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## Additional Op-Amp Circuits/ Temperature Sensing

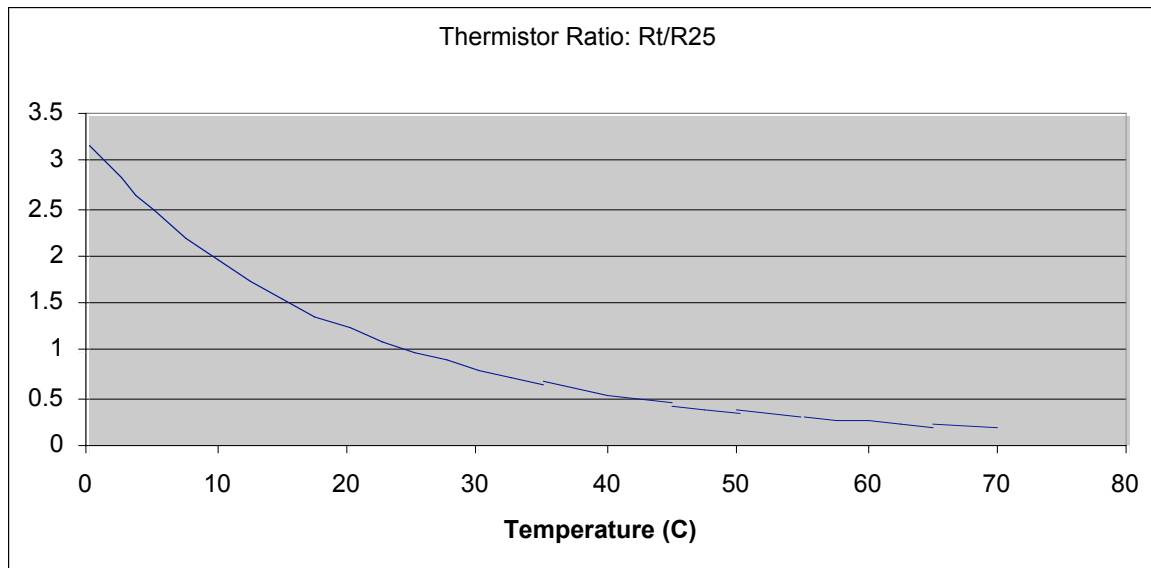
### OBJECTIVES:

To gain additional experience with design and construction of op-amp IC circuits, to explore the use of a basic sensing element, the thermistor, and to become familiar with the oscilloscope's X-Y mode.

### BACKGROUND:

A thermistor is a resistor with a large and well-defined temperature coefficient. Two types are available: those with positive temperature coefficients (PTC), where the resistance increases with temperature, and those with negative temperature coefficients (NTC), where the resistance decreases with temperature. The chart below shows the resistance variation of a typical NTC thermistor such as we will use in this lab. Notice that the variation is described generically as a ratio of the resistance at a given temperature to the resistance at 25°C; the curve goes through 1.0 at  $T=25$ .

Also notice that the curve is nonlinear. There is no single scale factor which can turn the resistance directly into a measurement of temperature. The reference listed, as well as many web sites, explains approaches to linearizing thermistors. For our lab we will simply use the thermistor as an approximation to linearity over a limited range of temperatures.



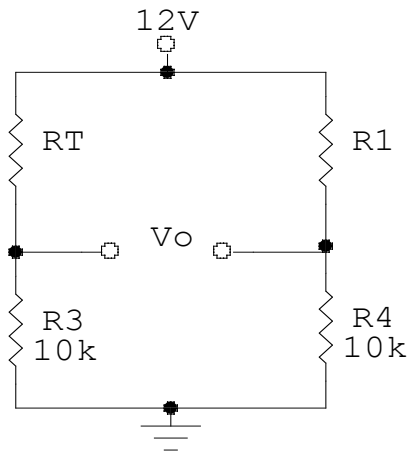
As a source of heat we will make use of the power dissipated in a resistor:  $P = I^2 R$ . It will become apparent that the physical size of a resistor has more to do with the power it is capable of dissipating than the actual resistance.

### PROCEDURE:

### Part 1. Finding an unknown resistance with a bridge circuit.

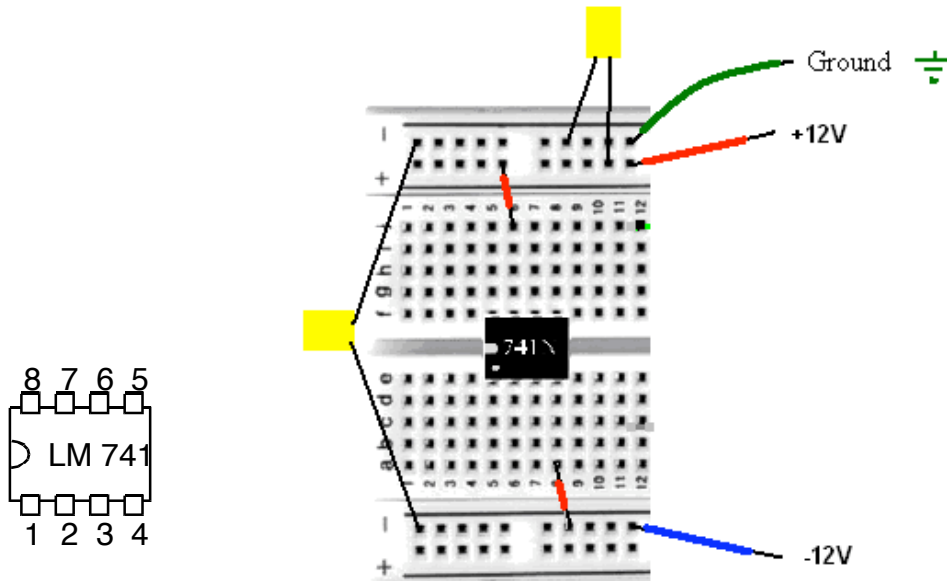
Before using the thermistor to measure temperature, we need to know its room-temperature resistance:  $R_{25}$  ( $R$  at  $25^{\circ}\text{C}$ ). We normally think of using an ohmmeter as the way to find an unknown resistance, but there is another method, which is to find a known resistance that just balances the unknown resistor in a bridge. Build the bridge circuit shown in figure 1 using the thermistor for  $R_T$ , the decade resistor box for  $R_1$ , and the bench DMM to measure the output voltage,  $V_o$ . Use the +20V output of the power supply as the +12V source. The bridge will be balanced ( $V_o=0$ ) when  $R_T$  and  $R_1$  are equal. Adjust the decade resistor box until  $V_o=0$ . What resistance ( $R_1$ ) accomplishes this?

Now remove the thermistor from the bridge and measure it directly with the ohmmeter. Do the readings agree? They should agree to within 5%, the tolerance of the bridge resistors.



### Part 2. OpAmp Circuit Construction

This lab uses the same LM741 op amp as the previous lab. Before building the rest of the circuit, carefully make the power connections to the op amp. As a reminder, the suggested power connection scheme is shown below. Two  $0.1\mu\text{F}$  bypass capacitors (the yellow components) are also shown connected between the  $\pm$  supplies and ground. As mentioned previously, these provide a local source of charge with low series impedance, which helps avoid unwanted oscillation.



### Part 3. Measuring temperature with a thermistor; the constant current source.

Since the data sheet<sup>1</sup> for the thermistor relates temperature to the ratio of resistances,  $R_t/R_{25}$ , a convenient way to measure temperature could be to measure this ratio. If a current of value  $1/R_{25}$  were forced through the thermistor, then the resulting voltage would be the ratio we're interested in. Satisfy yourself that the circuit of figure 2a would accomplish this.

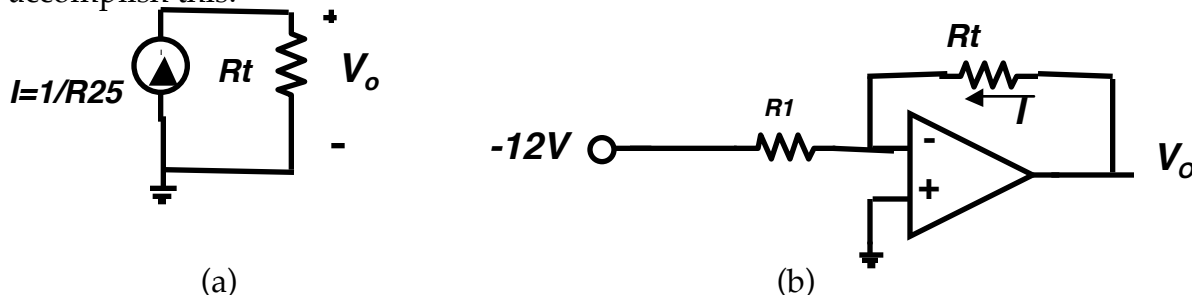


Figure 2

To realize this circuit we need a current source of value  $1/R_{25}$ . This is provided by the circuit of figure 2b. In this circuit, the op-amp and resistor  $R_1$  work to force a constant current,  $I=12V/R_1$ , through the thermistor. (If the  $-12V$  source were considered an input variable, this would be an example of a voltage-controlled current source.)

1. Build the circuit of figure 3a, using the decade resistor as  $R_1$ . Use the  $\pm 20V$  outputs of the power supply to create the  $\pm 12V$  sources, and use the  $+18V$  supply for V1. Be sure V1 is initially set to 0V. The thermistor needs to be thermally coupled to the 20\_ power resistor. Do this by clamping the thermistor to the power resistor, and the power resistor to the metal part of the breadboard, with a large paper clip, as shown in figure

<sup>1</sup> The data sheet for the thermistor is on the Laboratory webpage. The part number is: 334-NTC503-rc  
Rev. 1/4/2008

3b . You can use your calculator to determine the correct value of  $R_1$ , or you can just "dial" it in (adjust the decade resistor), recognizing that at room temperature, the output voltage  $V_o$  should equal 1.00V. In either case verify that with  $\pm 12V$  applied, but  $V_1=0$ , the output voltage is 1.00V. Adjust  $R_1$  as necessary to achieve this. Measure  $V_o$  with the bench DMM.

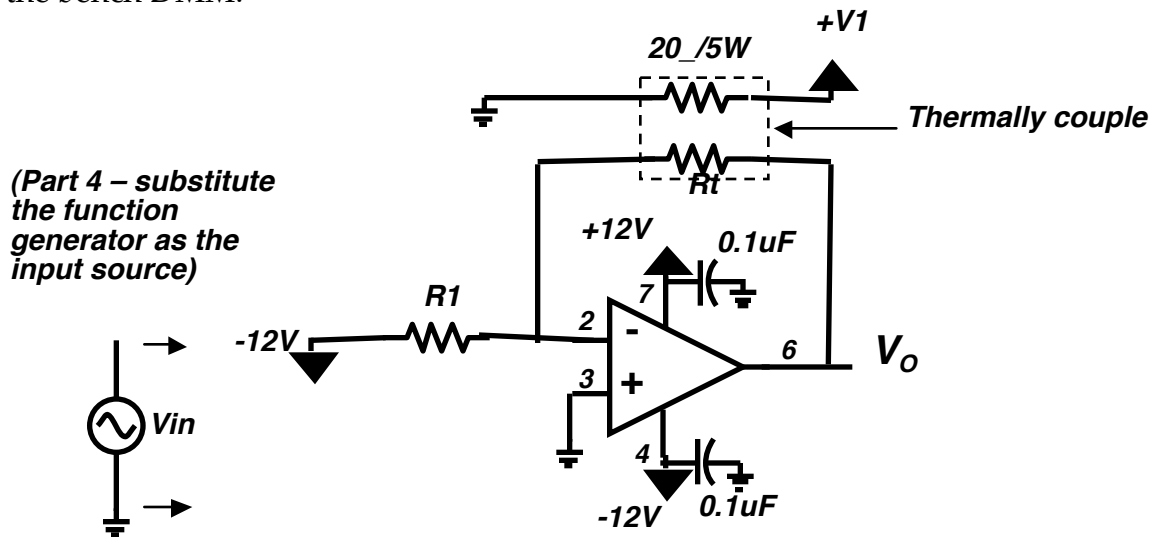


Figure 3a

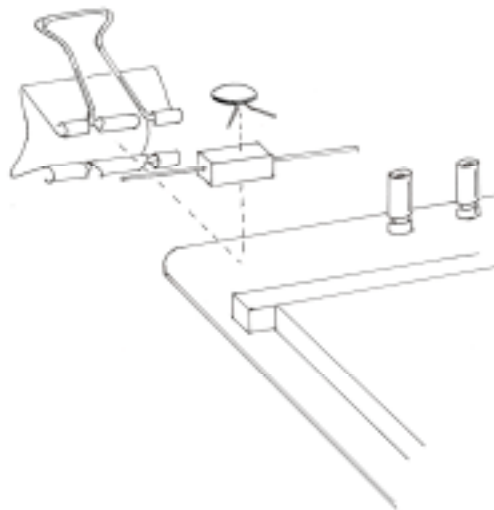


Figure 3b

*Caution: the power resistor will get hot in this next step*

The 20\_ power resistor is rated for maximum power dissipation of 5W. What value of source  $V_1$  will result in exactly 5W dissipation?

2. Turn up supply  $V_1$  to the voltage you just calculated. Monitor the ammeter on the power supply to verify that the current drawn is approximately 0.5A. Allow about 3 minutes for the temperature to stabilize, and record  $V_o$ . Since the power resistor is not well coupled (thermally) to a perfect heat sink, the temperature may not be completely stable; if so, just note the fact in your lab notebook and record the average value at the 3-minute mark. Remembering that  $V_o = R_t / R_{25}$ , use the data sheet for the thermistor to

determine the temperature of the power resistor, interpolating between table entries as necessary.

Turn V1 back down to 0V and allow the power resistor to cool. Monitor  $V_o$  to see when it has returned to 25C ( $V_o=1.00V$ ). Fanning it may help.

#### **Part 4: the oscilloscope X-Y mode**

So far in this lab we have used the oscilloscope for measuring voltage signals as functions of time. In this lab we will use the oscilloscope to measure one voltage as a function of another voltage. This is called the XY mode, and is useful for studying IV characteristics of devices, as well as phase relationships of sinusoids.

First, however, we will use the scope in the time-base mode (YT) to set the function generator output. The desired input signal will be a triangle wave at 1.0kHz, with a peak-to-peak voltage of 20V. To verify and/or change the scope's display mode, press the "DISPLAY" button, then look at the "Format" field. The two possibilities are YT (time base), or XY. For now we want YT.

Disconnect R1 from the -12V supply and reconnect it to the output of the function generator, as indicated in figure 3. Monitor this node (the function generator output) with channel 2 of the scope, and the op-amp output with channel 1. It should be obvious that channel 1 measures the voltage across the thermistor. As discussed in the previous section, the op-amp circuit acts as a voltage-controlled current source, the current being proportional to the function generator voltage, as measured on Channel 2. The exact relation to the thermistor current is  $I = -V_{in}/R1$  (note the negative sign). To obtain a noninverted measurement of the thermistor current, we cannot simply reverse the black and red clip leads from channel 2 of the scope, since the black lead is connected to ground inside the scope. We can, however, invert the measured signal using the scope's invert function. On the Channel 2 menu screen, simply press the Invert button to obtain Invert On. The two traces, Ch1 and Ch2, should be in phase on the display.

As a convenience in reading the thermistor current, change the decade resistor to exactly 100k\_. This will make the Channel 2 voltage be exactly 100,000 times the thermistor current.

Verify that both traces are clean triangle waves with reasonable amplitudes. Adjust the two traces on the scope so that they are both centered vertically, i.e., their zero levels are both exactly on the middle horizontal gridline. Now change to XY mode, using the DISPLAY menu. In this mode you can still adjust the Volts/Div sensitivity of each channel. You can also adjust the offsets, but be careful if you do, since that moves the (0,0) position away from the center of the display. Channel 1 is the horizontal variable (X), and Channel 2 is the vertical variable (Y).

1. Sketch the trace from the scope. For the vertical scale, indicate both the actual volts/div for channel 2, and the corresponding current in the thermistor ( $V/100k$ )
2. A resistor has a linear I-V characteristic with slope equal to  $(1/R)$ . What resistance do you calculate from your display for the thermistor?
3. Turn V1 back up to 10V and watch the slope of the XY trace change as the power resistor heats up. What resistance value do you calculate after the temperature has settled?
4. Turn V1 back to zero.

## Part 5. A differential temperature measurement: the difference amplifier

As a second method for measuring temperature we will take advantage of the inherent temperature variation of the forward voltage of a silicon diode. Although the diode will become a very familiar device in later courses, for this lab you are not required to understand its operation, apart from understanding the following mathematics:

The equation relating current,  $I$ , to voltage,  $V$ , in a forward biased (conducting) diode is

$I = I_o e^{qV/kT}$  or, alternately,  $V = (kT/q) \ln(I/I_o)$ .  $I_o$  is the *saturation current*, and is a constant for a given device;  $T$  is temperature in degrees K,  $q$  is the charge of an electron, and  $k$  is Boltzmann's constant. If two identical diodes are held at the same temperature and biased with constant currents, where the currents differ by some ratio (we'll use 10), then the difference in voltage between the two diodes is given by the following equation:

$$\frac{I_2}{I_1} = \frac{10I_1}{I_1} = 10 = \frac{I_o e^{qV_1/kT}}{I_o e^{qV_2/kT}} = e^{q(V_1 - V_2)/kT}, \text{ or } V_1 - V_2 = \Delta V = T(k/q) \cdot \ln(10) = T \cdot 200 \mu V / K$$

In the latter form it is evident that the difference in voltage is directly proportional to the absolute temperature.

If the differential voltage is measured at two different temperatures, then the temperature difference is given by  $\Delta V_1 - \Delta V_2 = (T_1 - T_2) \cdot 200 \mu V / K = \Delta T \cdot 200 \mu V / K$ , or  $\Delta T = (\Delta V_1 - \Delta V_2) / 200 \mu V / K$ .

If the diodes are not exactly matched (equal  $I_o$ ), or exactly at the same temperature, then there will, of course, be error in this calculation. For that reason, this approach is best used with diodes fabricated in the same piece of silicon.

Ref: Transducer Interfacing Handbook, Analog Devices, Norwood, MA 1980

**Experiment:** Leaving the +/-12V power supply connections to the op amp intact, and verifying that V1 is still set to 0, modify the circuit to that of figure 6. To assure that the two diodes are well matched we will use the MSD6100G, which integrates two diodes in a single device. Couple the MSD6100G to the power resistor as shown in figures 6b. Use the decade resistor box for R1. Also notice that the two resistors connecting the diodes to the 12V supply are different by a factor of 10. Measure the voltage drop across the resistors to verify that the currents actually differ by a factor of 10. If not, modify one of these so the currents are 10X different.



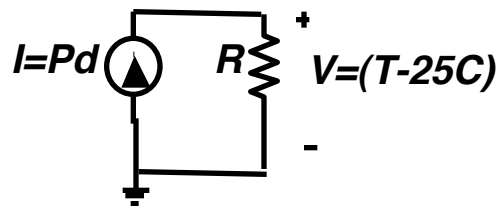
4. Using the equation given in the beginning of this section, calculate the temperature rise that occurred when V1 was turned up.

### Analysis questions

1. Use nodal analysis to derive the relationship between  $V_o$  and the resistor values in the bridge circuit in part 1 of this lab.

2. Use nodal analysis to derive the relationship between  $V_o$  and the two inputs of the differential amplifier in Fig. 6a.

3. The relation between heat-flow and temperature-rise can be modeled with circuit elements. Heat flow is analogous to current flow, temperature rise (or drop) is analogous to voltage rise (or drop), and thermal resistance (or inversely, thermal conductance) is analogous to electrical resistance (or conductance). If we consider the ambient atmosphere of the lab to be our "ground" reference, the equivalent thermal circuit is as shown below.



In step 2 of part 3 you determined the temperature of the power resistor when it was dissipating 5W. Using this temperature rise ( $T - 25C$ ) as the voltage,  $V$ , and  $P_d = 5W$  as  $I$ , calculate the effective thermal resistance,  $R$ , between the power resistor and the ambient atmosphere. What are the units of thermal resistance, given that thermal "current" has units of W and thermal "voltage" has units of C?

We will stop with this simple calculation, but a more accurate model would consider the different materials and/or mechanisms by which the heat flows, and assign separate thermal resistances for each. Then an equivalent series/parallel resistance could be found.

An example of detailed information on thermal resistance is the following application note from Caddock:

[http://www.caddock.com/Online\\_catalog/Mrktg\\_Lit/AEN0102.pdf](http://www.caddock.com/Online_catalog/Mrktg_Lit/AEN0102.pdf)