sensors are available with larger error tolerances, but many of these have very low operating current (on the order of 15µA, max) and are available in small packages (e.g., SC70).

Table 1. Maxim's Analog Temperature Sensors

Part	Description	Accuracy (±°C)	Accuracy Range (°C)	Operating Temp Range (°C)	Supply Voltage Range V_{CC} (V)
DS600	±0.5°C accurate analog-output sensor with temperature switch	0.5	-20 to +100	-40 to +125	+2.7 to +5.5
MAX6605	+2.7V to +5.5V analog temp sensor in SC70	3.8	-20 to +85	-55 to +125	+2.7 to +5.5
MAX6607	+1.8V temp sensor in SC70	5	-10 to +85	-20 to +85	+1.8 to +3.6
MAX6608	+1.8V temp sensor in SOT23	5	-10 to +85	-20 to +85	+1.8 to +3.6
MAX6610	Temp sensor and voltage reference in SOT23	3.7	-20 to +85	-40 to +125	+3.0 to +5.5
MAX6611	Temp sensor and voltage reference in SOT23	3.7	-20 to +85	-40 to +125	+4.5 to +5.5
MAX6612	High-slope, low-power, analog temp sensor	4.3	+60 to +100	-55 to +150	+2.4 to +5.5
MAX6613	+1.8V to +5.5V analog temp sensor	4.4	-20 to +85	-55 to +130	+1.8 to +5.5

Local Digital Temperature Sensor ICs

Integrating an analog temperature sensor with an ADC is an obvious way to create a temperature sensor with a direct digital interface. Such a device is normally called a digital temperature sensor, or a local digital temperature sensor. "Local" refers to the fact that the sensor measures its own temperature, as opposed to a remote sensor that measures the temperature of an external IC or discrete transistor.

There is a wide variety of digital temperature sensors available with various feature sets; see **Table 2** at the end of this section for a complete list of Maxim's local digital temperature sensors. **Figure 14** shows block diagrams for two digital temperature sensors. Figure 14a illustrates a sensor that simply measures temperature and clocks the resulting data out through a 3-wire digital interface. Figure 14b shows a device that includes several additional features, such as over-/undertemperature outputs, registers to set trip thresholds for these outputs, and EEPROM.
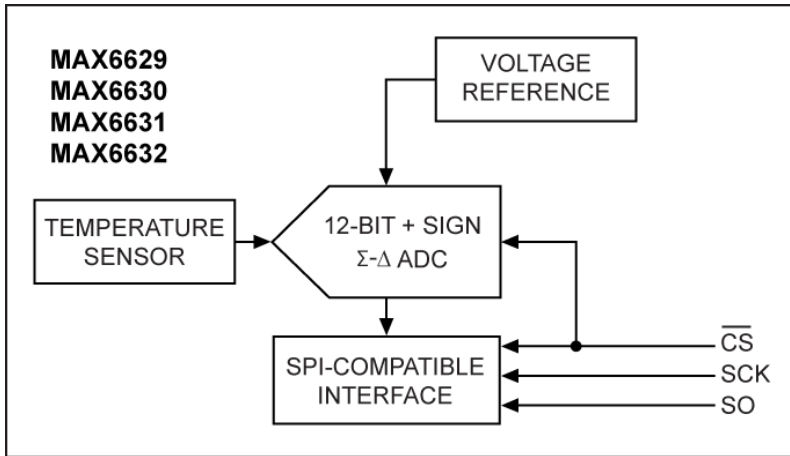
(a)
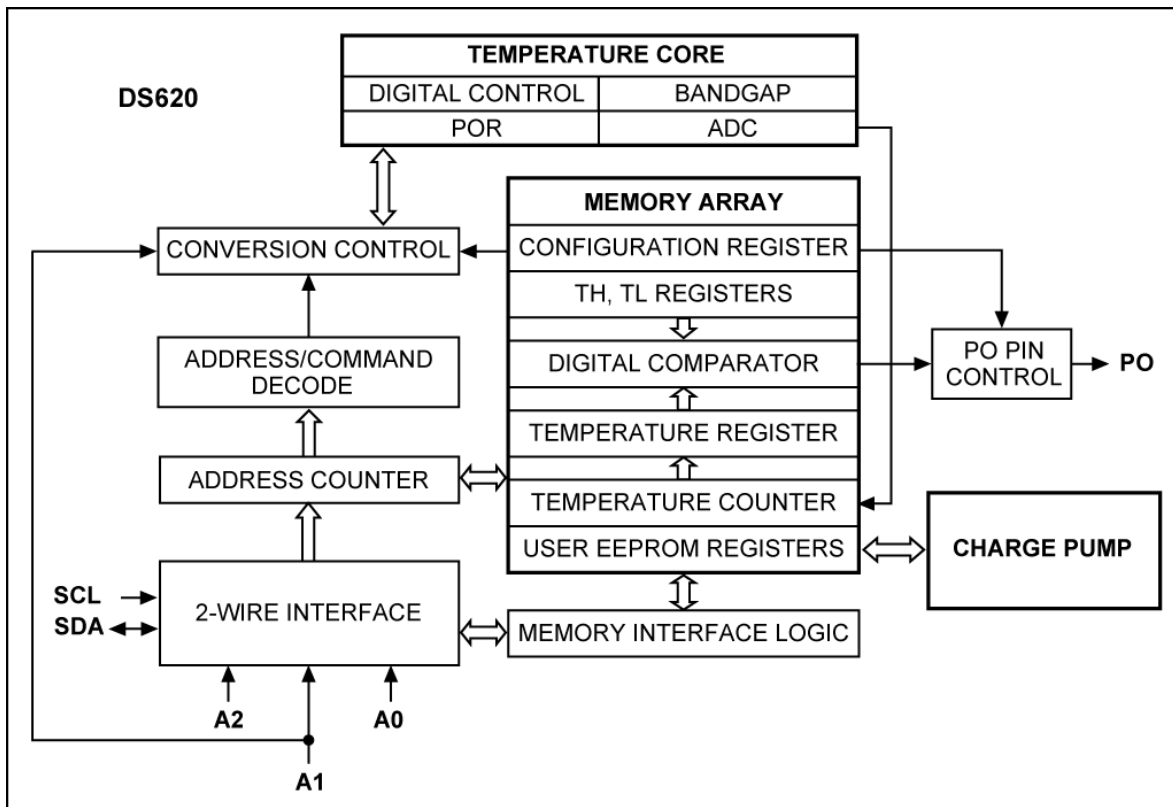
(b)

Figure 14. Block diagrams of local digital temperature sensors. (a) Simple sensor with serial digital output. (b) Sensor with additional functions, such as over-/undertemperature alarm outputs and user EEPROM.

Digital temperature sensors are available with guaranteed accuracy as good as ±0.5°C over a wide temperature range. One advantage of using a digital temperature sensor is that all of the errors involved in digitizing the temperature value are included within the sensor's accuracy specifications. In contrast, an analog temperature sensor's specified error must be added to that of any ADC, amplifier, voltage reference, or other component that is used with the sensor.

Other Digital Temperature Sensor Features

In addition to the basic temperature-sensing function, digital sensors can include various combinations of several other useful features, the most common of which are:

Overtemperature Outputs Most digital temperature sensors include one or more outputs that indicate that the measured temperature has gone beyond a preset (usually software-programmable) limit. The output may behave like a comparator output, with one state when temperature is above the threshold and the other state when temperature is below the threshold. Another common implementation is for the output to behave as an interrupt that is reset only in response to an action by the master.

Fault Queue When short-term temperature variations commonly occur, you may prefer that the overtemperature output is not asserted as a result of a single overthreshold measurement. Instead, it may be better to assert the output only after a few consecutive overthreshold measurements have taken place. A fault queue allows you to select the number of consecutive overthreshold measurements required before the output asserts.

Nonvolatile Memory Some digital sensors include nonvolatile memory (NVM) to store overtemperature thresholds. This can be useful if, for example, the sensor is to be used for system protection. With the correct values stored in the NVM threshold registers, the overtemperature detection function begins to operate immediately upon power-up, with no need for the master to write to the sensor.

Interfaces Digital temperature sensors are available with a wide variety of digital interfaces including I^2C, SMBus™, SPI™, 1-Wire®, and PWM.

I^2C/SMBus Timeout In systems using either I^2C or SMBus to communicate with the temperature sensor, communications errors can cause a slave to hold the bus low and prevent either the master or other slaves from using the bus. A solution often included in slave ICs like temperature sensors is known as "timeout." A timeout circuit monitors the bus and, when the data bus has been held in a low state for more than 35ms, for example, the IC's internal interface resets. If the IC has been holding the bus low, it releases the bus, allowing other devices to communicate. Bus timeout is an optional part of the SMBus specification. Because the I^2C specification allows very low clock speeds, timeout is not part of the I^2C specification. However, the timeout feature is included in many I^2C slave devices.

Table 2. Maxim's Local Digital Temperature Sensors

Part	Description	Interface	Accuracy (±°C)	Nonvolatile Memory	V_{CC} Range (V)
DS1620	Digital thermometer and thermostat	3-wire	0.5	✓	+2.7 to +5.5
DS1621	Digital thermometer and thermostat	2-wire	0.5	✓	+2.7 to +5.5

DS1624	Digital thermometer and memory	3-wire	0.5	✓	+2.7 to +5.5
DS1626	High-precision digital thermometer and thermostat	3-wire	0.5	✓	+2.7 to +5.5
DS1629	Digital thermometer and real-time clock	2-wire	2	✓	+2.2 to +5.5
DS1631	High-precision digital thermometer and thermostat	2-wire	0.5	✓	+2.2 to +5.5
DS1721	Digital thermometer and thermostat	2-wire	1	✓	+2.7 to +5.5
DS1722	Digital thermometer	3-wire	2		+2.65 to +5.5
DS1726	High-precision digital thermometer and thermostat	3-wire	1	✓	+2.7 to +5.5
DS1731	High-precision digital thermometer and thermostat	2-wire	1	✓	+2.2 to +5.5
DS1775	Digital thermometer and thermostat	2-wire	2		+2.7 to +5.5
DS1821	Programmable 1-Wire digital thermostat and thermometer	1-Wire	1	✓	+2.7 to +5.5
DS1822	Econo 1-Wire digital thermometer	1-Wire	2	✓	+3.0 to +5.5
DS1825	Programmable resolution, 1-Wire digital thermometer with 4-bit ID	1-Wire	0.5	✓	+3.0 to +3.7
DS18B20	Programmable resolution digital thermometer	1-Wire	0.5	✓	+3.0 to +5.5
DS18S20	High-precision digital thermometer	1-Wire	0.5	✓	+3.0 to +5.5
DS28	Digital thermometer with sequence detect and PIO	1-Wire	0.5	✓	+3.0 to +5.5
DS620	Low-voltage, ±0.5°C accuracy digital thermometer and thermostat	2-wire	0.5	✓	+1.7 to +3.5
DS75	Digital thermometer and thermostat	2-wire	2		+2.7 to +5.5
DS75LV	Low-voltage digital thermometer and thermostat	2-wire	2		+1.7 to +3.7
DS75LX	Digital thermometer and thermostat with extended addressing	2-wire	2		+1.7 to +3.7
DS7505	High-precision, DS75-compatible digital thermometer and thermostat	2-wire	0.5	✓	+1.7 to +3.7
LM75	Digital temperature sensor and thermal watchdog	2-wire	2		+3.0 to +5.5
MAX6575	Temp sensor with single-wire time-delay interface	1-Wire	4.5		+2.7 to +5.5
MAX6576	Temp sensor with single-wire period output	1-Wire	4.5		+2.7 to +5.5
MAX6577	Temp sensor with single-wire frequency output	1-Wire	3.5		+2.7 to +5.5
MAX6625	I²C, 9-bit temp sensor	2-wire	2		+3.0 to +5.5
MAX6626	I²C, 12-bit temp sensor	2-wire	2		+3.0 to +5.5
MAX6629	12-bit + sign digital temp sensor	3-wire	1		+3.0 to +5.5
MAX6630	12-bit + sign digital temp sensor	3-wire	1		+3.0 to +5.5
MAX6631	12-bit + sign digital temp sensor	3-wire	1		+3.0 to +5.5
MAX6632	12-bit + sign digital temp sensor	3-wire	1		+3.0 to +5.5
MAX6633	12-bit + sign I²C temp sensor with 4 I²C address pins	2-wire	1.5		+3.0 to +5.5
MAX6634	12-bit + sign I²C sensor with 3 address pins and user-programmable thresholds	2-wire	1.5		+3.0 to +5.5
MAX6635	12-bit + sign I²C sensor with 2 address pins and user-programmable thresholds	2-wire	1.5		+3.0 to +5.5
MAX6652	Temperature sensor and 4-channel voltage monitor	2-wire	3		+2.7 to +5.5
MAX6662	12-bit + sign SPI temp sensor	3-wire	2.5		+3.0 to +5.5
MAX6683	Temperature sensor and 4-channel voltage monitor	2-wire	4		+2.7 to +5.5
MAX7500	Digital temp sensor and thermal watchdog I²C bus with timeout; LM75 compatible	2-wire	2		+3.0 to +5.5
MAX7501/ MAX7502	Digital temp sensors and thermal watchdog I²C bus with timeout and reset	2-wire	2		+3.0 to +5.5
MAX7503/ MAX7504	Digital temp sensors and thermal watchdog I²C bus with reset	2-wire	2		+3.0 to +5.5

Remote Digital Temperature Sensors

A remote digital temperature sensor, also called a remote sensor or a thermal diode sensor, measures the temperature of an external transistor—either a discrete transistor or one that is integrated on the die of another IC, as shown in **Figure 15**. Microprocessors, FPGAs, and ASICs often include one or more sensing transistors (usually called "thermal diodes") similar to the one shown in Figure 15.
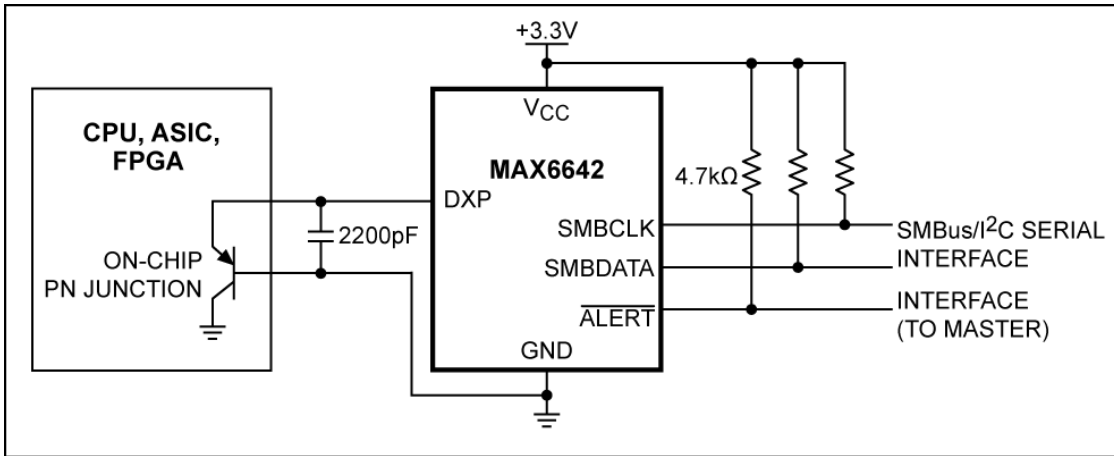

Figure 15. A remote temperature sensor monitoring the temperature of a sensing transistor (or thermal diode) on the die of an external IC.

Remote temperature sensors operate on a principle similar to the one shown in Figure 11, except that only one sensing transistor is used (see **Figure 16**). Why is only one sensing transistor used? There are two reasons. First, two transistors would require one or two more pins on both the target IC and the sensor IC. Second, the use of two transistors would require the manufacturer of the target IC to very precisely match those transistors. Any differences between the two transistors would lead to measurement errors that would be out of the control of the remote sensor IC's manufacturer. Using a single sensing transistor requires fewer pins and allows the key error sources to be controlled (and compensated) by the manufacturer of the remote sensor IC.
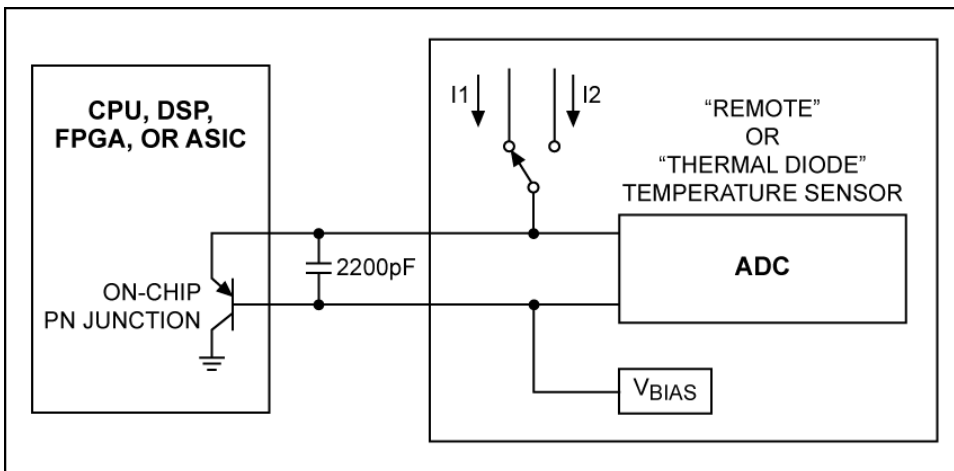

Figure 16. Simplified block diagram of a remote diode temperature sensor.

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The bias current through the transistor alternates between current sources I1 and I2, and the ADC measures the resulting V_{BE} while each current value flows. As before, the difference between the two V_{BE} values is directly proportional to absolute temperature.

$$V_{BE2} - V_{BE1} = n(kT/q)\ln(I_{C2}/I_{C1})$$

What is the advantage of measuring the die temperature of an external IC? First, consider the types of ICs that might have high die temperatures. These may be power supply ICs, high-speed microprocessors, DSPs, FPGAs, or ASICs. Power dissipation may vary significantly over a period of time depending on loading. If the die temperature rises to a value that is above the nominal operating temperature—to +100°C, for example—performance may suffer enough to cause the system to fail. A system that can monitor the die temperatures of sensitive components may be able to prevent failure by acting on the thermal data. The system might, for example, activate a cooling fan or reduce clock speeds to help reduce the die temperature of an overheated IC. If the temperature approaches a value high enough to cause irreversible damage, the system might shut itself down before damage can occur.

Figure 17 compares monitoring a high-temperature IC with a remote sensor and with a local sensor. The target IC starts at a low die temperature, which quickly rises to a high value. Note that the local sensor responds slowly to the change in the target's die temperature. This is because of the time required for temperature changes to propagate from the target's die through its lead frame and package, the PCB, and the local sensor's die. Several seconds are needed for the local sensor to respond to changes in the target's die temperature. Also, note that the local sensor's reading is much different from the target's die temperature. The local sensor is measuring board temperature, which is influenced by other devices on the board, chassis temperature, air temperature, and air flow. Therefore, it is unlikely that the local sensor will report a temperature that correlates well with the target's die temperature.
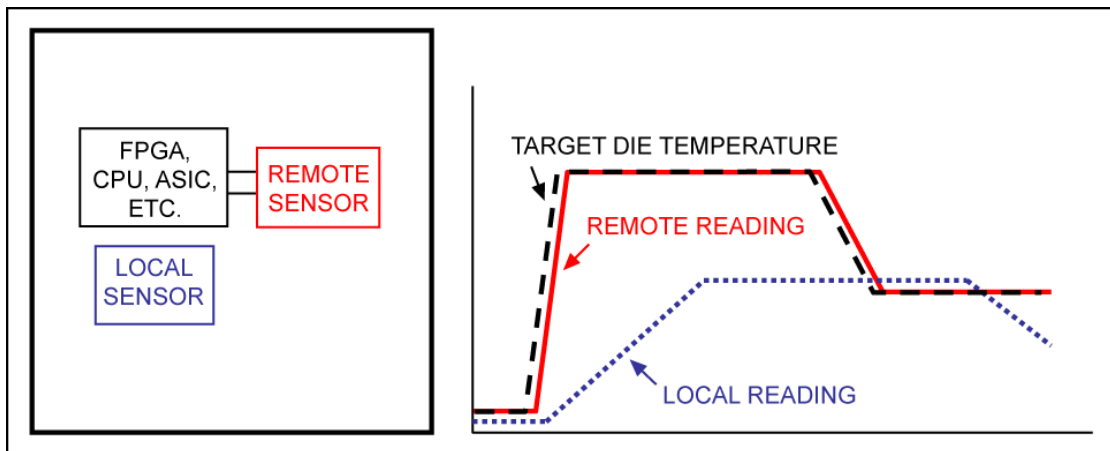
Figure 17. Comparison of the behavior of a local sensor and a remote sensor. Note that, when an external IC has a thermal diode available, a remote sensor can measure the die temperature of that IC much more quickly and accurately than a local sensor can.

As the figure illustrates, the behavior of the remote sensor differs significantly from that of the local sensor. The remote sensor responds quickly to changes in the target's die temperature. Because the remote sensor is measuring the actual temperature on the target die, the delay is just that of the remote sensor's ADC, which is usually on the order of 50µs to 100µs. Therefore,

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the remote sensor can follow the target's die temperature quickly. Because the remote temperature sensor is measuring the temperature of the target's die directly, the reported temperature will be very close (on the order of ±1°C) to the actual temperature.

A secondary advantage of remote temperature sensors is that they allow you to monitor more than one hot spot with a single IC. A basic single-remote sensor, like the MAX6642 in Figure 15, can monitor two temperatures: its own temperature plus an external temperature. The external location may be on the die of a target IC, as in Figure 15, or it may be a hot spot on a board that it monitors using a discrete transistor. Other remote sensors monitor as many as seven external temperatures; this allows a total of eight locations, consisting of ICs and board hot spots, to be monitored from a single chip. For example, the MAX6602, which has four remote diode inputs, might be used to monitor the temperatures of a pair of FPGAs with integrated thermal diodes, two board hot spots using discrete transistors, and the temperature of the board at the MAX6602's location. See **Table 3** at the end of this section for a complete list of Maxim's remote temperature sensors and the locations they can monitor.

Remote Temperature Sensor Error Sources

Various characteristics of the thermal diode or the circuit board can cause temperature measurement errors. Descriptions of the most common of these errors follow.

Parasitic Series Resistance Resistance in series with the thermal diode will affect the temperature reported by the remote sensor. If the sensor uses diode bias currents of 100µA and 10µA, the effect of IR drops on the differential voltage can be calculated as follows:

Begin with the equation for voltage due to two currents flowing through the transistor:

$$V_{BE2} - V_{BE1} = n(kT/q)\ln(I_{C2}/I_{C1})$$

If the series resistance equals 1Ω, the 100µA and 10µA bias currents will cause voltage drops across the resistor equal to 100µV and 10µV, respectively, resulting in a voltage difference of 90µV. Rearranging the above equation and assuming n = 1, we can see that this will cause an apparent temperature shift of:

$$T = (q \times 90µV)/[k \times \ln(10)] = 0.45°C$$

Most Maxim remote temperature sensors use 100µA and 10µA bias currents, and those currents are generally within 20% of the nominal values, so 0.45°C is a good approximation for these sensors.

If the series resistance is known (as is usually the case with PCB trace resistance), it is simple to calculate the expected increase in the temperature reading and subtract that value from the temperature reported by the sensor. Note that not all sensors will have the same 0.45°C/Ω sensitivity to series resistance. Some sensors use much higher diode bias currents, which will increase the sensitivity. Also note the tolerance of the bias current. A 20% tolerance would allow reasonably accurate estimates of the effect of series resistance. A +100%/-50% tolerance, for example, would make good estimates difficult.

When the series resistance is not known, a good solution is to use a sensor that has automatic resistance cancellation. Several of Maxim's remote sensors have this feature.

Ideality Factor Earlier, it was stated that the ideality factor of the PN junction is very close to 1.01, and that the actual value depends on process and transistor design. Most remote sensors are optimized for a specific ideality factor. For example, several of Maxim's remote sensors are optimized for an ideality factor of 1.008, which corresponds to the center of the distribution of several thermal diodes on many popular microprocessors.

If you use a thermal diode with a different ideality factor from the value for which the sensor was optimized, the reported temperature will differ from the actual temperature. The actual temperature can be easily calculated, so long as you know the ideality factor of your thermal diode, using the equation below:

$$T_{ACTUAL} = T_{MEASURED}(n_{DIODE}/n_{SENSOR})$$

Where:
T = temperature in °K
n_{SENSOR} = ideality factor for which the sensor is optimized
n_{DIODE} = ideality factor of the diode you are using

As an example, assume you have a sensor optimized for n = 1.008 and you use it to monitor temperature of a discrete diode with n = 1.01. At T = +300°K, the measured temperature will be:

$$T_{ACTUAL} = T_{MEASURED}(n_{DIODE}/n_{SENSOR}) = 300°K(1.01/1.008) = 300.6°K$$

The resulting error is, therefore, approximately +0.6°K.

Unit-to-unit variation in ideality factors depends on the repeatability of the microprocessor manufacturer's process. For manufacturers with consistent processes, the variation can be a fraction of a percent. A larger potential error can occur when the sensing transistor's current gain (or "beta") is extremely low.

Low-Beta-Sensing Transistors Note that the remote sensor in Figure 16 is forcing current through the sensing transistor's emitter, but the equation showing the relationship between ΔV_{BE} and temperature depends on a precise ratio of collector currents. As long as the transistor's current gain is high, this is a good approximation. If the transistor's current gain is very low, however, the ratio of collector currents may not match the ratio of emitter currents. Because a significant fraction of the emitter current is flowing through the base, any change in beta due to changes in temperature or current levels can potentially change the collector current ratio, thereby changing the reported temperature. A 10% change in the collector current ratio can cause roughly a 12°C change in the reported temperature.

Note that this is not a problem with discrete sensing transistors, because they have consistently high current gains. Some integrated sensing transistors built using specialized nanometer-scale processes that cannot support good PNP transistors may have very low betas (less than 1), and these have the potential for poor accuracy. When such transistors will be used, it is generally a good idea to use a remote sensor with "beta compensation." Beta

compensation uses circuit techniques that compensate for the effects of low-beta transistors, producing accurate temperature data for beta values as low as 0.1. Examples of Maxim's remote sensors with beta compensation are the MAX6693 and the MAX6581.

Is beta compensation always necessary when using low-beta-sensing transistors? Not at all. If beta is relatively uniform over the normal range of currents and temperatures, the effect of low beta may be small enough to ignore. As an example, **Figure 18** shows the results of measuring three samples of a 45nm microprocessor with a beta of 0.3. The temperature sensor is a standard device with no beta compensation. Note that the errors are less than ±1°C, even without the use of beta compensation. It is, therefore, advisable to understand the characteristics of the sense transistors you will be using, because some may require beta compensation, while others may not. Figure 18 illustrates this with error curves for three different samples of low-beta CPUs. The temperatures of these CPUs were measured using conventional remote temperature sensors that had no beta compensation. In total, nine CPUs were tested; the curves in Figure 18 show the maximum, minimum, and median results.
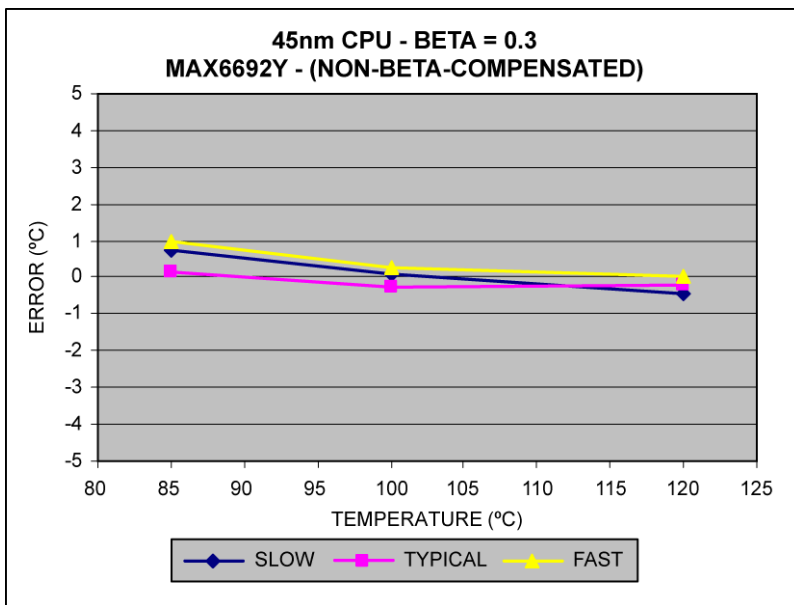

Figure 18. Three samples of a 45nm microprocessor with beta = 0.3 measured using conventional MAX6692Y remote temperature sensors. Note the low errors even without beta compensation.

Other Remote Sensor Features

As with local digital sensors, remote temperature sensors can include a variety of other useful features, summarized below:

Overtemperature Outputs Nearly all remote temperature sensors include at least one overtemperature output, and most include two or more. One of these outputs is typically an interrupt (or SMBus alert) that may also indicate problems such as shorted or open-circuit diodes. Other outputs are most often overtemperature comparator outputs.

Interfaces Most remote temperature-sensor ICs on the market were developed for PC applications and, therefore, feature an SMBus/I^{2}C-compatible interface. A few are available with other serial interfaces. Examples are the MAX6627 and MAX6628, which use an SPI-compatible interface.

I^{2}C/SMBus Timeout As mentioned in the *Local Digital Temperature Sensor ICs* section, bus timeout is an optional feature that can prevent I^{2}C/SMBus lockup resulting from communication errors.

Diode Fault Detection The majority of remote sensors have the ability to detect shorted or open-circuit thermal diodes. The manner in which a diode fault is indicated depends on the sensor. Faults can be indicated by an ALERT (interrupt) output, a bit in a status register, or a specific code (such as negative full scale) in the temperature data register.

Conversion Rate Control Most remote sensors can select any of several available temperature conversion rates. Since supply current depends partly on the conversion speed, this allows the designer to trade update rate against supply current.

Offset Registers Some remote sensors include offset registers that can add an offset to the measured temperature. This offset can be used to compensate for an error, such as might be caused by series resistance or a transistor ideality factor, which can affect the reported temperature value. In the absence of an offset register, the microcontroller (µC) that reads the sensor data can add an offset as needed.

Ideality Factor Registers The majority of sensing transistors used with remote sensors have ideality factors that fall within a relatively narrow range. When the ideality factor is outside of that range, correcting for the resulting error in reported temperature is relatively simple. To simplify this further, a few remote sensors also include registers that allow the ideality factor target value to be selected to match the ideality of the sensing transistor.

Data Averaging Transient noise in the system can sometimes cause remote diode measurement errors. There are various ways to counteract this effect. Maxim's remote sensors always average 10 readings before performing the analog-to-digital conversion. Some sensors average a few samples after conversion. Averaging can be beneficial when errors due to noise transients are random.

Table 3. Maxim's Remote Temperature Sensors

Part	Description	Remote Channels	Local Channels	Interface	Accuracy (±°C)	Alarm Outputs	Resistance Cancellation
MAX6581	8-channel precision temperature monitor with beta compensation	7	1	2-wire	1	2	Yes
MAX6602	5-channel precision temperature monitor with STBY	4	1	2-wire	1	2	Channel 1
MAX6622	5-channel, Penryn CPU-compatible, precision temperature monitor with STBY; DXN1 grounded	4	1	2-wire	1	2	Channel 1
MAX6627	Remote ±1°C digital temperature sensor with SPI interface	1	0	3-wire	1	0	No
MAX6628	Remote ±1°C digital temperature sensor with SPI interface	1	0	3-wire	1	0	No

MAX6636	7-channel, Penryn CPU-compatible precision temperature monitor with STBY; DXN1 grounded	6	1	2-wire	1	2	Channel 1
MAX6638	Precision temperature monitor with 2 independent SMBus interfaces	1	1	2-wire	2	2	No
MAX6642	±1°C, SMBus remote/local temperature sensor	1	1	2-wire	1	1	No
MAX6646	Remote/local sensors with +125°C default external overtemperature threshold	1	1	2-wire	1	2	No
MAX6647	Remote/local sensor with +125°C default external overtemperature threshold	1	1	2-wire	1	2	No
MAX6648	Remote/local sensor with +125°C default external overtemperature threshold	1	1	2-wire	0.8	2	No
MAX6649	Remote/local sensor with +125°C default external overtemperature threshold	1	1	2-wire	1	2	No
MAX6654	±1°C remote/local temperature sensor with resistance cancellation	1	1	2-wire	2	1	Yes
MAX6655	2-channel remote/local temperature sensor and 4-channel voltage monitor	2	1	2-wire	1.5	2	No
MAX6656	2-channel remote/local temperature sensor and 4-channel voltage monitor	2	1	2-wire	1.5	2	No
MAX6657	0°C to +125°C remote/local temperature sensor	1	1	2-wire	1	2	No
MAX6658	-55°C to +125°C remote/local temperature sensor	1	1	2-wire	1	2	No
MAX6659	-55°C to +125°C remote/local temperature sensor with 2 overtemperature alarms	1	1	2-wire	1	2	No
MAX6680	±1°C fail-safe remote/local temperature sensor	1	1	2-wire	1	2	No
MAX6681	±1°C fail-safe remote/local temperature sensor	1	1	2-wire	1	2	No
MAX6689	7-channel precision temperature monitor	6	1	2-wire	1	2	Channel 1
MAX6690	±2°C accurate remote/local temperature sensor with resistance cancellation	1	1	2-wire	2	1	Yes
MAX6692	Remote/local sensor with +85°C default external overtemperature alert	1	1	2-wire	0.8	2	No
MAX6695	Dual remote/local temperature sensors with fixed SMBus address	2	1	2-wire	1.5	3	No
MAX6696	Dual remote/local temperature sensors with 9 pin-selectable SMBus addresses	2	1	2-wire	1.5	3	No
MAX6697	7-channel precision temperature monitor	6	1	2-wire	1	2	Channel 1
MAX6698	7-channel precision temperature monitor (3 remote, 1 local, 3 thermistor)	6	1	2-wire	1	2	Channel 1
MAX6699	5-channel precision temperature monitor	4	1	2-wire	1	2	Channel 1

Other Types of Thermal Management Components

Thermal management involves more than simply sensing temperature. Several kinds of components use temperature data to perform a function, such as temperature threshold detection (in temperature switches), fan control, or sensor signal conditioning. Some of these are discussed below.

Temperature Switches

A temperature switch responds to temperature exceeding a predetermined threshold (also called a set point, trip point, or trip temperature). Effectively, it is like a combination of an analog temperature sensor and a comparator. The output is a logic gate. Temperature switches are simple, small, and low in cost, making them ideal for "fail-safe" system protection applications. They can operate independent of other components and, when an overtemperature event is detected, can act to protect the system by, for example, activating a cooling fan or disabling the power supply. Note that temperature switches can protect against low-temperature conditions as well (e.g., by stopping the charging of a battery when temperature is too low for safe charging).

Figure 19 is an example of a simple temperature switch with a factory-set trip temperature. One input can be strapped to V_{CC} or GND to set the hysteresis to either +2°C or +10°C. The output in this case is active-low and open-drain, but active-high push-pull versions are also available.
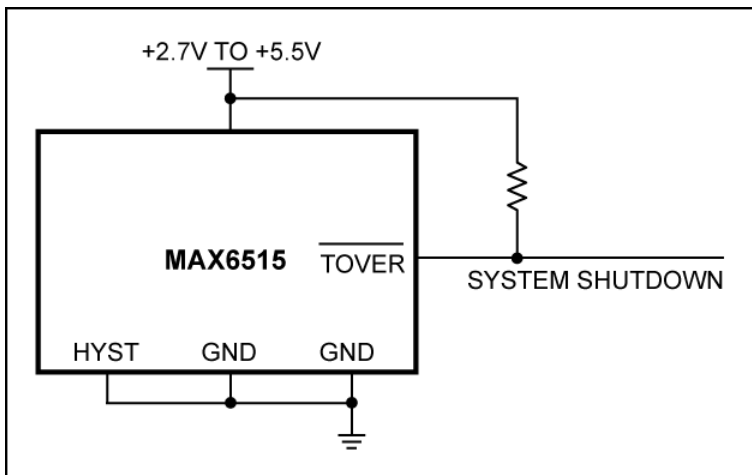

Figure 19. Temperature switch with a factory-set trip temperature.

For applications that require an adjustable trip temperature, temperature switches such as the MAX6509 in **Figure 20** have trip temperatures determined by an external resistor. Other temperature switches have trip temperatures determined by pin-strapping.
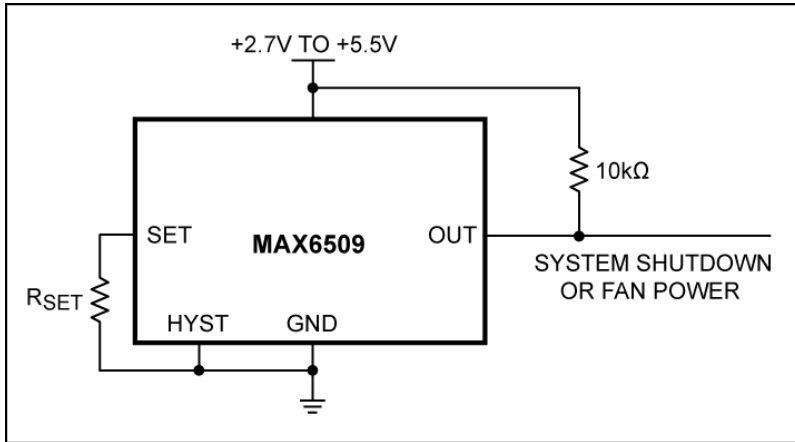
Figure 20. Temperature switch with a resistor-set trip temperature.

Table 4 summarizes the features of several of Maxim's temperature switches.

Table 4. Maxim's Temperature Switches

Part	Description	Sensor	Output Type	Output Polarity	Accuracy (±°C, max)
DS600	Resistor-adjustable threshold, precision temperature sensor, two outputs	Local	Open drain	1 high, 1 low	0.5
MAX6501	Factory thresholds from +35°C to +125°C in 10°C increments	Local	Open drain	Low	6
MAX6502	Factory thresholds from +35°C to +125°C in 10°C increments	Local	Push/pull	High	6
MAX6503	Factory thresholds from -45°C to +15°C in 10°C increments	Local	Open drain	Low	6
MAX6504	Factory thresholds from -45°C to +15°C in 10°C increments	Local	Push/pull	High	6
MAX6505	2 outputs (ALARM, WARN), factory thresholds from -40°C to +125°C in 5°C increments	Local	Open drain	Low	3.5
MAX6506	2 outputs (ALARM, WARN), factory thresholds from -40°C to +125°C in 5°C increments	Local	Push/pull	High	3.5
MAX6507	2 outputs (OVER, OK) factory thresholds from -40°C to +125°C in 5°C increments	Local	Open drain	Low	3.5
MAX6508	2 outputs (OVER, OK), factory thresholds from -40°C to +125°C in 5°C increments	Local	Push/pull	High	3.5
MAX6509	Resistor-programmable temperature switch	Local	Open drain	Low	4.7
MAX6510	Resistor-programmable temperature switch; open-drain and push-pull	Local	Selectable	Selectable	4.7
MAX6511	Measure remote temperature from +40°C to +125°C in 10°C factory-programmed increments	Remote	Push/pull	Low	5
MAX6512	Measure remote temperature from +40°C to +125°C in 10°C factory-programmed increments	Remote	Open drain	Low	5
MAX6513	Measure remote temperature from +40°C to +125°C in 10°C factory-programmed increments	Remote	Push/pull	High	5
MAX6514	Factory-set thresholds from -45°C to +115°C in 10°C increments	Local	Open drain	Low	2.5

MAX6515	Factory-set thresholds from -45°C to +115°C in 10°C increments	Local	Push/pull	High	2.5
MAX6516	Factory-set thresholds from -45°C to +115°C in 10°C increments, analog output	Local	Push/pull, analog	High	2.5
MAX6517	Factory-set thresholds from -45°C to +115°C in 10°C increments, analog output	Local	Open drain, analog	Low	2.5
MAX6518	Factory-set thresholds from -45°C to +115°C in 10°C increments, analog output	Local	Push/pull, analog	High	2.5
MAX6519	Factory-set thresholds from -45°C to +115°C in 10°C increments, analog output	Local	Open drain, analog	Low	2.5
MAX6685	Dual-output remote-junction switch	Remote	Open drain, push/pull	Low, high	1.5
MAX6686	Dual-output remote-junction switch	Remote	Open drain	Low	1.5
MAX6687	Dual-output +40°C to +115°C local and +120°C to +125°C remote-junction switch	Remote, local	Open drain	Low	3
MAX6688	Dual-output +40°C to +115°C local and +120°C to +125°C remote-junction switch	Remote, local	Push/pull	High	3

Fan Speed Controllers

Fans are used in electronic systems that require air flow to provide sufficient cooling for the various components. If you use a fan (or multiple fans) that can move enough air to sufficiently cool the system components under worst-case conditions (maximum ambient temperature, maximum power dissipation), that fan will keep the internal temperatures low enough to avoid component damage. However, the system will not normally be operating under worst-case conditions. In fact, the amount of time a system spends at or near the worst-case thermal conditions is often a small fraction of the system's operating life. Therefore, constantly running the fan at its nominal (full) speed is not necessary. Sometimes, no cooling is necessary; at other times, limited cooling is sufficient. In addition to being unnecessary, continuous full-speed cooling has disadvantages. These include:

Unnecessarily High Acoustic Noise Fans are noisy. Multiple fans are noisier still. The noise level increases with speed, so if the fan is operated at its full nominal speed continuously, the noise level will be higher than it needs to be. At a minimum, the excessive noise is unpleasant for people working nearby. At higher sound pressure levels, excessive fan noise can damage the hearing of those nearby. Therefore, any equipment that includes cooling fans and is operated in the presence of users should employ some method of reducing fan speed when full cooling is not needed. Reducing the annoyance level of fan noise can improve marketability of equipment. In some cases, maximum noise levels are mandated by legislation, effectively requiring some form of fan control.

Wasted Power Fan power dissipation varies dramatically, from small, fractional-watt fans used in compact equipment to large fans that require well over 100W of input power. A fan spinning at full speed when that speed is not needed is wasting power, increasing operating costs, and adding to the equipment's carbon footprint. Reducing fan speed when less cooling is needed can reduce the power waste, resulting in lower costs and lower overall carbon dioxide emissions.

Reduced Fan Lifetime Since the operating lifetime of a fan is related to the total number of revolutions, running the fan at less than full speed can increase the fan's operating life. If the fan's average speed can be cut in half, the fan's lifetime can roughly be doubled, which improves reliability and reduces maintenance costs.

There are, therefore, some good reasons to adjust the speed of your cooling fans so that they are spinning as slowly as practical within the system's thermal requirements.

Several different important functions are found in various combinations in specific fan control ICs. Some of these are listed below.

Control of Fan Speed This technique is performed either by adjusting the fan's power supply voltage or by generating a PWM signal whose duty cycle controls the speed of the fan.

Monitoring of Fan Speed Normally done by monitoring the fan's tachometer or "TACH" output, this method utilizes an output that produces a specific number of pulses per revolution. Sometimes this is done by monitoring the fan's supply current, although this is much less reliable.

Detecting Fan Failure This is usually done as part of the fan speed monitoring process. It can also be done by fans that have "fail" or "locked rotor" outputs instead of TACH outputs. Monitoring the speed of a fan when driven to its full speed also allows "predictive" fan-failure detection. As fans near end-of-life, they can begin to slow down. By detecting this phenomenon, a system can ensure that a fan near the end of its useful lifetime is replaced before failing completely.

Closed-Loop Control of Fan Speed This is a combination of fan speed control and monitoring. By monitoring the fan's tachometer signal, the speed of the fan can be adjusted to force it to a desired value (e.g., 3600RPM).

Ensuring Low Audibility of Speed Control Adjusting the speed of a fan to match the system's cooling requirements can help to reduce the average noise level produced by the fan. However, it is necessary to be aware that each time the fan's speed is changed, the change in noise level can be very apparent to anyone near the system. The best fan-control ICs include features that help to reduce the audibility of fan speed changes.

Monitoring of Temperature The fan controller can include one or more channels of temperature sensing.

Temperature-Based Fan Speed Control Temperature data can be used to adjust fan speed based on system-specific temperature-speed profiles.

Types of Fans

The best way to control the speed of a fan depends on the type of fan. Brushless DC (BLDC) fans are the most common type used to cool electronic equipment. These fans are available with power supply voltages of 5V, 12V, 24V, and 48V. 12V fans are the most common. 5V fans are often found in portable equipment, such as notebook PCs. 48V fans are commonly used in industrial and telecommunications equipment.

There are three categories of BLDC fans, referred to by the number of wires on the fan, as shown in **Figure 21**. The simplest is the 2-wire fan, which just has power supply connections.
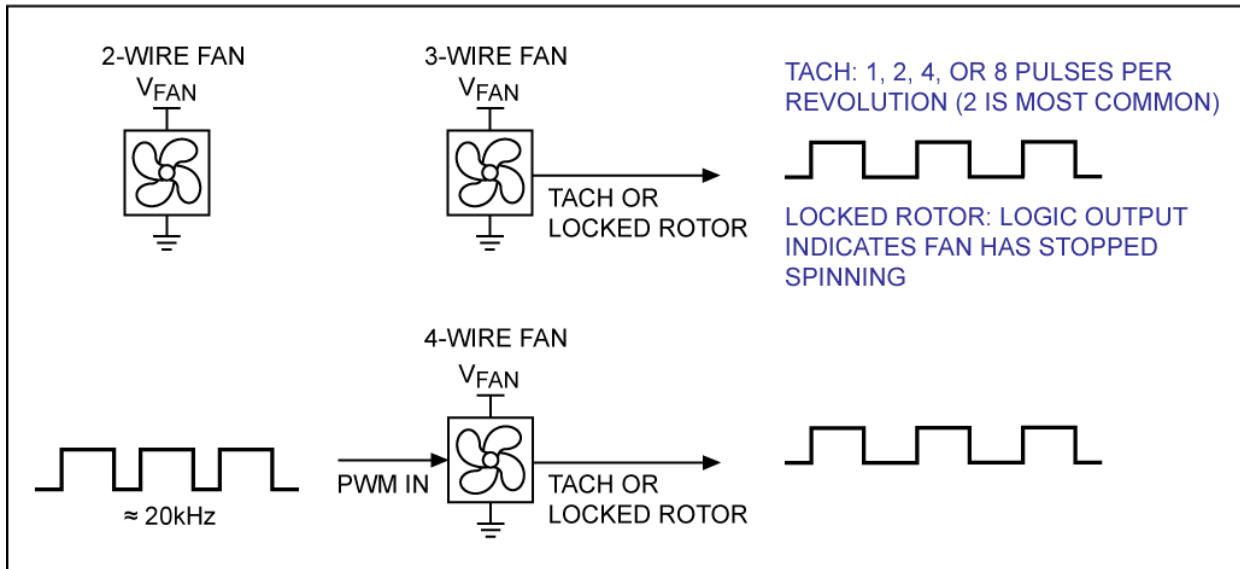
Figure 21. 2-, 3-, and 4-wire fans.

A 3-wire fan also has power supply connections, plus an additional wire that provides information about the fan's status. There are two standard functions for the third wire. This third wire may be a TACH output or a "locked-rotor" output.

A TACH output is usually an open-drain logic output that produces a series of pulses as the fan spins. Most fans produce two pulses per revolution, but fans producing one, four, or eight pulses per revolution are also available. By determining the period or frequency of the tachometer pulses, the fan's speed can be calculated. This data can then be used for closed-loop control of the fan's RPM by comparing the actual RPM with the target RPM and then adjusting the drive to the fan until the actual RPM matches the target RPM.

The tachometer signal can also be used to detect fan failure. For example, if a fan's speed is calculated to be 300RPM under full drive conditions, but its nominal speed is 4000RPM, it can be safely assumed that the fan has failed. Another use for the TACH output is to detect incipient fan failure. Prior to failing, many fans will spin more slowly at a given drive level than they did when new. By monitoring the fan's speed vs. drive profile, it is possible to determine that the fan is beginning to slow, thereby allowing the fan to be replaced before it has completely failed. This improves system reliability by preventing fan failures, and also reduces maintenance costs because "emergency" fan replacements and potential system damage become less likely.

The other common 3-wire function is a fan-failure or locked-rotor output that indicates that the fan has stopped spinning. While less flexible than a TACH output, the locked-rotor signal gives an unambiguous indication of fan failure or obstruction.

4-wire fans add a PWM speed-control input. By varying the duty cycle of the PWM waveform supplied to this input, the speed of the fan can be varied over a range of about 30% to 100% of the maximum speed. The recommended PWM frequency is in the range of 15kHz to 30kHz for

most fans, although some fans will accept input frequencies as low as 100Hz or as high as 100kHz. The logic levels are usually compatible with 3.3V or 5.0V logic.

Controlling Fan Speed

It is clear that basic speed control is easy to do with a 4-wire fan. A µC can generate a PWM waveform, as can most fan speed controller ICs. However, 4-wire fans are still less common than 2- and 3-wire units, so the variety of configurations is limited relative to the other types. In some cases, the right fan for the application is available only as a 2- or 3-wire unit. Controlling the speed of a 2-wire or 3-wire fan can be somewhat more involved, because these fans do not have a dedicated speed-control input. Instead, the speed of these fans must be controlled by modifying the supply voltage applied to the fans.

If you vary a fan's power supply voltage, the fan's speed will vary. **Figure 22** shows fan RPM vs. fan power supply voltage for a typical, low-cost 12V fan. The fan's speed in this example is roughly proportional to the supply voltage.
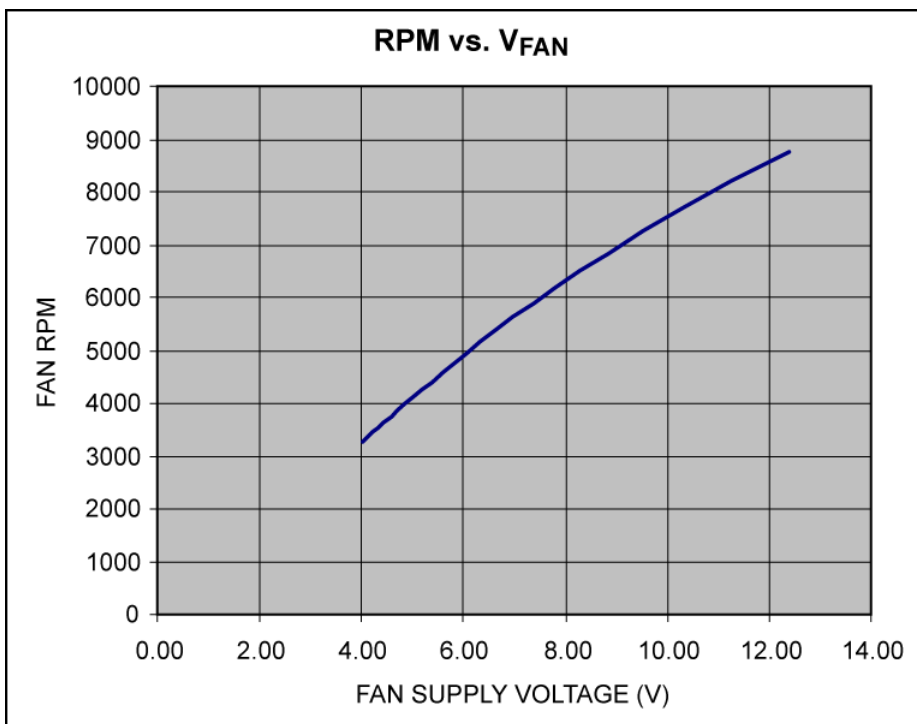
Figure 22. Fan RPM vs. power supply voltage for a typical 12V fan.

One way to vary the fan's power supply voltage is shown in **Figure 23**. The low-dropout voltage regulator (LDO) provides power to the fan. The digital-to-analog converter (DAC) controls the LDO's output voltage by driving its ADJUST input. This approach allows a µC to vary the fan's speed by writing control data to the DAC. Some dedicated fan control ICs implement a similar approach by integrating the DAC and LDO functions along with other features.

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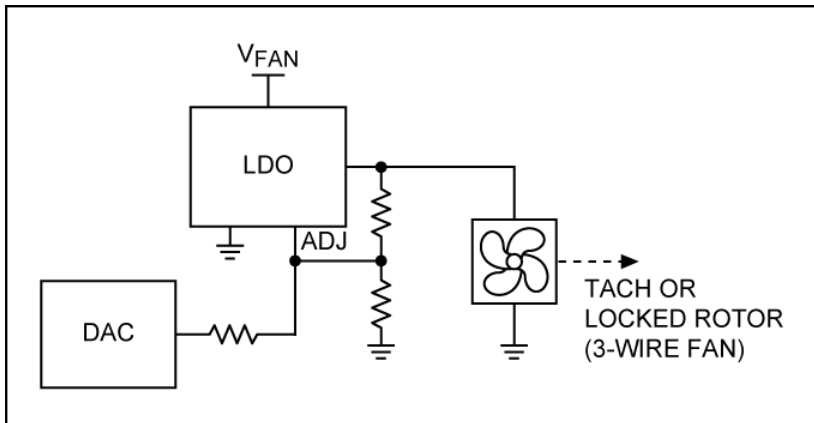
Figure 23. Some fan control ICs control the speed of a 2- or 3-wire fan by varying the power supply voltage.

A drawback to this technique is efficiency—the LDO will dissipate some power. Still, the overall power used is less than would result from operating the fan at full speed. Total power dissipation is roughly proportional to fan speed. Therefore, if the fan is normally operating at less than full speed, the circuit reduces overall power dissipation (**Figure 24**), which compares the power dissipation of the linear fan drive approach with that of PWM fan drive. This approach can be made more efficient, at a higher cost, by replacing the LDO with a switch-mode voltage regulator.
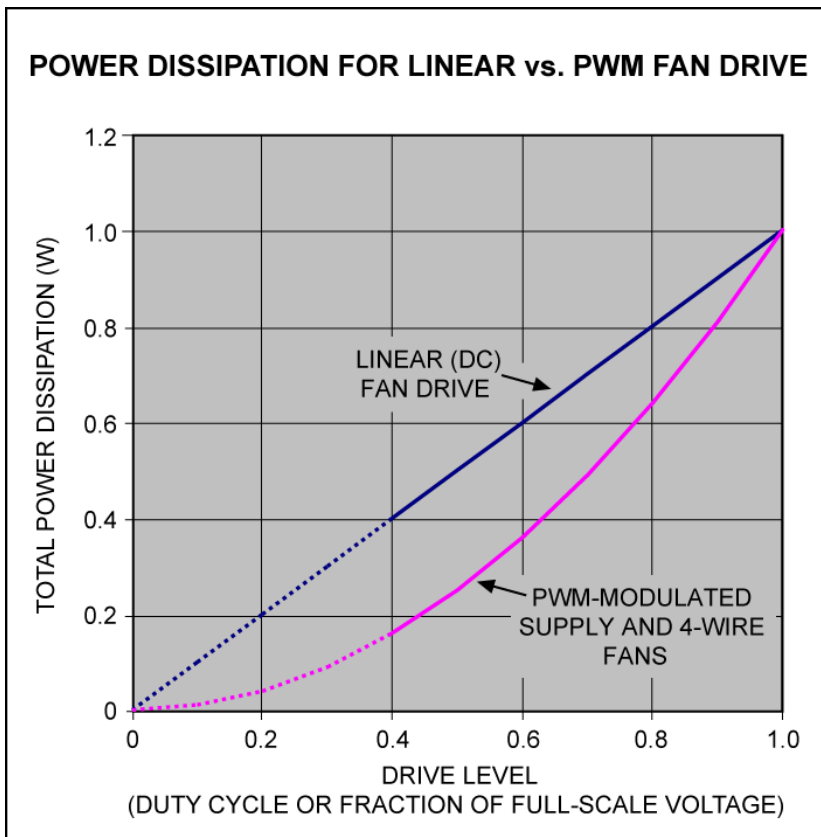
Figure 24. Comparison of power dissipation in linear (upper curve) and PWM fan drive (lower curve) approaches.

A lower cost, more efficient approach is shown in **Figure 25**. In this case, the fan's power supply is modulated by a PWM waveform—the power supply effectively turns on and off at a rate of roughly 30Hz. Because the pass transistor is always either fully on or fully off, its power dissipation is negligible compared to the power used by the fan.
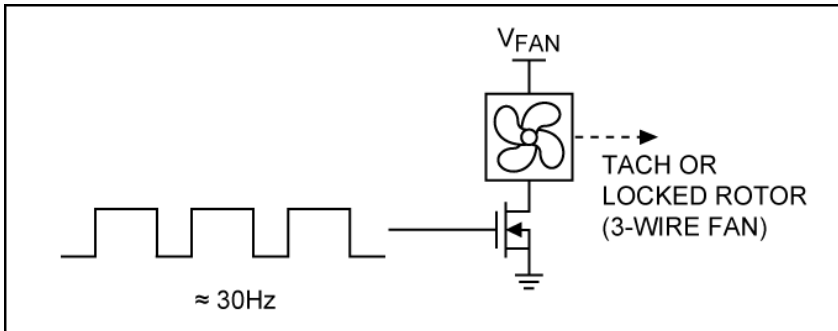
Figure 25. Controlling the speed of a 2- or 3-wire fan by pulse-width modulating the power supply using an n-channel FET on the low side of the fan.

Using an n-channel MOSFET (or an NPN) on the ground wire of the fan allows the pass device to be driven by a 3.3V or 5V logic-level PWM signal. The TACH or locked-rotor output is pulled up to the fan's power supply voltage. Alternatively, a p-channel MOSFET (or a PNP) can be used on the positive power supply wire instead. This results in a ground-referred TACH or locked-rotor output, but requires that the PWM signal swing up to V_{FAN}. Maxim makes several PWM fan speed controllers that are compatible with either n-channel or p-channel fan drive, including the MAX6615, MAX6616, MAX6639, MAX6640, MAX6641, and MAX6678.

PWM frequencies well below 30Hz are usually avoided when using this technique because, as frequencies decrease, there is an audible change in the fan's speed during the on and off periods of the PWM waveform. As the frequency increases beyond 35Hz or so, the "on" period can become too short to allow the fan's internal electronics to turn on and begin driving the fan.

This PWM approach suffers from three drawbacks. First, some fan manufacturers recommend against it due to concerns about fan reliability. If you are planning to drive a 2- or 3-wire fan with a pulse-width modulated power supply, be sure that the fan vendor allows the use of this technique.

The second drawback is noise. With some fans, the 30Hz pulse waveform causes the fan's motor mechanism to move in response to the pulses, resulting in an undesirable "ticking" or "clicking" sound emanating from the fan at a 30Hz rate. This is very audible with some fans, though nearly inaudible with others.

The third drawback is that during the "off" period of the PWM waveform, the fan produces no tachometer pulses. Therefore, fan speed can be monitored only during the "on" period. This can be a serious problem with low-RPM fans, as they may not produce even a single tachometer pulse cycle during a PWM "on" period. There are many different schemes to

overcome this problem with both varying levels of complexity and degrees of success. Some of these techniques will be discussed in later sections.

Minimizing the Effects of Fan Speed Control on Acoustical Noise

In some installations—for example, rooms that contain several servers, routers, or switches—the total noise level from multiple fans operating at full speed can be high enough to cause hearing damage to personnel who work near the equipment. In such a situation, the goal of the fan controller must be to reduce fan noise to the lowest practical level that still ensures safe operation of the electronics.

In an office or home environment, it is also important to minimize the noise level from the fan, but not so much for hearing protection as to reduce the degree to which the noise interferes with other sounds or disturbs the user. In addition to keeping noise levels low, it is important in these environments to minimize the audibility of any changes in noise levels. During normal operation of a fan control system, fan speeds will be adjusted in response to changes in environmental or operating conditions, such as ambient temperature and power dissipation. If the speed changes quickly, it is quite noticeable to the user. On the other hand, if the speed is changed at a slow rate, the change will be much less audible.

There are two key requirements for ensuring gradual fan speed changes that are difficult to hear. The first is sufficient resolution in the available fan speed values. The ear-brain system is readily able to recognize small changes in sound pressure level (SPL). If the fan is very quiet, a small number of speed steps (on the order of 8 to 10) may be sufficient. When the fan is louder, many times that number (approximately 50 to 100 or more) may be necessary to minimize the audibility of speed changes. The second requirement is a mechanism that limits the rate of fan speed change to a specific time period per speed-control increment. For example, if the PWM duty cycle can be set to one of 61 values, a 1% per second rate of change might be selected. This would cause a change of speed between 50% and 100% to take about 30 seconds. Most of Maxim's fan speed controllers include control over the rate of fan speed change.

Monitoring Fan Speed

The most obvious approach to monitoring fan speed is to count the number of tachometer pulses occurring during a fixed period of time, as shown in **Figure 26a**. This works well if it is possible to count a suitably large number of pulses during a sufficiently short period of time. As an example, a 3000RPM fan that produces two pulses per revolution will generate a 100Hz tachometer signal when operating at full speed. If we need to measure and update fan speed once per second, we will be able to count only 50 pulses when the fan is spinning at half speed. This may give enough resolution to determine that the fan is operating, but not enough for precision fan speed control.

The most widely used approach is for the fan controller to generate a reference clock, generally in the range of a few kHz, and count the number of clock cycles that occur during a fixed number of tachometer periods (usually 1, 2, or 4), as shown in **Figure 26b**. This allows a tachometer count to be completed in a few milliseconds, so the approach is compatible with closed-loop fan speed control.
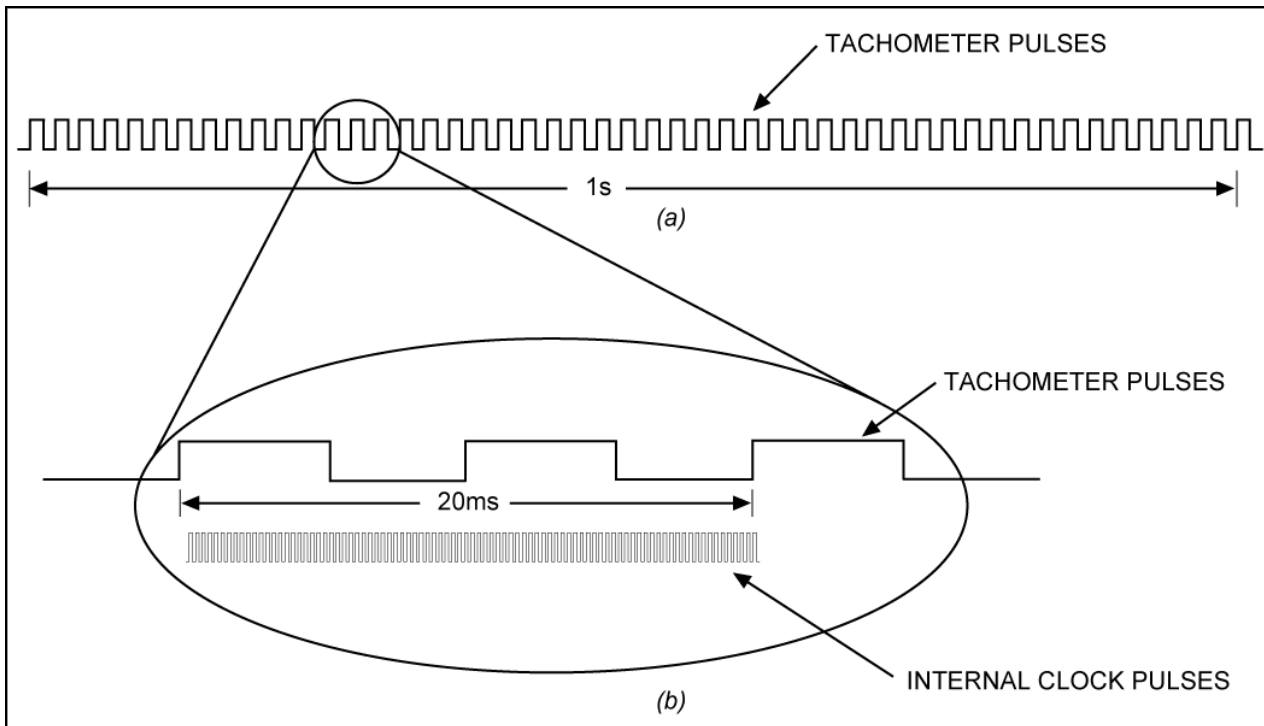
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Figure 26. (a) Monitoring fan speed by counting tachometer pulses for a period of 1s can result in low-resolution measurements. (b) Generating a clock signal with sufficiently high frequency, and then counting the number of clock pulses in a limited number of tachometer periods, provides more resolution and allows the fan's RPM to be controlled to within a tighter tolerance.

Some fan controller ICs include a feature that allows speed monitoring of 2-wire fans. This is done by adding a resistor between the system ground and the fan's ground wire. While the fan motor operates, its supply current variations create voltage drops on the sense resistor that are compared against a reference voltage by the fan controller IC. This technique has its limitations—supply current waveforms differ significantly from fan to fan, and also vary as fan speed changes, as shown in **Figure 27**. Therefore, supply current monitoring is more appropriate for detection of fan failure than for closed-loop fan speed control.
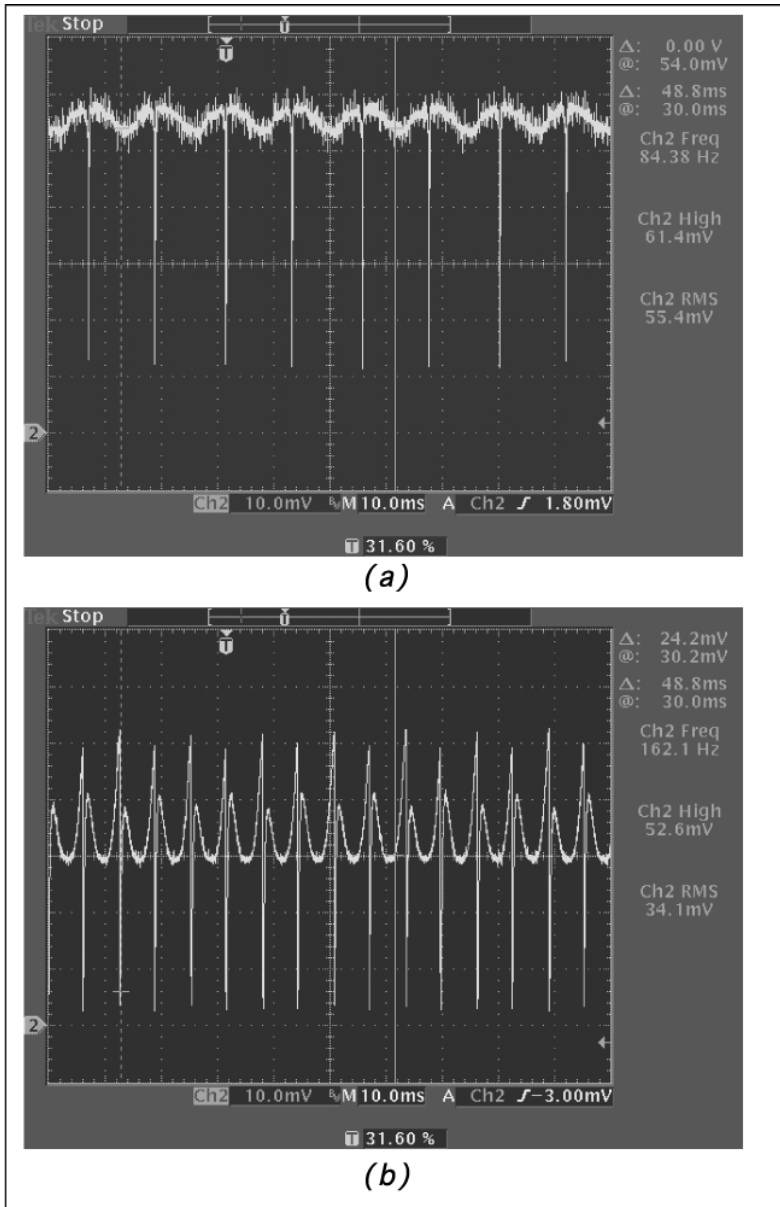
Figure 27. Examples of fan supply current waveforms. (a) A fan driven with half the nominal power supply voltage. (b) The same fan driven with the nominal power supply voltage.

Figure 28 shows a typical approach to monitoring fan speed using a sensing resistor to sense the fan's supply current. In this circuit, the IC's internal detection sensitivity is about 250mV. The approach is appropriate for linear drive and PWM power supply drive (either high side or low side).
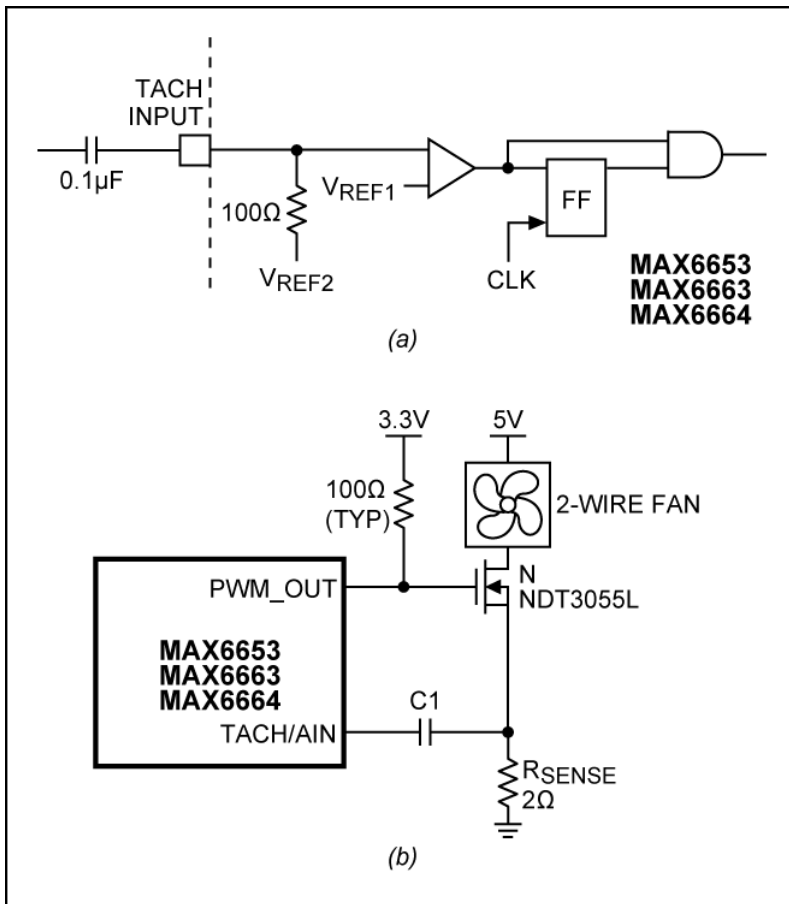
Figure 28. (a) Typical input stage for monitoring fan speed using the fan's supply current. (b) Using this input stage to monitor fan speed using a 2Ω sensing resistor.

As mentioned briefly in the *Controlling Fan Speed* section, a complication arises when a fan is driven by a pulse-width modulated power supply. During the portion of the PWM waveform when the fan's power supply is off, the fan cannot produce tachometer pulses. Fan controller ICs generally have an option that allows monitoring of the fan's tachometer signal only during the "on" portion of the PWM waveform, but there are cases in which the "on" period is too short to allow proper tachometer measurement.

As an example, consider a 2400RPM fan with two tachometer pulses per revolution. If this fan is driven by a 50% duty cycle, 30Hz-modulated power supply, it will be spinning at about half speed (1200RPM). This will result in a tachometer frequency of 40Hz, or a tachometer period of 25ms.

With a 30Hz PWM signal at 50% duty cycle, the power supply will be applied to the fan for 16.7ms during each PWM cycle. The fan's internal circuitry will, therefore, have only 16.7ms available to generate a 25ms tachometer signal, so the tachometer signal will not be usable. Note that a much faster fan would work better. For example, a 9600RPM fan would generate a tachometer signal with a period of 6.25ms, which would be compatible with the 30Hz PWM signal at 50% duty cycle.

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One solution to this problem is to periodically increase the "on" time of one cycle of the PWM waveform to a duration that is sufficient to measure the tachometer signal. This approach works, but its suitability depends on the fan being used. If the pulse needs to be stretched significantly, the pulse stretching will be audible. Audibility of the pulse stretching depends on the degree of stretching and also on the response time of the fan. If the fan responds quickly to supply voltage changes, the pulse stretching will be easy to hear.

Another way to solve this problem is to keep the fan's power supply active during the low portion of the PWM waveform. **Figure 29** illustrates this "keep-alive" approach. A p-channel FET drives the fan's high side. A diode provides 4.3V drive to the fan when the PWM is off. This keeps the fan's internal IC powered and continuously generating the tachometer signal so that the fan's speed can be monitored even during the "off" portion of the PWM waveform. A disadvantage of this circuit is that the fan is always powered. If necessary, this can be fixed by gating the 5V supply off when the fan needs to be off.
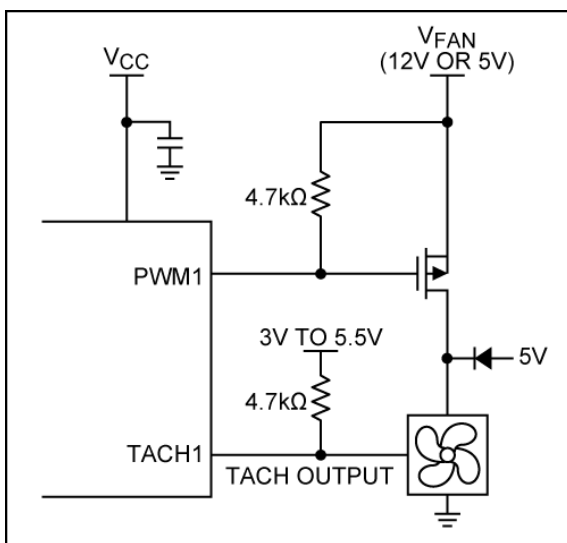
Figure 29. A "keep-alive" circuit enables the fan's tachometer signal even when the PWM waveform is off, thereby avoiding missing tachometer signals while pulse-width modulating the fan's power supply.

Closed-Loop RPM Control

In many cases, "fan speed control" is really "fan drive control"—for a given thermal condition, you provide the fan with a corresponding PWM duty cycle or supply voltage. The actual fan speed may vary from the nominal value by several percent due to fan-to-fan variations, power supply tolerance, and other uncertainties. This "open-loop" speed control is sufficiently precise in many systems.

In other cases, especially when acoustic noise levels or supply current are important, you may prefer to have control over the fan's actual RPM. When you can accurately monitor the tachometer, it becomes possible to control the fan's RPM by adjusting the drive level to produce the desired tachometer frequency (or period). Fan speed accuracy as good as ±1% can be achieved, depending on measurement resolution and clock accuracy. Closed-loop fan speed control is available in several of Maxim's fan controllers, including the MAX6620, MAX6639, MAX6640, MAX6650, MAX6651, MAX6660, and MAX6661.

Temperature Sensing

Most fan controller ICs can sense temperature, usually both local and remote. Since fan control is usually based on temperature, it makes sense in many systems for the fan controller to be able to measure temperature. Exceptions include systems where the fan controller is in a location that is physically separate from the temperatures of interest.

Closed-Loop, Temperature-Based (Thermal Closed-Loop) Fan Speed Control

Most fan controllers that have temperature-sensing capability are also able to control fan speed based on the measured temperature. The details can vary—most such fan controllers use some sort of straight-line mapping between temperature and fan drive, while others have a lookup table that associates a few temperature values with fan drive levels. Still others map temperatures to fan RPM values. The MAX6615, MAX6616, MAX6678, MAX6660, and MAX6661 use straight-line mapping of temperature to fan drive. The MAX6639 and MAX6640 use dual-slope mapping. Additional features of these fan control devices are shown in **Table 5**.

Table 5. Maxim's Fan Control Products

Part	Description	Remote Channels	Local Channels	Interface	Fan Outputs	Closed-Loop RPM	TACH Input
DS1780	2-channel CPU peripheral monitor	0	1	2-wire	1 linear	No	2
MAX6615	2-channel thermistor inputs, 1 local sensor, 2 fan controllers	2	1	2-wire	2 PWM	No	2
MAX6616	2-channel thermistor inputs, 1 local sensor, 2 fan controllers	2	1	2-wire	2 PWM	No	2
MAX6620	I²C quad linear fan controller with RPM control	0	0	2-wire	4 linear	Yes	4
MAX6639	2-channel temperature monitor with dual PWM fan speed controller for 2-, 3-, 4-wire fans	1	1	2-wire	2 PWM	Yes	2
MAX6640	2-channel temperature monitor with dual PWM fan speed controller for 2- and 3-wire fans	1	1	2-wire	2 PWM	Yes	2
MAX6643	Automatic, stand-alone fan controller	1	1	Pin strap, logic	1 PWM	No	2
MAX6644	Automatic, stand-alone fan controller	2	0	Pin strap, logic	1 PWM	No	2
MAX6645	Automatic, stand-alone fan controller	2	0	Pin strap, logic	1 PWM	No	2
MAX6650	Linear fan-speed regulator and monitor	0	0	2-wire	1 linear	Yes	Yes
MAX6651	Linear fan-speed regulator and 4-fan monitor	0	0	2-wire	1 linear	Yes	Yes
MAX6653	Temperature monitors and PWM fan controllers	1	1	2-wire	1 PWM	Yes	Yes
MAX6660	Remote-junction, temperature-controlled linear fan speed regulator	1	0	2-wire	1 linear	Yes	Yes
MAX6661	Remote-junction, temperature-controlled linear fan speed regulator	1	0	3-wire	1 linear	Yes	Yes
MAX6663	Temperature monitors and PWM fan controllers	1	1	2-wire	1 PWM	Yes	Yes
MAX6664	Temperature monitors and PWM fan controllers	1	1	2-wire	1 PWM	Yes	Yes
MAX6665	Fan on/off controller/driver and temperature switch with factory-programmed threshold	0	1	Pin strap	1 on/off	No	No
MAX6678	2-channel temperature monitor with dual PWM fan controller and 5 GPIOs	2	1	2-wire	2 PWM	No	No
MAX6684	Fan-failure detector and power switch	0	0	Logic	1 on/off	No	No

Signal Conditioners for Non-IC Temperature Sensors

The final type of thermal management product we will discuss works with thermistors, RTDs, or thermocouples to help interface those sensors to systems. Simplified examples of discrete circuits were shown in Figures 1, 6, and 10 for interfacing these sensors. Also available are integrated solutions that can simplify the design of these interface circuits and reduce cost.

Thermistor Conditioners

Figure 30 shows the MAX6698 multifunction temperature sensor. The MAX6698 combines a local temperature sensor, three remote-diode sensors, and three NTC thermistor channels in a single IC. Each thermistor channel is connected to the output of a voltage divider consisting of a thermistor ($R_{THER\_}$) and a fixed resistor ($R_{EX\_}$). A 1V-nominal voltage reference output (V_{REF}) drives the top of the voltage divider. The thermistor inputs (V_{THER1}–V_{THER3}) drive an 8-bit ADC with 5mV LSB. Because the thermistors have a negative temperature coefficient, the $V_{THER\_}$ inputs measure the voltage across the $R_{EX\_}$ resistors, producing an output code that increases with rising temperature.
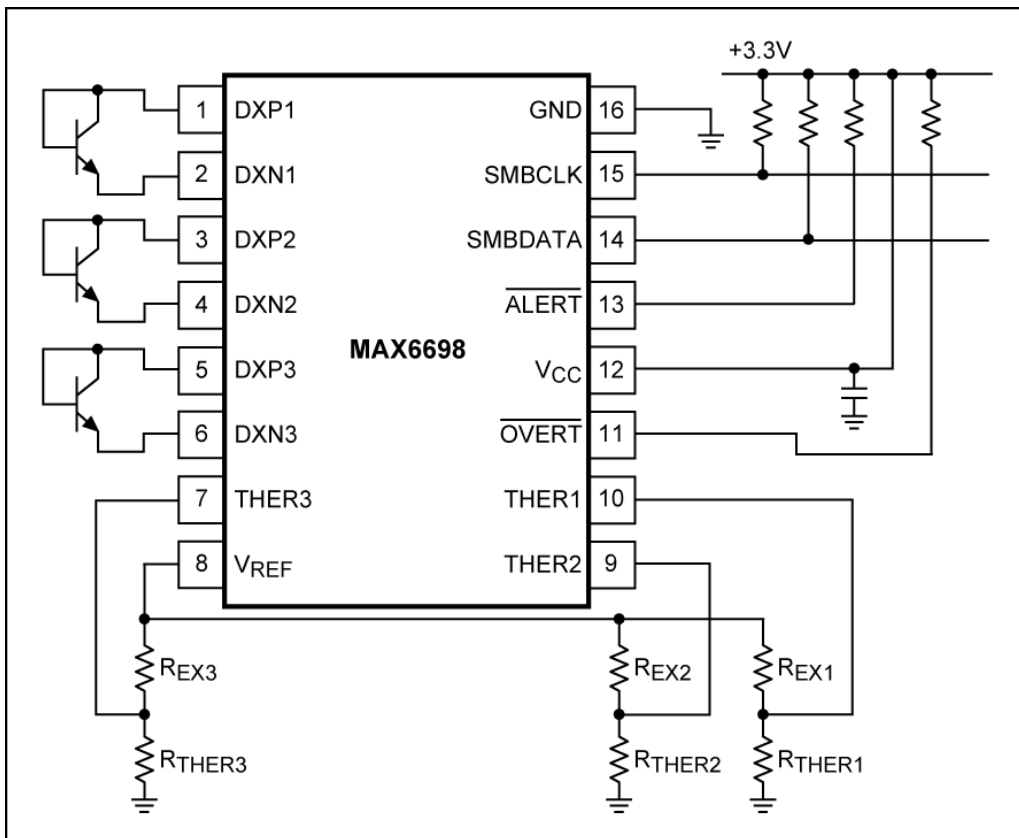
Figure 30. The MAX6698 includes a local temperature sensor, inputs for three external sensing transistors, and inputs for three NTC thermistors (R_{THER1}–R_{THER3}).

Thermistor resistance vs. temperature is a highly nonlinear function, so the output code will not correspond directly to the thermistor's temperature. The MAX6698 data sheet includes a table showing output code vs. temperature for one combination of thermistor and external resistor. For different thermistor-resistor combinations, create a spreadsheet to calculate the output code as a function of temperature.

Figure 31 shows a simpler circuit for thermistor conversion. The MAX6682 has an input for a single thermistor and a voltage reference output to drive the thermistor/resistor voltage divider. The digital data is serial and read only. As with the MAX6698, the data sheet includes a table showing how the output code maps to thermistor temperature for a common thermistor type.
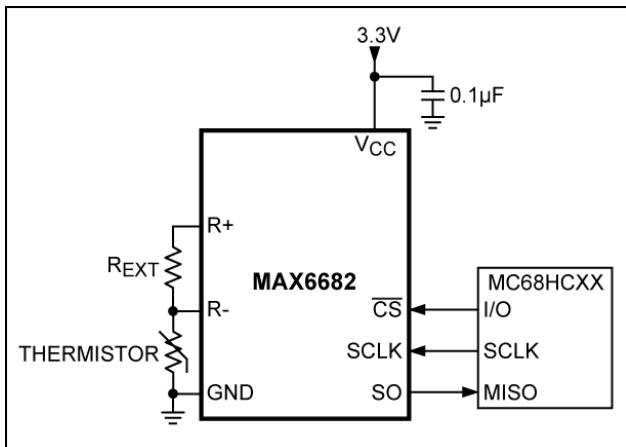
Figure 31. MAX6682 single thermistor-to-digital converter.

RTD Conditioners

Figure 32 shows the MAX6603, a dual conditioner for Pt-RTDs. It provides an excitation current source, gain, and input protection for two 200Ω Pt-RTDs. The outputs are ratiometric to the power supply voltage, which allows them to be digitized by an ADC that uses the supply voltage as its reference. The inputs can withstand ±5kV ESD events.
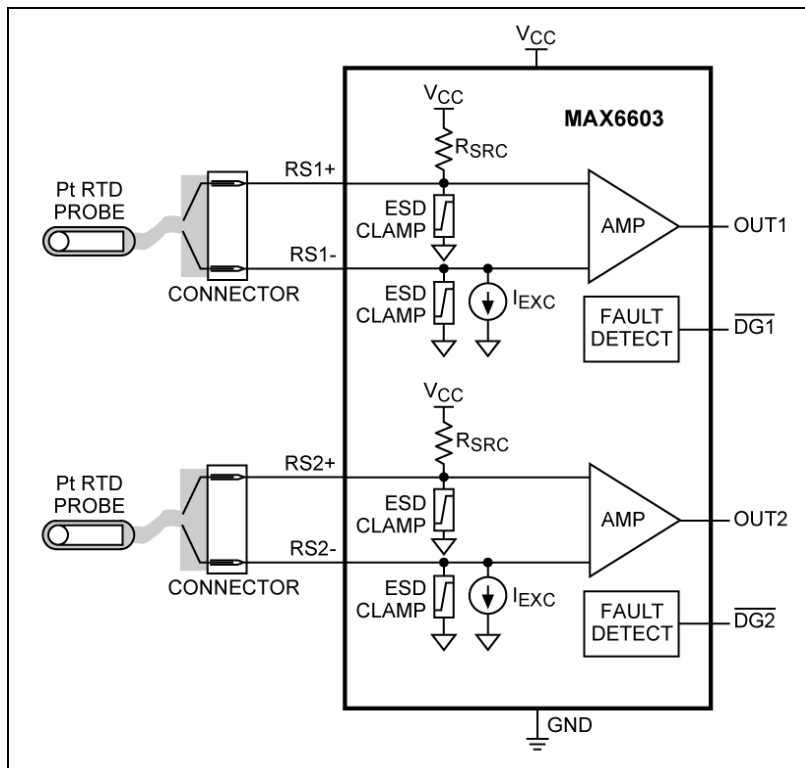
Figure 32. The MAX6603 provides bias current and gain for two 200Ω Pt-RTDs.

Thermocouple Conditioners

As discussed earlier in the *Thermocouples* section, signal conditioning for a thermocouple consists of a local temperature sensor, precision amplifier, ADC, and voltage reference. Maxim has two ICs that integrate all of these functions: the MAX6674 and MAX6675. Both ICs convert the output of a type K thermocouple into digital data. These conditioner ICs amplify and digitize the thermocouple output voltage and add the local temperature value to the result, thereby providing cold-junction compensation.

The MAX6675 measures type K thermocouple temperatures from 0°C to +1023.75°C with 12-bit (0.25°C) resolution. The MAX6674 has 10-bit (0.125°C) resolution and measures thermocouple temperatures from 0°C to +127.875°C. Both ICs detect open thermocouple connections and use a simple 3-wire (clock, data output, chip select) read-only interface. **Figure 33** shows a MAX6675 used with a type K thermistor. The MAX6675 is a complete hardware solution with no need for external components other than a bypass capacitor.
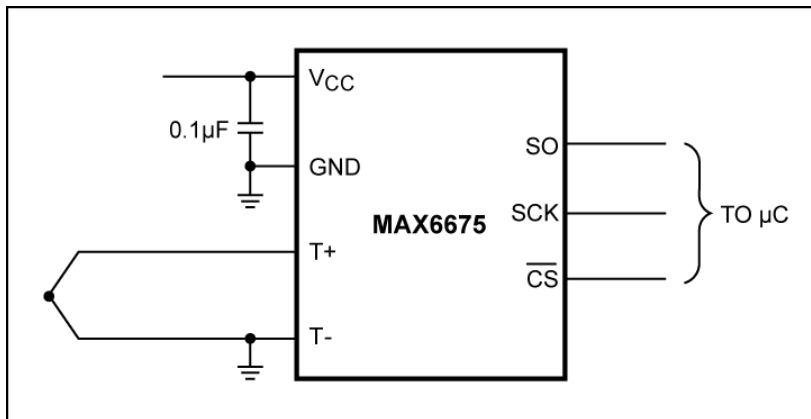
Figure 33. Integrated thermocouple-to-digital converter for type K thermocouples.

Table 6 provides further details about these two conditioner ICs, plus Maxim's other conditioners.

Table 6. Maxim's Signal Conditioners for Non-IC Temperature Sensors

Part	Description	Sensor Inputs	Local Sensors	Interface
MAX6603	2-channel, platinum RTD-to-voltage signal conditioner (200Ω RTD)	2	1	Analog
MAX6674	K-thermocouple to-digital converter (0°C to +128°C)	1	1	3-wire
MAX6675	K-thermocouple to-digital converter (0°C to +1024°C)	1	1	3-wire
MAX6682	Thermistor-to-digital converter	1	0	3-wire
MAX6691	4-channel, thermistor-to-pulse-width converter	4	0	Pulse
MAX6698	7-channel, precision temp monitor (3 remote, 1 local, 3 thermistor)	6	1	2-wire

Using Thermal Management Components—Principles and Application Circuits

Sensing Location: The Key to Choosing the Right Sensor Type

The first step in using a temperature sensor is to select the right kind of sensor for the application. To begin, you need to understand the target whose temperature is to be measured. Some common measurement targets are listed here, along with recommended sensor types.

Sensing PC Board Temperature
Surface-mount sensors are ideal for PC board measurement. RTDs, thermistors, and IC sensors are available in surface-mount packages and temperature ranges that are compatible with sensing the temperature of a PC board. Because of their inherent linearity and low cost, IC sensors are generally the best choice. ICs have additional features, such as digital interface or thermostat functions. These features usually give them the edge in terms of system cost, design complexity, and performance, as compared with other technologies.

One of the keys to measuring PC board temperature accurately is locating the sensor in the right place. It is common to measure the temperature of a specific component or group of components, either to ensure that the temperature does not exceed the safe operating range, or to compensate for temperature-induced changes in a component's performance. When the location of the sensor is critical, use temperature sensors in small packages, such as TDFN, SC70, or SOT23, that can be easily placed in the appropriate location. Digital outputs are useful when sensors need to be located in sites that may be electrically noisy or far from other temperature-related circuitry.

When multiple PC board locations need to be monitored, digital local sensors with I^2C, SMBus, or 1-Wire interfaces are especially useful because they allow devices with different slave addresses to reside on the same bus. Many popular I^2C sensors have inputs that can be used to select among several slave addresses. For example, the MAX7500 and DS75LX each have three address inputs. The MAX7500 address inputs can be connected to V_{CC} or GND, while the DS75LX address inputs have three-level logic (the third logic level is detected when an input is unconnected). Therefore, you can have up to 8 MAX7500s or as many as 27 DS75LXs on a single bus, for example.

Another useful approach to monitoring multiple PC board locations is to use multichannel remote sensors with discrete sensing transistors. An example is shown in **Figure 34**, where a MAX6697 monitors its internal temperature plus six external temperatures using discrete transistors. Therefore, a total of seven temperatures are monitored and only a single I^2C slave address is needed.

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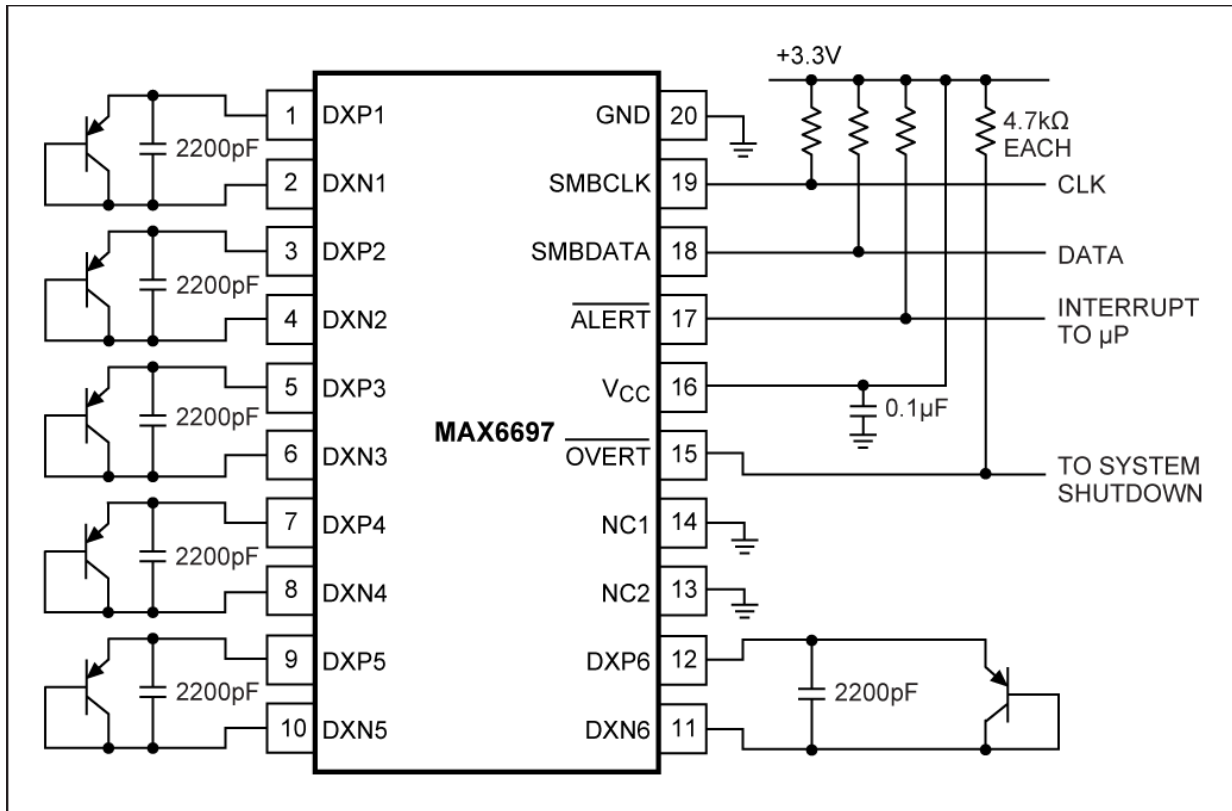
Figure 34. Monitoring seven different board locations with a single MAX6697. The external sensing transistors can be located near hot spots on the board.

Sensing Ambient Air Temperature

Ambient air temperature can be difficult to measure because the sensor's temperature must be at the same temperature as the air, but isolated from anything else (PC board, power supply, CPU) that might be at a different temperature. Thermistors, thermocouples, and RTDs are available with long leads that, if long enough and thin enough, isolate the sensing elements from the PC board temperature. If the sensing element is sufficiently isolated from the PC board, it will be at the ambient temperature. Of these three types of sensors, thermistors are the most likely to be used for general-purpose ambient temperature sensing because of their low cost and simple signal conditioning requirements. **Figure 35** shows how a thermistor, thermocouple, or RTD can be used to measure ambient temperature. In the figure, the thermistor is well-separated from the surface of the board, and the length of the leads provides thermal isolation from the board.

43
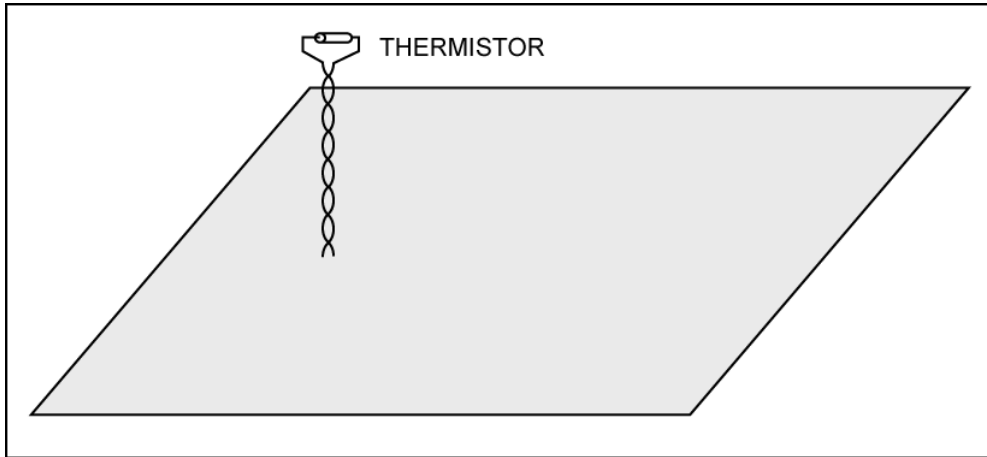
Figure 35. Thermistor monitoring air temperature. Note that the long thermistor leads provide thermal isolation from the board's surface.

Temperature sensor ICs in surface-mount packages are more difficult to use for measuring ambient temperature, because the best thermal path for an IC sensor is through its leads, which are at the same temperature as the PC board. If the PC board is at ambient temperature, a sensor mounted on the board will measure the ambient temperature. However, if the PC board contains components that dissipate enough power to raise its temperature above ambient, the IC will measure the elevated board temperature, not the ambient temperature. Note that even conventional IC packages, such as TO92s that raise the IC sensor above the PC board, conduct heat so well through their leads that the measured temperature is effectively equal to the PC board temperature. **Figure 36** shows a temperature sensor IC in a board-mounted TO92. The board-mounted sensor will do a good job of measuring board temperature, but will not measure ambient temperature.
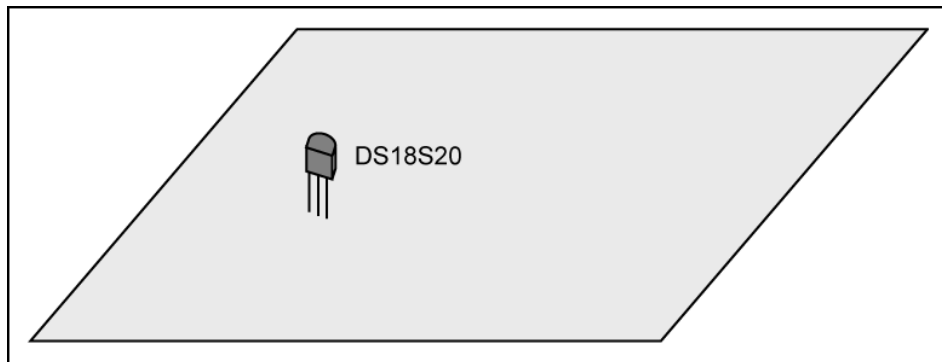
Figure 36. A board-mounted temperature sensor in a TO92 package. Although the TO92's leads raise the sensor above the board's surface, they have good enough thermal conductivity that the sensor measures board temperature, not air temperature.

Despite their sensitivity to board temperature, sensor ICs are often the best solution for measuring air temperature because they are not just sensors—they usually have additional features, such as digital outputs, addressability, or thermostat functions. To use a TO92 IC for ambient temperature sensing, use a twisted pair of wires to isolate the sensor from the board. As with a thermistor, if the wires are long enough and thin enough, you can achieve sufficient isolation to get accurate ambient temperature readings. **Figure 37** shows a TO92 sensor used this way; the sensor is the DS18S20, which uses Maxim's 1-Wire digital interface.

44
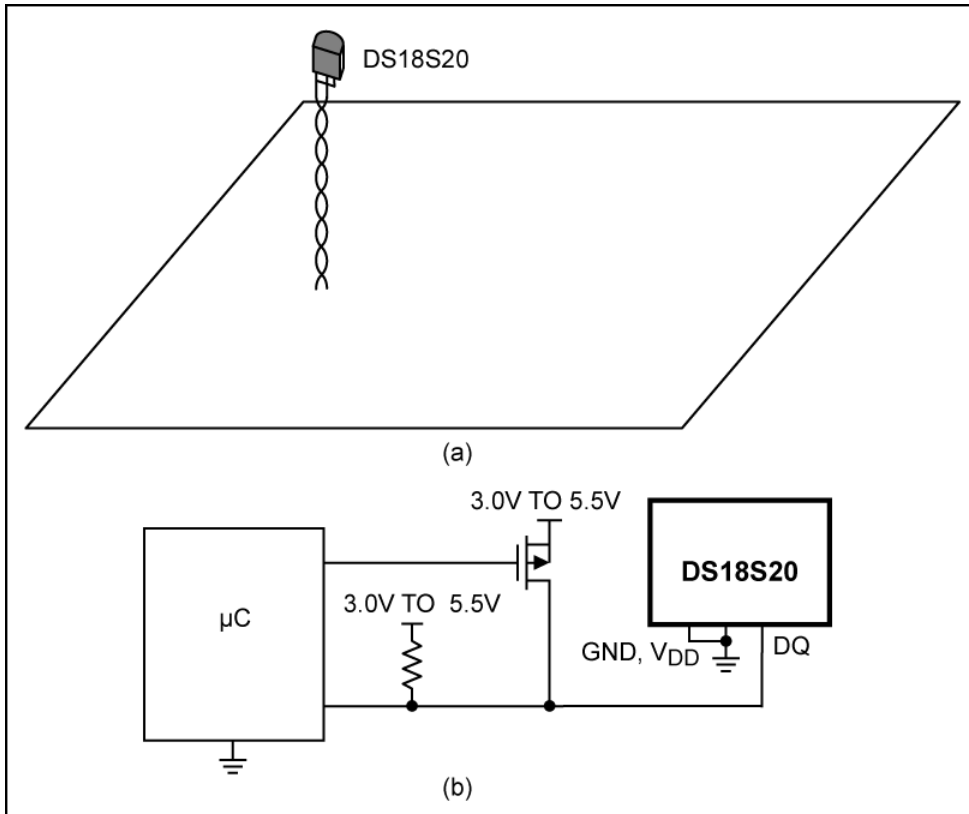
Figure 37. DS18S20 monitoring ambient temperature. (a) DS18S20 mounted at the end of a twisted pair of wires to isolate the sensor from the PC board. (b) The DS18S20 is powered by the data line. The data and power are controlled by the µC's I/O pins.

A thermal diode sensor can also be used to measure ambient temperature. In this case, a discrete sensing transistor is mounted on the end of the twisted pair. Any of Maxim's remote diode sensors can be used to measure the transistor's temperature.

Sensing Temperature of a CPU, Graphics Processor, FPGA, ASIC, Power Device, etc. (with an On-Chip Thermal Diode)

As discussed in the *Remote Digital Temperature Sensors* section, some components, especially high-performance ICs such as CPUs, GPUs, and FPGAs, include a bipolar transistor for the purpose of sensing temperature. This is usually a PNP with the collector grounded. The base and emitter are the "diode" connections. Because the thermal-sensing transistor is on the IC die, measurement accuracy is far better than with other sensing techniques, and thermal time constants are quite small. Maxim's remote-diode sensors are optimized for monitoring the temperature of such devices. Note that there are some differences in ideality factor and series resistance among thermal diodes on various ICs. The effects of these differences are described in the *Remote Diode Sensor Guidelines* section.

Sensing Temperature of a CPU, Graphics Processor, FPGA, ASIC, Power Device, etc. (with an On-Chip Thermistor)

Some ICs have no thermal diodes available, but instead have integrated thermistors to help monitor temperature (see the *Thermistors* section). As a general rule, these thermistors are difficult to use, with very low temperature coefficients and poor accuracy. Variations in the nominal 25°C resistance value correspond to errors of ±50°C or more, so they must be

calibrated at one or two temperatures before using. The low temperature coefficients result in resolutions on the order of 6°C/LSB for a typical thermistor converter such as the MAX6698.

Figure 38 shows a typical curve of thermistor channel code vs. temperature for the MAX6698 when used with one of these integrated thermistors. Note the low available resolution, though the results yielded are usable.
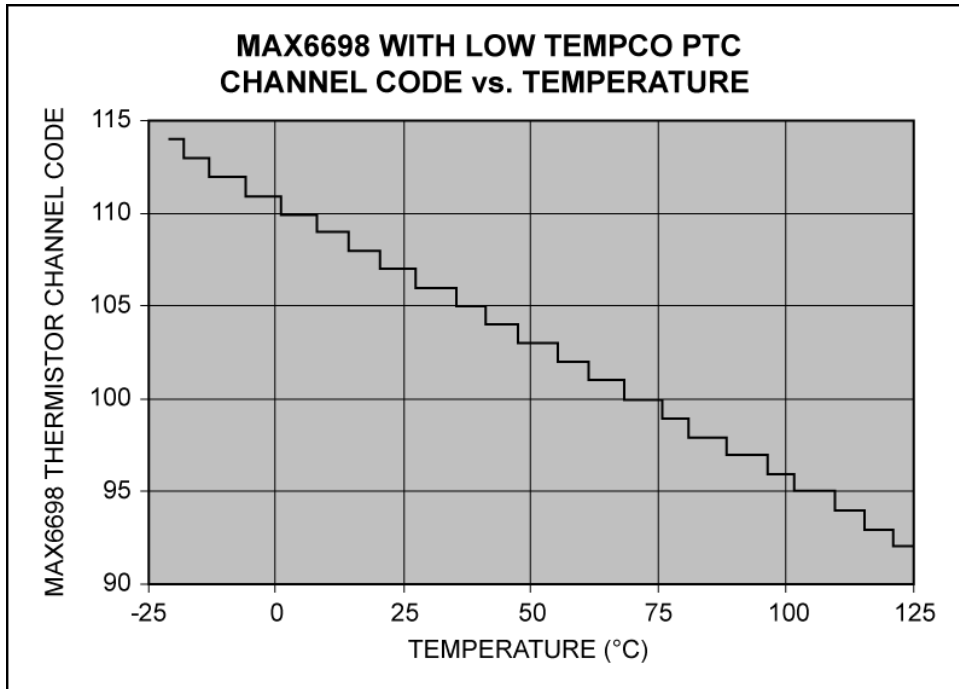
Figure 38. MAX6698 thermistor channel code vs. temperature when used with a 0.3%/°C integrated thermistor.

Remote Diode Sensor Guidelines

PC Board Layout Guidelines for Remote Sensors

Follow these guidelines for best results when using remote temperature sensors. The DXP is the anode connection and DXN is the cathode connection. Note that accuracy will depend on the amount of noise pickup, the effects of which are not easily predictable. Always verify accuracy before committing to a final layout.

1. Place the remote sensor as close as is practical to the thermal diode. In noisy environments, such as a computer motherboard, this distance can be up to about 20cm. This length can be increased if the worst noise sources are avoided. Noise sources include CRTs, clock generators, memory buses, and PCI buses.
2. Do not route the DXP-DXN traces across or in parallel to nearby fast digital signals, which can easily introduce +30°C error, even with good filtering.
3. Route the DXP and DXN traces in parallel and in close proximity to each other. Each parallel pair of traces should go to a thermal diode. Route these traces away from any higher voltage traces, such as +12VDC. Leakage currents from PC board contamination must be minimized; a 20MΩ leakage path from DXP to ground causes about +1°C error. If high-voltage traces are unavoidable, connect guard traces to GND on either side of the DXP-DXN traces (see **Figure 39**).
4. Route through as few vias and crossunders as possible to minimize copper/solder thermocouple effects.
5. Use wide traces when practical—5mil to 10mil traces are typical. Be aware of the effect of trace resistance on temperature readings when using long, narrow traces.
6. When the power supply is noisy, add a resistor (up to 47Ω) in series with V_{CC}.
7. Place a filter capacitor across the DXP-DXN inputs, located near the remote sensor IC. Use a value recommended in the sensor's data sheet.
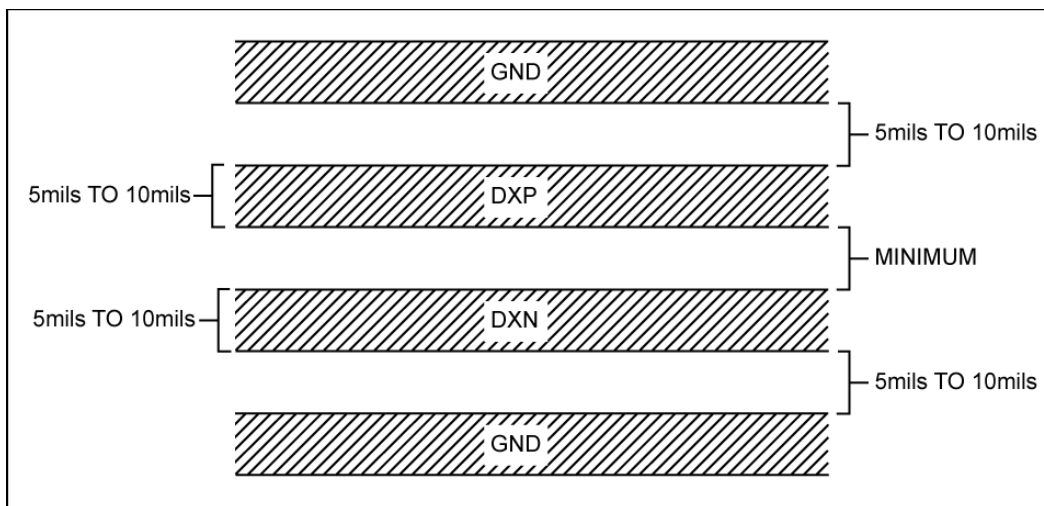
Figure 39. Recommended DXP-DXN PC board traces. The two outer guard traces are recommended if high-voltage traces will be near the DXN and DXP traces.

Cable Connections to Thermal Diodes Sometimes, thermal diodes need to be located at distances that exceed normal circuit board spans—when the diode is measuring temperature at the opposite end of a large chassis, for example. When distances and noise levels are moderate to low, a simple twisted pair will work well up to 3m or 4m. For longer distances (up to around 30m) or high noise levels, a shielded cable with the shield grounded at the remote sensor IC should be used. Belden 8451 cable works well for such applications. Remember that the series resistance will affect the temperature reading, so either use a sensor with resistance cancellation or calculate the effect of wire resistance and subtract that value from the reported temperature value. Also be aware of cable capacitance, which will reduce the maximum capacitor value that can be used at the thermal diode inputs

Using Discrete Thermal Diodes When the remote-sensing diode is a discrete transistor, connect its collector and base together. NPNs and PNPs work equally well for this purpose. **Table 7** lists examples of discrete transistors that are appropriate for use with remote temperature sensors. The transistor must be a small-signal type with a relatively high forward voltage; otherwise, the A/D input voltage range can be violated. The forward voltage at the highest expected temperature must be greater than 0.25V at 10µA, and at the lowest expected temperature, the forward voltage must be less than 0.95V at 100µA. Large power transistors must not be used. Ensure that the base resistance is less than 100Ω. Tight specifications for forward current gain (50 < beta < 150, for example) indicate that the manufacturer has good process controls and that the devices have consistent V_{BE} characteristics.

Table 7. Discrete NPN Transistors for Use as Thermal Diodes

Manufacturer	Model No.
Central Semiconductor (USA)	CMPT3904
Rohm Semiconductor (USA)	SST3904
Samsung (Korea)	KST3904-TF
Siemens (Germany)	SMBT3904
Zetex (England)	FMMT3904CT-ND

Manufacturers of discrete transistors do not typically specify or guarantee the ideality factor. This is normally not a problem since good-quality discrete transistors tend to have ideality factors that fall within a relatively narrow range. We have observed variations in remote temperature readings of less than ±2°C with a variety of discrete transistors. Still, it is good design practice to verify consistency of temperature readings with several discrete transistors from any manufacturer under consideration.

Thermal Diode Design Guidelines

Some IC vendors, such as those in the business of selling microprocessors and FPGAs, have been including thermal diodes in their products for years and have a good understanding of how to design these devices. For first-time designers of ICs that will incorporate thermal diodes, this section offers some instructive guidelines:

1. Minimize the internal resistance of the diode. As noted before, about +0.45°C error will result from each ohm of series resistance. If a transistor is used in a diode-connected configuration with the base connected to the collector, the base resistance can be a factor of beta higher. In this case, the collector resistance will not matter unless it causes the device to saturate at 100µA when diode-connected.

2. Maximize the transistor's beta to preserve the collector current ratio (and therefore accuracy) across temperature and current values.
3. The forward voltage of the diode must be within the input range of the temperature sensor ADC. It must be greater than 0.25V at 10µA forward current and less than 0.95V at 100µA forward current at all operating temperatures for which temperature sensing is needed.
4. In most processes, there is no isolated P/N junction. A diode-connected transistor will work if it meets the following constraints:
    A. If it is an NPN device, it must have all three terminals isolated from any of the supplies and be diode-connected with the base connected to the collector.
    B. If it is a PNP device, it is acceptable to connect the collector to ground, but the emitter and base must be isolated from any of the supplies.
5. Measurements should be taken on test structures to determine if they will work properly. Accuracy of the measurements is important—voltages should be accurate to 100µV, and the 10µA and 100µA test currents must be accurate to ±0.1%. The sense transistor should work well with any of Maxim's remote temperature sensors.
6. Noise coupled into the sense junction can cause temperature measurement errors. Take care to isolate the sensing device from noise sources, including digital signals and noisy power supplies.
    A. Physically separate the sense device and metal carrying fast digital signals. Also physically separate digital signals from the metal between the sense transistor and the bonding pads.
    B. Do not locate the bonding pads for the sense junction next to bonding pads for fast digital signals, especially near high-speed buffer outputs. If possible, locate the sense junction bonding pads next to pads that are DC inputs (for example, DC logic inputs used for pin-strapping).
    C. Surround the sensing device with n^+ and p^+ guard rings.
7. A typical structure for a vertical PNP with a substrate collector is shown in **Figure 40**. The ten emitters are connected together. Each emitter is 20µm by 2.5µm.
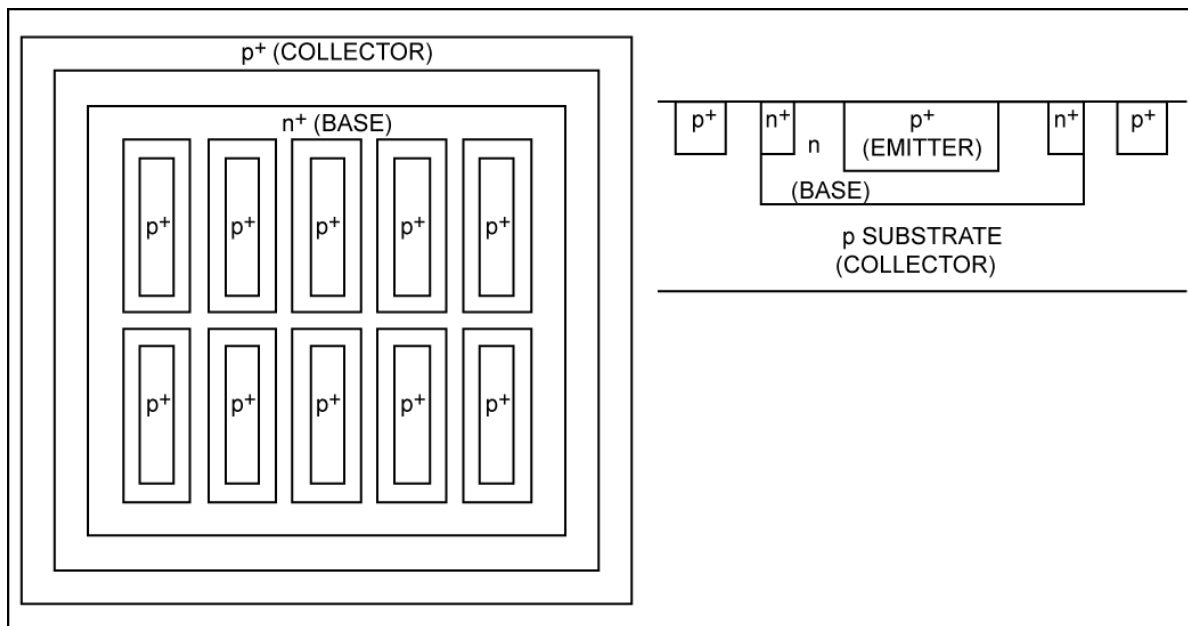
Figure 40. Example of an integrated PNP thermal diode design.

Application Examples

4-Wire, RTD-to-Digital Conversion

Because we measure RTD resistance to determine temperature, any appreciable resistance in the RTD's leads will cause errors in temperature measurement. This is not a problem when the RTD is near the measurement circuitry, but for long distances, you should use a 3-wire or 4-wire connection to eliminate lead-resistance errors. The circuit in **Figure 41** is a 4-wire RTD interface using the MAX1402 oversampling ADC. The MAX1402 has two matched current sources, one of which provides excitation current for the RTD (in this case, a Pt100). Because the excitation current does not flow through the sense leads, lead resistance will not affect the temperature measurement accuracy. The second current source drives a precision resistor to generate the reference voltage for the ADC.
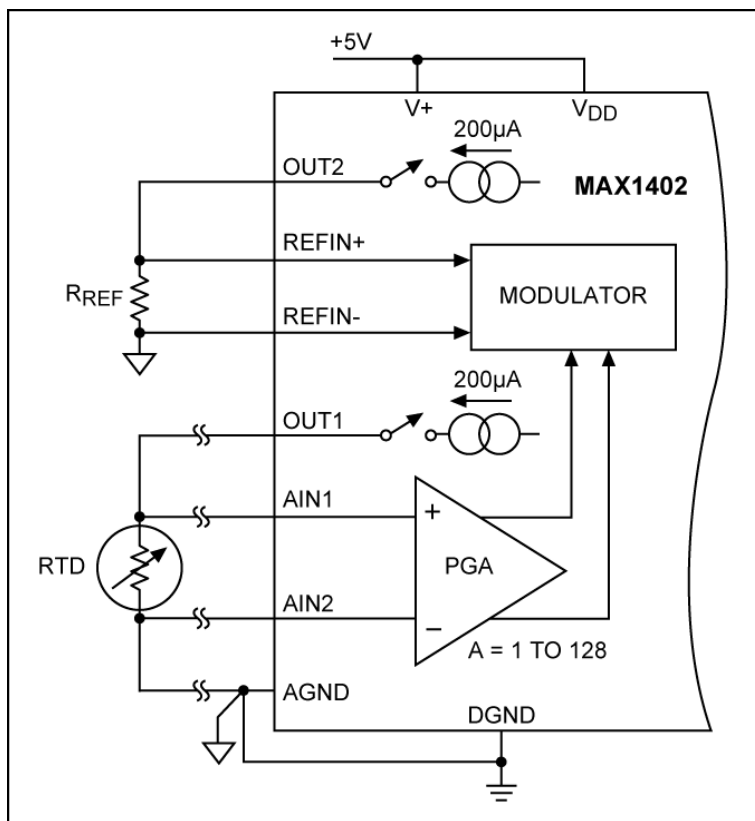
Figure 41. 4-wire interface for a Pt100 RTD.

For best accuracy when using an RTD, apply linearity correction to the resulting data to compensate for the Pt100's nonlinearity. Also use gain correction to compensate for the tolerance of the reference resistor and mismatch between the current sources.

You can avoid the digital linearity correction by applying a small amount of positive feedback to an amplifier circuit, as shown in **Figure 42**. This circuit does not compensate for long leads, so it should be used when the RTD is located near the measurement circuitry. **Figure 43** shows the error curve for a Pt100 when linearized by the circuit in Figure 42. For more details, refer to Maxim application note 3450, "Positive Analog Feedback Compensates Pt100 Transducer."

50
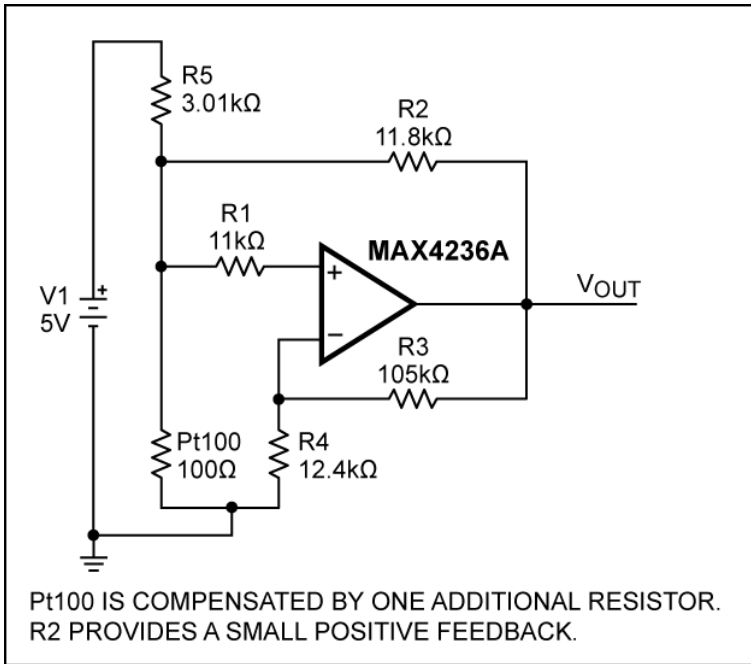
Figure 42. Pt100 linearizer circuit.
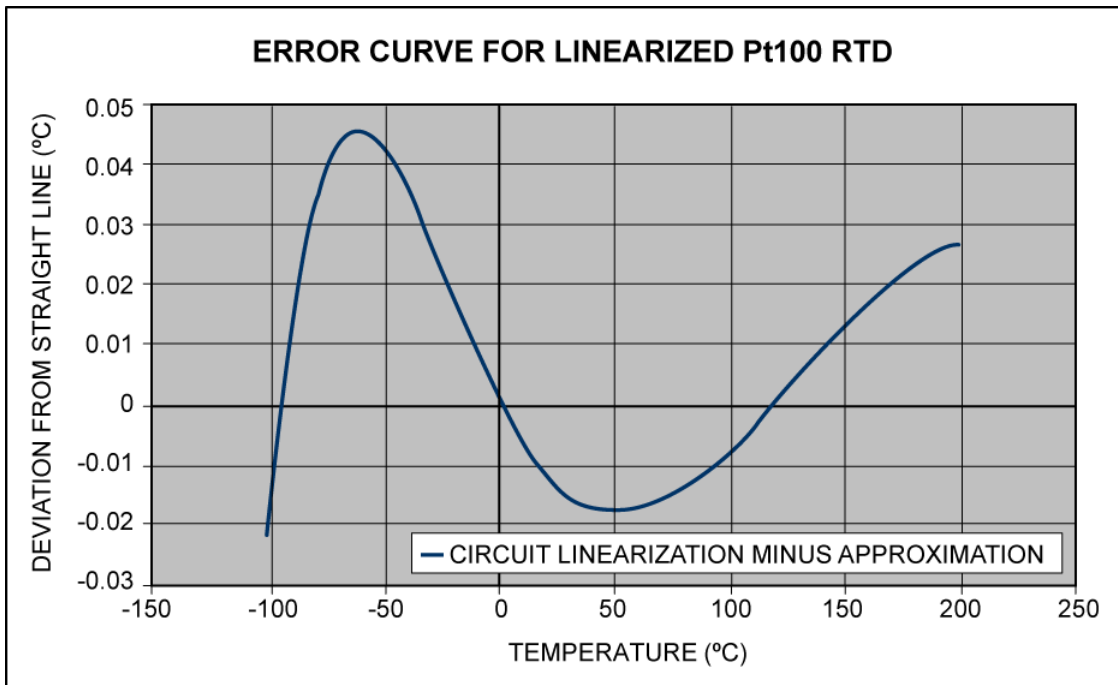
Figure 43. Error curve showing the deviation from linearity between -100°C and +200°C for the output of the circuit in Figure 42.

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Thermocouple Interface Circuits

As discussed in the *Thermocouples* section, a thermocouple interface circuit normally includes a high-resolution ADC, a cold-junction temperature sensor, a voltage reference, and a precision amplifier. The circuit shown in **Figure 44** uses an ADC (the MX7705) with an internal programmable gain amplifier (PGA), which eliminates the need for an external precision amplifier. Cold-junction temperature is measured using a MAX6627 remote diode sensor and an external diode-connected transistor located at the thermocouple connector. Adding the cold-junction temperature to the apparent temperature measured by the ADC corrects for the thermocouples created by linking the thermocouple connector to the system. Negative temperatures can be accommodated by the MAX7705, whose input common-mode range extends 30mV below ground. This circuit can be adapted to work with all major thermocouple types.
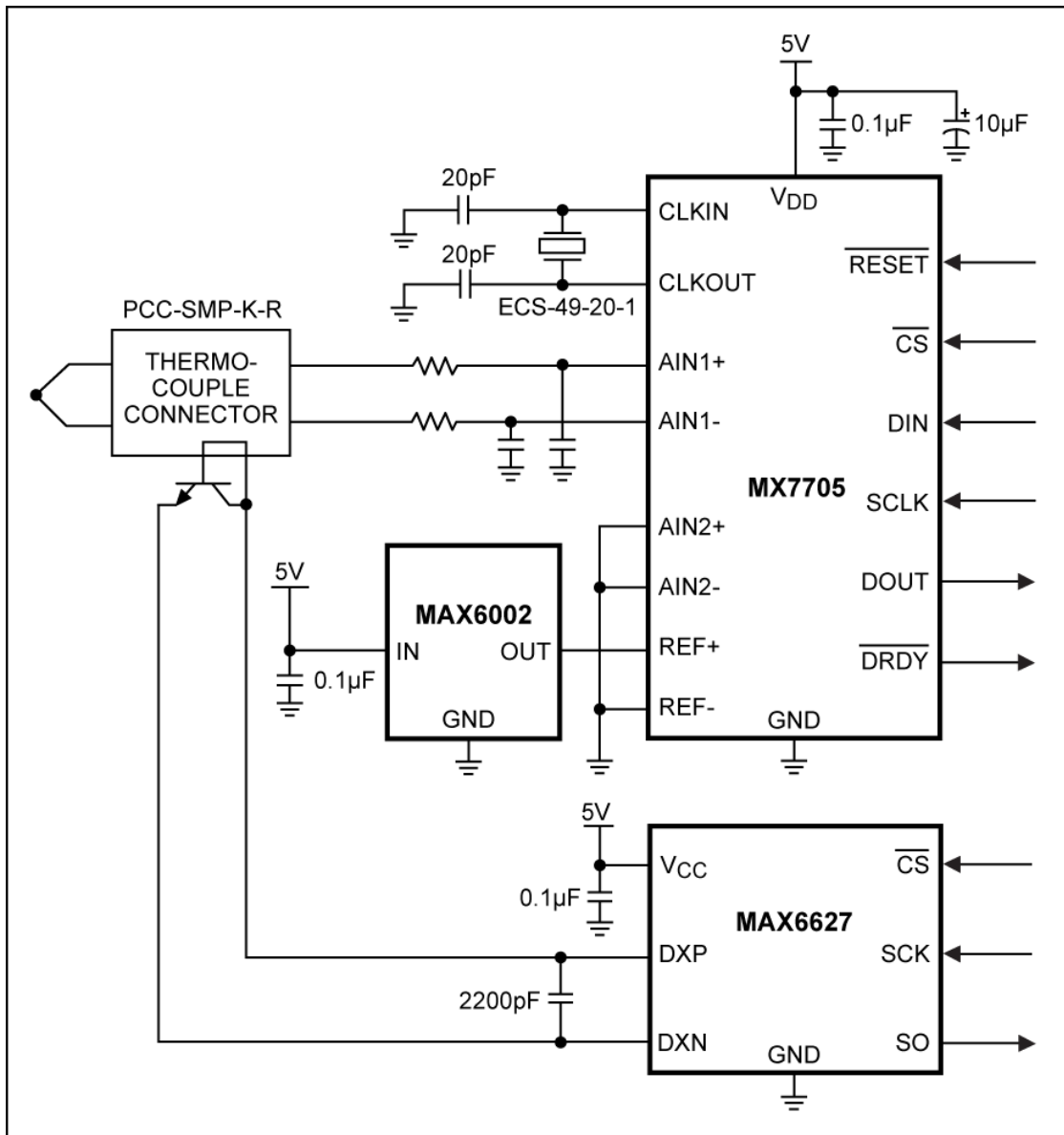
Figure 44. Thermocouple measurement circuit. The MX7705 measures the thermocouple output, and the MAX6627 and external transistor measure the cold-junction temperature.

Figure 45 shows a fully integrated thermocouple-to-digital circuit. This circuit measures positive temperature values from a type K thermocouple and requires no external components. The maximum measured temperature is +1024.75°C. Linearization of the thermocouple's transfer function is done externally by the µC. The 12-bit resolution results in an LSB value of 0.25°C.
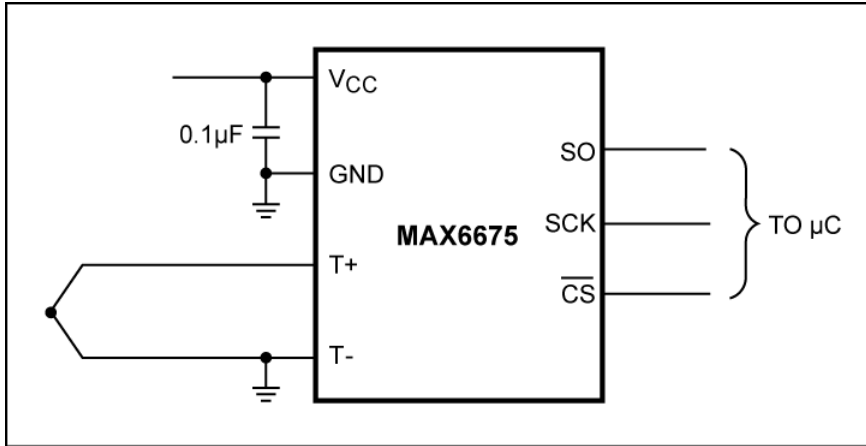
Figure 45. Integrated thermocouple-to-digital converter for type K thermocouples.

IR-Linked Temperature Sensor

When galvanic isolation or improved EMI immunity is needed, an IR link between the temperature sensor and the system can be an excellent solution. The circuits in **Figure 46** implement such a link and use a MAX6576 temperature-to-period sensor. For full design details, refer to Maxim application note 3457, "IR-link temperature sensor allows isolation of the temp sensor."
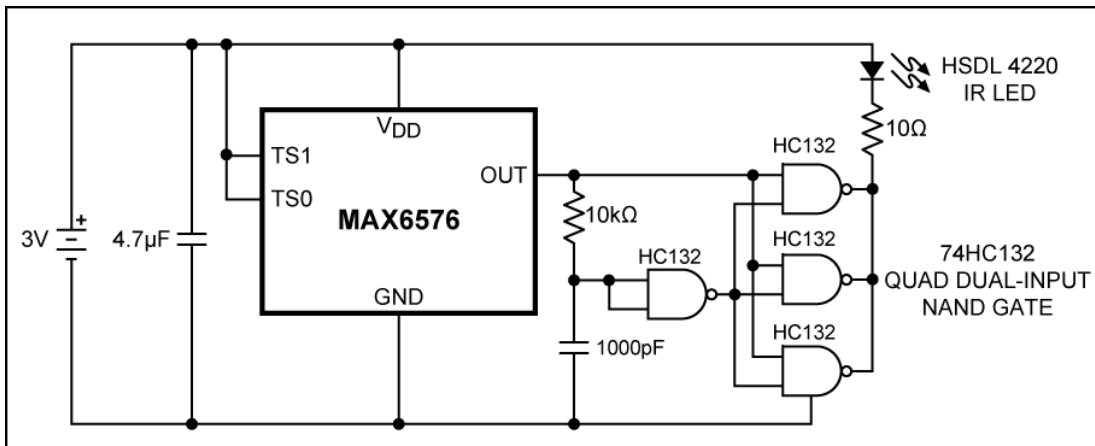
(a)
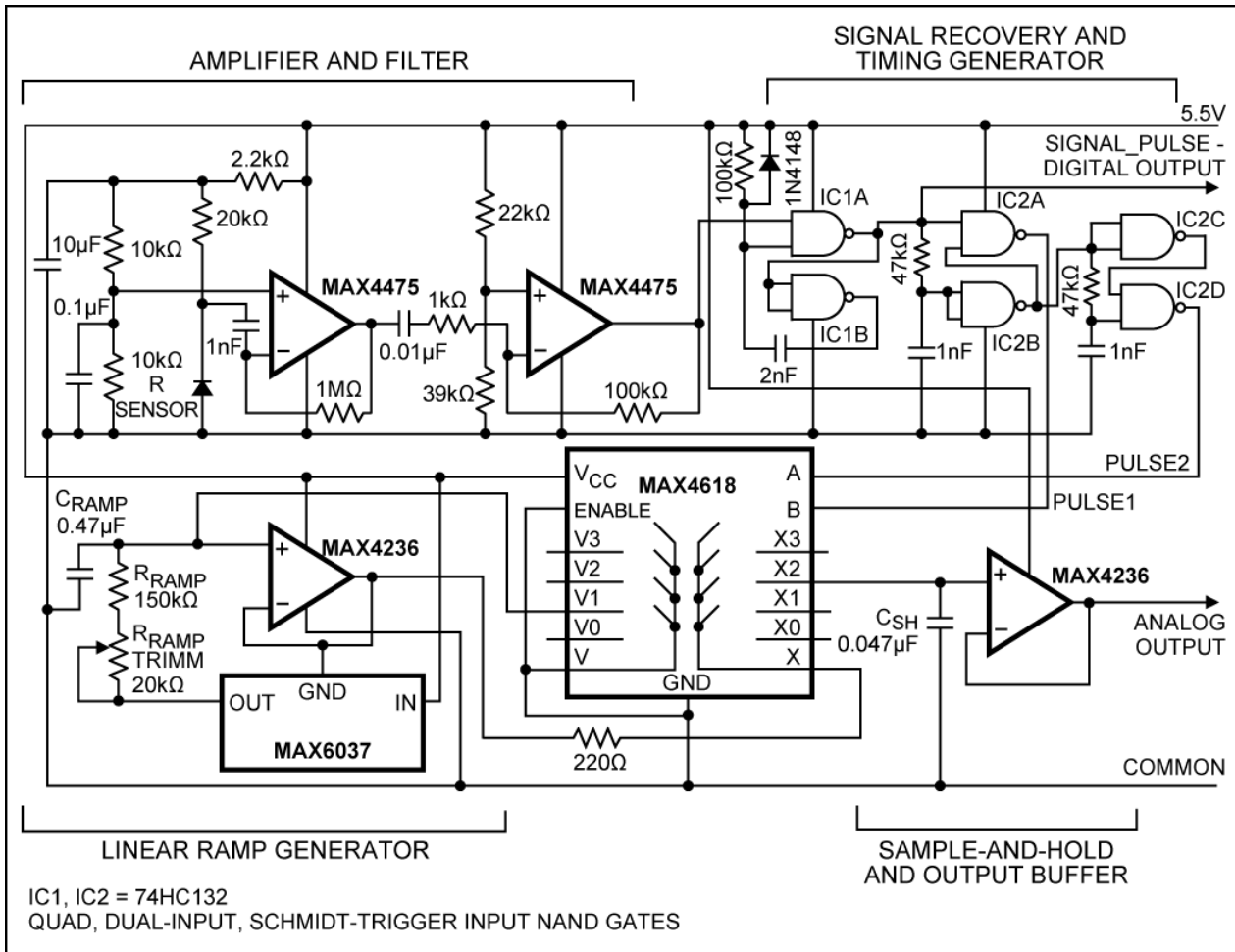
(b)

Figure 46. IR-linked temperature sensor. (a) Sensor and transmitter. (b) Receiver.

RS-232-Powered Temperature Sensor

The circuit in **Figure 47** powers a MAX6576 temperature-to-period sensor from an RS-232 interface IC, which also conveys the sensor's output waveform to the system. The MAX6576's output waveform has a period that is directly related to temperature. More details can be found in Maxim application note 3424, "RS-232-powered temperature sensor."
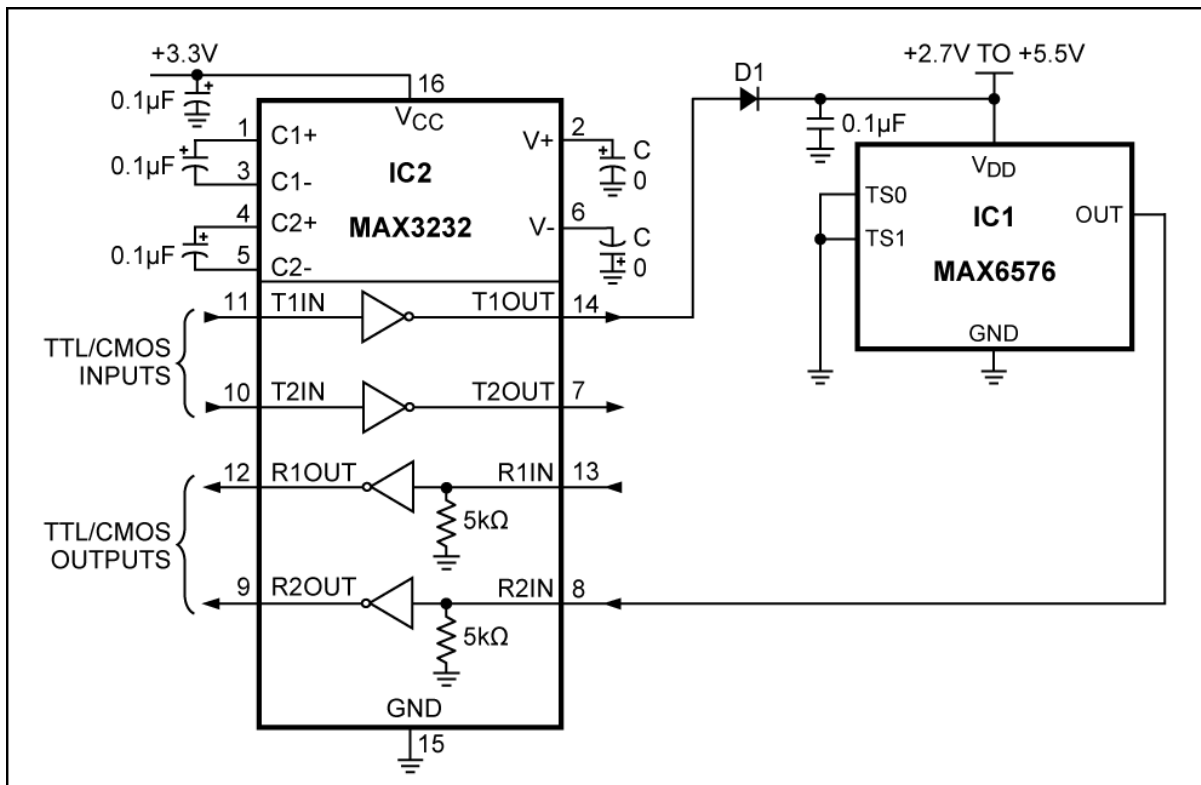
Figure 47. RS-232-powered temperature sensor.

Fan Control Circuits

Pulse-Width-Modulated, Fan Power Supply Drive

As discussed in the *Controlling Fan Speed* section, this approach is simple and appropriate when the drawbacks of increased noise and more difficult tachometer sensing are not issues. **Figure 48** shows high-side and low-side versions that work with several Maxim fan controllers, including the MAX6615, MAX6616, MAX6639, MAX6640, MAX6653, and MAX6678. Figure 48a is a high-side drive circuit. Note that the PWM signal polarity needs to be negative and the PWM output must be able to pull up to the fan's supply voltage. In Figure 48b's low-side drive circuit, note that the PWM polarity is positive. The PWM output needs to be pulled up only high enough to turn on the n-channel FET. For both circuits, pulse stretching may be needed to ensure proper operation of the tachometer counter—this is especially true for slower fans.
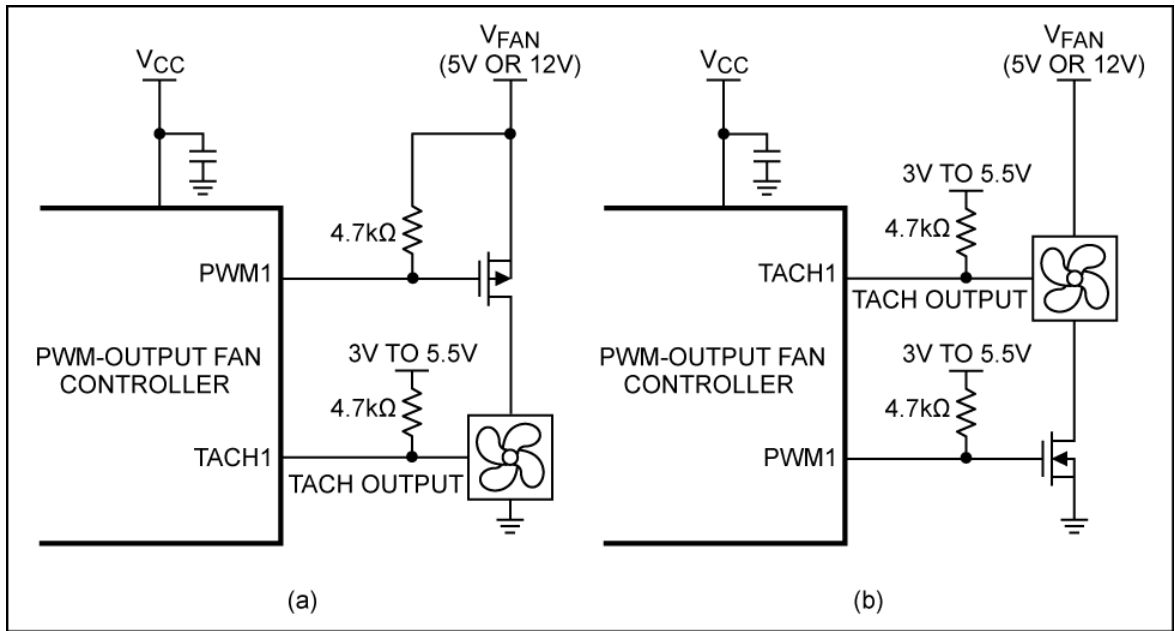
Figure 48. 3-wire fan control circuits using pulse-width modulation of the fan's power supply. 2-wire fans can be controlled with the same circuits, but do not have tachometer outputs. (a) High-side drive. (b) Low-side drive.

4-Wire Fan Drive

4-wire fans normally require a high-frequency (20kHz to 50kHz) PWM signal for fan control. The circuit in **Figure 49** shows the MAX6639 dual fan speed controller used with two 4-wire fans. The MAX6639 also includes two temperature-sensing channels, and is capable of controlling fan RPM as a function of measured temperature.
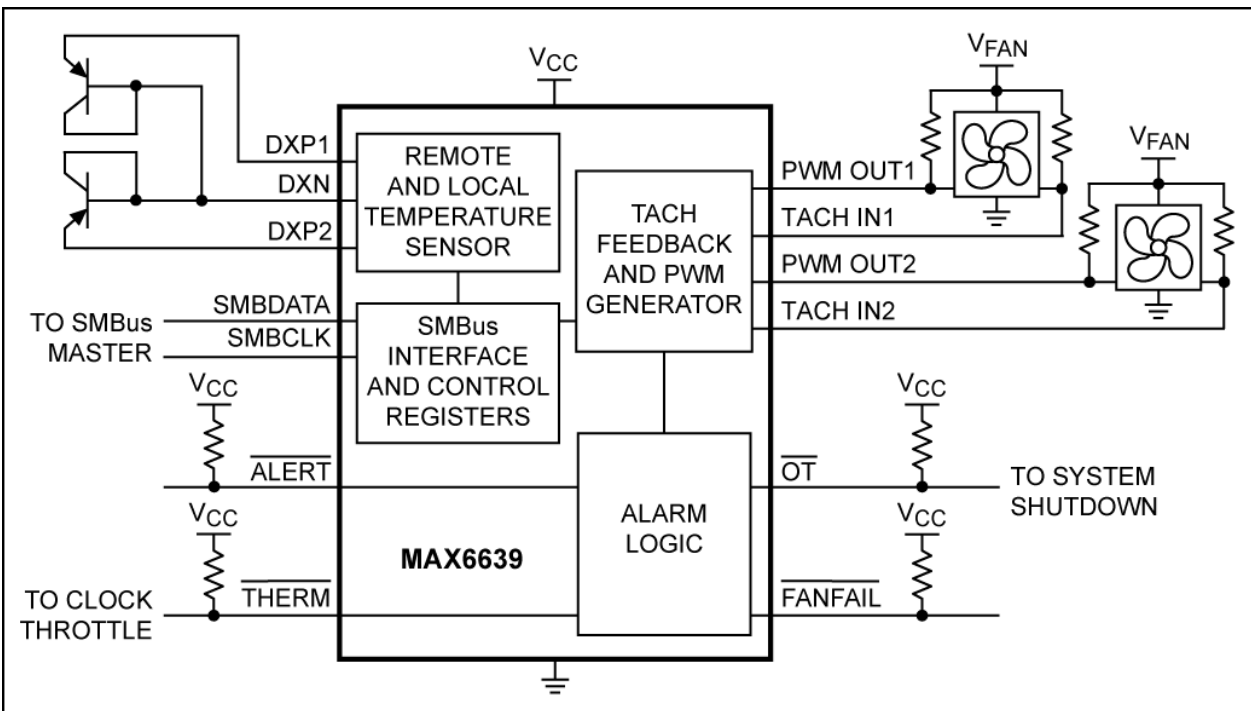
Figure 49. The MAX6639 controlling two 4-wire fans; it measures two temperatures and can control fan RPM based on the measured temperature.

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Converting PWM Control Signals to Linear Fan Drive

Most fan control ICs generate PWM signals to control fan speed. These signals are appropriate for 4-wire fans and, when used to modulate the power supply, can often be used with 2- and 3-wire fans as well. When a pulse-width-modulated power supply is not acceptable, you must drive a 2- or 3-wire fan with a linear voltage to adjust speed. If the fan controller generates PWM for fan speed control, one of the following circuits can be used to convert the PWM signal to a linear voltage.

Discrete PWM-to-Linear Fan Drive The circuit in **Figure 50** is appropriate for use with most PWM fan control ICs. It filters the PWM signal, and amplifies and buffers the resulting DC voltage to drive the fan. The 2.2µF capacitor is necessary for filtering low-frequency (100Hz) PWM waveforms. Speed controllers like the MAX6639 have higher frequency PWM (above 20kHz), which allows the 2.2µF capacitor to be replaced with a smaller value. It is good practice to use the highest PWM frequency available. The circuit shown will work with all of Maxim's PWM-output fan controllers, including the MAX6615, MAX6616, MAX6639, MAX6640, MAX6653, and MAX6678.
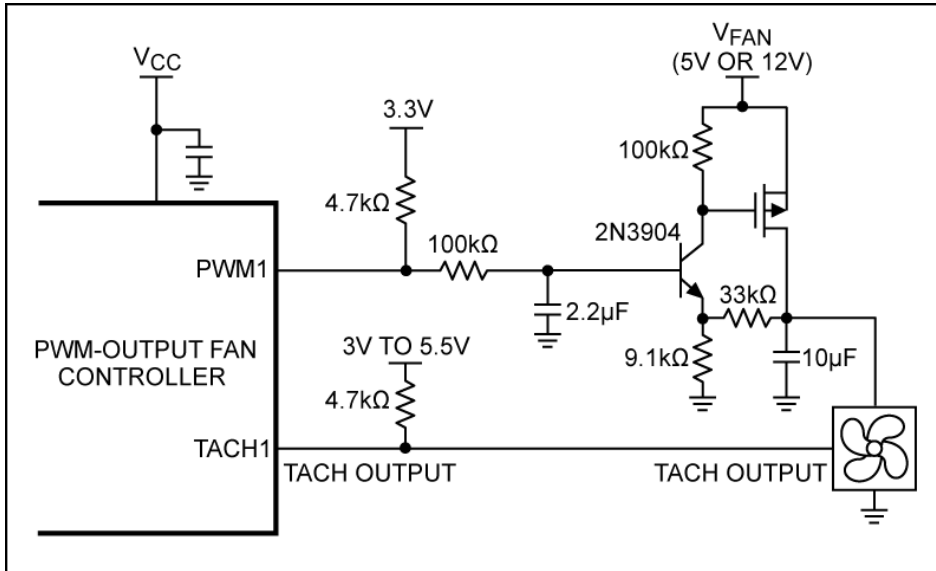
Figure 50. Circuit for converting PWM fan control signals to a linear supply voltage.

Note that using linear pass transistors, as in Figure 50, will result in some wasted power. When the fan's power supply voltage is half of the nominal supply voltage, the pass device will dissipate approximately 25% of the fan's nominal full-speed power. The circuit in **Figure 51** uses a simple switching power supply to provide the fan with a variable power supply voltage without dissipating power in a linear pass transistor; use the highest PWM frequency (25kHz) available from the MAX6639.
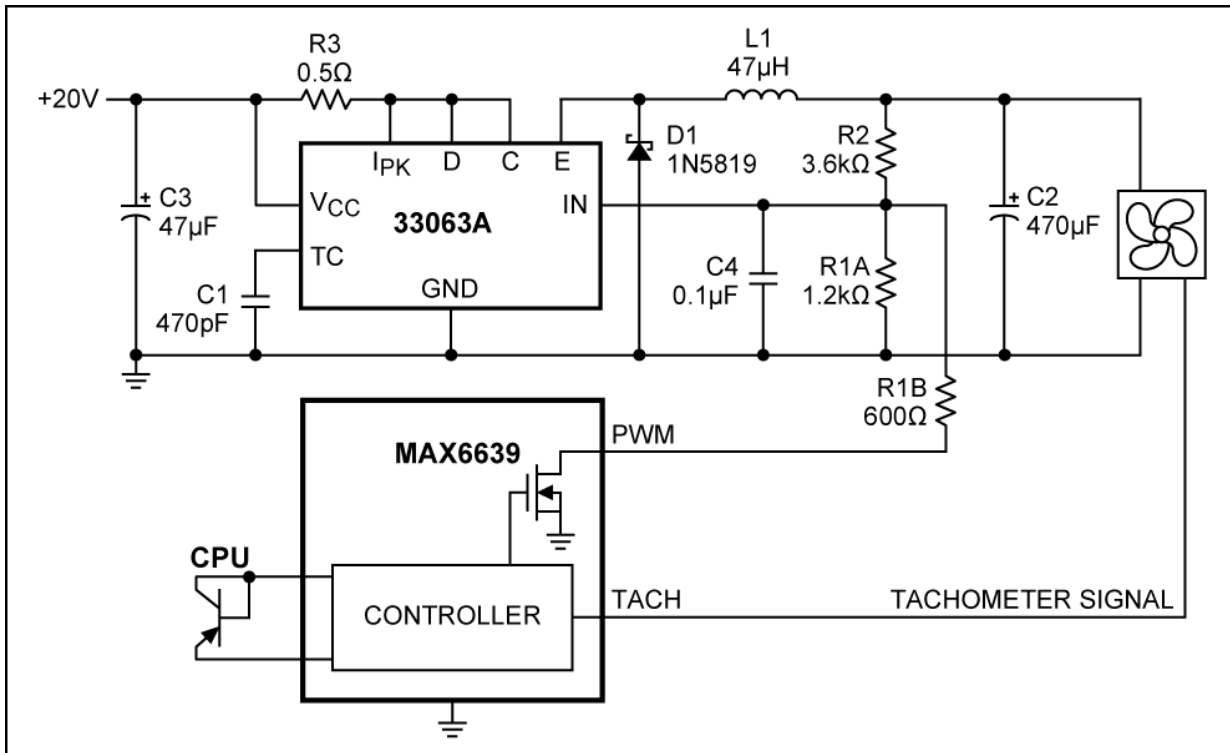
Figure 51. Linear drive from a PWM-output fan controller using an external switch-mode voltage regulator.

Linear Fan Drive

A few Maxim products—notably the MAX6620, MAX6650, MAX6651, MAX6660, and MAX6661—drive fans with a linear power supply voltage. The MAX6620, which controls the RPM of up to four 12V fans, is shown in **Figure 52**. External PNPs or p-channel MOSFETs serve as the pass devices.

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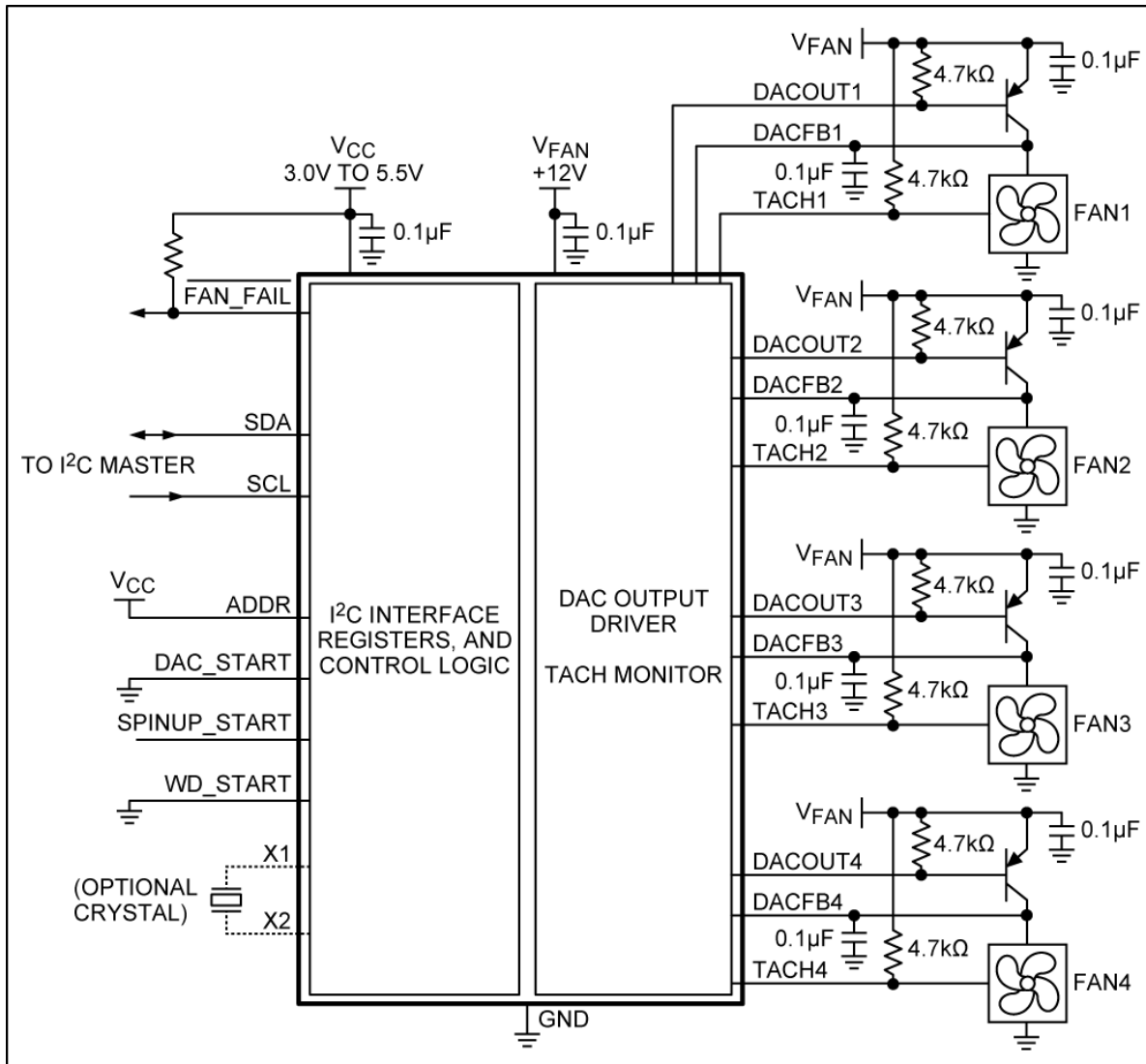
Figure 52. The MAX6620 shown here is a 4-channel linear fan speed controller using external pass transistors to supply variable power to the fans.

High-Voltage Fan Control

The majority of BLDC fans operate from 5V or 12V power supplies, and most fan speed control ICs operate from supplies in the range of 3.0V to 5.5V. However, many fans operate from 24V or 48V supplies, sometimes requiring changes in the external circuitry before using them with standard speed-control ICs.

48V, 4-Wire Fan Speed Control

4-wire fans are easy to adapt to high-voltage operation, because the fan controller is not exposed to the high voltage. The fan's PWM input is compatible with normal logic levels, and its output is open drain, so it can be pulled up to the fan controller's supply voltage—3.3V, for example. The circuit in **Figure 53** illustrates the concept of controlling a high-voltage 4-wire fan; it is the same as a 12V fan control circuit, except for the fan's power supply voltage. Any PWM-output fan controller IC will work with 48V fans.
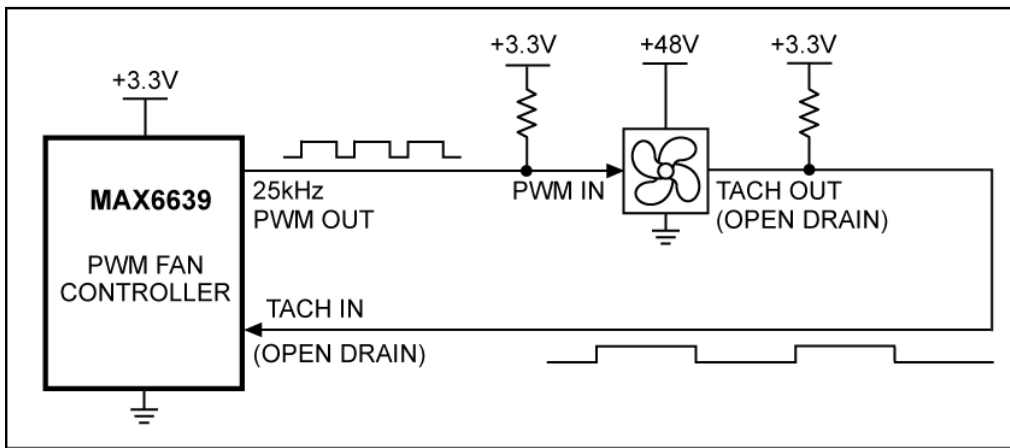
Figure 53. Controlling a 48V 4-wire fan. No special precautions are needed—any PWM-output fan controller with an appropriate output frequency available will work.

48V, PWM Power Supply Fan Speed Controller

Fan control circuits that pulse-width modulate +5V and +12V power supplies, such as those in Figure 48, can be modified to work with 48V fans (see **Figure 54**). Because the MAX6639's PWM output cannot be pulled up to +48V, a transistor is used to level-shift the PWM signal so that it swings between +48V and ground. The resulting high-voltage PWM is applied to the gate of transistor that supplies power to the fan.
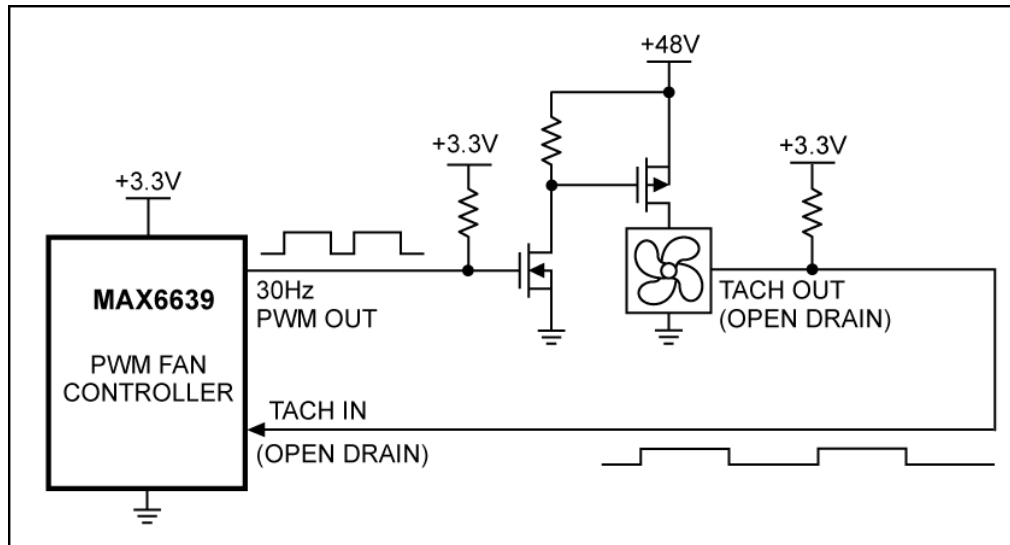
Figure 54. Controlling a 48V 2- or 3-wire fan by modulating the power supply with a PWM signal.

48V, Linear Fan Speed Controller

The MAX6650 and MAX6651 are fan RPM controllers designed for use with 12V fans. In the standard configuration, an n-channel FET drives the low side of the fan and the tachometer signal from the fan drives the IC's TACH input(s). Voltage feedback is taken from the FET's drain (the fan's ground terminal).

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When a 48V fan is used with the MAX6650 or MAX6651, a FET with a higher voltage rating must be selected, and the voltage feedback from the drain and the tachometer signal from the fan must be attenuated so that they do not exceed the IC's maximum input voltage of 13.2V. The circuit in **Figure 55** shows how this is done. For more details, refer to Maxim application note 3361, "Using the MAX6650 and MAX6651 Fan Speed Regulators with 24V and 48V Fans."
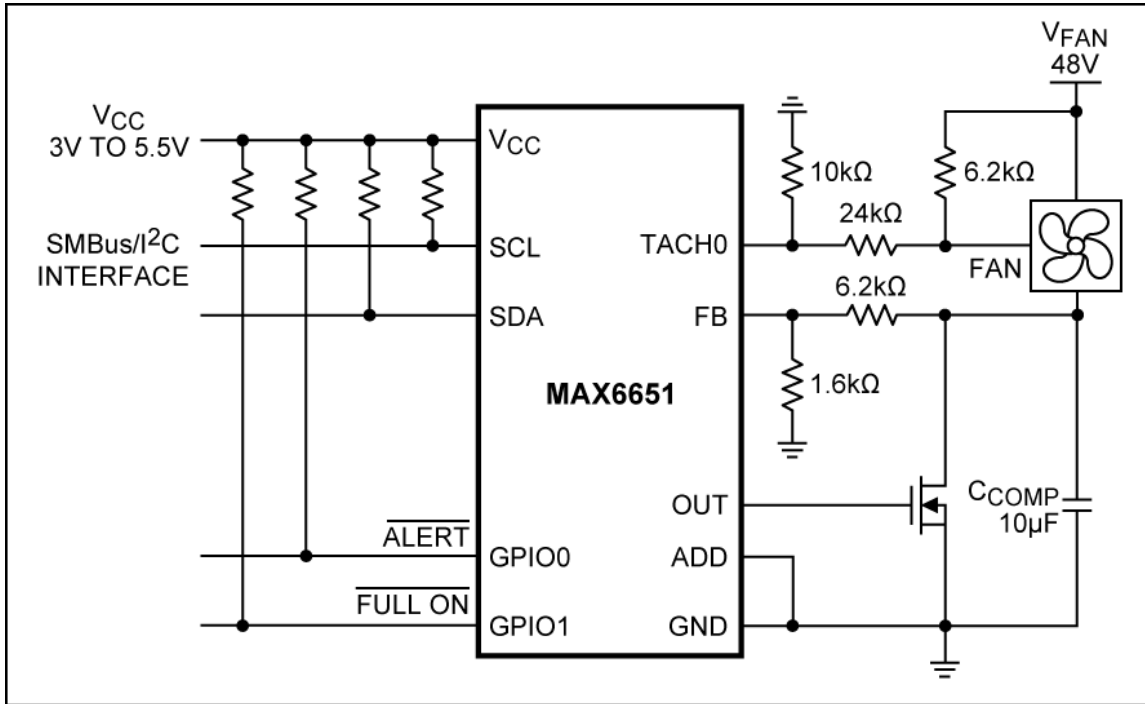
Figure 55. 48V, linear fan RPM controller. The feedback and tachometer signals are attenuated for compatibility with the MAX6651's input voltage tolerance.

Stand-Alone Fan Control Circuits

While fan control based on programmable ICs and microcontrollers provides excellent flexibility and performance, there are many cases that are better serve by a very simple fan control scheme that requires no programming or complex ICs. Some examples follow.

Basic On/Off Fan Controllers Using Temperature Switches

Simply activating a fan at a high temperature and turning it off at a low temperature is a simple, reliable, low–cost method of temperature control, but it creates sudden changes in noise level. This approach is therefore most appropriate when the equipment is isolated from users, or when the normal operating temperature is stable enough that the fan will not be continuously cycling on and off.

Temperature switches are ideal for this function. A few variations are described below.

Local Sensing, Factory-Set Threshold The circuits in **Figure 56** switch the fan on and off either by enabling the power supply of a 2- or 3-wire fan, as in Figure 56a ,or by driving the PWM speed control input of a 4-wire fan, as in Figure 56b.
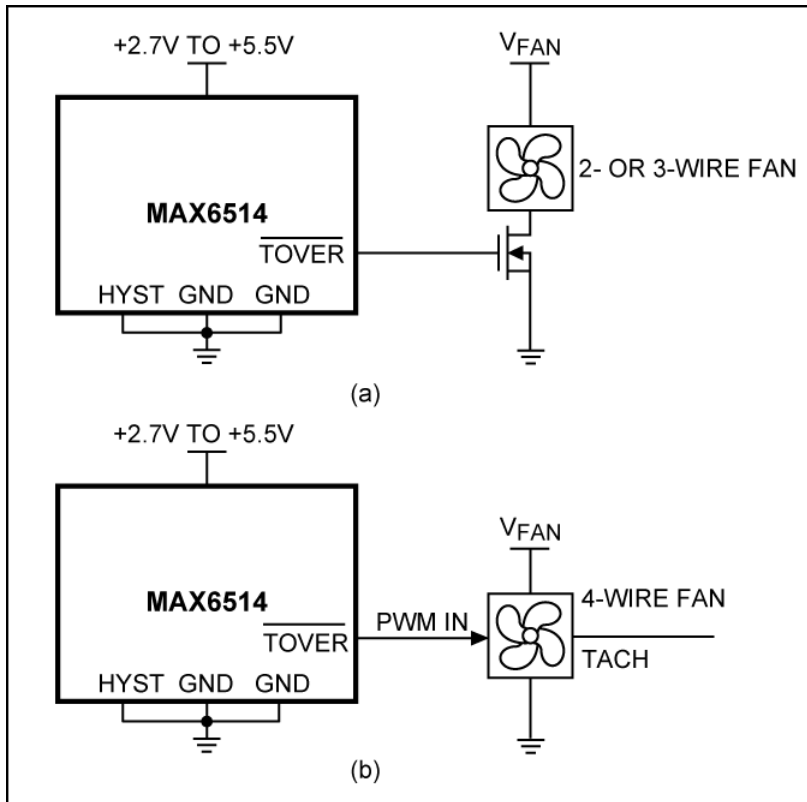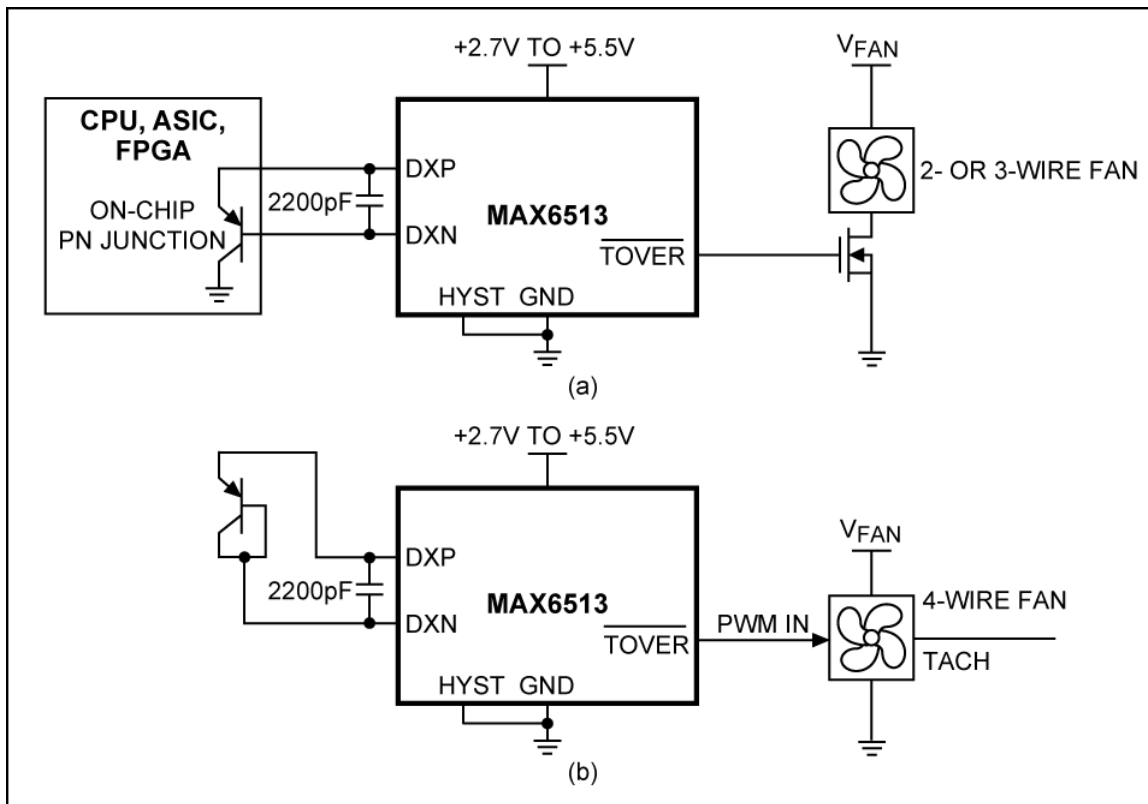

Figure 56. Local on/off fan controllers with factory-set thresholds. (a) Uses a temperature switch and a FET to enable the fan's power supply for 2- and 3-wire fans. (b) The temperature switch's output directly drives a 4-wire fan's PWM input to activate the fan.

Local Sensing, Adjustable Threshold The circuits in **Figure 57** are similar to those in Figure 56, except that they use the MAX6510, an adjustable temperature switch whose threshold temperature is set by an external resistor. The OUTSET pin needs to be connected to V_{CC} to make the output active-high.
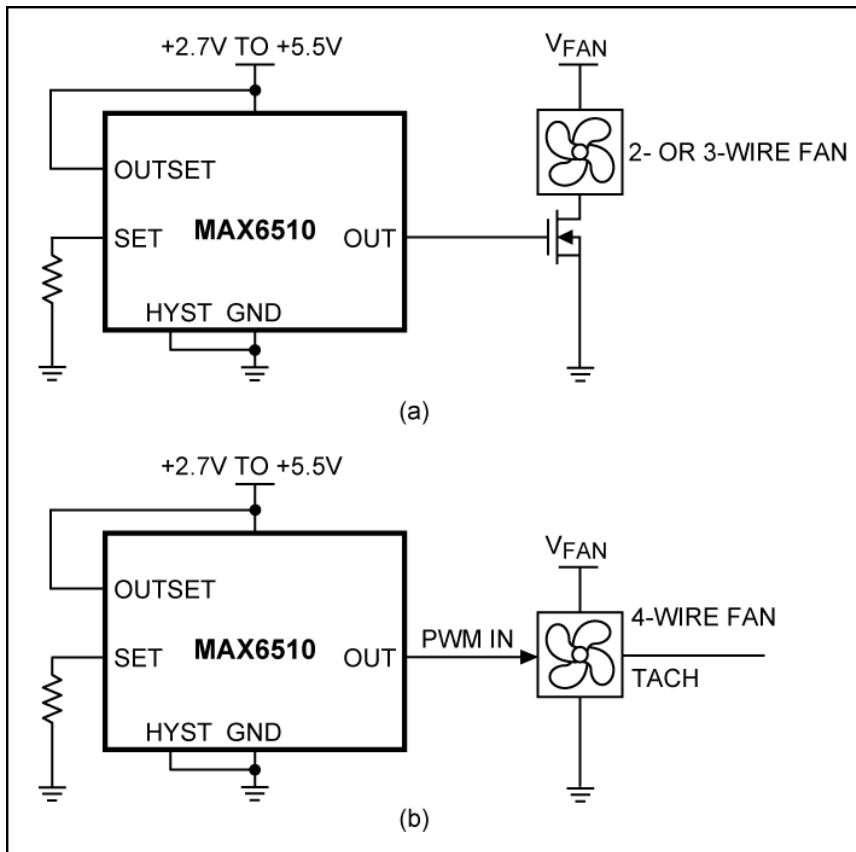
Figure 57. Local on/off fan controllers with adjustable thresholds. (a) Using a temperature switch and a FET to enable the fan's power supply for 2- and 3-wire fans. (b) The temperature switch's output directly drives a 4-wire fan's PWM input to activate the fan. The external resistor sets the trip threshold.

Remote Sensing, Factory-Set Threshold The fan on/off controllers in the two previous figures use local temperature switches, so they make the decision to activate the fan based on board temperature. When the decision needs to be made based on either air temperature or the temperature of an IC through a thermal diode, a remote temperature switch is a better choice. The circuits in **Figure 58** are similar to those in Figures 56 and 57, but use a remote-sensing temperature switch to determine whether the temperature has exceeded the factory-set threshold. The circuit in Figure 58a monitors the die temperature of an external IC using a thermal diode on the die of that IC. When the temperature exceeds the trip threshold, the MAX6513 turns on the transistor that supplies power to the fan. In Figure 58b, the MAX6513 monitors a discrete transistor that is used to sense air temperature. In this case, the MAX6513's output drives the PWM input of a 4-wire fan, activating the fan when the air temperature exceeds the trip threshold.

Figure 58. Remote, on/off fan controllers with factory-set thresholds. (a) Uses a remote temperature switch and a FET to enable the fan's power supply for 2- and 3-wire fans. (b) The temperature switch's output directly drives a 4-wire fan's PWM input to activate the fan.

Simple, Two-Speed Fan Controller

Some systems normally operate at a temperature high enough that the fan must be spinning, but low enough that it can safely operate at a low speed. In these cases, a two-speed (low and high) fan controller is a good solution. The circuit in **Figure 59** is an example of such a fan controller. It uses the MAX6668, which is a remote temperature switch with an internal power transistor capable of driving a 250mA, 12V fan. The threshold temperature is selected at the factory. The MAX6668 is an on/off fan controller but, by adding an external discrete PNP transistor, it can be used to build a two-speed fan controller.
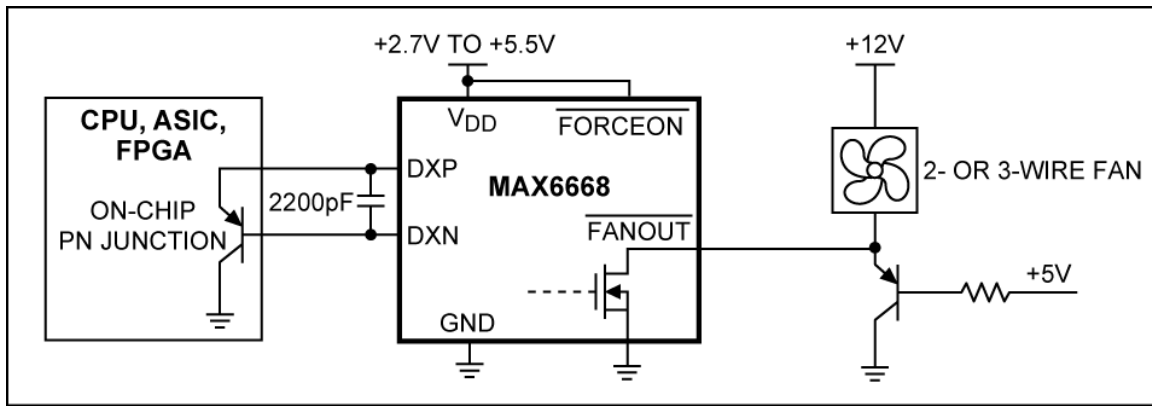
Figure 59. Remote, two-speed fan controller with factory-set threshold. Below the threshold, the fan runs at approximately half speed. Above the threshold, it runs at full speed.

In Figure 59, the MAX6668's open-drain, n-channel FET is off at temperatures below the threshold. While the FET is off, the PNP drives the ground lead of the fan. With the PNP's base connected to +5V, the voltage across the fan is a little over 6V, enough to ensure low-speed operation for most small fans. Be sure to verify operation of your fan with a 6V power supply before using this circuit. When the threshold is exceeded, the internal FET supplies 12V to the fan, causing it to run at full speed.

Fan Failsafe Circuit

Some systems control a fan's speed using a µC or fan speed controller IC located some distance from the fan. If a problem occurs due to an interrupted connection to the PWM signal or a µC hang, for example, a temperature switch can serve as a fail-safe circuit to ensure that the fan will spin at full speed if the temperature rises above a predetermined threshold value. The circuit in **Figure 60** accomplishes this. The MAX6514 temperature switch's output is OR-ed with the PWM signal. If the temperature of the MAX6514 rises above its threshold value, the fan will be driven to full speed.
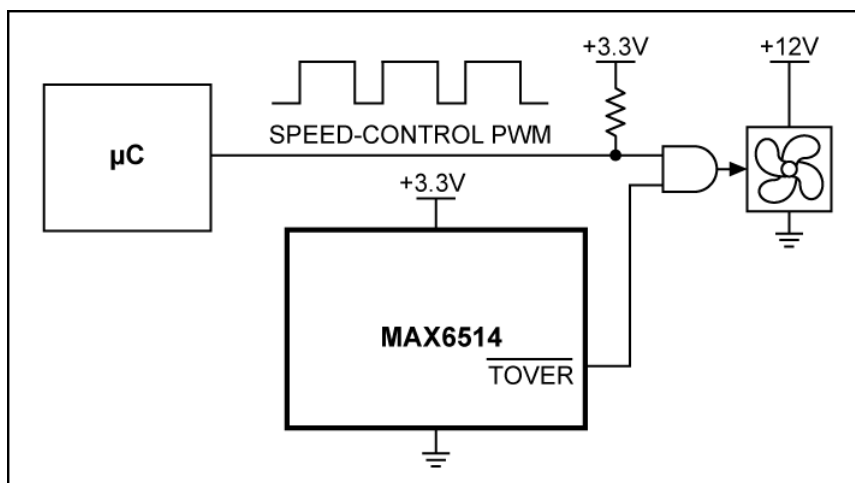
Figure 60. Fan failsafe circuit with factory-set trip threshold.

Multispeed, Stand-Alone Fan Control

Most fan controllers with many speeds and a controlled rate of change between speeds must be programmed using a µC. The circuit in **Figure 61** is based on the MAX6643, one of a unique family of fan controllers whose characteristics are set up by pin-strapping instead of over a bus. The MAX6643 senses temperature using an internal sensor and, optionally, an external transistor. It produces a single PWM output, but has two TACH inputs. Two fans can, therefore, be driven with the same PWM signal while both are monitored independently.
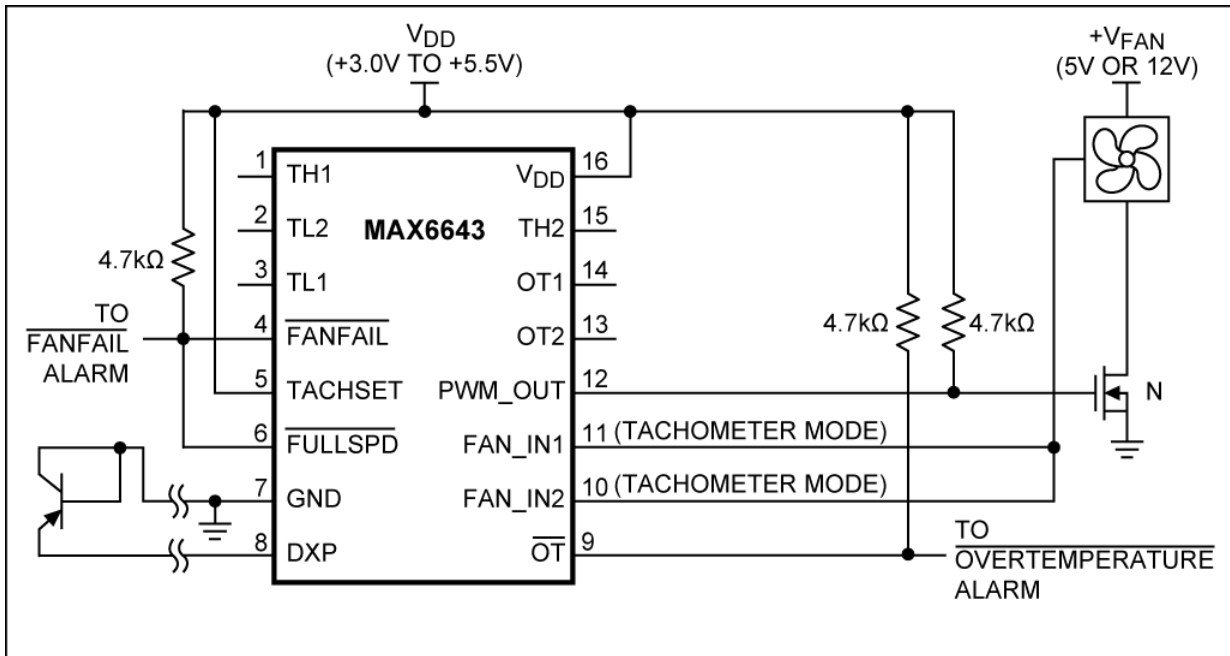
Figure 61. MAX6643 stand-alone, automatic fan speed controller.

Temperature Switches

In-Circuit Temperature Switch Testing

When a temperature switch is used for system protection, the trip temperature is normally set to a value well above the operating range of the system. So how do you verify at the board level that a temperature switch with a fixed threshold is functional? One way would be to raise the board's temperature to a value greater than the trip threshold, but this often is neither desirable nor practical. Another method is shown in **Figure 62**. The MAX6517 in this figure is one of several Maxim temperature switches that also have an analog voltage output with a negative temperature coefficient. To test functionality of the temperature switch, you can simply short the analog output to ground. The MAX6517 responds as though the temperature just increased, and the active-low TOVER output asserts, thus verifying that the protection function is active.
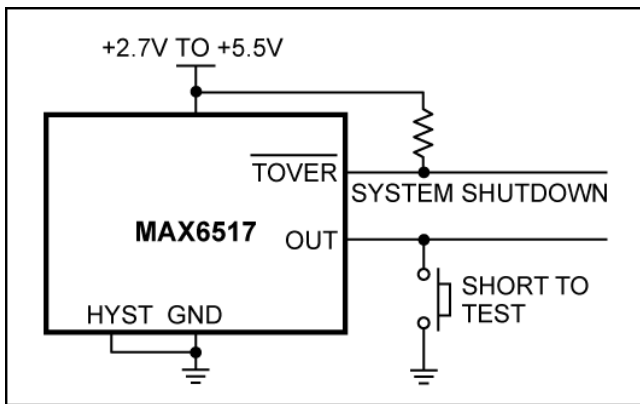
Figure 62. A simple way to verify temperature switch operation at the board level is to short the analog voltage output to ground. This makes the temperature switch react as though the temperature is high: the active-low TOVER output trips, thus verifying functionality.

Thermal Crowbar

Some thermal protection approaches require shutting down the affected system in such a way that it cannot independently recover. One approach to doing this is with a power supply "crowbar"—shorting the power supply until the main power fuse blows. The circuit in **Figure 63** does this with two temperature switches that monitor two separate hot spots. If only one hot spot is to be monitored, one of the temperature switches and the OR gate can be eliminated. A high-temperature condition turns on the silicon-controlled rectifier (SCR), which shorts the power supply and blows the fuse.
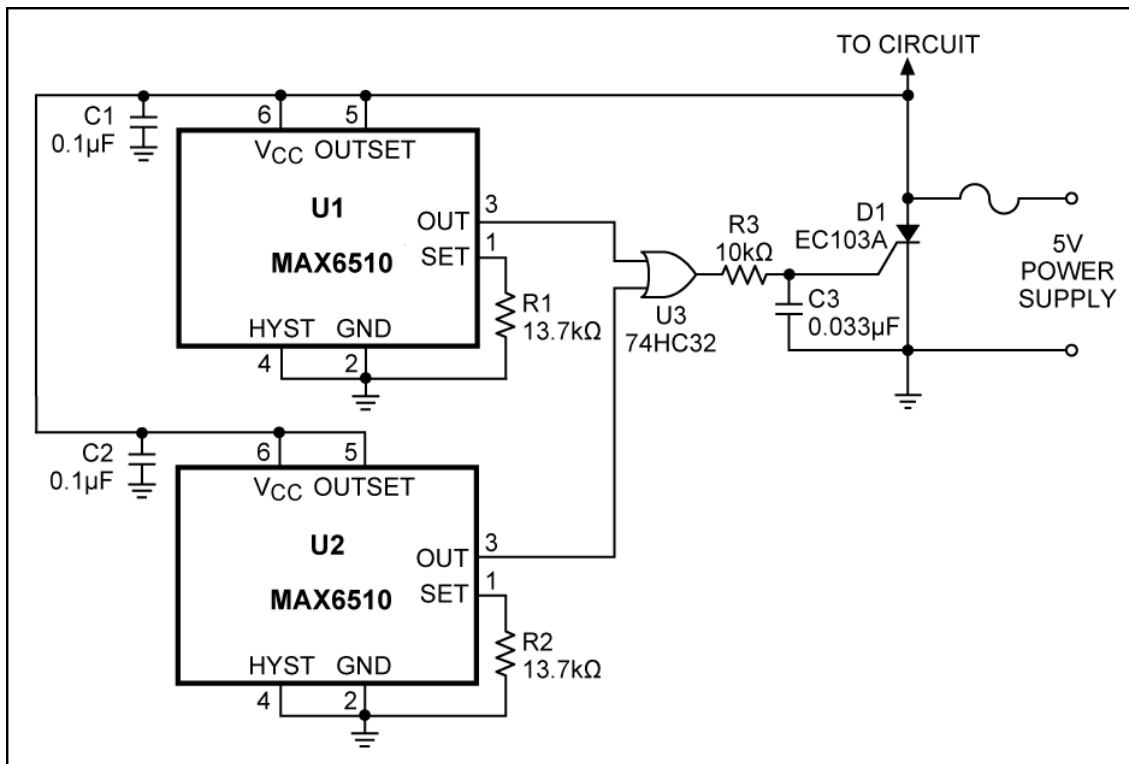
Figure 63. Overtemperature crowbar circuit with two temperature switches. If either temperature switch is hot enough to trip, SCR D1 will turn on, thus shorting the power supply and blowing the fuse.

Find current information about all of Maxim's thermal management products at **www.maxim-ic.com/thermal-management**.