CG1111 Engineering Principles and Practice I

DC Circuit Principles II - Wheatstone Bridge

(Week 3, Studio 2)

Time	Duration (mins)	Activity
0:00	15	Briefing on Activity #1
0:15	30	Activity #1: Deriving the key equation for the Wheatstone Bridge
0:45	10	Discussion on Activity #1's results, and briefing on Activity #2
0:55	85	Activity #2: An experiment using Wheatstone Bridge to estimate the change in resistance
2:20	10	Discussion on Activity #2's results
2:30	5	Final discussions and wrap-up

Introduction:

- In many engineering applications, we often need to sense and measure changes in physical quantities, such as temperature, light intensity, etc. Many such sensors rely on the correlation between changes in electrical resistance of certain materials to the changes in the physical quantities.
- However, sometimes the change in resistance is **very small** compared to the original resistance.
- You would not weigh a cat by weighing a ship with and without a cat on board. Likewise, it will be difficult to measure very small changes in the resistance by directly measuring the material's resistance. As an example, suppose we have a 1 MΩ resistance, and we want to measure a small change in resistance of 1 Ω, resulting from a small temperature change. There is no ohmmeter that can reliably measure a change in resistance of 1 part in a million.

- In this studio, you will get to experience how the Wheatstone bridge circuit can be used to accurately measure changes in resistance.
- Figure 1 below shows a bridge network circuit (also known as ***Wheatstone bridge***). It is usually used to measure small changes in a resistance, e.g., due to temperature changes, or due to light intensity changes. The Wheatstone bridge can be set up such that $\boldsymbol{V_{AB} = 0}$ when the sensor's resistance R_4 is at its **reference value**. Then, any change in R_4, say ΔR, would result in a non-zero V_{AB}. **By measuring $\boldsymbol{V_{AB}}$, we can calculate $\boldsymbol{\Delta R}$.**
- Therefore, the Wheatstone bridge serves to "balance out" the reference value of R_4, leaving only the signal due to ΔR.

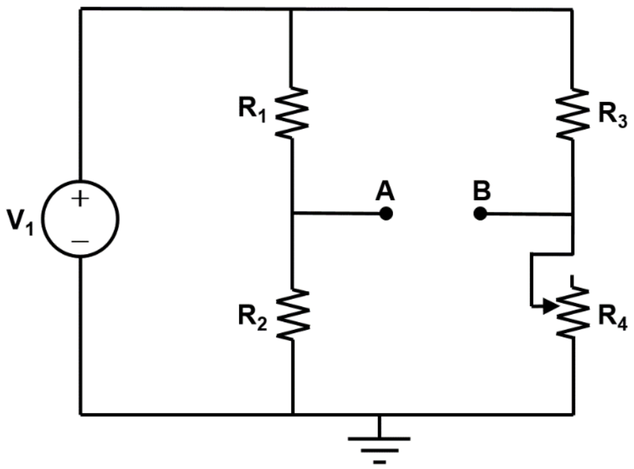

Figure 1: A Wheatstone bridge circuit.

<u>Activity #1: Deriving the key equation for the Wheatstone Bridge (30 mins)</u>

Objectives:

- Understand the working principle of a bridge network – the Wheatstone Bridge
- Able to apply ***Potential Divider Principle***
- Able to calculate the potential difference between two nodes in a circuit, and appreciate the concept of **voltage polarity**

Materials:

- Learning journal
- Pen or pencil

Procedure:

1. Write down the expression for voltage V_A w.r.t. the common ground, in terms of supply voltage V_1 and the relevant resistances, by applying the *Potential Divider Principle*.

2. Similarly, write down the expression for voltage V_B w.r.t. the common ground.

3. Now, write down the expression for the voltage V_{AB} (i.e., the voltage of **node A w.r.t. node B**). Is it the same as V_{BA}? (Note: Do not expand the expression yet, otherwise you get an unnecessarily complicated expression.)

4. Suppose resistance R_4 is the variable resistance of a sensor, given by $R + \Delta R$, where ΔR is its change in resistance from its reference value R. For example, a temperature sensor may have a reference resistance of R at 25°C. Further suppose that R_1, R_2, and R_3 are all chosen to be equal to R. Now, rewrite V_{AB} in terms of V_1, R, and ΔR (by substituting R and ΔR into your previous expression from Step 3). Before you combine the two fractions, divide both the numerator and the denominator by R, and treat the term $\frac{\Delta R}{R}$ like a variable.

5. Finally, manipulate the equation in Step 4 to express $\frac{\Delta R}{R}$ in terms of V_{AB} and V_1. This is the **key equation** for the **Wheatstone bridge**. Notice that you can calculate ΔR by simply measuring V_{AB}. This eliminates the need for a super-sensitive ohmmeter that can measure a tiny change in R_4.

Activity #2: An experiment using Wheatstone Bridge to estimate the change in resistance (85 mins)

Objectives:

- Verify the working principle of the Wheatstone Bridge
- Familiarize with the use of variable resistors

Equipment and Materials:

- Breadboard and connecting wires
- USB breakout cable + USB power adapter/USB portable battery
- Digital multimeter
- Multi-turn 1 kΩ variable resistors (4 per student)
- Trimming tool for adjusting the resistances (from your toolkit box)

Procedure:

1. Measure the voltage across the '+' (red) and '–' (black) terminals of your USB breakout cable (connected to USB power adapter) using the multimeter, and note down its value as V_1.

2. Using the breadboard, construct the circuit shown in Figure 1, where V_1 is the voltage supply from the USB breakout cable, and $R_1 = R_2 = R_3 = R_4 = 500\ \Omega$. Use the multi-turn variable resistors for all these four resistances by trimming them carefully to 500 Ω with the help of the digital multimeter serving as an Ohmmeter. Figure 2 shows the pin layout of the multi-turn variable resistor. Just like the previous studio's variable resistor, you only need to connect the middle pin (#2) and one other pin (either pin #1 or pin #3). However, **do not bend the unused pin** as it damages the variable resistor.

   Figure 3 shows a suggested circuit layout. You can also design your own circuit layout.

   Important: You must only measure the resistance of a resistor **after disconnecting it from the rest of the circuit**. Otherwise, you are not measuring the correct value. One suggestion is to plug the variable resistor into another location on the breadboard that is isolated from the rest of the circuit, and, with the help of two wires, you can measure the resistance easily using the multimeter (see Figure 4). (Be patient! It takes 1-2 seconds before the resistance measurement stabilizes on the multimeter.)

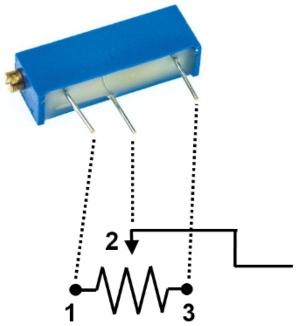

Figure 2: Multi-turn trimmer (variable resistor) pin layout.

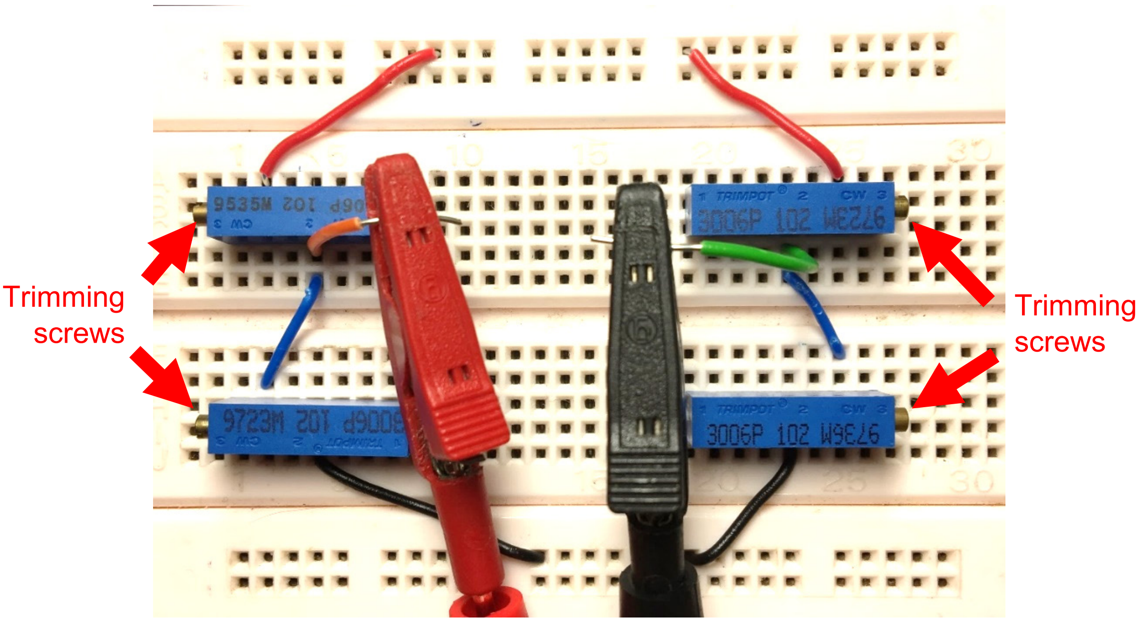

Figure 3: Suggested circuit layout.

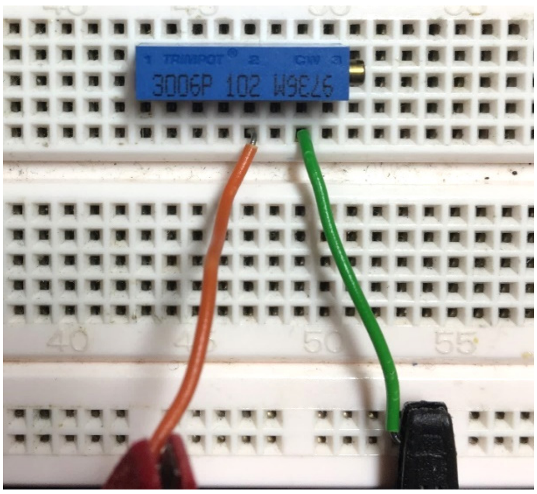

Figure 4: You must measure the resistance only when the resistor is not connected to the rest of the circuit. Try doing it at another location on the breadboard.

3. Now, using the digital multimeter as a voltmeter, measure the voltage V_{AB}. If you have trimmed the resistances satisfactorily, the voltage V_{AB} should be very close to 0 mV. If the absolute value of your measured V_{AB} is more than 2 mV, you should recheck your four resistances to try to get them as close to 500 Ω as possible.

4. Remove the resistance R_4 from the bridge network. Using the trimming tool, trim the resistance $\boldsymbol{R_4}$ to 480 Ω while using the digital multimeter to measure the resistance. Note that the multimeter may take a few seconds to have a stable reading.

5. Insert resistance R_4 back into the bridge network. Measure the voltage V_{AB} and tabulate the reading using the format shown in Table I. Using the equation you have derived in Activity #1, calculate the resistance from the measured voltage V_{AB}.

Table I

Resistance R_4	Voltage V_{AB}	Calculated resistance (500 Ω + ΔR)
480 Ω		
490 Ω		
510 Ω		
520 Ω		

6. Repeat Steps 4 and 5 for the remaining resistance values given in Table I. Compare the calculated resistance values with the measured resistances and explain any sources of error.

7. The equation you have derived in Activity #1 is non-linear. For sensor devices that have sufficient computation capability, there is no issue calculating the value of ΔR from the measured voltage V_{AB} using this non-linear equation. However, there may exist certain sensor devices in which their computational power may be very limited. Suppose it is known that $\Delta R << R$, manipulate the equation in Step 4 of Activity #1 to obtain a linear approximation such that $\Delta R \approx kV_{AB}$, where k is a constant.

8. Using the **linear approximation** that you have obtained in Step 7, calculate the resistance values again for the voltage V_{AB} values in Table I. You can add one more column to your Table I, to obtain Table II below.

Table II

Resistance R_4	Voltage V_{AB}	Calculated resistance using precise equation (500 Ω + ΔR)	Calculated resistance using linear approximation (500 Ω + ΔR)
480 Ω			
490 Ω			
510 Ω			
520 Ω			

9. Compare the resistance values obtained using the linear approximation with those obtained using the precise equation. Do you think the linear approximation is appropriate for the above experiment? Why?

END OF STUDIO SESSION