

Experiment 1: Signals, Instrumentation, and Elementary Circuits

Objectives

The objectives of this experiment are to gain some experience with the tools we use in this lab course (i.e., the electronic test and measuring equipment) and to further our practical understanding of voltage dividers.

Prerequisites

Before doing this experiment, students should be able to:

- Determine the values of series and parallel combinations of resistors.
- Identify the audible frequency spectrum in humans.
- Identify the value of standard, low wattage resistors from the color and pattern of their stripes.
- Download and install software on a Windows machine.

Learning Outcomes. Students will be able to:

- Build, test and simulate a simple resistive voltage divider and demonstrate conditions under which measurement devices (oscilloscope) significantly affect the operation of the circuit. Then, use the changes in voltages caused by the measurement devices to determine the resistance of the measurement device.
- Be able to build simple resistive circuits driven by constant and periodic voltage sources using a small breadboard (aka protoboard).
- Use an oscilloscope to measure and display the voltages in a simple resistive circuit driven by a sinusoidal voltage from a signal generator.
- Simulate and display the voltages in a simple resistive circuit driven by a sinusoidal voltage source.
- Fully annotate voltage plots obtained both from physical and simulated experiments, including such signal characteristics as frequency (both types), period, amplitude, average or DC offset, etc., and identify where on a standard circuit diagram the voltages are found.
- Comprehend a series of questions posed about simple circuits and answer the questions using fully annotated data obtained both from physical and simulated experiments.
- Develop the circuit model of a physical battery using an ideal voltage source and an ideal resistor.
- Calculate the power delivered by a battery and dissipated in a resistor.

Equipment Required

- ADALM2000 with Scopy software
- Breadboard
- Batteries
- Two 100 Ω resistors, two 1 M Ω resistors and two 1 k Ω resistors.
- Speaker
- 220 μ F capacitor

A. Sine Waves and Hearing

In this exercise, a signal generator will be used to produce electrical signals with various shapes, including sine waves. Our objective is to learn about the basic properties of sine waves and related signals by seeing them, hearing them and analyzing them with the oscilloscope and audio output capabilities of the M2K. You will need a speaker or a set of ear buds to hear the audio. We will also demonstrate some interesting facts about human hearing and speech.

Background

Equipment: What formerly would require the use of an entire workbench of equipment can now be accomplished using the M2K (ADALM2000) (see Figure A-1 below) and a computer running the Scopy GUI. This board, coupled with the Scopy software, can produce the same functionality as each of the following pieces of equipment: a two-channel oscilloscope (scope), a digital voltmeter (DVM), two DC power supplies, a two-channel signal generator, and a 16-channel digital I/O board. The digital voltmeter (DVM) has 2 channels – Analog Input 1+ (Orange) and Analog Input 2+ (Violet). The oscilloscope is a measuring device that lets you view a plot of a voltage signal vs. time. The DC power supplies generate constant DC voltage signals (like a battery). The signal generator provides a voltage signal that varies with time. The PC is an integral part of the equipment setup; you will use it in Part C to simulate many of the circuits you will build in this experiment (using SPICE software), as well as to operate the M2K via Scopy.



Figure A-1.

In this experiment we will use the signal generator and the oscilloscope. The signal generator is used to create electrical signals with various shapes, including sine waves. The signal generator can be programmed to generate waves with specified amplitude and frequency. Ear buds and speakers convert an electrical signal to sound that we then can hear. The oscilloscope displays a picture of the signal and can also do some simple analysis. The combination of the oscilloscope and audio output allows us to see with our eyes what we are hearing with our ears. We can also determine a mathematical representation of the sound that can then be used for system analysis. The two signal generators are labeled as Analog Output 1 W1 (Yellow) and Analog Output 2 W2 (Yellow/White). We will only need one of the signal generators in this experiment (Analog Output W1). See Figure A-2.

The Sine Wave Equation: All of us should have studied the sine and cosine trigonometric functions in math and physics classes. A sine wave is described by an equation of the form $v(t) = A\sin(2\pi ft) = A\sin(\omega t)$, where the variable t represents time. We use the term "wave" because the shape is similar to a water wave that you might see on an ocean or a lake. As shown in Figure A-3, a sine wave is characterized by two parameters, called amplitude (A) and frequency (f). The amplitude A determines the maximum value that the sine wave achieves along the vertical axis. The sine wave takes on values between $+A$ and $-A$ at various times.

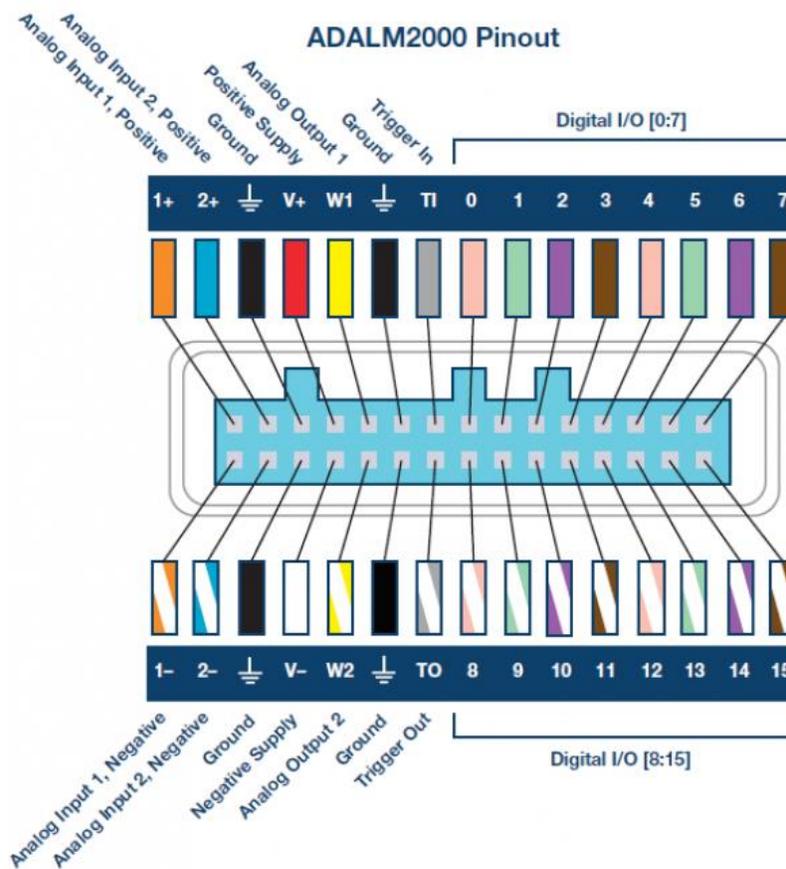


Figure A-1: ADALM2000 pin-out diagram.

The frequency f of the sine wave can be understood as follows. Notice that the sine wave reaches its peak value of $+A$ at regular intervals. The time between adjacent peaks is called the period of the sine wave. The period is denoted by the letter T and it is measured in units of seconds (sec). The frequency is defined as the number of times per second that the sine wave achieves the peak value of $+A$. Since adjacent peaks are separated by T sec, the wave achieves $1/T$ peaks per second. Hence the frequency f is equal to $1/T$, and the units of frequency are sec^{-1} . Another name for the unit sec^{-1} is Hertz, or Hz for short. It is customary to denote the product $2\pi f$ as ω , where ω is called the angular frequency. (In physics, this is the rate of change of the angle in a rotating system, and

is called angular velocity.) Note that one of the most common mistakes made in this class is to confuse f and ω .

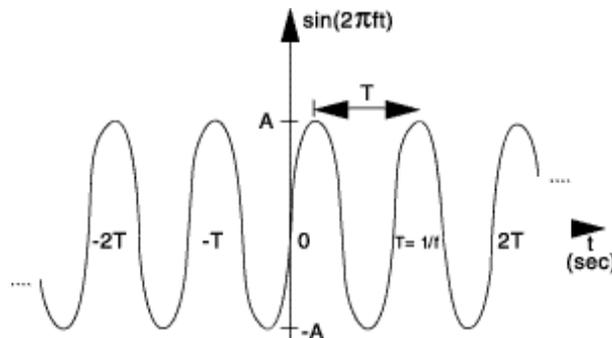


Figure A-3: Sine wave with amplitude A , frequency f , and period T .

Adding a DC Offset: If we add a DC offset voltage to the sine wave signal, as shown in Figure A-3, it moves the wave up or down such that it is centered around the DC offset. The equation becomes $v(t) = A\sin(2\pi ft) + V_{DC}$. The AC and DC parts of the signal can sometimes be treated as two mutually exclusive entities. Figure A-4 shows a sinusoidal (cosine) signal with $A = 2\text{ V}$, $T = 1.0\text{ ms}$, and $V_{DC} = 5\text{ V}$.

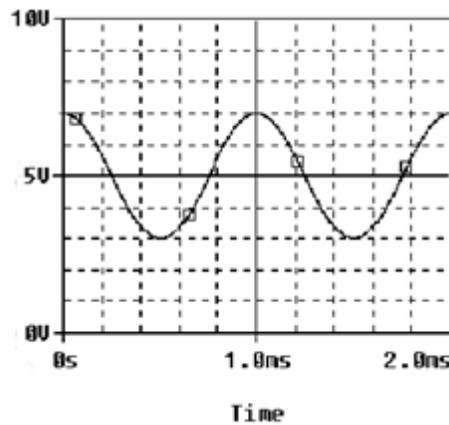


Figure A-4.

Scalar Measurement of Sine Waves: Measurement devices do not usually give us the voltage amplitude A directly. Rather they determine V_{p-p} (the peak-to-peak voltage) or V_{RMS} (the RMS voltage). The peak-to-peak amplitude is the difference between the largest positive value of the sine wave and the largest negative value of the sine wave, so should be equal to $A - (-A) = 2A$. The RMS value is determined by taking the square root of the average of the square of the voltage.

Since the voltages here are sinusoids $V_{RMS} = V/\sqrt{2} \approx A/1.414 \approx 0.707A$. Note that if there is an offset, $V_{RMS} = \sqrt{V_{DC}^2 + \frac{A^2}{2}}$. (Can you prove this?)

Impedance and Resistance: You are already familiar with the term *resistance*. It is a measure of the degree to which a resistor opposes the flow of electrons. Circuits that have a combination of components (some of which are not resistors) also affect the flow of electrons. However, the behavior of these circuits is more complicated because it varies with the frequency of the signal. We call this more-complicated response “*impedance*.” Both resistance and impedance are measured in Ohms, Ω , and the terms are often used interchangeably.

Human Hearing: We are exposed to a wide variety of sounds every day. We hear a sound after our brain processes the sensations recorded by our ears. Two attributes that are commonly used to characterize sounds are loudness and pitch. Loudness, of course, refers to how loud or intense we perceive the sound to be. Pitch refers to whether we perceive the sound to be high or low. For example, the sound of an ambulance siren has a higher pitch than the sound of a fog horn. Keep in mind that your ear is a biological system. It is designed to hear certain pitches better than others even though, technically, they may both have the same loudness.

Procedure

A.1) Setting up a Sine Wave on the Signal Generator

For the first experiment, we need to set up a sinusoidal voltage.

Assuming you have already installed the driver software, Scopy, and connected the M2K as described in Experiment 0, open the Scopy software. Click on the M2K image, then click “Connect”. Scopy will do a calibration and then display the tools. Select the Signal Generator and the Oscilloscope. If you left click, hold and slide you can detach each instrument to be able to see both at the same time. You can also double-click to detach if this is allowed in your Preferences. First, we will set the frequency. The frequency of the signal generator is adjusted as follows:

- Make sure that you choose the channel you are setting up by using the buttons on the lower left corner:

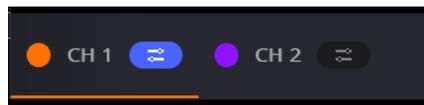


Figure A-5.

- You only need one signal generator in this experiment.
- Select “Waveform”
- Use the drop-down menu to choose Sine
- Amplitude: 400 mVolts p-p
- Frequency: 1 kHz

Run Button

- Other settings should be left as they are.

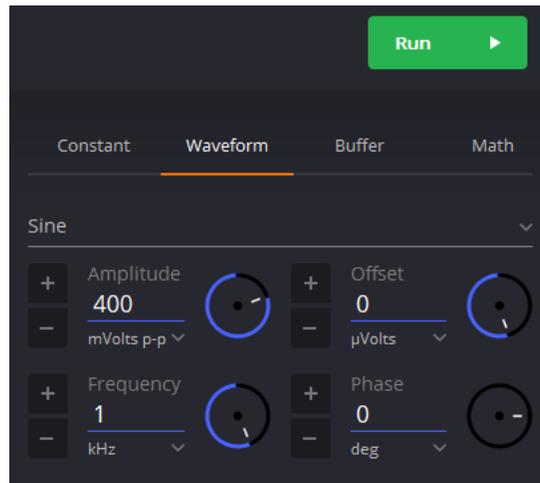


Figure A-6.

A.2) Setting up the Oscilloscope

- On the oscilloscope (scope) select channel 1 (CH 1) on the lower left corner. The time and voltage scale settings are found on the right-hand side of the oscilloscope window.
- Set Horizontal to 200 $\mu\text{s}/\text{div}$, 0 for position. Set Vertical to 100m Volts/div, 0 for position.
- To make a measurement, connect the source (W1) to oscilloscope input (1+) and the other oscilloscope input (1-) to ground.
- When you are ready, press the green “Run” button on the Signal Generator and the “Run” button on the oscilloscope. If you cannot see a signal on the oscilloscope, double-check to make sure all of the settings are correct.
- Change the Signal Generator frequency up or down as desired. How does this change the signal on the oscilloscope? (The purpose of this step is to see what kind of signals this setup can produce. Take a little time to play around with different frequencies, voltage amplitudes, signal shapes, etc.)
- Return the Signal Generator settings back to 1 kHz and 400 mVolts p-p with no offset. Use the ‘Print’ button to create a pdf of the oscilloscope screen. **The image in this pdf will be included in your report document. For the report you must clearly label both the amplitude and period of the signal you have measured.**

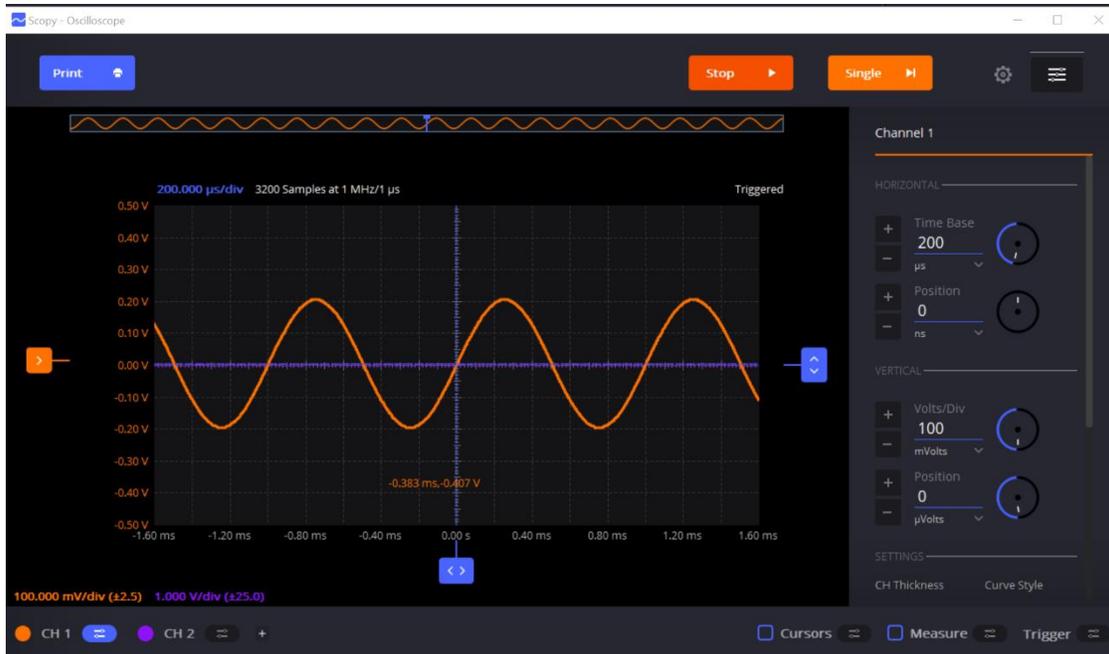


Figure A-7.

A.3) Using the Output from M2K (Building our first circuit.)

We now wish to connect a simple circuit using a capacitor and the speaker from the parts kit.

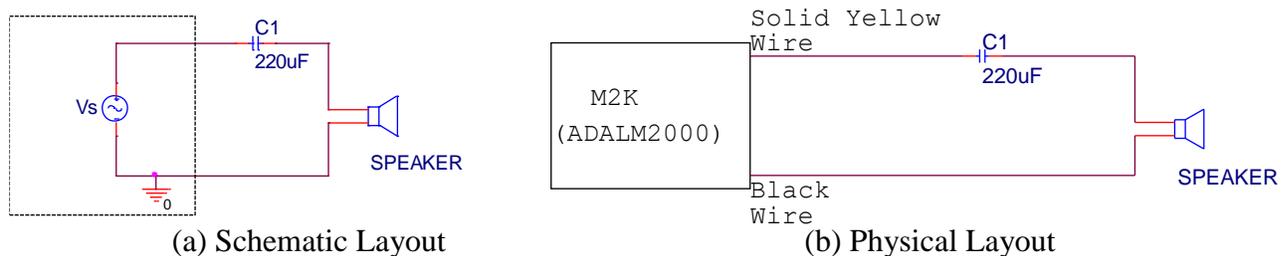


Figure A-8.

- Start by building the circuit using your breadboard.** The circuit you will build is shown on the left in Figure A-8(a). It consists of a sinusoidal source, V_s , a capacitor and a speaker. The $220 \mu\text{F}$ capacitor is in your parts kit. It is an electrolytic capacitor, which means there is a conductive media in the can (as opposed to the ceramic capacitors). On the side of the capacitor, you should see the value written as $220 \mu\text{F}$. The capacitor also has polarity, which means one side should be negative and the other side should be positive. You can identify the negative side by looking for the ‘grayish/whitish’ stripe with a ‘minus’ sign in it. That side should be connected to the speaker. We will violate the polarity rule for electrolytic capacitors but with low voltages over short periods of time. There will be reverse leakage current which in other situations could cause the circuit or the capacitor to fail. The speaker in your parts kit should be large and pretty easy to identify.

Question: why do we need a capacitor in this circuit (an audiophile question)?

- Figure A-8(b) is the physical layout for your breadboard. The sinusoidal source and ground shown in the schematic are provided by the M2K. In effect, everything inside the ‘dashed box’ of the schematic is hidden from you. Connecting the solid yellow wire to the capacitor and the black wire to the speaker implements the sinusoidal source and the ground.
- Once you have the circuit built, set your Signal Generator Channel 1 (the solid yellow wire) to a 250 Hz, 0.5 V amplitude sinusoidal wave. Listening to the speaker, adjust the volume of the signal by changing the amplitude of the signal. Find the minimum voltage that allows you to hear the speaker. Increase the amplitude and find a volume that you find most comfortable, neither too loud or too soft. **What is the value of the voltage amplitude that you have selected?**
- Now let’s investigate how our perception of loudness changes as the frequency of the sine wave is varied. With the sine wave amplitude fixed at your comfortable level, vary the frequency over the range from 100 Hz to 10,000 Hz. Try switching through the following frequencies, without changing the signal amplitude: 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10,000 Hz. Which frequency do you hear the loudest? If you have problems discerning significant differences in loudness, try changing the amplitude of the sinusoid and repeat.
- Generate a tone at the frequency that appears loudest. Does the pitch of this tone seem to be one that you commonly hear in speech, music, and automobile traffic? (See the chart at <http://jayrose.com/tutorial/freqpaint.html> for help.)

Don't be Afraid to Experiment with the Equipment!

At this point, you will have put the signal generator and oscilloscope through some basic tasks. Experiment with the other features of the signal generator and see what happens. For example, change the DC offset, the shape of the signal, add some phase/time delay, etc. Some very interesting and annoying waves can be produced. Play around a little and then find a particular set of operating conditions that you find the most interesting. Under what circumstances might you experience the sounds you have produced or, more generally, when might you encounter a waveform like the one you have displayed on your oscilloscope?

Summary

You should now know how to set up voltage signals with the signal generator feature, and connect the signal generator output to the oscilloscope input, and display it using the oscilloscope feature. You should also have a cursory understanding of pitch/frequency and amplitude/volume relationships, and know how these relate to human hearing.

B. Voltage Dividers and Measuring Equipment

In this part of the experiment you will learn that equipment isn't ideal and that "real" behavior must be accounted for when making measurements. You will investigate batteries and measure their effective internal resistance; they aren't ideal voltage sources. You will also look at the behavior of two voltage dividers when a DC voltage and an AC voltage are applied. You will use circuit analysis to examine the behavior of these circuits.

Background

Impedance: Every piece of electrical equipment has an effect on the circuit you connect it to. Just as it is impossible to design a dynamic mechanical system without friction (that resists motion), it is impossible to design an electrical system without impedance (that resists the flow of electrons). Impedance has two effects on an electrical system. It changes the value of the voltage and its phase. If the impedance affects only magnitude, then we call it resistance. Each electrical measurement device has an internal impedance, and this is also true for the M2K. The impedances we will concern ourselves with in this class are listed in table B-1 below: (These values aren't exactly correct, but they still can be used to make the point.)

Table B-1

Device	Impedance (Magnitude Only)
M2K Oscilloscope Input	1 M Ω
DMM (DC voltage) Input	10 M Ω
DMM (AC voltage) Input	1 M Ω
M2K Signal Generator Output	very small
DC Power Supply (any) Output	negligible
Batteries	0.4 to 32 Ω

Note that presently we are only concerned about the effect of the equipment on the magnitude (resistance component) of the impedance. Also note that the instruments we're using are designed to have minimal effect on any circuit they are connected to. In this part of the experiment, we will examine how much of an effect the equipment has.

Voltage Dividers: In order to analyze the effect of the equipment, we need to understand a fundamental concept of circuit analysis called a voltage divider. Basically, when a voltage in a circuit is across two or more resistances, it divides between them in proportion to the resistances. That is, the larger resistance will have a larger voltage drop. That voltage drop will be proportional to the size of that resistance divided by the total resistance of the circuit.

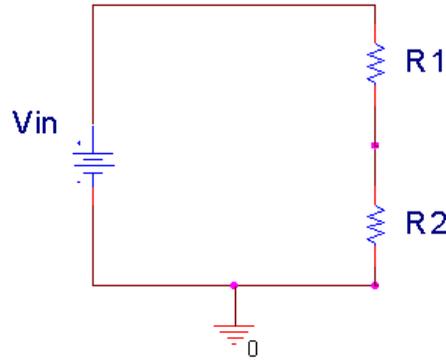


Figure B-1.

In Figure B-1 above, V_{in} is divided between R_1 and R_2 . Mathematically, this can be expressed:

$$V_{in} = V_{R1} + V_{R2}, \quad V_{R1} = \frac{R_1}{R_1 + R_2} V_{in}, \quad V_{R2} = \frac{R_2}{R_1 + R_2} V_{in}$$

Note that $R_1 + R_2$ is the total resistance of the circuit. We can use a voltage divider approach to determine how much effect a device has on a circuit, or in this case, just the reverse – the effect that a circuit has on a device. In the simple electrical model of the battery shown in Figure B-2, the internal resistance of the battery depends on the battery size and chemistry. This is a simple model that ignores much of the internal chemistry including changes as the battery is discharged. The default assumption *normally* is that the voltage output of a battery doesn't change with the load. We will investigate how this works in an actual circuit.

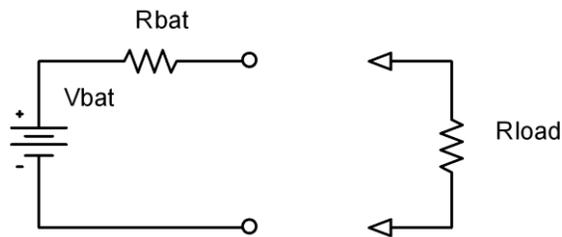


Figure B-2.

We will measure the output of the battery using the M2K, both with and without a load resistor. Remember that R_{bat} represents the internal model of the battery – ***You do not add this resistor to the circuit!*** R_{load} represents the load, or input resistance of whatever circuit you connect to the source. Using the voltage divider rule, the voltage drop across the load is given by:

$$V_{measured} = \frac{R_{load}}{R_{bat} + R_{load}} V_{bat}$$

Series and Parallel Circuits: Another fundamental concept we need to understand in order to analyze the circuits we will build is how to mathematically combine resistances. If any number of resistances are connected in series, you simply add them to find the total resistance. If any number of resistances are wired in parallel, the total resistance is the reciprocal of the sum of the reciprocals of all of the resistances. This is summarized in Figure B-3.

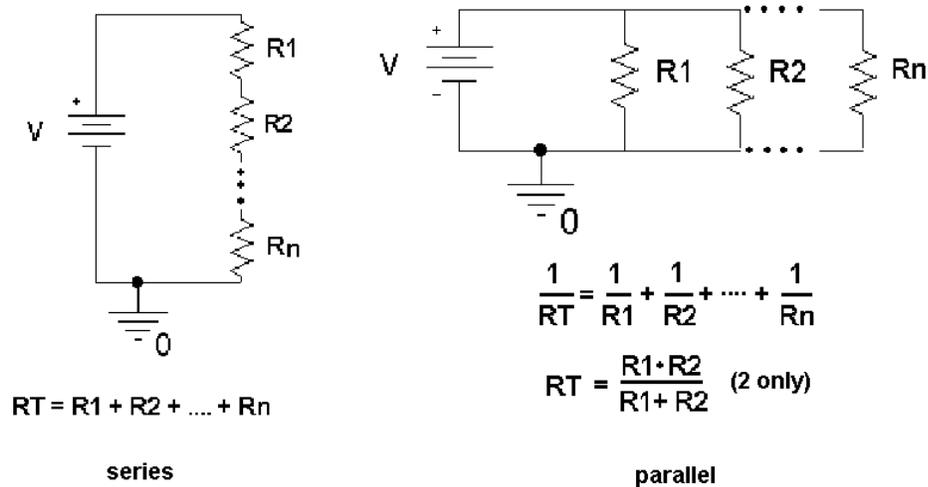


Figure B-3.

Note that the voltage divider rule applies only to series circuits. Any time we use our measuring devices to measure the voltage across a device, as illustrated in Figure B-4, we are combining that device in parallel with the resistance we are measuring. So just connecting the oscilloscope will affect the quantity to be measured. In this case the effective load resistance on the battery is R_{total} and it is the parallel combination of the oscilloscope impedance ($1\text{ M}\Omega$) with the resistance of the load resistor (R_{load}). This results in total load resistance, R_{total} .

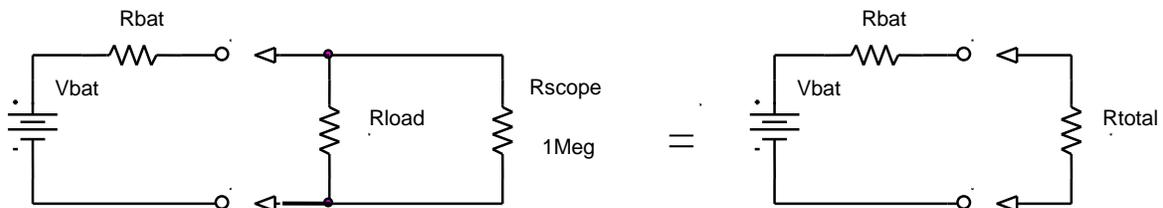


Figure B-4.

Once you have the total load resistance, R_{total} , you can use the voltage divider rule to find the internal resistance of the battery. Note that, since the voltage drop across any number of resistors in parallel is the same, $V_{R_{total}}$ is equal to $V_{R_{load}}$.

Other Basic Circuit Components: There are two other basic circuit components: capacitors and inductors. To combine capacitors in series, take the reciprocal of the sum of the reciprocals. To combine capacitors in parallel, simply add the capacitances. [Note: This is the opposite of combining resistors, but similar to conductances.] Inductors combine like resistors. To combine inductors in series, add them. To combine them in parallel, take the reciprocal of the sum of the reciprocals.

$$\begin{array}{ll} \text{series:} & \frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n} & L_T = L_1 + L_2 + \cdots + L_n \\ \text{parallel:} & C_T = C_1 + C_2 + \cdots + C_n & \frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n} \end{array}$$

Experiment

B.1) Some DC Measurements

We will look at what happens when we apply a load to a battery. We will be using batteries extensively in this course, so understanding their basic electrical properties is critical. We will be making DC measurements, like we do with a typical multi-meter. For this section, shut off the oscilloscope, go to the main Scopy window and select Voltmeter. When this is enabled, it will use the same inputs for the oscilloscope channels. Hence, it is better to turn the oscilloscope off to avoid confusion.

- **Measure the voltage of a 9V “Heavy Duty” battery without any load.** Simply attach the clip to the battery and plug them into the breadboard and then connect the leads from the breadboard to the 1+ (Scope Channel 1 Positive (orange)) and 1- (Scope Channel 1 Negative (orange-white)). Note that, when we make most measurements in this course, they will be single-ended (referenced to ground). Then you need to touch the 1+ wire to the point of interest. To do this, **the negative input (1-) must be connected to GND.** When we make what are called differential measurements, we use the two wires but do not connect one to ground. We will return to that in a future experiment. In this case the load is an open circuit (infinite resistance) because we have added no load to the battery; the input resistance of the M2K is also so large compared to the range of battery resistance listed above in Table B-1, that it can also be ignored. Record the value of the voltage you measure. (It will also be useful to check your measurement with your multimeter.)
- **Now add a load to the battery, as in Figure B-5.** The load is two 100 Ω resistors in series. We will discuss why two resistors are used a little later. Set up the circuit so that you can add and remove the load quickly, leaving it disconnected unless you are making a measurement. This just means you should wire it so that it is easy to pull out and reinstall one end of one resistor. **You should only connect the load to the battery for a short moment (a second or two)** long enough to make the measurement. If you leave the resistors connected, your battery will drain down quickly and will definitely not last a full

semester. Record the voltage displayed in the Voltmeter window of the M2K with the resistive load disconnected. **Then connect the resistors, quickly record the new voltage, and quickly disconnect the load.** You may want to repeat this a few times to find the typical change of voltage with and without the load. Remember to record the unloaded battery voltage as well as the change in voltage. In the figure, A1+ is 1+ and A1- is 1-. The A reminds us that this is an analog measurement.

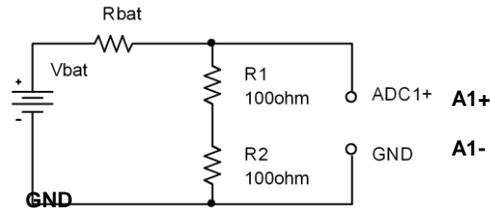


Figure B-5. Use the results from this experiment to determine the value of R_{bat} .

- Repeat the experiment with a different battery (with a different voltage). If you use a low voltage battery it may be wise to load it with only one 100 Ω resistor.
- If you have the resources, investigate several other battery types.

B.2) Some AC Measurements

Part B.1 showed that the load can affect the equipment, in this case a battery. Now we will look at how the instrument can affect the circuit. The M2K oscilloscope can load the circuit and affect circuit measurements

Now you can shut off the Voltmeter and turn on the Oscilloscope again.

- Use the signal generator, W1, of the M2K to put an AC signal on a resistor divider circuit as shown in Figure B-6. Set the Signal Generator frequency to 1 kHz and Amplitude to 0.5 V (since the goal is 1 V_{p-p}). Use $R_1 = 1 \text{ k}\Omega$ and $R_2 = 1 \text{ k}\Omega$. Measure the voltages and compare with those you would expect theoretically.

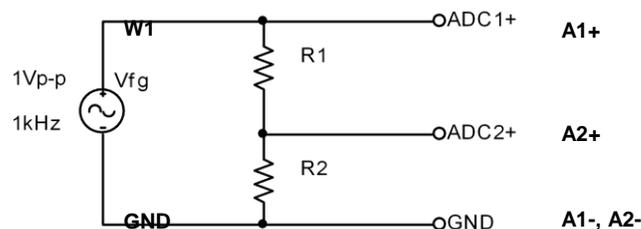


Figure B-6.

Make all the connections on your breadboard. In the circuit above, A1+ is Analog Input 1+, A1- is 1-, A2+ is 2+, and A2- is 2-. GND is Ground. The Signal Generator output is W1. Only one

ground connection is needed for the M2K because the Signal Generators (W1 & W2) are connected internally to common ground.

- Calculate the ratio of the voltage measured on 2+ to the voltage on 1+.
- Repeat the experiment using $R_1 = R_2 = 1 \text{ M}\Omega$ resistors.
- The more exact model of this measurement is given in Figure B-7, where RA1+ and RA2+ represent the effective internal input resistances of the analog input channels of the M2K. The effective input resistance of A1+ can be ignored (Do you know why?), but the input resistance of A2+ effects the measurement. Using the measurements above, estimate the value of RA2+.

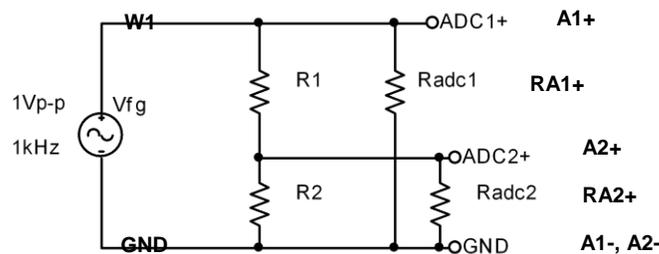


Figure B-7.

Useful Hint:

You can change the thickness of the line segment by scrolling down the Channel control on the right hand side of the oscilloscope tool.

B.3) Power Calculations and Impedance Matching

Now we will look at the power associated with the battery circuit.

- **Power Ratings:** In part B.1 you used two resistors in series. The effective resistance of resistors in series is simply the sum of the resistances. So why use two 100Ω resistors in series when we could use one 200Ω resistor? Power rating is the answer. $P = IV = I^2R = V^2 / R$ where P is the power, V , I , and R are the voltage, current, and resistance of the load. The power is in Watts if you use Volts, Amperes and Ohms. Our resistors have a power rating of $\frac{1}{4}$ watt.
 - Calculate the total power delivered by the battery for part B.1 for just the 9V battery (or other battery) measurements.
 - Calculate the power per resistor. Now is it clear why we used 2 resistors rather than one for this measurement?
 - Calculate the total power delivered by the battery for part B.1 for the other battery you used.
- **Impedance matching:** Impedance matching is important with weak signals, not with batteries. Even so, the concept can be demonstrated using our circuits. *Don't wire this circuit; it would cause excessive heating and a rapid discharge of the battery.*

For this part assume that you have a 9 V battery with an internal resistance of $30\ \Omega$. Using Figure B-2, calculate the voltage that would be measured across the load if the load resistance is $100\ \Omega$, $60\ \Omega$, $30\ \Omega$, $20\ \Omega$, and $15\ \Omega$. For each load resistance, determine the power that would be dissipated in the load resistor. Plot the power dissipated vs. the load resistance.

If you did this correctly, you will see that the maximum power in the load occurs when the load resistance is equal to the internal battery resistance. This is called impedance matching. (In EE 2240 we called this the Maximum Power Transfer Theorem.)

Summary

You should now understand how to calculate the effective resistance of resistors in series and/or in parallel. You have an appreciation of AC and DC signals, and that the load and/or the equipment affects the voltages and currents in the circuit. Lastly you should be comfortable with using the M2K, including the signal generator, the oscilloscope and the voltmeter.

References

- <https://wiki.analog.com/university/tools/m2k/scopy/siggen>
- <https://wiki.analog.com/university/tools/m2k/scopy/oscilloscope>
- <https://wiki.analog.com/university/tools/m2k/scopy/voltmeter>