LAB #4
WHEATSTONE BRIDGE: MEASURING RESISTANCE

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ABSTRACT

In this lab, nine resistors were measured with a Wheatstone bridge built from two ratio arms, a decade resistance box, and a galvanometer. Three versions of the bridge were used: a 1/100 ratio for small resistors, a 1:1 ratio for mid-range resistors, and a 100:1 ratio for large ones. Every bridge estimate landed within 2.8% of the value read by a digital multimeter (DMM), and five of the nine landed within 1%. The most accurate result came from the 470 Ω resistor at 0.17%, while the least accurate came from the 200 kΩ resistor at 2.77%, where the decade box simply ran out of resolution.

♦ INTRODUCTION

The mission of this lab is to measure resistance the old-fashioned way: by balancing a bridge instead of simply trusting a meter. A Wheatstone bridge compares an unknown resistor, R_x, against three known ones. When the galvanometer across the middle of the bridge reads zero, the bridge is balanced, and R_x follows from a simple ratio [1].

Three bridges were built, each with a different ratio between R_2 and R_1, so each one covers a different range of resistance. Every estimate was then checked against a DMM reading of the same resistor. The bridge proved accurate to within a few percent across five decades of resistance, and the results also show where each version starts to struggle. The low-ratio bridge is sensitive to stray contact resistance; the high-ratio bridge is limited by how finely the decade box can be set and by how faint the galvanometer signal becomes.

♦ THEORY

Fig. 1 in the Appendix shows the bridge with its nodes labeled. R_1 and R_3 form the left branch, R_2 and R_x form the right branch, and the galvanometer G connects nodes a and b.

At balance, the galvanometer current i_g is zero. With no current in G, KCL at nodes a and b gives $i_1 = i_3$ and $i_2 = i_x$. Nodes a and b also sit at the same potential, so KVL around the upper and lower loops gives [3]

$$R_1 i_1 = R_2 i_2 \tag{1}$$

$$R_3 i_3 = R_x i_x \tag{2}$$

Dividing (2) by (1) cancels the currents and leaves the balance equation:

$$R_x = \frac{R_2}{R_1} R_3 = k R_3 \tag{3}$$

The ratio $k = R_2/R_1$ acts as a multiplier on the decade box. A ratio of 1/100 lets the box resolve fractions of an ohm, while a ratio of 100 lets a setting of a few kilohms stand in for a resistor near 1 MΩ. Because (3) depends only on the ratio, the measured values of R_1 and R_2 were used in place of their nominal values [2].

Power Limit

Each 1/8 W resistor must stay under 0.125 W. In a branch of two series resistors R

and R′, the power in R is $P = V_s^2 R/(R + R')^2$, so the largest safe supply voltage is

$$V_{s,\max} = (R + R')\sqrt{\frac{P_{\max}}{R}} \tag{8}$$

♦ PROCEDURE

An outline of the experiment is given in the Lab 4 worksheet [2]. The bridge circuit is shown in Fig. 1, and the original data sheets are included in the Appendix.

I. R_1 and R_2 for each bridge were measured with the DMM before being placed on the breadboard.

II. The bridge was wired as in Fig. 1, with the decade resistance box as R_3 and the galvanometer across nodes a and b.

III. A modest supply voltage was applied so that none of the 1/8 W resistors were over-powered.

IV. For each unknown resistor, R_3 was stepped dial by dial until the galvanometer read zero, and that setting was recorded.

V. R_x was calculated from (3) using the measured R_1 and R_2.

VI. Steps I through V were repeated for three ratios:

a. Bridge 1: R_1 = 100 kΩ, R_2 = 1 kΩ, used for 10 Ω, 100 Ω, and 470 Ω.

b. Bridge 2: $R_1 = R_2$ = 10 kΩ, used for 4.7 kΩ, 20 kΩ, and 68 kΩ.

c. Bridge 3: R_1 = 1 kΩ, R_2 = 100 kΩ, used for 200 kΩ, 470 kΩ, and 1 MΩ.

VII. Each unknown resistor was then measured directly with the DMM for comparison.

♦ RESULTS

Tables 1 through 3 hold the bridge data for each ratio. The measured R_1 and R_2 are the DMM values that were plugged into (3), and the R_3 column is the decade box setting at which the galvanometer read zero. Table 4 lists the direct DMM reading of every unknown resistor.

Table 1: Bridge 1 ($k = R_2/R_1 \approx 1/100$)

R_x (Nominal)	R_1 Nominal	R_2 Nominal	R_1 Measured	R_2 Measured	R_3 Decade Box	R_x Estimate
10 Ω	100 kΩ	1 kΩ	97.051 kΩ	0.9849 kΩ	990 Ω	10.047 Ω
100 Ω	100 kΩ	1 kΩ	97.051 kΩ	0.9849 kΩ	9,800 Ω	99.45 Ω
470 Ω	100 kΩ	1 kΩ	97.051 kΩ	0.9849 kΩ	45,500 Ω	461.75 Ω

Table 2: Bridge 2 ($k = R_2/R_1 \approx 1$)

R_x (Nominal)	R_1 Nominal	R_2 Nominal	R_1 Measured	R_2 Measured	R_3 Decade Box	R_x Estimate
4.7 kΩ	10 kΩ	10 kΩ	9.794 kΩ	9.788 kΩ	4,670 Ω	4,667.14 Ω
20 kΩ	10 kΩ	10 kΩ	9.794 kΩ	9.788 kΩ	19,300 Ω	19,288.18 Ω
68 kΩ	10 kΩ	10 kΩ	9.794 kΩ	9.788 kΩ	66,000 Ω	65,959.57 Ω

Table 3: Bridge 3 ($k = R_2/R_1 \approx 100$)

R_x (Nominal)	R_1 Nominal	R_2 Nominal	R_1 Measured	R_2 Measured	R_3 Decade Box	R_x Estimate
200 kΩ	1 kΩ	100 kΩ	0.9767 kΩ	98.18 kΩ	1,900 Ω	190,992.12 Ω
470 kΩ	1 kΩ	100 kΩ	0.9767 kΩ	98.18 kΩ	4,600 Ω	462,401.97 Ω
1 MΩ	1 kΩ	100 kΩ	0.9767 kΩ	98.18 kΩ	9,900 Ω	995,169.45 Ω

Table 4: DMM Measurement of Each Unknown Resistor

R_x (Nominal)	Measured Resistance
10 Ω	9.857 Ω
100 Ω	98.719 Ω
470 Ω	462.53 Ω
4.7 kΩ	4.6495 kΩ
20 kΩ	19.619 kΩ
68 kΩ	67.445 kΩ
200 kΩ	196.43 kΩ
470 kΩ	459.72 kΩ
1 MΩ	0.9866 MΩ

Table 5 compares the two methods, treating the DMM as the reference. The percent difference is $|R_{bridge} - R_{DMM}| / R_{DMM} \times 100\%$. The last column checks each DMM reading against the nominal value to confirm that every part sits inside its ±5% tolerance. Fig. 2 in the Appendix plots the same differences grouped by bridge.

Table 5: Bridge Estimate Compared with DMM Measurement

Bridge	R_x (Nominal)	Bridge Estimate	DMM Reading	Bridge vs. DMM	DMM vs. Nominal
1	10 Ω	10.047 Ω	9.857 Ω	1.93%	−1.43%
1	100 Ω	99.45 Ω	98.719 Ω	0.74%	−1.28%
1	470 Ω	461.75 Ω	462.53 Ω	0.17%	−1.59%
2	4.7 kΩ	4.667 kΩ	4.6495 kΩ	0.38%	−1.07%
2	20 kΩ	19.288 kΩ	19.619 kΩ	1.69%	−1.91%
2	68 kΩ	65.960 kΩ	67.445 kΩ	2.20%	−0.82%
3	200 kΩ	190.99 kΩ	196.43 kΩ	2.77%	−1.79%
3	470 kΩ	462.40 kΩ	459.72 kΩ	0.58%	−2.19%
3	1 MΩ	995.17 kΩ	986.6 kΩ	0.87%	−1.34%

♦ DISCUSSION

Bridge 1 ($R_2/R_1 \approx 1/100$)

Bridge 1 had the finest resolution of the three. With $k \approx 1/100$, a 10 Ω step on the decade box moves the estimate by only about 0.1 Ω. Its best result came from the 470 Ω resistor, which matched the DMM to 0.17%.

Its worst result came from the 10 Ω resistor at 1.93%. The bridge read 10.047 Ω while the DMM read 9.857 Ω, a gap of about 0.19 Ω. At that scale, the breadboard contacts and jumper wires in the R_x arm start to matter; a few tenths of an ohm of contact resistance is enough to cover the whole difference. That stray resistance adds directly to R_x in (2), so the bridge should read high, and it did. The DMM reading, taken right at the resistor leads, avoids most of that path.

Bridge 1 also shows why the worksheet insists on measured values. R_1 read 97.051 kΩ, almost 3% below its nominal 100 kΩ. Had the nominal ratio of 1/100 been used, the 470 Ω estimate would have been 455.00 Ω instead of 461.75 Ω, turning a 0.17% difference into a 1.63% one.

Bridge 2 ($R_2/R_1 \approx 1$)

Bridge 2 was excellent at the bottom of its range and less consistent at the top. The 4.7 kΩ resistor matched the DMM to 0.38%. The two ratio arms were nearly identical at 9.794 kΩ and 9.788 kΩ, so almost all of the uncertainty comes from the R_3 setting.

That is where the 20 kΩ and 68 kΩ results slipped, at 1.69% and 2.20%. Both settings were recorded with the lower dials at zero (19,300 Ω and 66,000 Ω), which suggests the null was judged on the coarser dials. For 68 kΩ, a single step of the 1 kΩ dial is already 1.5% of R_3. Larger resistances also mean less current through the bridge, so the galvanometer barely reacts to a small mismatch, and a slight twitch of the needle is easy to miss. Unlike Bridge 3, this error is not built into the circuit; a higher supply voltage, which Bridge 2 can easily tolerate (Table 6), or more patience on the lower dials would have tightened both results.

Bridge 3 ($R_2/R_1 \approx 100$)

Bridge 3 trades resolution for range. With $k \approx 100$, every ohm on the decade box counts as roughly 100 Ω of R_x, so a single step on the 100 Ω dial is worth about 10 kΩ. The 200 kΩ resistor balanced at R_3 = 1,900 Ω, where half a step is already 2.63% of the reading. Its 2.77% difference is about the size of that half step, so resolution alone accounts for nearly all of it.

The 1 MΩ resistor fared better at 0.87%, since its larger R_3 setting of 9,900 Ω makes each step a smaller fraction. However, it also had the weakest null in the entire lab; with resistances this large, very little current reaches the galvanometer when the bridge is slightly off balance. Resistances this large are also more exposed to leakage across the breadboard and to noise pickup, both of which nudge the result by small amounts.

The 470 kΩ resistor did even better. It balanced at R_3 = 4,600 Ω, which gives 462.40 kΩ against a DMM reading of 459.72 kΩ, a difference of 0.58%. With a setting in the thousands, each 100 Ω step is only about 2% of R_3, so the ×100 multiplier did less damage here than it did at 200 kΩ.

Overall Accuracy

Across all three bridges, a result is only as good as the ratio arms and the finest R_3 step at which the null is still visible. Bridge 1 is limited by stray resistance, Bridge 2 by the coarse dials used at its high end, and Bridge 3 by both resolution and a weak null. Every DMM reading fell within the ±5% tolerance of its nominal value (Table 5), and every bridge estimate did as well.

♦ QUESTIONS FROM LAB HANDOUT

1. Discuss the accuracy of the three different Wheatstone bridges and the reasons why each one is more or less accurate.

Bridge 1 was the most accurate on average, with a mean difference of 0.95% from the DMM. Bridges 2 and 3 were close behind at 1.42% and 1.41%. The reasons are covered in the Discussion above: contact resistance hurts Bridge 1 at 10 Ω, coarse dial settings hurt Bridge 2 at 20 kΩ and 68 kΩ, and the ×100 multiplier combined with a weak galvanometer signal hurts Bridge 3. Even so, Bridge 3 is the least precise by design; it produced the single worst result (2.77%), and its errors come from the circuit itself rather than from how it was used.

2. Calculate the maximum voltage you can measure using our decade resistance boxes and for each of the three Wheatstone bridges.

A Wheatstone bridge measures resistance rather than voltage, so this question was answered two ways: the largest resistance each bridge can measure, and the largest supply voltage each bridge can safely take.

From (3), the largest measurable resistance is $R_{x,max} = k \cdot R_{3,max}$. Taking the decade box maximum as $R_{3,max}$ = 200 kΩ, Bridge 1 tops out near 2 kΩ, Bridge 2 near 200 kΩ, and Bridge 3 near 20 MΩ. That is why Bridge 3 was the only reasonable choice for the 1 MΩ resistor.

The supply limit comes from (4). For each measurement, both branches were checked, and the resistor closest to its 1/8 W rating set the limit. Table 6 lists the lowest limit for each bridge. The limiting parts were R_2 during the 10 Ω test on Bridge 1, R_2 during the 4.7 kΩ test on Bridge 2, and R_1 during the 200 kΩ test on Bridge 3. The decade box is excluded, since it is not a 1/8 W part.

Table 6: Maximum Resistance and Maximum Safe Supply Voltage

Bridge	$R_{x,max}$	$V_{s,max}$
1 (k = 0.01015)	2.03 kΩ	11.2 V
2 (k = 0.9994)	199.9 kΩ	51.6 V
3 (k = 100.52)	20.1 MΩ	32.5 V

Bridge 1 is the most fragile, since its 1 kΩ arm carries nearly the full supply when R_x is only 10 Ω. Bridge 2 can take more voltage than a typical bench supply provides, so in practice it is limited by the supply, not the resistors.

♦ CONCLUSION

The Wheatstone bridge measured resistors from 10 Ω to 1 MΩ, and every estimate stayed within 2.8% of the DMM. Choosing the right ratio was the key design decision. A small k gives fine resolution for small resistors, a large k extends the range to megohms at the cost of resolution and null sensitivity, and a 1:1 ratio sits comfortably in between. Using measured values for R_1 and R_2 made a visible difference, especially on Bridge 1, where R_1 sat almost 3% below its nominal value.

♦ ACKNOWLEDGEMENTS

The Objective, component list, and Procedure were given and paraphrased from the ECE 263 Lab 4 worksheet [2]. Fig. 1 was redrawn from the worksheet circuit.

♦ REFERENCES

[1] J. W. Nilsson and S. A. Riedel, *Electric Circuits*, 12th ed., ch. 3. Hoboken, NJ, USA: Pearson, 2022.

APPENDIX

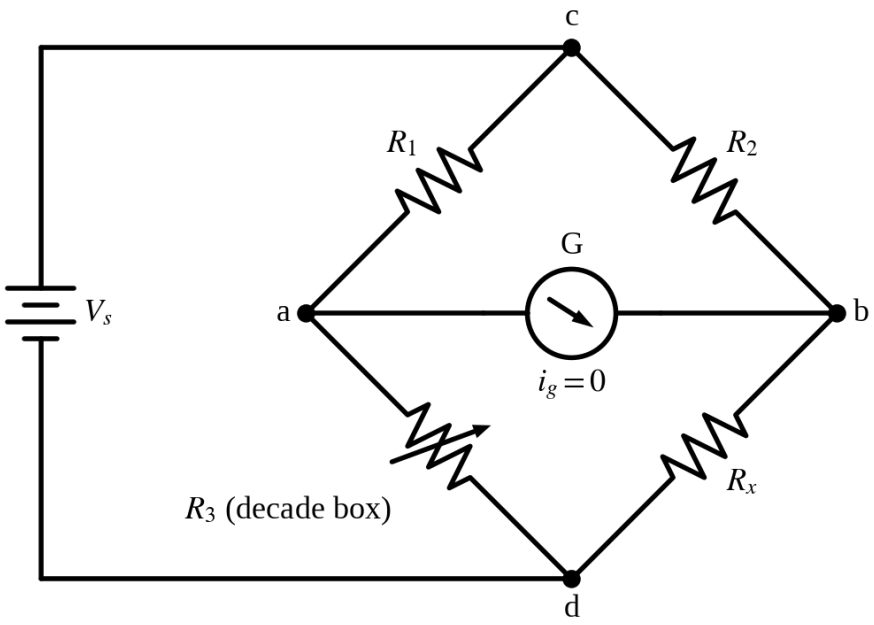


Fig 1. ***Wheatstone bridge with labeled nodes (redrawn from [2])***

APPENDIX

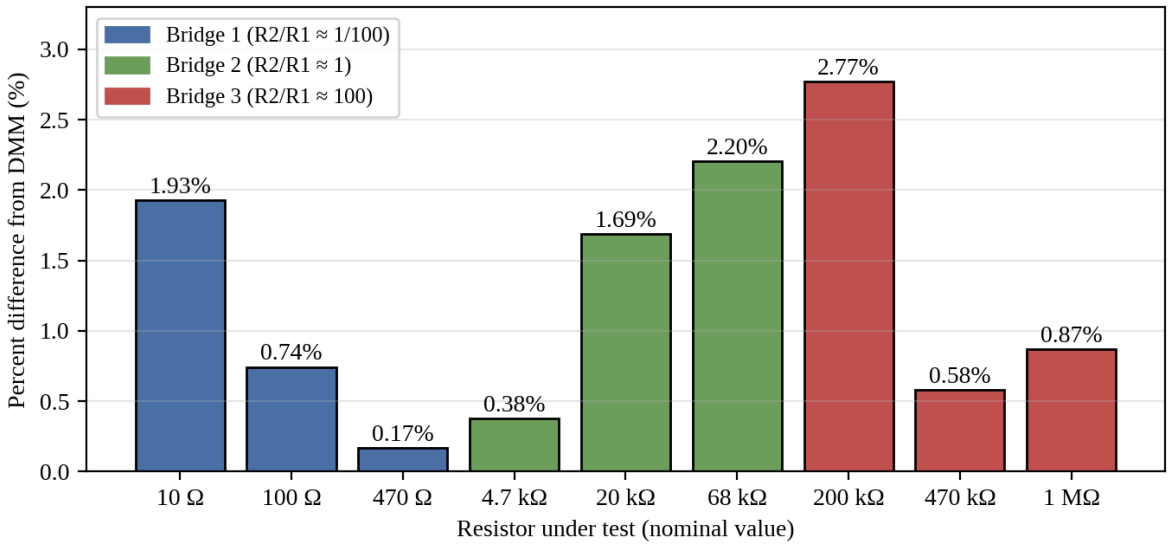


Fig 2. ***Percent difference between bridge estimate and DMM reading, grouped by bridge***

APPENDIX

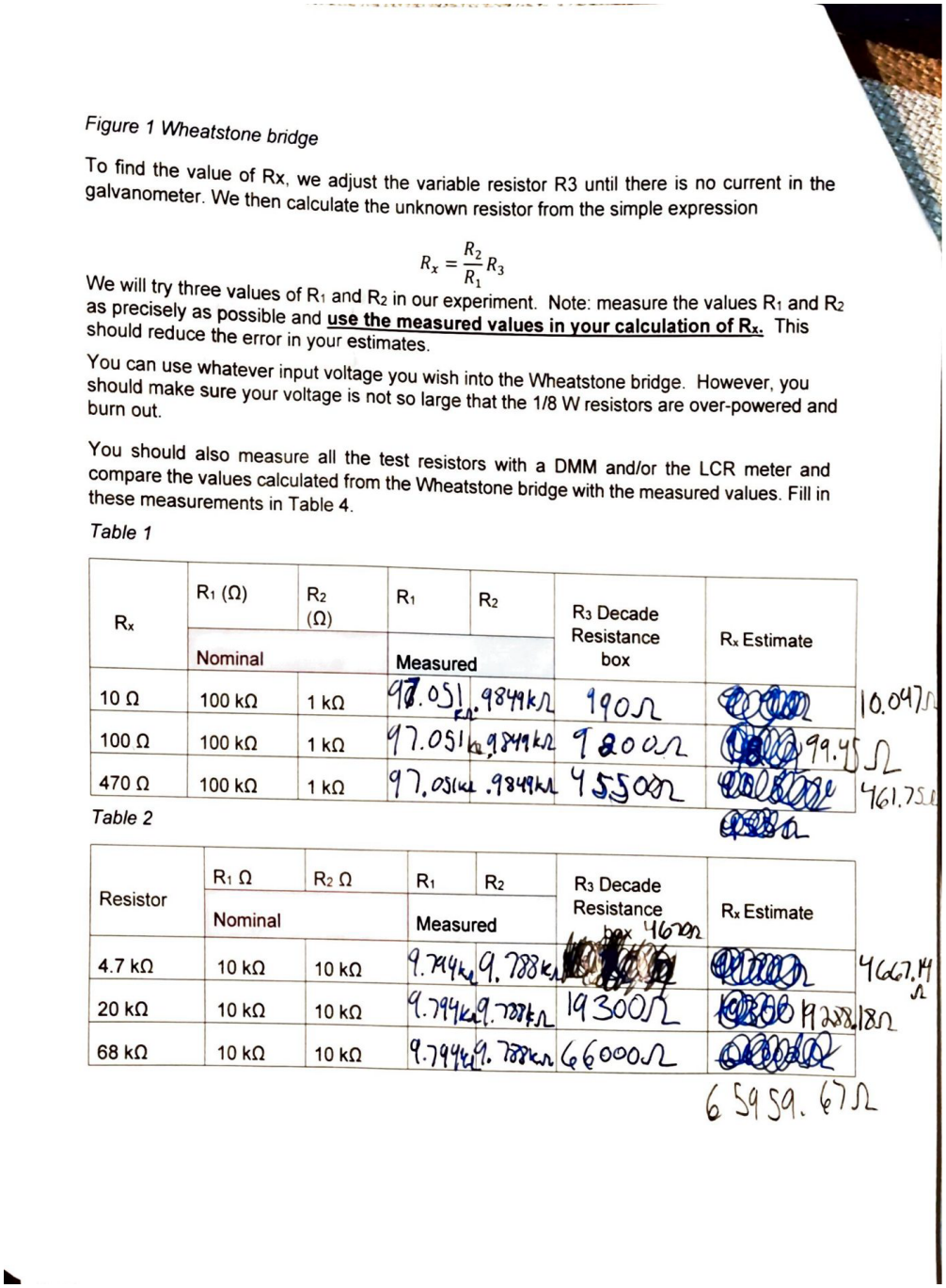


Figure 1 Wheatstone bridge

To find the value of Rx, we adjust the variable resistor R3 until there is no current in the galvanometer. We then calculate the unknown resistor from the simple expression

$$R_x = \frac{R_2}{R_1} R_3$$

We will try three values of R_1 and R_2 in our experiment. Note: measure the values R_1 and R_2 as precisely as possible and **use the measured values in your calculation of R_x.** This should reduce the error in your estimates.

You can use whatever input voltage you wish into the Wheatstone bridge. However, you should make sure your voltage is not so large that the 1/8 W resistors are over-powered and burn out.

You should also measure all the test resistors with a DMM and/or the LCR meter and compare the values calculated from the Wheatstone bridge with the measured values. Fill in these measurements in Table 4.

Table 1

R_x	R_1 (Ω)	R_2 (Ω)	R_1	R_2	R_3 Decade Resistance box	R_x Estimate
	Nominal		Measured			
10 Ω	100 kΩ	1 kΩ	97.051kΩ	.9849kΩ	990Ω	10.047Ω
100 Ω	100 kΩ	1 kΩ	97.051kΩ	.9849kΩ	9800Ω	99.45Ω
470 Ω	100 kΩ	1 kΩ	97.051kΩ	.9849kΩ	45500Ω	461.75Ω

Table 2

Resistor	R_1 Ω	R_2 Ω	R_1	R_2	R_3 Decade Resistance box 46700Ω	R_x Estimate
	Nominal		Measured			
4.7 kΩ	10 kΩ	10 kΩ	9.794kΩ	9.788kΩ		4667.14Ω
20 kΩ	10 kΩ	10 kΩ	9.794kΩ	9.788kΩ	19300Ω	19258.18Ω
68 kΩ	10 kΩ	10 kΩ	9.794kΩ	9.788kΩ	66000Ω	65959.67Ω

Fig 3. ***Original lab worksheet data, Tables 1 and 2***

APPENDIX

20,009,000 10000ΩΩ

Table 3

Resistor	R_1 Ω	R_2 Ω	R_1	R_2	R_3 Decade Resistance box	R_x Estimate
	Nominal		Measured			
200 kΩ	1 kΩ	100 kΩ	.9767 kΩ	98.18kΩ	1900Ω	19 099.12Ω
470 kΩ	1 kΩ	100 kΩ	.9767kΩ	98.18kΩ	460Ω	46 240.20Ω
1 MΩ	1 kΩ	100 kΩ	.9767 kΩ	98.18kΩ	[redacted]	995169.45Ω

[redacted]
9900Ω

Table 4

R_x	Measured Resistance
10 Ω	9.857
100 Ω	98.719Ω
470 Ω	462.53Ω
4.7 kΩ	4.6495 kΩ
20 kΩ	19.619 kΩ
68 kΩ	67.495 kΩ
200 kΩ	196.43 kΩ
470 kΩ	45.972 kΩ
1 MΩ	.9866 MΩ

3 Submission

This lab **REQUIRES** a formal lab report. Be sure to include Tables 1, 2, and 3 in your report.

Include in your discussion, a discussion about the accuracy the three different Wheatstone bridges. Discuss reasons why each Wheatstone bridge is more/less accurate. Don't be afraid to draw circuits and use equations to justify your explanation.

Calculate the maximum voltage you can measure using our decade resistance boxes and for each of the three Wheatstone bridges.

Fig 4. ***Original lab worksheet data, Tables 3 and 4***