EK307 Lab: Resistor Networks

Your name__________ Giacomo Cappelletto __________

Your collaborators name __________ Worked Alone __________

Lab objectives:

- Identifying resistors
- Resistor networks
- Ohm meter
- Voltage divider
- Current divider
- Test equipment limitations

In the previous lab we got familiar with the multimeter and the breadboard. We made a rather boring circuit and a more interesting one where we lit up an LED. In this lab we will construct some resistor networks, analyze, and measure them. The lecture part of this class is about modeling how electronic components behave using mathematical equations. We want to see how the models compare to physical components.

Deliverables:

- Demonstrate your working circuit from figure 3 to a TA.
- Upload a copy of this completed lab worksheet to Blackboard. Fill in all items that are boxed.

Identifying resistors:

For most engineers the resistor resistance and power rating are the most important parameters when selecting resistors for a design. If you are designing wireless transmitters you would need to care about other parameters, yet, we neglect electromagnetics in EK307. The resistors in your kit are mostly ½ watt carbon film resistors. This means they can reliably dissipate ½ watt of power or less. More than that and they will get very hot and degrade or literally go up in smoke. They cost $0.007 each or less in quantities of thousands. The resistance value is encoded on the body of the resistor as colored bands. Here is a video demonstrating how to read the common 5% tolerance resistors. https://youtu.be/UINnKXSdIJw There is also a chart in the appendix of this lab. Some people are not able to see the color codes. If you can't it is fine to use the multimeter to measure the values. I have long since memorized most of the color codes just because I used them so much. We don't expect you to do that. A good way to speed up EK307 circuit construction is to figure out the values of your kit resistors and then somehow organize them. A popular way is to stick the resistor leads into a piece of foam and write the values on the foam. Note, if you do this with your OP amps be sure the foam is conductive! Foam is notorious for holding electrical charges that can damage semiconductors.

A: Make an Ohm meter:

Some students do not have multimeters yet. We will turn this inconvenience into a learning opportunity by making our own Ohm meter using the Arduino and a resistor. Watch this video

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https://youtu.be/TDno13PUXxo for the engineering design and instructions about making and using this meter.

1. Use the same Zmeter software as last week. Unless your reprogrammed it, it will still be on the Arduino. The code is here: https://github.com/EkZosuls/Zmeter/blob/master/Zmeter.ino
2. Connect a 1,000 Ohm resistor to the Arduino 5V supply. The other end plugs into the breadboard in an unused column.
3. Connect the Arduino A2 pin to this column.
4. Connect a jumper wire to the same column.
5. Connect another jumper wire to GND.
6. Run the software, open up the Arduino serial monitor window.
7. Enter an “r” or “R” into the serial monitor and hit return.
8. Now your Zmeter will be returning resistance values. If the two leads are not connected to anything the meter should be reading: “Out of range high”. This is normal.
9. Use the two jumpers to measure resistance of resistors.

Figure 1: Your voltage divider circuit.

10. Note this will not work on a live circuit. If the resistors are less than 10 Ohms or greater than 100k then the accuracy will be poor.
11. Grab four resistors of different values and measure their resistance with you home brew ohmmeter. Note the published values and measured values in the table below. If you cannot read the published values use another multimeter to determine the values.

Published value of a resistor (from the color code)	Measured value.
100 OHMS	99.89 OHMS
2 kOHMS	2002.93 OHMS
10 kOHMS	10130.43 OHMS
100 kOHMS	127000.00 OHMS

B: Construct and test a voltage divider:

12. Choose two resistors of different values that are in the range of 1000 Ω (1 kΩ) to 100,000 Ω (100 kΩ). Determine their published values using the color code. If you can’t distinguish the colors, you can find the published values by working backwards. To do this measure the resistance and look at the official E24 preferred number sequence to find the published value. https://en.wikipedia.org/wiki/E_series_of_preferred_numbers

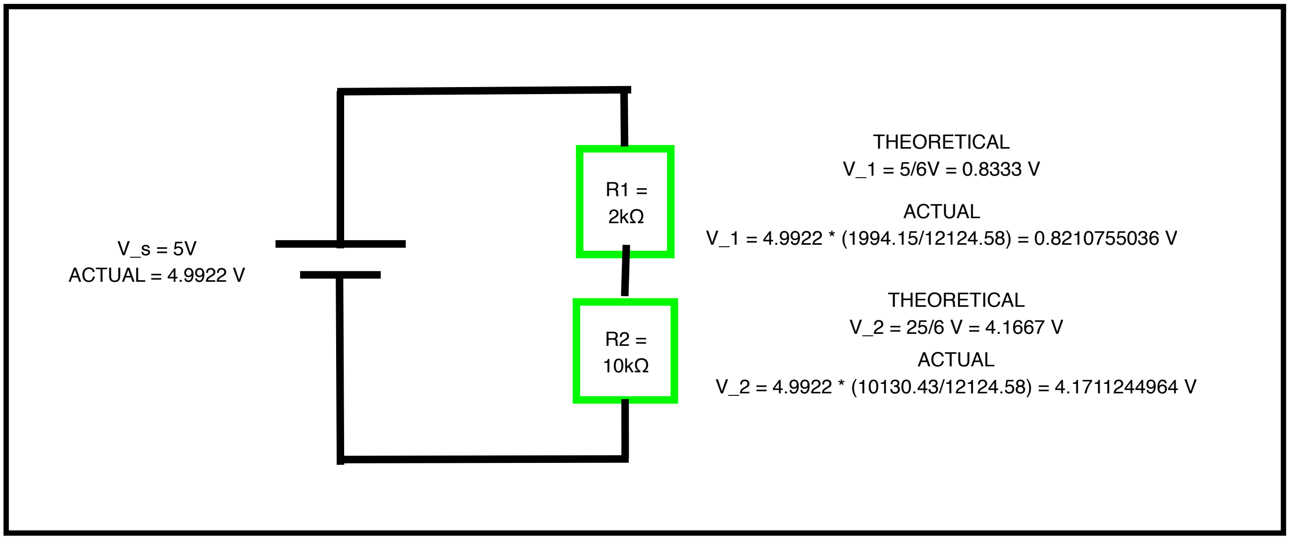


Figure 1: Your voltage divider circuit

13. Arbitrarily name one resistor R1 and the other R2.
14. Sketch a schematic in figure 1 of a voltage divider that uses the two resistors you chose. The voltage source for the divider is the Arduino 5V supply, same as lab 1.
15. Analyze the circuit to find the theoretical voltage on the output of your divider. Use the published resistor values, not the measured values.
16. Use your multimeter and or Zmeter to measure the actual resistance values of the two resistors.

    Note them here: R1 [1994.15 Ω] R2 [10130.43 Ω]

17. Construct the circuit on your breadboard. The breadboard layout can be like your lab day 1 LED circuit. The difference is the LED is swapped out for a resistor.
18. Power up the Arduino by connecting to USB. As always, as soon as you plug it in make sure the ON LED on the Arduino is glowing brightly. If not, pull the plug immediately and check for short circuits.
    a. To check for a short, you can visually look for them or use the multimeter continuity setting to trace the circuit.
    b. If your convinced the Arduino is not working, disconnect the one jumper connected to the 5V pin on the Arduino and then plug it in again and look for the ON LED. If it comes on, yes there is a short. If it doesn't make sure the charger and USB cable are working. Here we are assuming no other pins on the Arduino are shorted or drawing too much current.
    c. If you pull the Arduino off the breadboard and the only connection to it is the plugged in USB cable, then the Arduino might be bad.
19. If the ON LED is glowing, its time to measure the voltage on the input of the divider. Write it down on your schematic (figure 1). This is the voltage coming from the Arduino 5V pin. Note it wont be exactly 5V. On mine it is about 4.75 volts. This is OK. We will talk about why it is a few hundred millivolts lower later in the semester.
20. Measure the voltage at the voltage divider output. Write it on figure 1.

21. Are you getting the theoretical voltage divider output you calculated in step 14?

At R1: Calculated = 0.8333 V, Actual = 0.8252 V	At R2: Calculated = 4,1667 V, Actual = 4.1646 V

Close enough

22. Calculate the voltage divider output voltage using the measured values of the resistors and the 5V power supply voltage. Note it on your schematic figure 1.
23. You just completed an exercise that circuit designers do all the time. You analyzed your theoretical circuit, tested it, and noted the differences. What is the percent error between the theoretical output voltage calculation in step 14 and the measured output voltage in step 19?

E% = (4.9922-5)/5 *100 = -0,156 %

24. The impact of the error really depends on the use of the circuit. If this divider is a precision reference voltage on a science instrument heading to the moon we might be concerned if it was off by 0.1%. If it is part of a guitar amplifier we probably would be OK with 10%. In fact, it might sound better the farther off spec it is.

C: Models and reality:

In this section we will make a measurement that appears nonsensical until further inspection. When we draw schematics and analyze circuit voltages and currents only the items we specifically model get included in the math formulas. On 'paper' we assume a voltmeter has infinite resistance (open circuit) between its two test leads. And an ammeter has zero resistance (short circuit) between its test leads.

25. Why are these two conditions advantageous when measuring voltage and current?

A voltmeter with infinite resistance implies that no current will flow through it (all current will flow through the leads we are measuring instead) therefore not altering the voltage measurement. Conversely, an ammeter with no resistance does not affect the current of the circuit (since its in series), allowing for a correct measurement of the current.

26. Find a 10 MegΩ (10,000,000Ω) resistor from your kit or the component bench.
27. Construct the circuit in figure 2 panel A. It is a 10 Meg resistor with one lead connected to the Arduino 5V.
28. Set your meter to measure voltage. The multimeter red or V lead is connected to the free end of the resistor. The multimeter black or com lead is connected to GND (figure 2, panel C).
29. Record the voltage here:

From a theoretical standpoint we have an inconsistency, if the voltmeter truly looks like an open circuit how is there a drop across the resistor? Remember for there to be a voltage drop across the resistor there needs to be a current. In equation form this is V = IR.

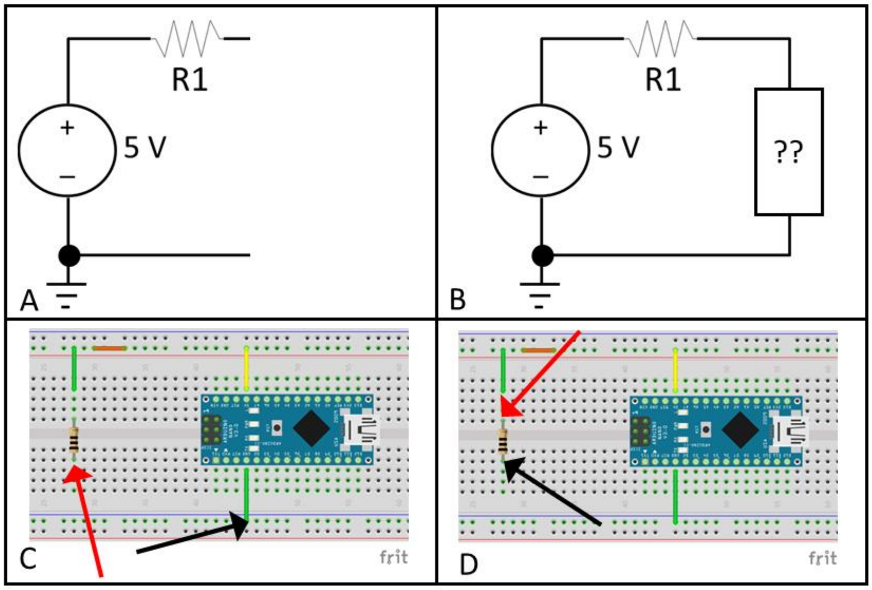


Figure 2: **A**: the schematic of circuit 2. **B**: the schematic of the circuit with a non-ideal voltmeter in the loop. **C**: The implementation of the circuit for step 16. The red and black arrows represent the multimeter leads. **D**: The test scenario in step 18.

30. Now measure the voltage across the resistor (figure 2, panel D). What is it?

2.6801 V

31. It appears that Ohm's law doesn't work. Or is it that we are omitting a critical element from out model??

What is happening is we are seeing the effect of a non-ideal behavior in the multimeter voltmeter system. It actually *has* a finite resistance across its leads (figure 2, panel C). You can calculate what it is.

32. When you had the voltmeter connected in the figure 2 panel A configuration you were measuring the voltage across the meter. In this circuit there is a loop that consists of the Arduino 5V power supply, the 10 Meg resistor, and the meter. We know the voltage of the power supply because we measured it in the previous lab (it is approximately 4.75 volts). We know the voltage across the meter. Thus we can calculate the voltage across the 10 Meg resistor by using the law that says the voltage in a loop must sum to zero. Calculate the voltage across the 10 Meg resistor:

-4.9922 V

33. Because we now know the voltage across the 10 Meg resistor and we know its resistance is approximately 10 Meg, we can use Ohms law to find the current through it.

I = V/R = -2.6801/10*10^6 = -0,0000004992 A = -0.2680 µA

34. Lastly, we know that the current in the loop is the same, meaning the current going through the 10 Meg equals the current draw from the Arduino 5V, equals the current through the meter, equals the current into the Arduino GND. Meaning we have the current through the meter and the voltage across it. Thus, we can calculate the value of the non-ideal resistance inside the voltmeter using Ohm's law. Write down your result:

Same loop current flows through the meter,
so R_meter = (4.9922 - 2.6801)/
(2.6801*10^-6) = 862.691,691 = 8.6269 MΩ

There are two important take away points from this exercise:

- If you don't model an effect or phenomenon, then it won't be accounted for in your model. Often it isn't practical or we don't completely understand a system to model every scenario (If we did why would be model it anyway). This applies to anything in life. Think of the Covid 19 crisis as an example: Not many people imagined it could happen. Those who did and took action were a minority. Worldwide pandemic was not in the contingency schedule or financial plan of the majority of people, governments, or institutions.
- Measurement tools are not perfect. I always recommend to experimenters: "Get to know your instruments". Read the manuals, be curious, perform tests like the exercise you just did. It's like test driving a car before you buy it (or race it!).

D: Current division experiment

Now we will make the circuit in figure 3. It is a combination of voltage divider and current divider. R1 (10k) is in series with R2 (10k) || R3 (10Meg). (|| is shorthand for in parallel with)

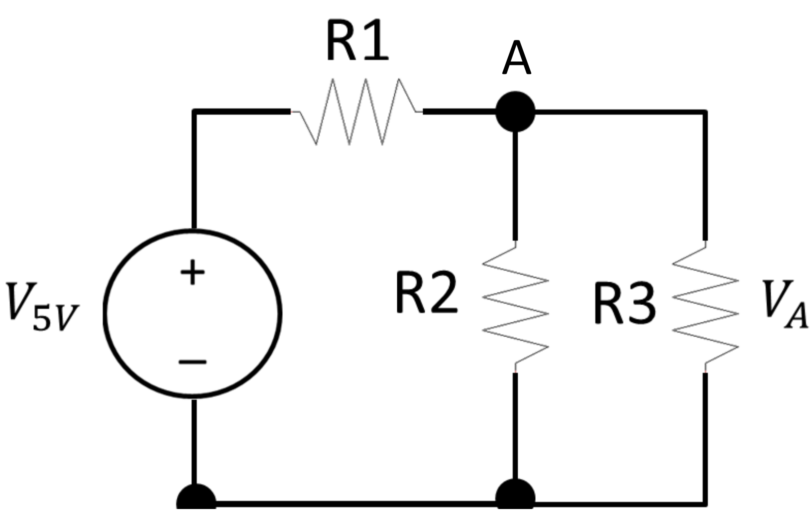


Figure 3: Voltage divider and current divider. R2 in parallel with R3 divides current. The parallel combination of R2 and R3 divides the input voltage with R1. V_A is the output voltage across the R2||R3.

35. Identity the resistors and construct the circuit on your breadboard.
36. Power up the Arduino while minding the ON LED as we did in step 18.
37. Measure and note the two node voltages, they are the 5V and the voltage at node A (with respect to ground) on the schematic (figure 3). V_{5V} is a notation that specifies the voltage at the 5V with respect to GND.

V_{5V} = 4.9922 V V_A = 2.3812 V

38. To save some time for experimenting, I'll state that the theoretical voltage V_A is 2.37 V assuming your Arduino 5V is actually 4.75 volts as mine was.
39. Now that you have the node voltages you can calculate the current through each resistor. I_{R1} notation specifies the current through R1. Note that current doesn't have a reference like the voltage does. It is a flow variable where voltage is a potential.

IR1 = 4.74999525*10^-4 =47.5 mA   IR2 = ~47.5 mA   IR3 = ~47.5 µA

40. Thinking back to the *Models and reality* section of the lab, are we missing an element in our schematic and model when we connect the multimeter to and measure the voltage at node V_A?
41. Why is this circuit less susceptible to the internal non-ideal resistance of the multimeter?

When we measure the voltage at point A using a multimeter, the meter connects an internal resistor (about 10 MΩ) between point A and ground. In our circuit, R2 is 10 kΩ and R3 is 10 MΩ. R2 and R3 are already in parallel. If we add another 10 MΩ (from the meter) in parallel, it barely changes the total resistance

If you are not sure, I'll drop some hints: Consider that the internal resistance of the voltmeter when it is measuring VA is in parallel with two resistors. What do you know about equivalence of parallel resistors? Even if you have not memorized the parallel resistor equivalence, we know that if there are resistors in parallel that the voltage across them is the same. Thus we can use V/R = I to find the current. Based in this equation, given equal voltages, a lower resistor will flow more current. Thus it will dominate the current flux through node V_A.

42. To prove this, calculate the equivalent parallel resistance of R2, R3 and the multimeter.

Before: Req = 10 kΩ || 10 MΩ ≈ 9.99 kΩ
After: Req = 10 kΩ || 10 MΩ || 10 MΩ ≈ 9.99 kΩ

43. Which of the parallel resistor values is the equivalent resistance closest to? R2

Some things to think about:

- If there are multiple resistors in parallel and there are large differences in their resistances, the lowest value resistance will dominate the equivalence. In this example the 10 Meg and the meter resistance had very little effect on the parallel resistance.

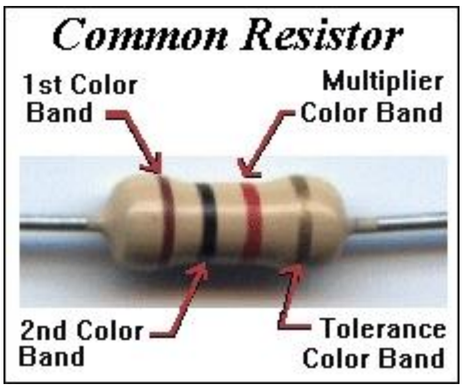
- Going a step farther we can say that if we are measuring voltages in circuits with resistances significantly lower than our voltmeter then the effect of the voltmeter non-ideal resistance is negligible.
- When engineers design circuits they have to consider these things. One specification you may hear is ‘seeding the value of your resistors’. This means if you are designing a voltage divider or any circuit that has to be measureable with this voltmeter than you can’t use very large values of resistance. How large is a judgement call based on the precision specifications of your circuit. For a rule of thumb when using elements such as Arduinos, OP amps, solderless breadboards, and small LEDs, I seed my resistor values at roughly 10 kΩ in order to keep most of the resistors in the circuit in the 1 kΩ to 500 kΩ range. We will see more why in the next few labs.

44. Submit your filled out version of this worksheet to Blackboard.
45. Done!

Resistor Color Codes:

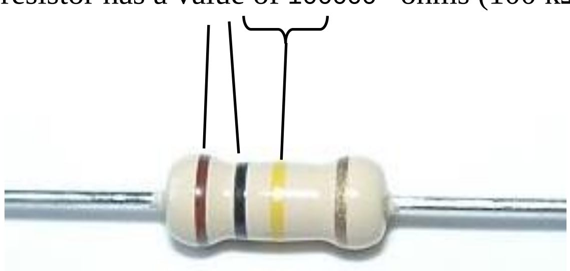
The value and percent tolerance of a common resistor are indicated by a series of colored bands, in which each color represents a digit:

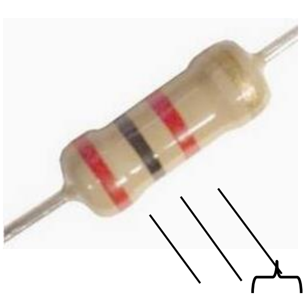
0	1	2	3	4	5	6	7	8	9



To determine the value of a given resistor, position the gold or silver “tolerance band” on the right-hand side, as shown t the left. Next convert the colored bands into three digits. The resistor value is equal to the first two digits, reading from left to right, followed by the number of zeros indicated by third “multiplier” band.

Thus, for example, for the resistor shown below, **Brown** = 1, **Black** = 0, and Yellow = 4, so the resistor has a value of 100000   ohms (100 kΩ).





2 0 0 0

Similarly, the resistor to the left has a value of Red = 2, **Black** = 0, and Red = 2, or 2 0 00 ohms (2 kΩ).