

## Op Amp Precision Design: PCB Layout Techniques

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### INTRODUCTION

This application note covers Printed Circuit Board (PCB) effects encountered in high (DC) precision op amp circuits. It provides techniques for improving the performance, giving more flexibility in solving a given design problem. It demonstrates one important factor necessary to convert a good schematic into a working precision design.

This material is for engineers that design slow precision circuits, including those with op amps. It is aimed at those engineers with little experience in this kind of design, but can also help experienced engineers that are looking for alternate solutions to a design problem.

The information in this application note can be applied to all precision (DC) analog designs, with some thought and diligence. The focus is on common op amp circuits so that the reader can quickly convert this material into improvements on their own op amp designs.

Additional material at the end of the application note includes references to the literature and the schematic of a PCB used in the design example.

### Key Words and Phrases

- Op Amp
- Temperature
- Thermal Gradient
- Thermocouple Junction
- Thermoelectric Voltage
- IC Sockets
- Contact Potential
- PCB Surface Contamination

### Related Application Notes

The following application notes, together with this one, form a series about precision op amp design topics. They cover both theory and practical methods to improve a design's performance.

- AN1177 on DC Errors [1]
- AN1228 on Random Noise [2]

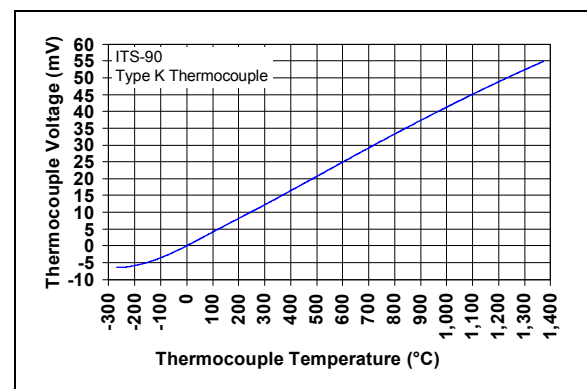
### THERMOCOUPLE JUNCTION BEHAVIOR

Most electrical engineers are aware that thermocouples are a common temperature sensor [4]. What is not so commonly known is that every PCB design includes many unintended thermocouple junctions that modify the signal voltages. This section covers the physics behind this effect and gives practical illustrations.

#### Seebeck Effect

When two dissimilar conductors (or semi-conductors) are joined together, and their junction is heated, a voltage results between them (Seebeck or thermoelectric voltage); this is known as the Seebeck effect. This voltage is roughly proportional to absolute temperature. There are many references that discuss this effect in detail, including the "Temperature Products" section of reference [7]; see especially pages Z-13, Z-14 and Z-23 through Z-32.

Figure 1 shows the Seebeck voltage as a function of temperature for the standard type K thermocouple. Notice that the response is not strictly linear, but can be linearized over small temperature ranges (e.g.,  $\pm 10^\circ\text{C}$ ).



**FIGURE 1:** Type K Thermocouple's Response.

Most thermocouple junctions behave in a similar manner. The following are examples of thermocouple junctions on a PCB:

- Components soldered to a copper pad
- Wires mechanically attached to the PCB
- Jumpers
- Solder joints
- PCB vias

The linearized relationship between temperature and thermoelectric voltage, for small temperature ranges, is given in [Equation 1](#). The Seebeck coefficients for the junctions found on PCBs are typically, but not always, below  $\pm 100 \mu\text{V}/^\circ\text{C}$ .

## EQUATION 1: SEEBECK VOLTAGE

$$\Delta V_{TH} \approx k_J(T_J - T_{REF})$$

$$V_{TH} = V_{REF} + \Delta V_{TH}$$

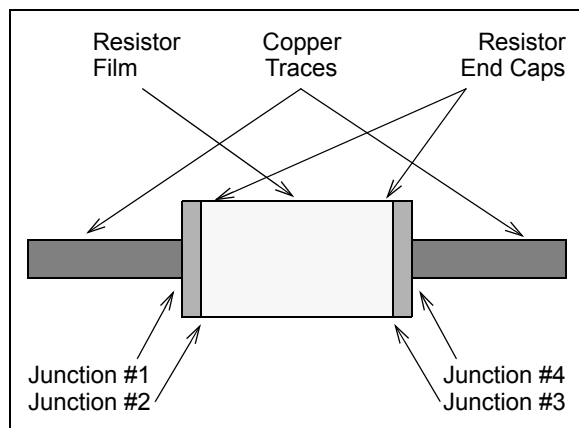
Where:

|                 |   |   |
|-----------------|---|---|
| $\Delta V_{TH}$ | = | Change in Seebeck voltage (V)                     |
| $k_J$           | = | Seebeck coefficient ( $\text{V}/^\circ\text{C}$ ) |
| $T_J$           | = | Junction Temperature ( $^\circ\text{C}$ )         |
| $T_{REF}$       | = | Reference Temperature ( $^\circ\text{C}$ )        |
| $V_{TH}$        | = | Seebeck voltage (V)                               |
| $V_{REF}$       | = | Seebeck voltage at $T_{REF}$ (V)                  |

## Illustrations Using a Resistor

Three different temperature profiles will be shown that illustrate how thermocouple junctions behave on PCB designs. Obviously, many other components will also produce thermoelectric voltages (e.g., PCB edge connectors).

[Figure 2](#) shows a surface mount resistor with two metal (copper) traces on a PCB. The resistor is built with end caps for soldering to the PCB and a very thin conducting film that produces the desired resistance. Thus, there are three conductor types shown in this figure, with four junctions.



**FIGURE 2:** Resistor and Metal Traces on PCB.

For illustrative purposes, we'll use the arbitrary values shown in [Table 1](#). Notice that junctions 1 and 4 are the same, but the values are shown with opposite polarities; this is one way to account for the direction current flows through these junctions (the same applies to junctions 2 and 3).

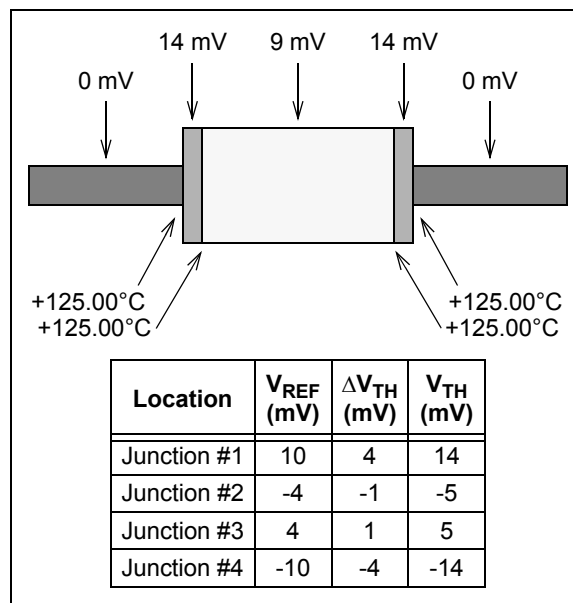
**TABLE 1: ASSUMED THERMOCOUPLE JUNCTION PARAMETERS**

| Junction No. | $V_{REF}$ (mV) | $k_J$ ( $\mu\text{V}/^\circ\text{C}$ ) |
|--------------|----------------|--|
| 1            | 10             | 40                                     |
| 2            | -4             | -10                                    |
| 3            | 4              | 10                                     |
| 4            | -10            | -40                                    |

**Note 1:**  $V_{REF}$  and  $k_J$  have polarities that assume a left to right horizontal direction.  
**Note 2:**  $T_{REF} = 25^\circ\text{C}$ .

## CONSTANT TEMPERATURE

In this illustration, temperature is constant across the PCB. This means that the junctions are at the same temperature. Let's also assume that this temperature is  $+125^\circ\text{C}$  and that the voltage on the left trace is 0V. The results are shown in [Figure 3](#). Notice that  $V_{TH}$  is the voltage change from one conductor to the next.



**FIGURE 3:** Constant Temperature Results.

## TEMPERATURE CHANGE IN THE NORMAL DIRECTION

In this illustration, temperature changes vertically in [Figure 2](#) (normal to the resistor's axial direction), but does not change in the axial direction (horizontally).

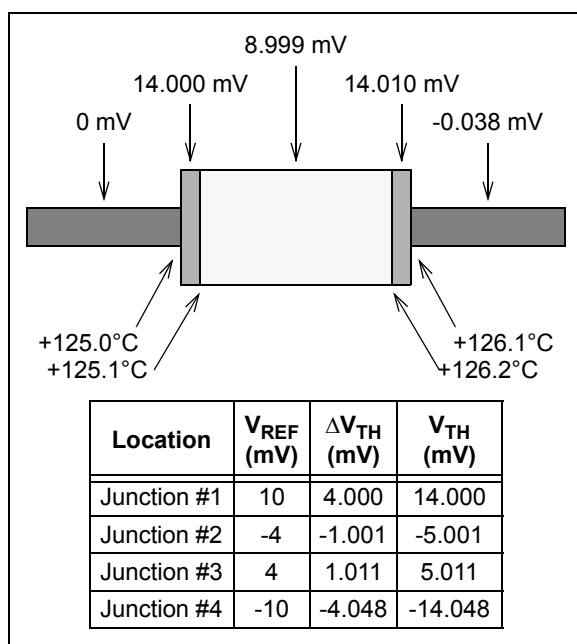
The metal areas maintain almost constant voltages in the normal direction, so this case is basically the same as the previous one.

**Note:** When temperature is constant along the direction of current flow, the net change in thermoelectric voltage between two conductors of the same material is zero.

## TEMPERATURE CHANGE IN THE AXIAL DIRECTION

In this illustration, temperature changes horizontally in [Figure 2](#) (along the resistor's axial direction), but does not change in the normal direction (vertically). Let's assume 0V on the left copper trace, +125°C at Junction #1, a temperature gradient of 10°C/in (0.394°C/mm) from left to right (0 in the vertical direction) and a 1206 SMD resistor.

The resistor is 0.12 in long (3.05 mm) and 0.06 in wide (1.52 mm). Assume the end caps are about 0.01 in long (0.25 mm) and the metal film is about 0.10 in long (2.54 mm). The results are shown in [Figure 4](#).



**FIGURE 4:** Axial Gradient Results.

Thus, the temperature gradient of 10°C/in (1.2°C increase from left to right) caused a total of -38 μV to appear across this resistor. Notice that adding the same temperature change to all junction temperatures will not change this result.

**Note:** Shifting all of the junction temperatures by the same amount does not change the temperature gradient. This means that the voltage drop between any two points in the circuit using the same conductive material is the same (assuming we are within the linear region of response).

## PREVENTING LARGE THERMOELECTRIC VOLTAGES

This section includes several general techniques that prevent the appearance of large temperature gradients at critical components.

### Reduced heat generation

When a PCB's thermal gradient is mainly caused by components attached to it, then find components that dissipate less power. This can be easy to do (e.g., change resistors) or hard (change a PICmicro® microcontroller).

Increasing the load resistance, and other resistor values, also reduces the dissipated power. Choose lower power supply voltages, where possible, to further reduce the dissipated power.

### Redirect the Heat Flow

Changing the direction that heat flows on a PCB, or in its immediate environment, can significantly reduce temperature gradients. The goal is to create nearly constant temperatures in critical areas.

### ALTERNATE HEAT PATHS

Adding heat sinks to parts that dissipate a lot of power will redirect the heat to the surrounding air. One form of heat sink that is often overlooked is either ground planes or power planes in the PCB; they have the advantage of making temperature gradients on a PCB lower because of their large (horizontal) thermal conductivity.

Adding a fan to a design will also redirect heat to the surrounding air, which reduces the temperature drop on the PCB. This approach, however, is usually avoided to minimize other design issues (random temperature fluctuations, acoustic noise, power, cost, etc.). It is important to minimize air (convection) currents near critical components. Enclose either the parts with significant temperature rise, or the critical parts. Conformal coating may also help.

### ISOLATION FROM HEAT GENERATORS

It is possible to thermally isolate critical areas on the PCB. Regions with little or no metal act like a good thermal insulator. Signals that need to cross these regions can be sent through series resistors, which will also act as poorly conducting thermal elements.

Place heat sources as far away from critical points as possible. Since many heat sources are in the external environment, it can be important to place these critical points far away from the edges of the PCB. Components that dissipate a lot of power should be kept far away from critical areas of the PCB.

Low profile components will have reduced exposure to the external environment. They may have the additional advantage of reduced electrical crosstalk.

Thermal barriers, such as conformal coating and PCB enclosures, can be helpful too. They usually do not have to be added unless there are other compelling reasons to do so.

## Slow Temperature Changes

In some applications, sudden changes in thermoelectric voltages can also be a concern.

Avoid power-up and power-down thermal transient problems by minimizing the currents drawn during these times. Also, reducing the times can help.

Quick changes in voltages at heavy loads can be another source of concern. If the load cannot be made lighter, then isolation is usually the best approach to solving this problem.

## CURING THERMOELECTRIC VOLTAGE EFFECTS

This section focuses on methods that minimize the effects of a given temperature gradient. They can be powerful aids in improving a design because they tend to be low cost.

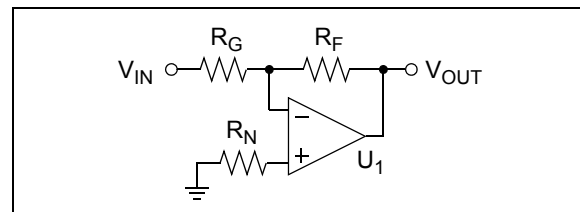
### Metallurgy

Critical points, that need to have the same total thermoelectric voltage, should use the same conductive material. For example, the inputs to an op amp should connect to the same materials. The PCB traces will match well, but components with different constructions may be a source of problems.

It is possible to find combinations of metals and solders that have low Seebeck coefficients. While this obviously reduces voltage errors, this can be complicated and expensive to implement in manufacturing.

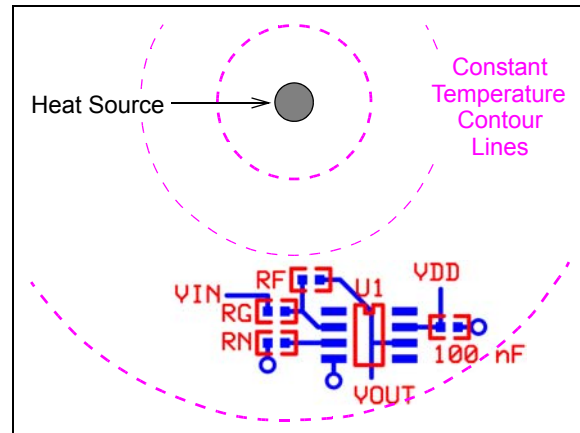
### Following Contour Lines

Place critical components so that their current flow follows constant temperature contour lines; this minimizes their thermoelectric voltages. [Figure 5](#) shows an inverting amplifier that will be used to illustrate this concept;  $R_N$ ,  $R_G$  and  $R_F$  are the critical components in this circuit.



**FIGURE 5:** *Inverting Amplifier.*

[Figure 6](#) shows one implementation of this concept. Constant temperature contour lines become reasonably straight when they are far from the heat source. Placing the resistors in parallel with these lines minimizes the temperature drop across them.



**FIGURE 6:** *Resistors Aligned with Contour Lines.*

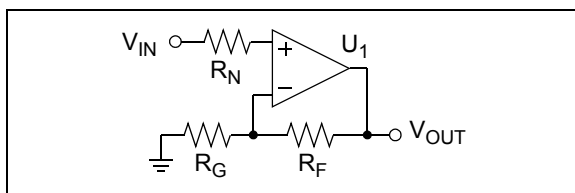
The main drawback to this technique is that the contour lines change when the external thermal environment changes. For instance, picking up a PCB with your hands adds heat to the PCB, usually at locations not accounted for in the design.

## Cancellation of Thermoelectric Voltages

It is possible to cancel thermoelectric voltages when the temperature gradient is constant. Several examples will be given to make this technique easy to understand.

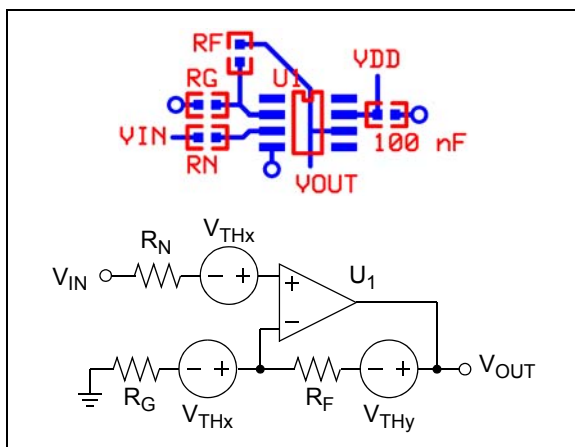
### TRADITIONAL OP AMP LAYOUT APPROACH

Figure 7 shows a non-inverting amplifier that needs to have the resistors' thermoelectric voltage effect minimized. The traditional approach is to lay out the input resistors ( $R_N$  and  $R_G$ ) close together, at equal distances from the op amp input pins and in parallel.



**FIGURE 7:** Non-inverting Amplifier.

Figure 8 shows one layout that follows the traditional approach, together with a circuit diagram that includes the resulting thermoelectric voltages ( $V_{THx}$  and  $V_{THy}$ ).  $V_{THx}$  is positive on the right side of a horizontally oriented component (e.g.,  $R_N$ ).  $V_{THy}$  is positive on the top side of a vertically oriented component (e.g.,  $R_F$ ).



**FIGURE 8:** One Possible Layout (not recommended) and its Thermoelectric Voltage Model.

The output has a simple relationship to the inputs ( $V_{IN}$  and the three thermal sources  $V_{THx}$  and  $V_{THy}$ ):

### EQUATION 2:

$$\begin{aligned} G_N &= 1 + R_F/R_G \\ V_{OUT} &= (V_{IN} + V_{THx})G_N - V_{THx}(G_N - 1) + V_{THy} \\ &= V_{IN}G_N + V_{THx} + V_{THy} \end{aligned}$$

When the gain ( $G_N$ ) is high, the thermoelectric voltage's contribution to the output error is relatively small. This layout may be good enough in that case. Notice that the cancellation between  $R_N$  and  $R_G$  is critical to good performance.

When the gain is low, or the very best performance is desired, this layout needs to be improved. The following sections give additional guidance that will help achieve this goal.

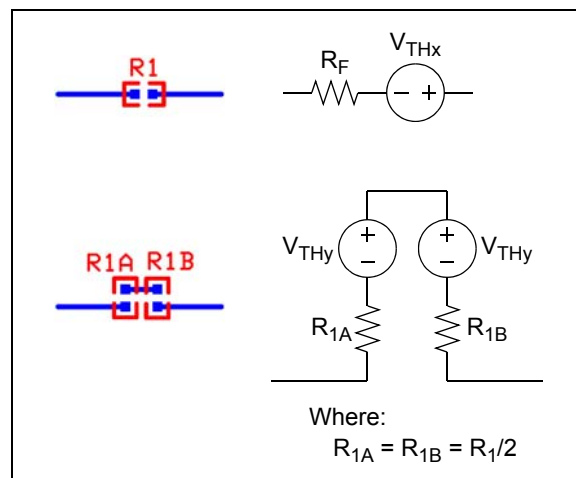
### SINGLE RESISTOR SUBSTITUTIONS

A single resistor on a PCB will produce a thermoelectric voltage, as discussed before. Replacing that resistor with two resistors that are properly aligned will cancel the two resulting thermoelectric voltages.

Figure 9 shows the original resistor and its model on the top, and a two series resistor substitution and its model on the bottom.

The original resistor has a thermally induced voltage  $V_{THx}$  that is based on the temperature gradient in the x-direction (horizontal).

The two resistors on the bottom have thermally induced voltages  $V_{THy}$  that are based on the temperature gradient in the y-direction (vertical); they are equal because the temperature gradient is constant and the resistor lengths are equal. Due to their parallel alignment, these voltages cancel; the net thermally induced voltage for this combination (as laid out) is zero.



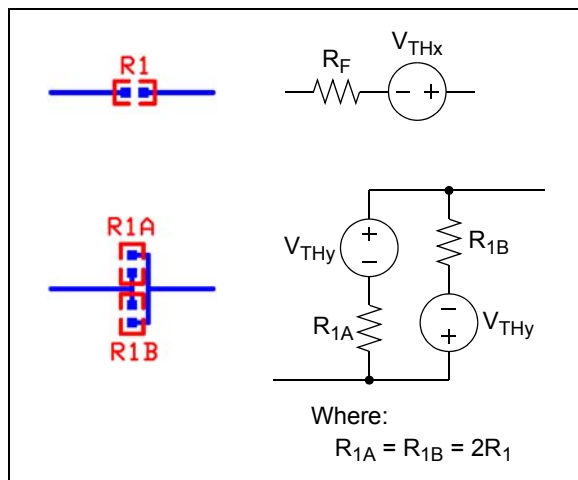
**FIGURE 9:** Series Resistor Substitution.

**Note:** The orientation of these two resistors ( $R_{1A}$  and  $R_{1B}$ ) is critical to canceling the thermoelectric voltages.

Figure 10 shows the original resistor and its model on the top, and a two parallel resistor substitution and its model on the bottom.

The original resistor has a thermally induced voltage  $V_{THx}$  that is based on the temperature gradient in the x-direction (horizontal).

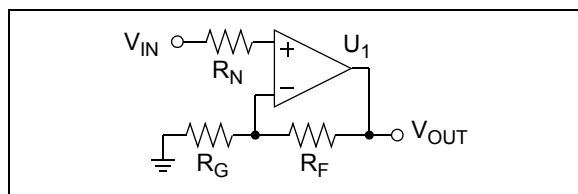
The two resistors on the bottom have thermally induced voltages  $V_{THy}$  that are based on the temperature gradient in the y-direction (vertical); they are equal because the temperature gradient is constant and the resistor lengths are equal. Due to their orientation, and because  $R_{1A} = R_{1B}$ , these voltages produce currents that cancel. The net thermally induced voltage for this combination (as laid out) is zero.



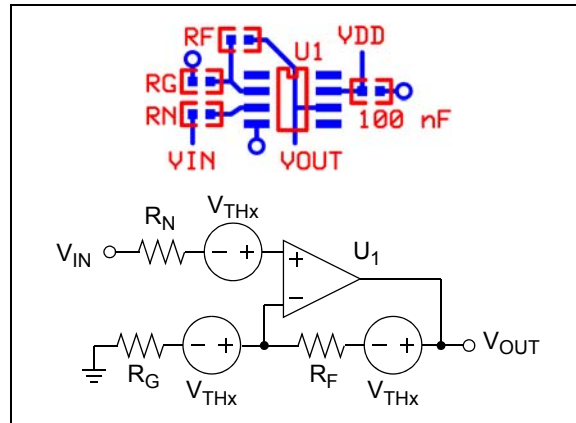
**FIGURE 10:** Parallel Resistor Substitution.

## NON-INVERTING AMPLIFIER

Figure 11 shows a non-inverting amplifier. We will start with the layout in Figure 12 (previously shown in Figure 6). The resistor  $R_F$  is horizontal so that all of the thermoelectric voltages may be (hopefully) cancelled. The model shows how the thermoelectric voltages modify the circuit.



**FIGURE 11:** Non-inverting Amplifier.



**FIGURE 12:** First Layout (not recommended) and its Thermoelectric Voltage Model.

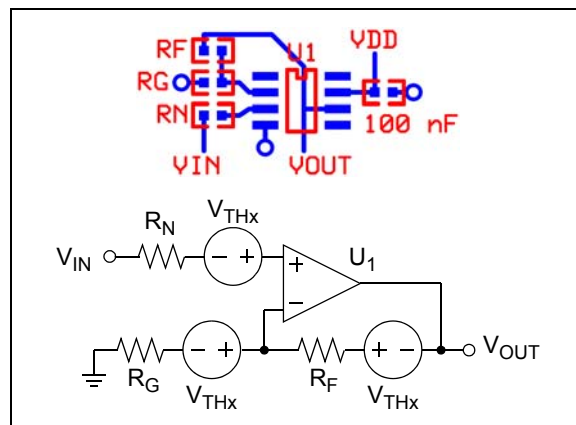
The output has a simple relationship to the inputs ( $V_{IN}$  and the three  $V_{THx}$  sources):

## EQUATION 3:

$$\begin{aligned} G_N &= 1 + R_F/R_G \\ V_{OUT} &= (V_{IN} + V_{THx})G_N - V_{THx}(G_N - 1) + V_{THx} \\ &= V_{IN}G_N + 2V_{THx} \end{aligned}$$

When the gain ( $G_N$ ) is high, the thermoelectric voltage's contribution to the output error is relatively small. This layout may be good enough in that case. Notice that the cancellation between  $R_N$  and  $R_G$  is critical.

We have a better layout shown in Figure 13. Recognizing that subtracting the last term in the  $V_{OUT}$  equation (middle equation in Figure 3) completely cancels the thermoelectric voltages, the resistor  $R_F$  was oriented in the reverse direction.



**FIGURE 13:** Second Layout and its Thermoelectric Voltage Model.



With the reversed direction for  $R_F$ , the output voltage is now:

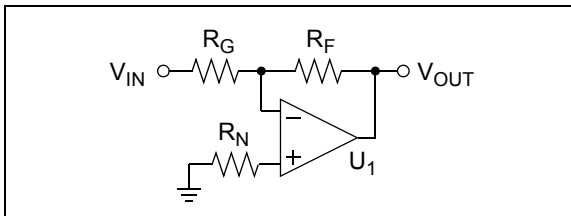
## EQUATION 4:

$$\begin{aligned} G_N &= 1 + R_F/R_G \\ V_{OUT} &= (V_{IN} + V_{THx})G_N - V_{THx}(G_N - 1) - V_{THx} \\ &= V_{IN}G_N \end{aligned}$$

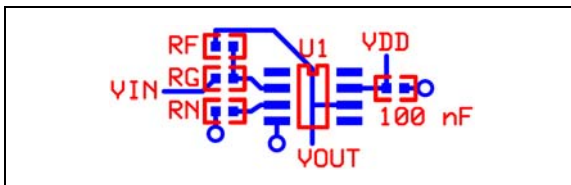
The cancellation between  $R_N$  and  $R_G$  is critical to this layout; the change to  $R_F$ 's position is also important.

## INVERTING AMPLIFIER

Figure 14 shows an inverting amplifier. Because it uses the same components as the non-inverting amplifier, the resistor layout is the same; see Figure 15.



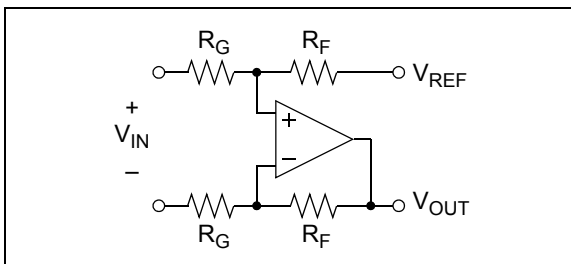
**FIGURE 14:** Inverting Amplifier.



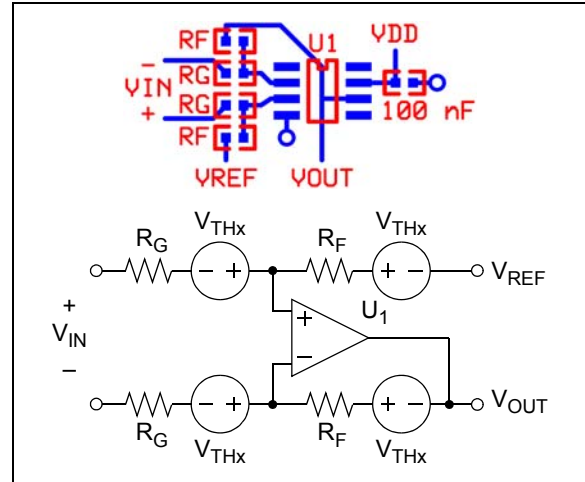
**FIGURE 15:** Inverting Amplifier Layout.

## DIFFERENCE AMPLIFIER

Figure 16 shows a difference amplifier. This topology has an inherent symmetry between the non-inverting and inverting signal paths, which lends itself to cancelling the thermoelectric voltages. Figure 17 shows the layout and its model.



**FIGURE 16:** Difference Amplifier.



**FIGURE 17:** Difference Amplifier Layout and its Thermoelectric Voltage Model.

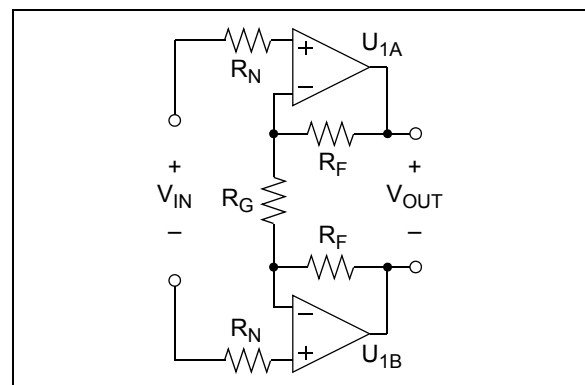
The output has a simple relationship to the inputs ( $V_{IN}$ ,  $V_{REF}$  and the four  $V_{THx}$  sources):

## EQUATION 5:

$$\begin{aligned} G &= R_F/R_G \\ V_{OUT} &= (V_{IN} + V_{THx} - V_{THx})G \\ &\quad + (V_{REF} + V_{THx} - V_{THx}) \\ &= V_{IN}G + V_{REF} \end{aligned}$$

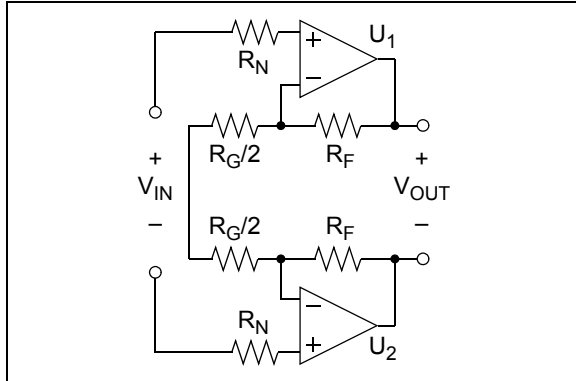
## INSTRUMENTATION AMPLIFIER INPUT STAGE

Figure 18 shows an instrumentation amplifier input stage, which is sometimes used to drive the input of a differential ADC. While this is a symmetrical circuit, achieving good thermoelectric voltage cancellation on the PCB presents difficulties. It is best to use a dual op amp, so the  $R_F$  resistors have to be on both sides of the op amp, while  $R_G$  connects both sides; the distances between resistors are too large to be practical (thermal gradient is not constant).

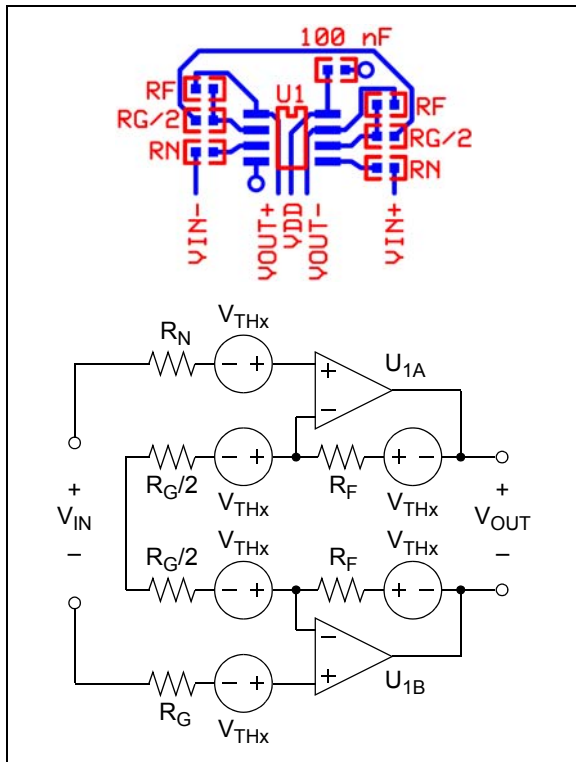


**FIGURE 18:** Instrumentation Amplifier Input Stage (not recommended).

The solution to this problem is very simple; split  $R_G$  into two equal series resistors so that we can use the non-inverting layout (i.e., [Figure 13](#)) on both sides of the dual op amp. Each side of this amplifier will cancel its thermoelectric voltages independently; this is shown in [Figure 19](#) and [Figure 20](#).



**FIGURE 19:** Instrumentation Amplifier Input Stage.



**FIGURE 20:** Instrumentation Amplifier Input Stage Layout and its Thermoelectric Voltage Model.

The  $V_{THx}$  sources cancel, for the reasons already given, so the differential output voltage is simply:

## EQUATION 6:

$$G = 1 + 2R_F/R_G$$

$$V_{OUT} = V_{IN}G$$

## MODIFICATIONS FOR NON-CONSTANT TEMPERATURE GRADIENTS

Temperature gradients are never exactly constant. One cause is the wide range of thermal conductivities (e.g., traces vs. FR4) on a PCB, which causes complex temperature profiles. Another cause is that many heat sources act like point sources, and the heat is mainly conducted by a two dimensional object (the PCB); the temperature changes rapidly near the source and slower far away.

Non-constant temperature gradients will cause the temperature profile to have significant curvature, which causes all of the previous techniques to have less than perfect success. Usually, the curvature is small enough so that those techniques are still worth using. Other times, additional measures are needed to overcome the problems caused by the curvature.

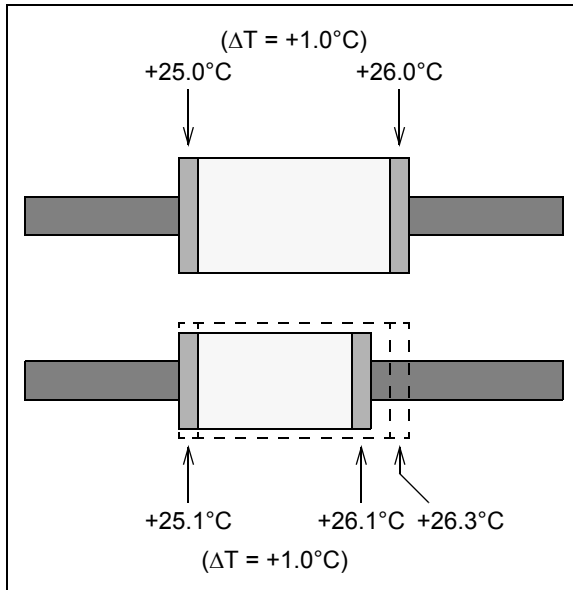
One method is to minimize the size of critical components (e.g., resistors). If we assume that temperature has a quadratic shape, then using components that are half as long should reduce the non-linearity error to about one quarter the size.

Another method is to keep all heat sources and sinks far away from the critical components. This makes the contour lines straighter.

The contour lines can be deliberately changed in shape. Using a ground plane (also power planes) to conduct heat away from the sources helps equalize the temperatures, which reduces the non-linear errors. Adding guard traces or thermal heat sinks that surround the critical components also help equalize the temperatures.

We can deliberately mismatch the sizes of the critical components so that the cancellation becomes closer to exact. In order to match resistors, for instance, we need to make sure that the temperature change across each of the matched resistors is equal; see [Figure 21](#) for an illustration.





**FIGURE 21:** Example of Mismatching the Component Sizes.

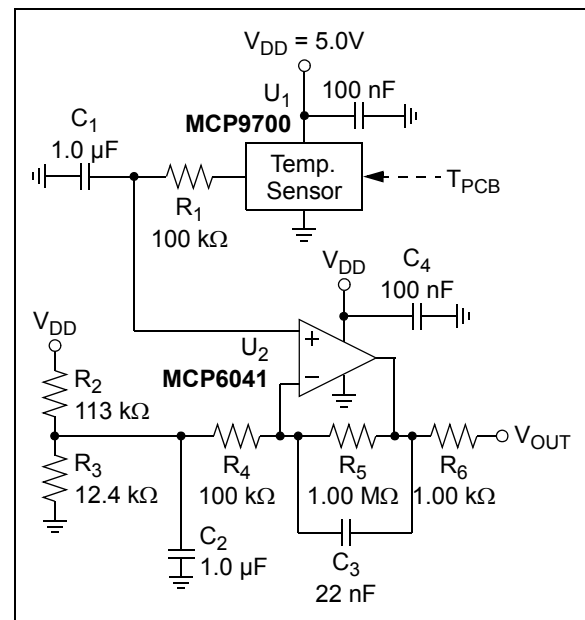
## MEASUREMENT OF TEMPERATURE RELATED QUANTITIES

While the techniques previously shown are a great help in producing an initial PCB layout, it is important to verify that your design functions as specified. This section includes methods for measuring the response of individual components and of a PCB. With this information, it is possible to make intelligent design tweaks.

### TEMPERATURE

There are many ways to measure temperature [3, 4, 5]. We could use thermocouples, RTDs, thermistors, diodes, ICs or thermal imagers (infrared cameras) to measure the temperature.

Figure 22 shows a circuit based on the MCP9700 IC temperature sensor. Because all of the components draw very little current, their effect on PCB temperature will be minimal. There is also enough filtering and gain to make  $V_{OUT}$  easy to interpret. This circuit can be built on a very small board of its own, which can be easily placed on top of the PCB of interest.



**FIGURE 22:** IC Temperature Sensor Circuit.

The MCP9700 outputs a voltage of about 500 mV plus 10.0 mV/°C times the board temperature ( $T_{PCB}$ , in °C). The amplifier provides a gain of 10 V/V centered on 500 mV (when  $V_{DD} = 5.0V$ ), giving:

### EQUATION 7:

$$V_{OUT} = (500 \text{ mV}) + T_{PCB}(100 \text{ mV/}^{\circ}\text{C})$$

Since the MCP9700 outputs a voltage proportional to temperature,  $V_{OUT}$  needs to be sampled by an ADC that uses an absolute voltage reference.

The absolute accuracy of this circuit does not support our application, so it is important to calibrate the errors. Leave the PCB in a powered off state (except for the temperature sensor) for several minutes. Measure  $V_{OUT}$  at each point, with adequate averaging. Then, power up the PCB and measure the new  $V_{OUT}$  values; the changes in  $V_{OUT}$  from the calibration value represents the change in  $T_{PCB}$  from the no power condition.

## THERMAL GRADIENTS

To measure thermal gradients, simply measure the temperature at several points on the PCB. The gradient is then the change in temperature divided by the distance between points. More points give better resolution on the gradient, but reduce the accuracy of the numerical derivative.

## PACKAGE THETA\_JA

The way to estimate a component's temperature rise ( $\Delta T$  in  $^{\circ}\text{C}$ ) of a component is to multiply its dissipated power ( $P$  in W) by the package thermal resistance ( $\theta_{JA}$  in  $^{\circ}\text{C}/\text{W}$ ). This helps establish temperature maximum points.

To measure  $\theta_{JA}$ , when it is not given in a data sheet, place the temperature sensor at the IC (usually, a thermocouple between the package and the PCB). Insert a small resistor in the supply to measure the supply current when on ( $I_{DD}$  in A). Measure the change in temperature ( $\Delta T$  in  $^{\circ}\text{C}$ ) between the off and on conditions, supply voltage ( $V_{DD}$  in V) and  $I_{DD}$ . Then,

## EQUATION 8:

$$\theta_{JA} = \frac{\Delta T}{V_{DD} I_{DD}}$$

## THERMOELECTRIC VOLTAGES

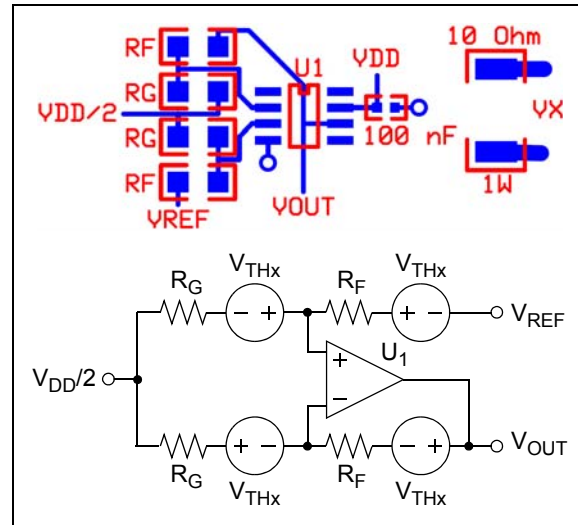
The easiest way to measure thermoelectric voltages is to thermally imbalance a difference amplifier circuit. The thermoelectric voltages have a polarity that adds (instead of cancelling) in Figure 23 (compare to Figure 17). The differential input voltage is zero, and the resistors are larger, to emphasize the thermoelectric voltages.

The large resistor on the right of the layout can be used to generate a horizontal temperature gradient at the resistors  $R_G$  and  $R_F$ . The gain ( $G$ ) is set high to make the measurements more accurate. The thermoelectric voltage ( $V_{THx}$ ) across one resistor is:

## EQUATION 9:

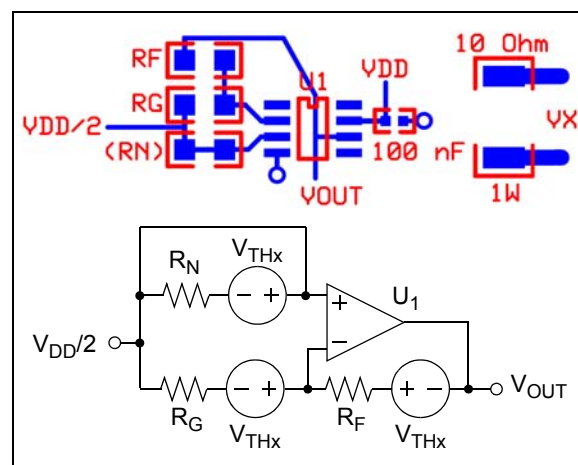
$$G = R_F / R_G$$

$$V_{THx} = \frac{V_{OUT} - V_{REF}}{2G + 2}$$



**FIGURE 23:** Difference Amplifier with Deliberately Unbalanced Thermoelectric Voltages and Heat Generating Resistor.

We can also place a short across one component, of a matched pair, with a copper trace on the PCB. Figure 24 shows a non-inverting amplifier layout that shorts  $R_N$  (compare to Figure 13) to unbalance the thermoelectric voltages. It also connects the two inputs together, and uses larger resistors, to simplify measurements ( $V_{OUT} = V_{DD}/2$ , ideally). The short is easily removed from the PCB.



**FIGURE 24:** Shorted Resistor ( $R_N$ ) that Unbalances Thermoelectric Voltages.

With the unbalance, we now have the thermoelectric voltage:

#### EQUATION 10:

$$G_N = I + R_F/R_G$$

$$V_{THx} = \frac{V_{OUT} - V_{DD}/2}{-G_N}$$

#### TROUBLESHOOTING TIPS AND TRICKS

Using a strip chart to track the change in critical DC voltages over time helps locate the physical source of the errors. Not only can it show how large the change is between two different thermal conditions (e.g., on and off), but it shows the time constants of these shifts. They can be roughly divided into the following three categories:

- Time constant  $\ll 1$  s, within component (e.g., thermal crosstalk within an op amp)
- Time constant  $\approx 1$  s, single component (e.g., in an eight lead SOIC package)
- Time constant  $\gg 1$  s, PCB and its environment

To quickly and easily change the temperature at one location on a PCB, do the following. Use a clean drinking straw to blow air at the location (component) of interest. Use a piece of paper to re-direct the airflow away from other nearby components. When troubleshooting, the paper can be used to divide a PCB area in half to help locate the problem component. This approach does not give exact numbers, but can be used to quickly find problem components on a PCB.

You can use a heat sink (with electrically insulating heat sink compound) to reduce the temperature difference between two critical points on your PCB. The greater the area covered at both ends of the heat sink, the quicker and better will this thermal “short” work.

## MISCELLANEOUS EFFECTS

While thermoelectric voltages are usually the dominant error source in high precision designs, there are other error sources that need to be controlled.

### Socketed Components

Sometimes, for convenience on the bench, a PCB has sockets for critical components (e.g., an op amp). While these sockets make it easy to change components, they cause significant DC errors in high precision designs.

The problem is that the socket and the IC pins are made of different metals, and are mechanically forced into contact. In this situation, there is a (contact) voltage potential developed between the metals (the Volta effect). Physicists explain this phenomenon through the difference between their work functions. In our bench tests of our auto-zeroed op amps, we saw voltage potentials of  $\pm 1 \mu\text{V}$  to  $\pm 2 \mu\text{V}$  due to the IC socket.

The solution is very simple; do not use sockets for critical components. Instead, solder all critical components to the PCB.

### PCB Surface Contamination

#### CLEANING

It is well known that surface contamination of a PCB will create high resistance leakage paths for current (moisture due to high humidity is a common contaminant). Bench work with Microchip's auto-zeroed op amps has demonstrated that this effect can cause appreciable voltage shifts, even in well designed circuits.

Our experience has been that a standard PCB clean step is very helpful, but may not eliminate the problem. An additional cleaning step using isopropyl alcohol is needed to clean the residue left by some PCB cleaning solvents. This can then be blown dry using compressed air (with an in-line moisture trap).

#### COATING

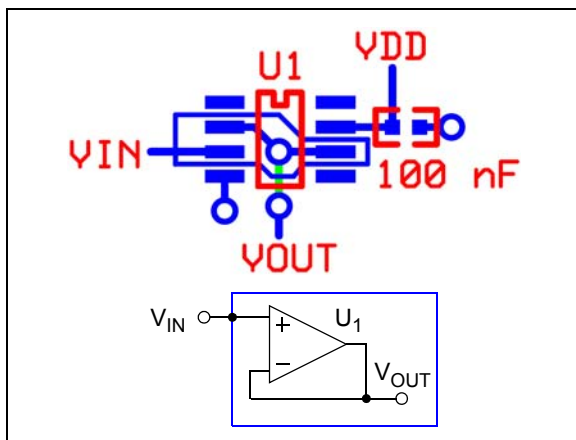
In order to maintain the PCB cleanliness after the initial clean, it is necessary to coat the PCB surface. The coating needs to be a barrier to moisture and other contaminants. A conformal coating of epoxy or silicone rubber will do the job in many applications.

#### GUARD RINGS

Guard traces placed around critical signal traces can significantly reduce PCB surface leakage currents. Surface leakage is caused by humidity, dust or other contamination on the board. Under low humidity conditions, a typical resistance between nearby traces is  $10^{12} \Omega$ . A 5V difference would cause 5 pA of current to flow.

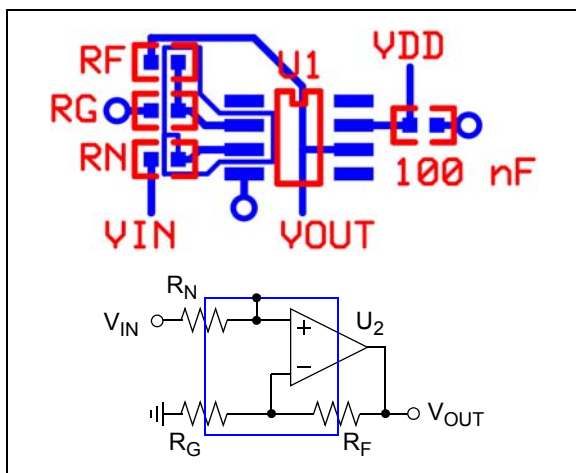
The guard ring is biased at the same voltage as the sensitive pin(s), and is driven by a low impedance source. For instance, the input pins of an op amp need protection from its other pins, which may be at substantially different voltages.

Figure 25 shows a unity gain buffer with a guard ring (the layout plots in this section are at a larger scale for better viewing). This guard ring is biased by the input voltage source ( $V_{IN}$ ) and protects (surrounds) both inputs on the PCB surface. Since  $V_{OUT}$  is shorted to the inverting input, it is also surrounded by the guard ring. The output signal traces go through a via to another layer, then back to the same surface through another via outside of the guard ring; they are protected because they are driven by  $V_{OUT}$ .



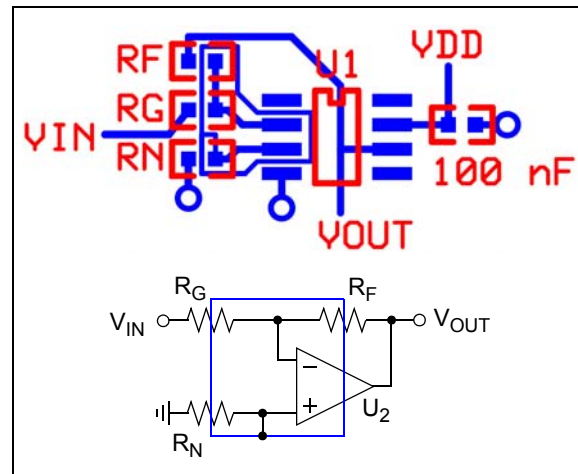
**FIGURE 25:** Guard Ring for Unity Gain Buffer.

Figure 26 shows how a guard ring is implemented for a non-inverting amplifier. It surrounds the traces connected to the two inputs. It is connected to the non-inverting input because  $V_{IN}$  and  $R_N$  form a low impedance source in good designs.



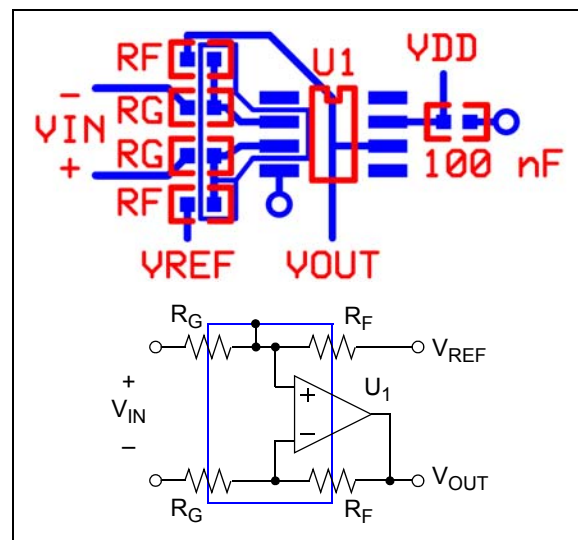
**FIGURE 26:** Guard Ring for Non-inverting Gain Amplifier.

Figure 27 shows an inverting amplifier with a guard ring. The only change from a non-inverting amplifier is where  $R_N$  and  $R_G$  are connected to.



**FIGURE 27:** Guard Ring for Inverting Gain Amplifier.

Figure 28 shows a difference amplifier with a guard ring. The only change from the non-inverting amplifier is the additional  $R_F$  resistor connected to  $V_{REF}$ .



**FIGURE 28:** Guard Ring for Difference Amplifier.

For op amps in through hole packages (e.g., PDIP), guard rings are needed on both top and bottom surfaces. Otherwise, the guard ring topology is basically the same.

## TEFLON STANDOFFS

Another option, for circuits that need the lowest leakage currents, is to place critical circuit nodes on teflon standoffs.

## DESIGN EXAMPLE

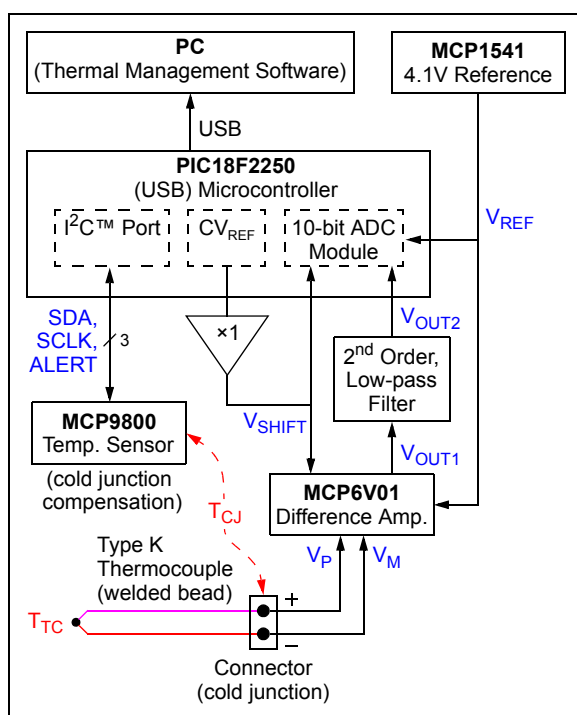
This section goes over the thermal design of a thermocouple PCB available from Microchip. This PCB has the following descriptors:

- MCP6V01 Thermocouple Auto-Zeroed Reference Design
- 104-00169-R2
- MCP6V01RD-TCPL

The application of this PCB is discussed in detail in reference [6].

## Circuit Description

Figure 29 shows the general functionality of this design (the schematic is shown in Figure A-1).



**FIGURE 29:** Thermocouple Circuit's Block Diagram.

The (type K) thermocouple senses temperature at its hot junction ( $T_{TC}$ ) and produces a voltage at the cold junction (at temperature  $T_{CJ}$ ). The conversion constant for type K thermocouples is roughly  $40 \mu V/^{\circ}C$ . This voltage ( $V_P - V_M$ ) is input to the Difference Amplifier (MCP6V01).

The MCP9800 senses temperature at the Type K Thermocouple's cold junction ( $T_{CJ}$ ). The result is sent to the PICmicro microcontroller via an I<sup>2</sup>C™ bus. The PICmicro's firmware corrects the measured temperature for  $T_{CJ}$ .

The difference amplifier uses the MCP6V01 auto-zeroed op amp to amplify the thermocouple's output voltage. The  $V_{REF}$  input shifts the output voltage down so that the temperature range includes  $-100^{\circ}C$ .

The  $V_{SHIFT}$  input shifts the output voltage, using a digital POT internal to the PICmicro ( $CV_{REF}$ ), so that the temperature range is segmented into 16 smaller ranges; this allows us to cover the  $-100^{\circ}C$  to  $+1000^{\circ}C$  range with reasonable accuracy.

The MCP1541 provides an absolute reference voltage because the thermocouple's voltage depends only on temperature (not on  $V_{DD}$ ). It sets the nominal  $V_{OUT}$  and serves as the reference for the ADC internal to the PICmicro.

The 2<sup>nd</sup> Order, Low-pass Filter reduces noise and aliasing at the ADC input. A double R-C filter was chosen to minimize DC errors and complexity.

$CV_{REF}$  is a digital POT with low accuracy and highly variable output resistance. The buffer ( $\times 1$  amplifier) eliminates the output impedance problem, producing the voltage  $V_{SHIFT}$ . Since  $CV_{REF}$  has 16 levels, we can shift  $V_{OUT1}$  by 16 different amounts, creating 16 smaller ranges; this adds 4 bits resolution to the measured results (the most significant bits). The 10 bits produced by the ADC are the least significant bits; they describe the measured values within one of the 16 different smaller ranges.

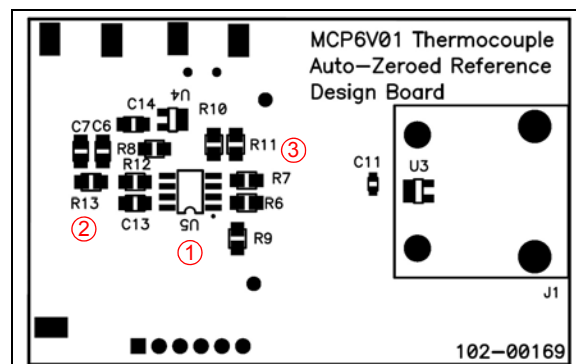
$V_{SHIFT}$  is brought back into the PICmicro so that it can be sampled by the ADC. This gives  $V_{SHIFT}$  values the same accuracy as the ADC ("10 bits"), which is significantly better than  $CV_{REF}$ 's accuracy. The measured value of  $V_{OUT2}$  is adjusted by this measured  $V_{SHIFT}$  value.

The overall accuracy of this mixed signal solution is set by the 10-bit ADC. The resolution is 14 bits, but the accuracy cannot be better than the ADC, since it calibrates the measurements.

## PCB Layout

In the figures in this section (Figure 30 through Figure 35), the red numbers (inside the circles) point to key design choices, which are described by a list after each figure.

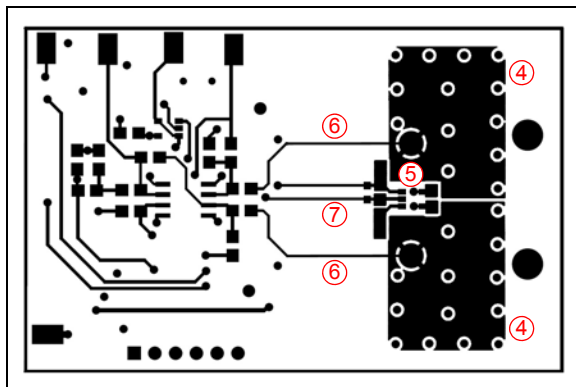
Figure 30 shows the top silk screen layer of the PCB designed for the MCP6V01 Thermocouple Auto-Zeroed Reference Design.



**FIGURE 30:** 1<sup>st</sup> Layer – Top Silk.

1. The Difference Amplifier is as close to the sensor as possible, and is on the opposite PCB surface from the PICmicro microcontroller. This minimizes electrical and thermal crosstalk between the two active devices.
2. Small resistors (0805 SMD) reduce the thermoelectric voltages, for a given temperature gradient.
3. The resistors that are a part of the Difference Amplifier play a critical role in this design's accuracy.
  - a) R6 and R7 are at the input from the thermocouple, and give a gain of 1000 V/V to  $V_{OUT1}$ . They are arranged so that their thermoelectric voltages cancel.
  - b) R9 and R10 are at the input from the range selection circuitry ( $V_{SHIFT}$ ), and give a gain of 17.9 V/V to  $V_{OUT1}$ . Changing their location and orientation on the PCB might improve the performance.
  - c) R8 and R11 convert the inputs to the output voltage ( $V_{OUT1}$ ). Changing their location and orientation may not improve the performance enough to be worth the trouble.

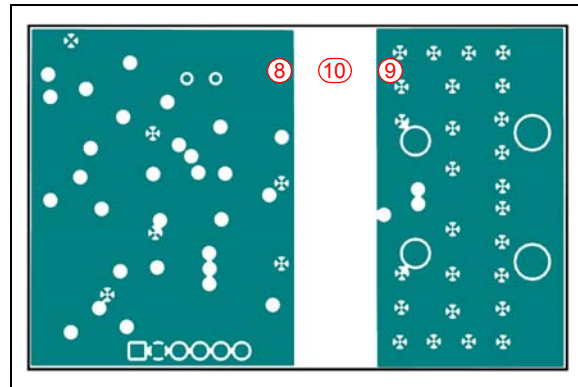
Figure 31 shows the top metal layer of the PCB. The sensitive analog and sensor circuitry is connected to this layer.



**FIGURE 31:** 1<sup>st</sup> Layer – Top Metal.

4. Metal fill, connected to the ground plane, minimizes thermal gradients at the cold junction connector.
5. The MCP9800 Temperature Sensor (cold junction compensation) is centered at the cold junction connector to give the most accurate reading possible.
6. Sensor traces are separated from power (top layer) and digital (bottom layer) traces to reduce crosstalk.
7. The MCP9800's power traces are kept short, straight and above ground plane for minimal crosstalk.

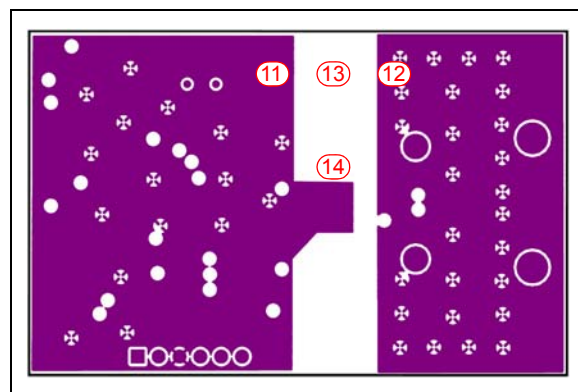
Figure 32 shows the power plane. It minimizes noise conducted through the power supplies and isolates the analog and digital signals.



**FIGURE 32:** 2<sup>nd</sup> Layer – Power Plane.

8. The power plane on the left helps keep the temperature relatively constant near the auto-zeroed op amp. It also provides isolation from the PICmicro microcontroller's electrical and thermal outputs.
9. The power plane on the right helps keep the temperature relatively constant near the thermocouple's cold junction and MCP9800 cold junction temperature sensor.
10. The FR4 gap provides attenuation to heat flow (a relatively high temperature drop) between the active components on the left (MCP6V01 and PIC18F2550) and the sensors on the right (thermocouple and MCP9800).

Figure 33 shows the ground plane. It also minimizes noise conducted through the power supplies and isolates the analog and digital signals.



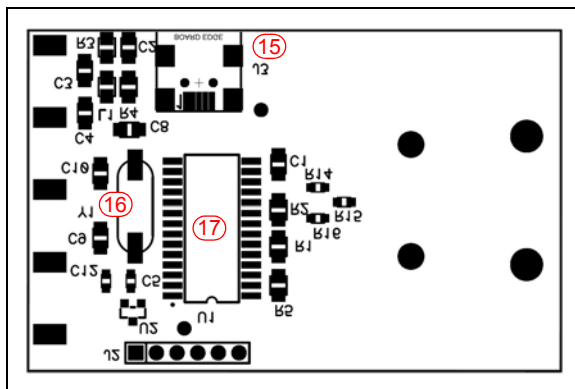
**FIGURE 33:** 3<sup>rd</sup> Layer – Ground Plane.

11. Same function as #8.
12. Same function as #9.
13. Same function as #10.



14. This ground plane extension provides better isolation between digital signals and the MCP9800's power supply. It also helps protect the thermocouple signal lines. However, it increases the thermal conduction between the left and right sides of the PCB.

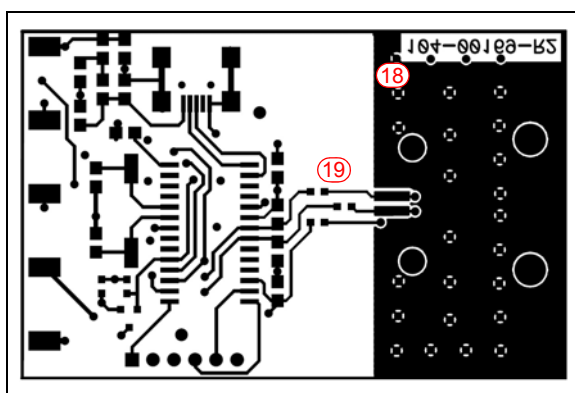
Figure 34 shows the bottom silk layer.



**FIGURE 34:** 4<sup>th</sup> Layer – Bottom Silk.

15. The USB connector and its components are isolated from the rest of the circuit.
16. The crystal (XTAL) oscillator is as far from everything else as possible, except from the clock input pins of the PICmicro microcontroller.
17. The PICmicro microcontroller produces both thermal and electrical crosstalk, so it is isolated from the analog components.

Figure 35 shows the bottom metal layer of the PCB. The digital circuitry is connected to this layer.



**FIGURE 35:** 4<sup>th</sup> Layer – Bottom Metal.

18. Metal fill, connected to the ground plane, minimizes thermal gradients at the cold junction.
19. The digital traces that run under the ground plane extension have series resistors inserted inside the FR4 gap. This reduces the thermal conduction between the sides that solid traces would produce; otherwise, these traces would become the worst case thermal conductor between PICmicro and the temperature sensors.

## SUMMARY

This application note covers thermal effects on Printed Circuit Boards (PCB) encountered in high (DC) precision op amp circuits. Causes, effects and fixes have been covered.

Thermocouple junctions are everywhere on a PCB. The Seebeck effect tells us that these junctions create a thermoelectric voltage. This was shown to produce a voltage across resistors (and other components) in the presence of a temperature gradient.

Preventing large thermoelectric voltages from occurring is usually the most efficient way to deal with thermocouple junctions. The amount of heat generated on the PCB can be reduced, and the heat flow redirected away from critical circuit areas. It also pays to keep any temperature changes from occurring too quickly.

Any remaining thermoelectric voltage effects need to be reduced. Choosing the metals, in critical areas, to have approximately the same work function will minimize the thermoelectric coefficients of the metal junctions. Critical components can be oriented so that they follow constant temperature contour lines. It is possible to cancel most of the thermoelectric voltage effects at the input of op amps by correctly orienting them. Smaller components, spaced closer together, will also help.

Once a design has been implemented on a PCB, it pays to measure its thermal response. Information on where to focus design effort can greatly speed up the design process. Information has been given on measuring temperature, thermal gradients, packages'  $\theta_{JA}$  and troubleshooting tips and tricks.

Two PCB related effects that are not related to thermocouple junctions were also covered. The existence of contact potential in socketed components emphasizes the need to solder critical components to the PCB. Leakage currents due to PCB surface contaminants are reduced using: cleaning, conformal coating, guard rings and teflon standoffs.

A design example using the MCP6V01 Thermocouple Auto-zeroed Reference Design PCB illustrates the theory and recommendations given in this application note. The circuit operation is described, then the PCB layout choices are covered in detail.

At the end of this application note are given references to the literature and an appendix with the design example's schematic.

## REFERENCES

### Related Application Notes

- [1] AN1177, *“Op Amp Precision Design: DC Errors,”* Kumen Blake; Microchip Technology Inc., DS01177, 2008.
- [2] AN1228, *“Op Amp Precision Design: Random Noise,”* Kumen Blake; Microchip Technology Inc., DS01228, 2008.

### Other Application Notes

- [3] AN990, *“Analog Sensor Conditioning Circuits – An Overview,”* Kumen Blake; Microchip Technology Inc., 2005.
- [4] AN684, *“Single Supply Temperature Sensing with Thermocouples,”* Bonnie C. Baker; Microchip Technology Inc., DS00684, 1998.
- [5] AN679, *“Temperature Sensing Technologies,”* Bonnie Baker, Microchip Technology Inc., DS00679, 1998.

### Other References

- [6] User's Guide, *“MCP6V01 Thermocouple Auto-Zeroed Reference Design,”* Microchip Technology Inc., DS51738, 2008.
- [7] *“The OMEGA® Made in the USA Handbook™,”* Vol. 1, OMEGA Engineering, Inc., 2002.

## APPENDIX A: PCB SCHEMATIC (MCP6V01 THERMOCOUPLE AUTO-ZEROED REFERENCE DESIGN)

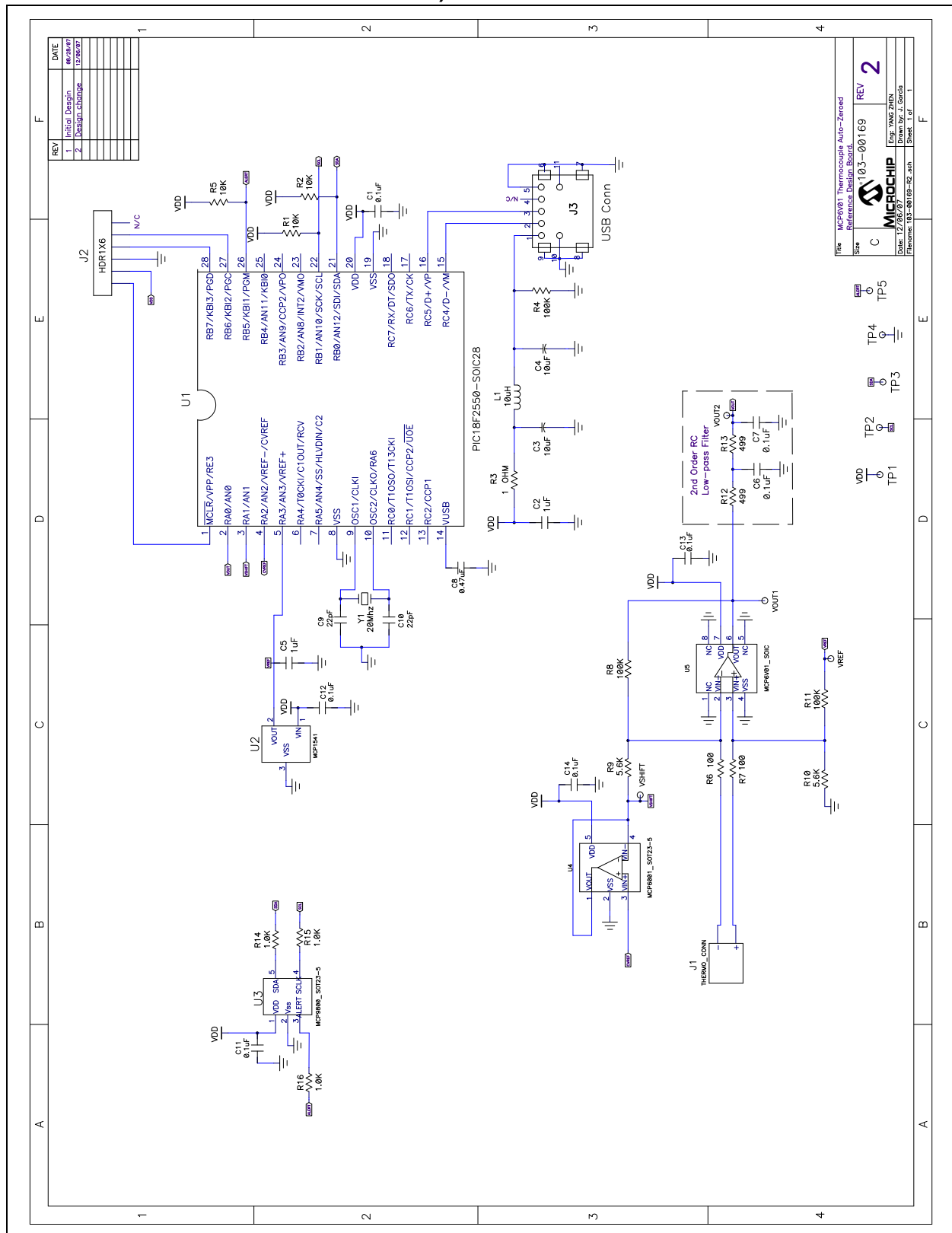


FIGURE A-1: Thermocouple Circuit's Schematic.

NOTES:

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