

AN-460 LM34/LM35 Precision Monolithic Temperature Sensors

ABSTRACT

This application report discusses the details and uses of the Texas Instruments LM34 and LM35 as precision temperature sensors..

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1 Introduction

Most commonly-used electrical temperature sensors are difficult to apply. For example, thermocouples have low output levels and require cold junction compensation. Thermistors are nonlinear. In addition, the outputs of these sensors are not linearly proportional to any temperature scale. Early monolithic sensors, such as the LM3911, LM134 and LM135, overcame many of these difficulties, but their outputs are related to the Kelvin temperature scale rather than the more popular Celsius and Fahrenheit scales. Fortunately, in 1983 two I.C.'s, the LM34 Precision Fahrenheit Temperature Sensor and the LM35 Precision Celsius Temperature Sensor, were introduced.

The LM34 has an output of 10 mV/°F with a typical nonlinearity of only $\pm 0.35^\circ\text{F}$ over a -50 to $+300^\circ\text{F}$ temperature range, and is accurate to within $\pm 0.4^\circ\text{F}$ typically at room temperature (77°F). The LM34's low output impedance and linear output characteristic make interfacing with readout or control circuitry easy. An inherent strength of the LM34 over other currently available temperature sensors is that it is not as susceptible to large errors in its output from low level leakage currents. For instance, many monolithic temperature sensors have an output of only $1\text{ }\mu\text{A}/^\circ\text{K}$. This leads to a 1°K error for only $1\text{ }\mu\text{A}$ of leakage current. On the other hand, the LM34 may be operated as a current mode device providing $20\text{ }\mu\text{A}/^\circ\text{F}$ of output current. The same $1\text{ }\mu\text{A}$ of leakage current will cause an error in the LM34's output of only 0.05°F (or 0.03°K after scaling).

Low cost and high accuracy are maintained by performing trimming and calibration procedures at the wafer level. The device may be operated with either single or dual supplies. With less than $70\text{ }\mu\text{A}$ of current drain, the LM34 has very little self-heating (less than 0.2°F in still air), and comes in a TO-46 metal can package, a SO-8 small outline package and a TO-92 plastic package.

2 Forerunners to the LM34

The making of a temperature sensor depends upon exploiting a property of some material which is a changing function of temperature. Preferably this function will be a linear function for the temperature range of interest. The base-emitter voltage (V_{BE}) of a silicon NPN transistor has such a temperature dependence over small ranges of temperature.

Unfortunately, the value of V_{BE} varies over a production range and thus the room temperature calibration error is not specified nor ensured in production. Additionally, the temperature coefficient of about $-2\text{ mV}/^\circ\text{C}$ also has a tolerance and spread in production. Furthermore, while the tempo may appear linear over a narrow temperature, there is a definite nonlinearity as large as 3°C or 4°C over a full -55°C to $+150^\circ\text{C}$ temperature range.

Another approach has been developed where the difference in the base-emitter voltage of two transistors operated at different current densities is used as a measure of temperature. It can be shown that when two transistors, Q1 and Q2, are operated at different emitter current densities, the difference in their base-emitter voltages, ΔV_{BE} , is:

$$\Delta V_{\text{BE}} = V_{\text{BE1}} - V_{\text{BE2}} = \frac{kT}{q} \ln \left(\frac{J_{\text{E1}}}{J_{\text{E2}}} \right) \quad (1)$$

where k is Boltzman's constant, q is the charge on an electron, T is absolute temperature in degrees Kelvin and J_{E1} and J_{E2} are the emitter current densities of Q1 and Q2 respectively. A circuit realizing this function is shown in Figure 1.

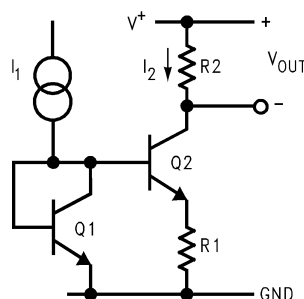


Figure 1.

Equation 1 implies that as long as the ratio of I_{E1} to I_{E2} is held constant, then ΔV_{BE} is a linear function of temperature (this is not exactly true over the whole temperature range, but a correction circuit for the nonlinearity of V_{BE1} and V_{BE2} will be discussed later). The linearity of this ΔV_{BE} with temperature is good enough that most of today's monolithic temperature sensors are based upon this principle.

An early monolithic temperature sensor using the above principle is shown in Figure 2. This sensor outputs a voltage which is related to the absolute temperature scale by a factor of 10 mV per degree Kelvin and is known as the LM135. The circuit has a ΔV_{BE} of approximately:

$$(0.2 \text{ mV}/^{\circ}\text{K}) \times (T) \quad (2)$$

developed across resistor R. The amplifier acts as a servo to enforce this condition. The ΔV_{BE} appearing across resistor R is then multiplied by the resistor string consisting of R and the 26R and 23R resistors for an output voltage of $(10 \text{ mV}/^{\circ}\text{K}) \times (T)$. The resistor marked 100R is used for offset trimming. This circuit has been very popular, but such Kelvin temperature sensors have the disadvantage of a large constant output voltage of 2.73V which must be subtracted for use as a Celsius-scaled temperature sensor.

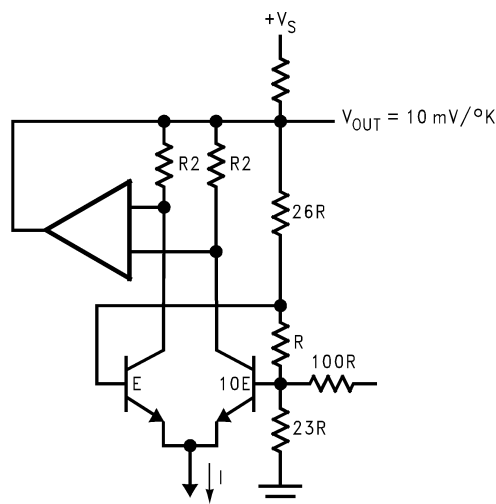


Figure 2.

Various sensors have been developed with outputs which are proportional to the Celsius temperature scale, but are rather expensive and difficult to calibrate due to the large number of calibration steps which have to be performed. Gerard C.M. Meijer [4] has developed a circuit which claims to be inherently calibrated if properly trimmed at any one temperature. The basic structure of Meijer's circuit is shown in Figure 3. The output current has a temperature coefficient of $1 \mu\text{A}/^{\circ}\text{C}$. The circuit works as follows: a current which is proportional to absolute temperature, I_{PTAT} , is generated by a current source. Then a current which is proportional to the V_{BE} drop of transistor Q4 is subtracted from I_{PTAT} to get the output current, I_O . Transistor Q4 is biased by means of a PNP current mirror and transistor Q3, which is used as a feedback amplifier. In Meijer's paper it is claimed that the calibration procedure is straightforward and can be performed at any temperature by trimming resistor R4 to adjust the sensitivity, dI_O/dT , and then trimming a resistor in the PTAT current source to give the correct value of output current for the temperature at which the calibration is being performed.

Meijer's Celsius temperature sensor has problems due to its small output signal (that is, the output may have errors caused by leakage currents). Another problem is the trim scheme requires the trimming of two resistors to a very high degree of accuracy. To overcome these problems, the circuits of Figure 4 (an LM34 Fahrenheit temperature sensor) and Figure 5 (an LM35 Celsius temperature sensor) have been developed to have a simpler calibration procedure, an output voltage with a relatively large tempco, and a curvature compensation circuit to account for the non-linear characteristics of V_{BE} versus temperature. Basically, what happens is transistors Q1 and Q2 develop a ΔV_{BE} across resistor R1. This voltage is multiplied across resistor nR1. Thus at the non-inverting input of amplifier A2 is a voltage two diode drops below the voltage across resistor nR1. This voltage is then amplified by amplifier A2 to give an output proportional to whichever temperature scale is desired by a factor of 10 mV per degree.

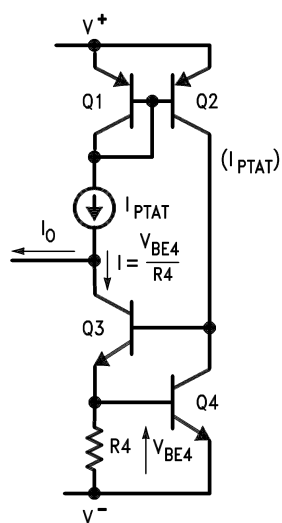


Figure 3.

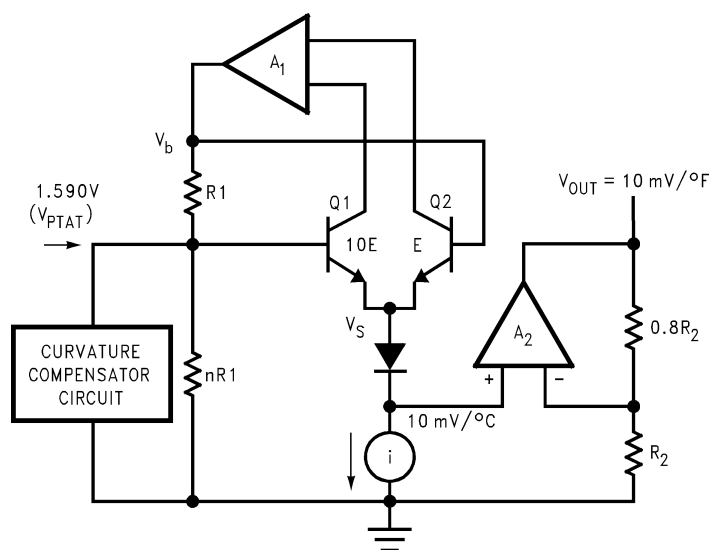


Figure 4.

4 Easy Calibration Procedure

The circuit may be calibrated at any temperature by adjusting the value of the resistor ratio factor n . Note that the value of n is dependent on the actual value of the voltage drop from the two diodes since n is adjusted to give a correct value of voltage at the output and not to a theoretical value for PTAT. The calibration procedure is easily carried out by opening or shorting the links of a quasi-binary trim network, like the one shown in Figure 6. The links may be opened to add resistance by blowing an aluminum fuse, or a resistor may be shorted out of the circuit by carrying out a “zener-zap”. The analysis in the next section shows that when the circuit is calibrated at a given temperature, then the circuit will be accurate for the full temperature range.

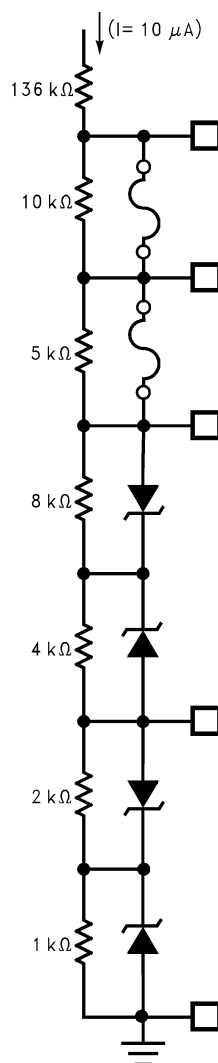


Figure 6.

5 How the Calibration Procedure Works

Widlar [5] has shown that a good approximation for the base-emitter voltage of a transistor is:

$$V_{BE} = V_{G0} \left(1 - \frac{T}{T_0} \right) + V_{beo} \left(\frac{T}{T_0} \right) + \frac{nkT}{q} \ln \left(\frac{T_0}{T} \right) + \frac{kT}{q} \ln \frac{I_C}{I_{C0}} \quad (4)$$

where:

T is the temperature in °Kelvin

T₀ is a reference temperature

V_{G0} is the bandgap of silicon, typically 1.22V

V_{beo} is the transistor's base-emitter voltage at the reference temperature, T₀

Equation 4 can be re-written as:

$$V_{BE} = (\text{sum of linear temp terms}) + (\text{sum of non-linear temp terms}) \quad (5)$$

where the first two terms of Equation 1 are linear and the last two terms are non-linear. The non-linear terms were shown by Widlar to be relatively small and thus will be considered later.

Let us define a base voltage, V_b, which is a linear function of temperature as: V_b = C₁ × T. This voltage may be represented by the circuit in Figure 1. The emitter voltage is V_e = V_b - V_{be} which becomes:

$$V_e = C_1 T - V_{G0} \left(1 - \frac{T}{T_0} \right) - V_{beo} \left(\frac{T}{T_0} \right). \quad (6)$$

If V_e is defined as being equal to C₂ at T = T₀, then Equation 6 may be solved for C₁. Doing so gives:

$$C_1 = \frac{V_{beo} + C_2}{T_0} \quad (7)$$

Using this value for C₁ in the equation for V_e gives:

$$V_e = C_2 \frac{T}{T_0} + V_{G0} \left(\frac{T - T_0}{T_0} \right) \quad (8)$$

If V_e is differentiated with respect to temperature, T, Equation 7 becomes dV_e/dT = (C₂ + V_{G0})/T₀.

This equation shows that if V_b is adjusted at T₀ to give V_e = C₂, then the rate of change of V_e with respect to temperature will be a constant, independent of the value of V_b, the transistor's beta or V_{be}. To proceed, consider the case where V_e = C₂ = 0 at T₀ = 0°C. Then:

$$\frac{dV_e}{dT} = \frac{V_{G0}}{273.7} = 4.47 \text{ mV/}^\circ\text{C} \quad (9)$$

Therefore, if V_e is trimmed to be equal to (4.47 mV) T (in °C) for each degree of displacement from 0°C, then the trimming can be done at ambient temperatures.

In practice, the two non-linear terms in Equation 1 are found to be quadratic for positive temperatures. Tsividis [6] showed that the bandgap voltage, V₀, is not linear with respect to temperature and causes nonlinear terms which become significant for negative temperatures (below 0°C). The sum of these errors causes an error term which has an approximately square-law characteristic and is thus compensated by the curvature compensation circuit of Figure 7.

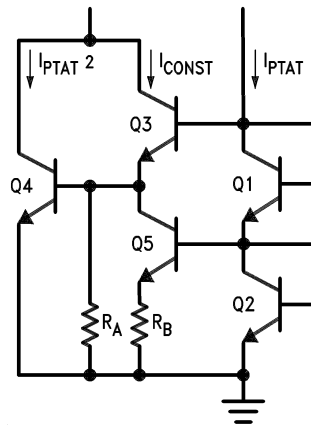


Figure 7.

6 A Unique Compensation Circuit

As mentioned earlier, the base-emitter voltage, V_{BE} , is not a linear function with respect to temperature. In practice, the nonlinearity of this function may be approximated as having a square-law characteristic. Therefore, the inherent non-linearity of the transistor and diode may be corrected by introducing a current with a square-law characteristic into the indicated node of Figure 4. Here's how the circuit of Figure 7 works: transistors Q1 and Q2 are used to establish currents in the other three transistors. The current through Q1 and Q2 is linearly proportional to absolute temperature, I_{PTAT} , as is the current through transistor Q5 and resistor R_B . The current through resistor R_A is a decreasing function of temperature since it is proportional to the V_{BE} of transistor Q4. The emitter current of Q3 is equal to the sum of the current through Q5 and the current through R_A , and thus Q3's collector current is a constant with respect to temperature. The current through transistor Q4, I_{C4} , will be used to compensate for the V_{BE} nonlinearities and is found with the use of the following equation:

$$I_{C4} = I_S \left(e^{\frac{qV_{BE4}}{KT}} - 1 \right) \approx I_S e^{\frac{qV_{BE4}}{KT}} \quad (10)$$

where $V_{BE4} = V_{BE1} + V_{BE2} - V_{BE3}$.

From the above logarithmic relationship, it is apparent that I_{C4} becomes:

$$I_{C4} = \frac{I_{C1} I_{C2}}{I_{C3}} = \frac{I_{PTAT}^2}{I_{CONST}} \quad (11)$$

Thus, a current that has a square law characteristic and is PTAT [2], is generated for use as a means of curvature correction.

7 Processing and Layout

The sensor is constructed using conventional bipolar epitaxial linear processing. SiCr thin-film resistors are used in place of their diffused counterparts as a result of their better tempco matching, an important consideration for resistors which must track over temperature. Such resistors include R1 and nR1 of the bandgap circuit.

Another point of interest in the construction of the device centers around transistors Q1 and Q2 of [Figure 4](#). In order for the circuit to retain its accuracy over temperature, the leakage currents of each transistor, which can become quite significant at high temperatures, must be equal so that their effects will cancel one another. If the geometries of the two transistors were equivalent, then their leakage currents would be also, but since Q1 has ten times the emitter area of Q2, the accuracy of the device could suffer. To correct the problem, the circuit is built with Q1 and Q2 each replaced by a transistor group consisting of both Q1 and Q2. These transistor groups have equivalent geometries so that their leakage currents will cancel, but only one transistor of each group, representing Q1 in one group and Q2 in the other pair is used in the temperature sensing circuit. A circuit diagram demonstrating this idea is shown in [Figure 8](#).

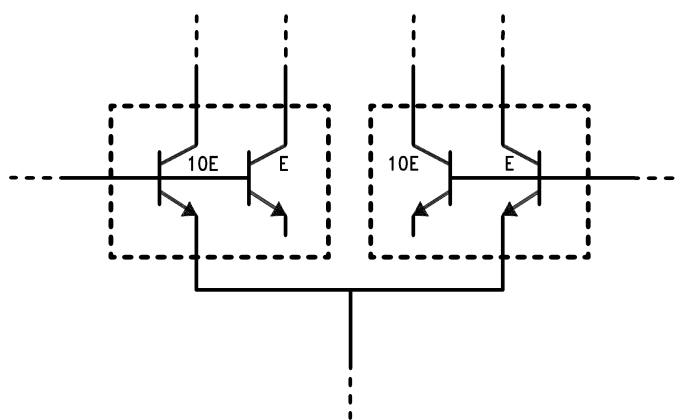


Figure 8.

8 Using the LM34

The LM34 is a versatile device which may be used for a wide variety of applications, including oven controllers and remote temperature sensing. The device is easy to use (there are only three terminals) and will be within 0.02°F of a surface to which it is either glued or cemented. The TO-46 package allows the user to solder the sensor to a metal surface, but in doing so, the GND pin will be at the same potential as that metal. For applications where a steady reading is desired despite small changes in temperature, the user can solder the TO-46 package to a thermal mass. Conversely, the thermal time constant may be decreased to speed up response time by soldering the sensor to a small heat fin.

9 Fahrenheit Temperature Sensors

As mentioned earlier, the LM34 is easy to use and may be operated with either single or dual supplies. [Figure 9](#) shows a simple Fahrenheit temperature sensor using a single supply. The output in this configuration is limited to positive temperatures. The sensor can be used with a single supply over the full -50°F to $+300^{\circ}\text{F}$ temperature range, as seen in [Figure 10](#), simply by adding a resistor from the output pin to ground, connecting two diodes in series between the GND pin and the circuit ground, and taking a differential reading. This allows the LM34 to sink the necessary current required for negative temperatures. If dual supplies are available, the sensor may be used over the full temperature range by merely adding a pull-down resistor from the output to the negative supply as shown in [Figure 11](#). The value of this resistor should be $| -V_S | / 50 \mu\text{A}$.

For applications where the sensor has to be located quite a distance from the readout circuitry, it is often expensive and inconvenient to use the standard 3-wire connection. To overcome this problem, the LM34 may be connected as a two-wire remote temperature sensor. Two circuits to do this are shown in [Figure 12](#) and [Figure 13](#). When connected as a remote temperature sensor, the LM34 may be thought of as a temperature-dependent current source. In both configurations the current has both a relatively large value,

$$(20 \mu\text{A}/^{\circ}\text{F}) \times (T_A + 3^{\circ}\text{F}), \quad (12)$$

and less offset when compared to other sensors. In fact, the current per degree Fahrenheit is large enough to make the output relatively immune to leakage currents in the wiring.

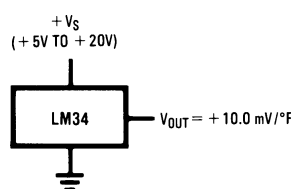


Figure 9. Basic Fahrenheit Temperature Sensor
($+5^{\circ}$ to $+300^{\circ}\text{F}$)

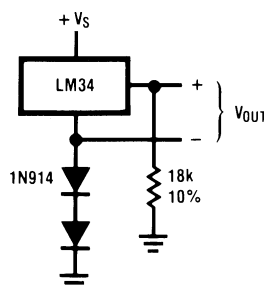


Figure 10. Temperature Sensor, Single Supply,
(-50° to $+300^{\circ}\text{F}$)

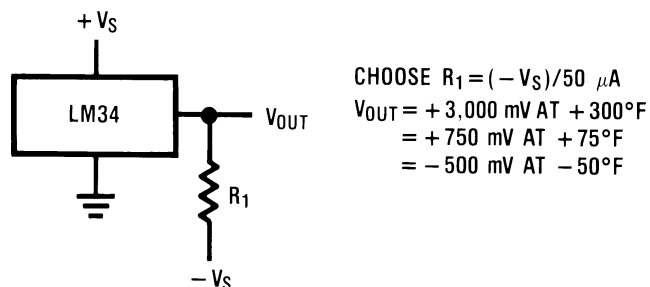
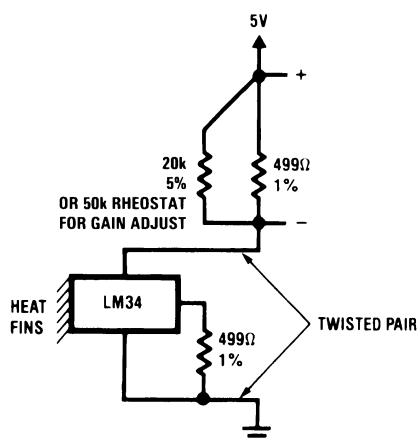


Figure 11. Full-Range Fahrenheit Temperature Sensor



$$V_{OUT} = 10 \text{ mV}/^\circ\text{F} (T_A + 3^\circ\text{F})$$

from $+3^\circ\text{F}$ to $+100^\circ\text{F}$

Figure 12. Two-Wire Remote Temperature Sensor (Grounded Sensor)

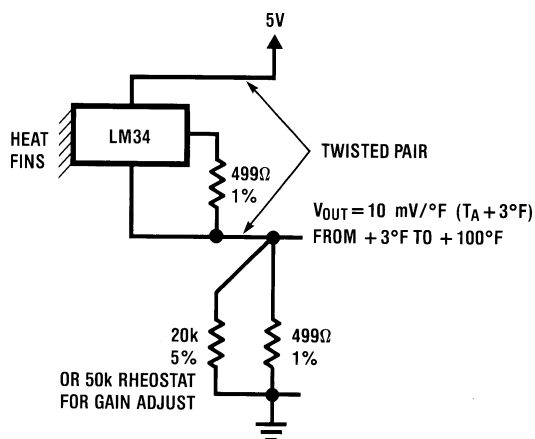
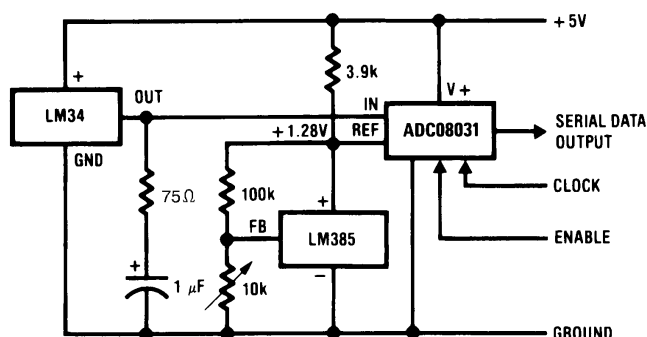


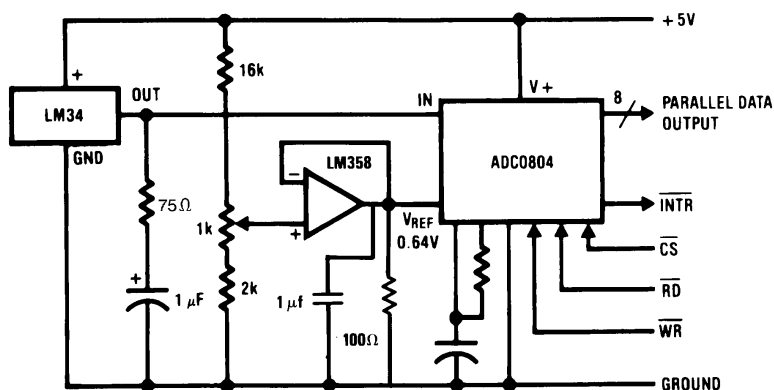
Figure 13. Two-Wire Temperature Sensor (Output Referred to Ground)

10 Temperature to Digital Converters

For interfacing with digital systems, the output of the LM34 may be sent through an analog to digital converter (ADC) to provide either serial or parallel data outputs as shown in Figure 14 and Figure 15. Both circuits have a 0 to +128°F scale. The scales are set by adjusting an external voltage reference to each ADC so that the full 8 bits of resolution will be applied over a reduced analog input range. The serial output ADC uses an LM385 micropower voltage reference diode to set its scale adjust (V_{REF} pin) to 1.28V, while the parallel output ADC uses half of an LM358 low power dual op amp configured as a voltage follower to set its $V_{REF}/2$ pin to 0.64V. Both circuits are operated with standard 5V supplies.



**Figure 14. Temperature-to-Digital Converter
(Serial Output, +128°F Full Scale)**



**Figure 15. Temperature-to-Digital Converter
(Parallel TRI-STATE Outputs for Standard Data Bus to μ P Interface, 128°F Full Scale)**

13 Indoor/Outdoor Thermometer

An indoor/outdoor thermometer capable of displaying temperatures all the way down to -50°F is shown in Figure 18.

Two sensor outputs are multiplexed through a CD4066 quad bilateral switch and then displayed one at a time on a DVM such as Texmate's PM-35X. The LMC555 timer is run as an astable multivibrator at 0.2 Hz so that each temperature reading will be displayed for approximately 2.5 seconds. The RC filter on the sensors outputs are to compensate for the capacitive loading of the cable. An LMC7660 can be used to provide the negative supply voltage for the circuit.

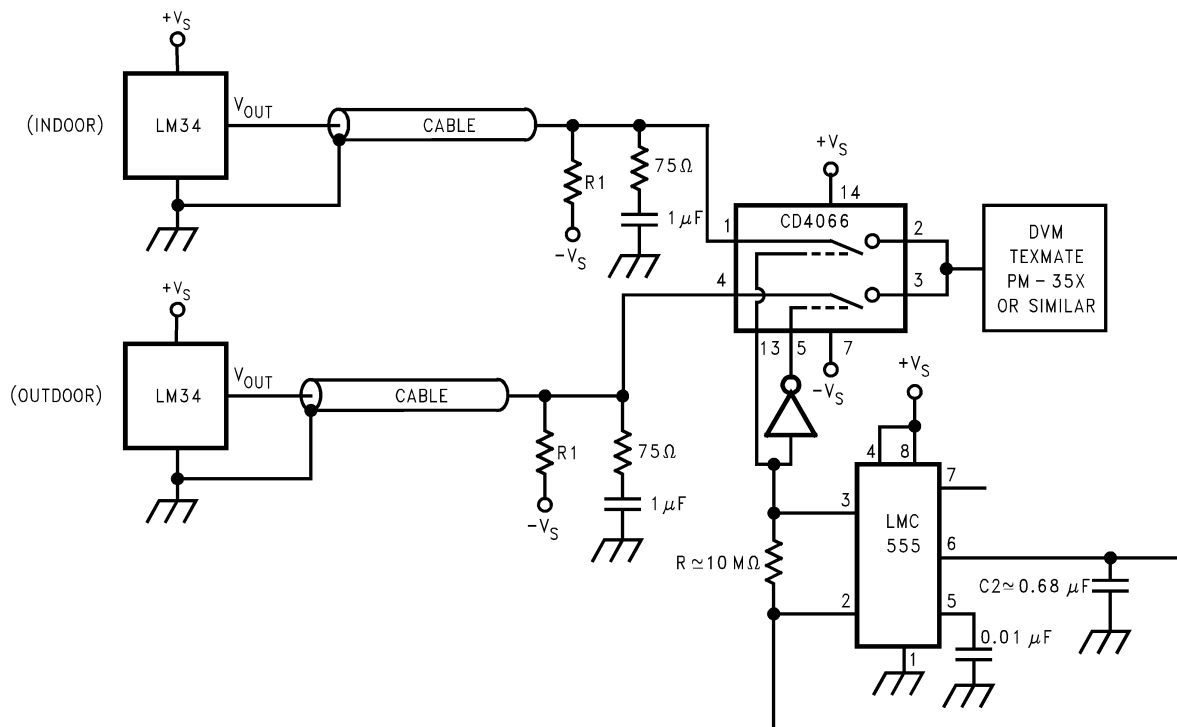


Figure 18.

15 Differential Thermometer

The differential thermometer shown in Figure 20 produces an output voltage which is proportional to the temperature difference between two sensors. This is accomplished by using a difference amplifier to subtract the sensor outputs from one another and then multiplying the difference by a factor of ten to provide a single-ended output of 100 mV per degree of differential temperature.

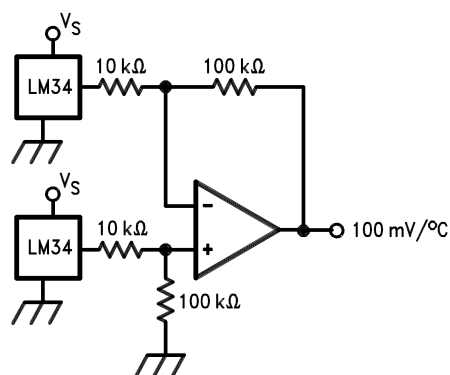
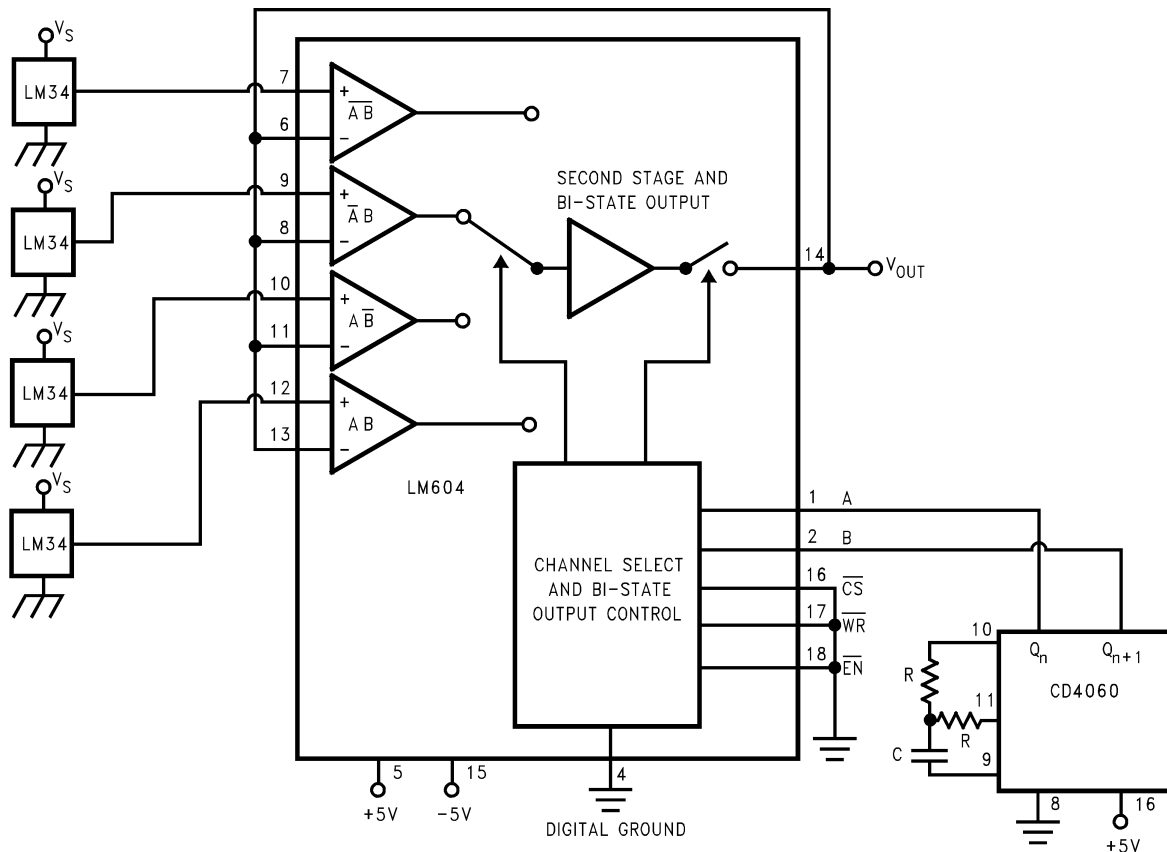


Figure 20. Differential Thermometer

16 Temperature Scanner

In some applications it is important to monitor several temperatures periodically, rather than continuously. The circuit shown in Figure 21 does this with the aid of an LM604 Mux Amp. Each channel is multiplexed to the output according to the AB channel select. The CD4060 ripple binary counter has an on-board oscillator for continuous updating of the channel selects.



$$\text{rate} = \frac{0.56}{RC} \left(\frac{1}{2^{n-1}} \right)$$

If Q_4 and Q_5 are used with $R = 13\text{k}$ and $C = 510\text{ pF}$, the rate will be 10 kHz.

Figure 21. Temperature Monitoring

17 Conclusion

As can be seen, the LM34 and LM35 are easy-to-use temperature sensors with excellent linearity. These sensors can be used with minimal external circuitry for a wide variety of applications and do not require any elaborate scaling schemes nor offset voltage subtraction to reproduce the Fahrenheit and Celsius temperature scales, respectively.

18 References

1. R.A. Pease, "A Fahrenheit Temperature Sensor", presented at the ISSCC Conference, February 24, 1984.
2. R.A. Pease, "A New Celsius Temperature Sensor", National Semiconductor Corp., 1983.
3. Robert Dobkin, "Monolithic Temperature Transducer", in *Dig. Tech. Papers*, Int. Solid State Circuits Conf., 1974, pp. 126, 127, 239, 240.
4. Gerard C.M. Meijer, "An IC Temperature Sensor with an Intrinsic Reference", *IEEE Journal of Solid State Circuits*, VOL SC-15, June 1980, pp. 370–373.
5. R.J. Widlar, "An Exact Expression for the Thermal Variation of the Emitter—Base Voltage of Bipolar Transistors", *Proc. IEEE*, January 1967.
6. Y.P. Tsividis, "Accurate Analysis of Temperature Effects in $I_C - V_{BE}$ Characteristics with Application to Bandgap Reference Sources", *IEEE Journal of Solid-State Circuits*, December 1980, pp. 1076–1084.
7. Michael P. Timko, "A Two-Terminal IC Temperature Transducer", *IEEE Journal of Solid-State Circuits*, December 1976, pp. 784–788.

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