Objective:
The purpose of this laboratory is to demonstrate how operational amplifiers can be used to measure weak signals that depends on mechanical effects. A simple temperature sensor will be constructed and investigated.

Equipment:
1 - Analog Probe Kit
1 - Breadboard
1 - DC Power Supply
1 - Digital Multimeter

Components:
3 - L741 Op-amps
2 - 2 kΩ Resistors
2 - 1 kΩ Resistors
2 - 10 kΩ Resistors
1 – 240 Ω Resistor
1 - 2 kΩ Thermistor
1 - 5 kΩ Potentiometer

Background:
Op amps are often used to amplify the weak signals from sensors and produce output voltages that are functions of some mechanical variable, such as force, speed, pressure, or temperature. In this experiment, you will build and test a temperature sensor.

A very common temperature sensitive device is a thermistor. A thermistor is simply a piece of material whose electrical resistance is a function of temperature. Typically, thermistors are made of semiconductors (silicon is an example), and these devices become less resistive as their temperature rises. In this experiment, you will use a thermistor that has a resistance of 2 kΩ at 25°C and has a temperature coefficient of -3.83 %/°C, which means that it’s resistance changes −3.83% for every 1.0°C increase in temperature.

The circuit shown in Figure 1 is a simple temperature sensor. This circuit incorporates a number of sub-circuits that, together, will produce an output voltage that is a direct indication of the temperature.

The four resistors on the far right form a famous configuration called a Wheatstone bridge. Wheatstone bridges have been used for over a century in measurement circuits. A Wheatstone Bridge is simply two pairs of series resistors, connected in parallel across a
voltage source. If all the resistors in the bridge are of the same value (2kΩ in this case),
the voltage difference \( V_a - V_b \) between the right and left nodes of the bridge would be
zero. If, however, one of the four resistors were different from the other three (call this
the “test” resistor), the voltage between these same nodes would become nonzero, and the
value of this voltage will be an indication of whether the change of this resistance is
positive or negative. This means there is a direct correlation between the value of \( V_a - V_b \)
and the value of the “test” resistor.

The two op-amps in the center of this circuit are configured as unity-gain buffers. Here,
the output voltages should be identical to the input voltages, and no current flows at the
input terminals. This means that the difference between the output voltages of these
buffers equals their input voltages \( (V_a = V_c \text{ and } V_b = V_d) \) and there will be no “load” on
the Wheatstone bridge. This means that \( V_a - V_b \) is a function only of the resistor values
in the Wheatstone bridge and not affected by any loads connected to the outputs of the op
amps.

The final op-amp in this circuit is configured as a differential amplifier, where the output
is proportional to the difference between the voltages between the outputs of the two
unity gain buffers.

![Figure 1: Circuit Schematic – Simple Temperature Sensor](image)

Procedure:
1. Construct the circuit shown in Figure 1. Set the +/-20V supply of the DC power
   supply to +/-10V use them to supply power to the op amps. Set the +6V supply of
   the DC power supply to +6V and use it to power the Wheatstone bridge. All
   connections to “ground” should be connected to the common (black) node of DC
   supply. Note that in this case, “ground” simply means a common node. All
   voltages should be measured with respect to ground.

2. You should notice that the output voltage \( V_o \) varies with the setting of the
   potentiometer. Set the potentiometer so that the output voltage \( V_o \) equals zero.
   (This means that the potentiometer resistance equals the thermistor resistance.)
   Measure and record the voltages \( V_a, V_b, V_c, \text{ and } V_d \). Check to see if \( V_a = V_c \) and
   \( V_b = V_d \).
3. Using circuit analysis, derive a theoretical formula for $V_a$ and a theoretical value for $V_b$. Assume that the potentiometer resistance is $2k\Omega$ and that the thermistor resistance is $2k\Omega + \Delta R$, where the value $\Delta R$ depends on the thermistor temperature.

Q1: Assuming that the thermistor resistance is $2k\Omega + \Delta R$, what is the theoretical formula for $V_a$ as a function of $\Delta R$?

Q2: Assuming that the potentiometer resistance is $2k\Omega$, what is the theoretical value for $V_b$?

4. Using circuit analysis, derive a formula for the output voltage, $V_o$, as a function of the voltages $V_c$ and $V_d$. Assume that the op amp is ideal. You should find that $V_o$ is a function of the difference between $V_c$ and $V_d$, which indicates that this is a difference amplifier.

Q3: Assuming that the op amp is ideal, what is the theoretical formula for $V_o$ as a function of $V_c$ and $V_d$?

5. Next, pinch the thermistor between two fingers. The output voltage $V_o$ should start to change and the LED should light. Keep your fingers on the thermistor until the output voltage, $V_o$, stabilizes and note this voltage. At the same time, measure the voltages $V_c$ and $V_d$. Calculate the gain of the difference amplifier which is $G = \frac{V_o}{V_c - V_d}$.

Q4: What is measured gain of the difference amplifier? How does the measured gain compare to the theoretical gain (from the theoretical formula)?

6. Combine previously derived formulas to derive a formula for $V_o$ as a function of temperature. Remember that $V_a = V_c$ and $V_b = V_d$. Also recall that the thermistor resistance changes by $-3.83 \%/{}^\circ C$. Assume that the potentiometer resistance is $2k\Omega$ and that the thermistor resistance is $2k\Omega$ at $25^\circ C$.

Q5: What is the theoretical formula for $V_o$ as a function of temperature under these assumptions?

Q6: What is the theoretical output voltage at body temperature ($37^\circ C$)? At body temperature, how does the theoretical voltage compare to the measured voltage?