18-100: Intro to Electrical and Computer Engineering
LAB06: Filters Lab
Writeup Due: Monday, March 21, 2022 at 10 PM ET

Name: Kevin Wang

Andrew ID: kqw

How to submit labs:

Download from this file from *Canvas* and edit it with whatever PDF editor you're most comfortable with. Some recommendations from other students and courses that use Gradescope include:

pdfescape.com	A web-based PDF editor that works on most, if not all, devices.
Preview	Pre-installed default MacOS PDF Editor.
iAnnotate	A cross-platform editor for mobile devices (iOS/Android).

If you have difficulties inserting your image into the PDF, simply append them as an extra page to the END of your lab packet and mark the given box. ***Do NOT insert between pages.***

If you'd prefer not to edit a PDF, you can print the document, write your answers in neatly and scan it as a PDF. *(Note: We do not recommend this as unreadable lab reports will not be graded!).* Once you've completed the lab, upload and submit it to *Gradescope*.

Note that while you may work with other students on completing the lab, this writeup is to be completed alone. Do not exchange or copy measurements, plots, code, calculations, or answer in the lab writeup.

Your lab grade will consist of two components:

1. Answers to all lab questions in your lab handout. The questions consist of measurements taken during the lab activities, calculations on those measurements and questions on the lab material.
2. A demonstration of your working lab circuits and conceptual understanding of the material. These demos are scheduled on an individual basis with your group TA.

Question:	1	2	3	Total
Points:	9	12	9	30
Score:				

1. Introduction to Signals

Electrical signals form the foundation of how we convey information in ECE. In this section, we're going to look at a few different *analog* signals in both the *time domain* and the *frequency domain*. To do this, we will use two different tools: the `Signal Generator` and the `Spectrum Analyzer`.

The most basic signal we will look at is a **sine wave**:

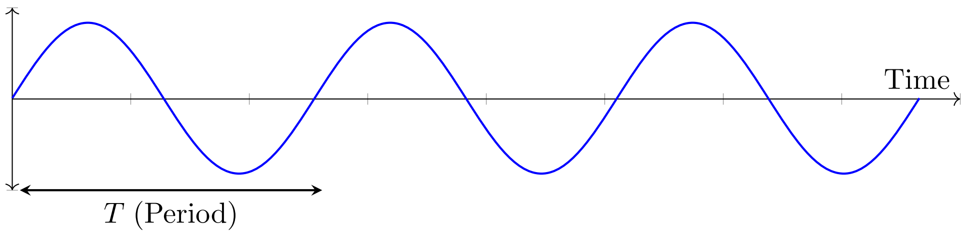
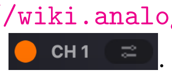


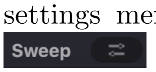
Figure 1: A Sine Wave

In Scopy, open the `Signal Generator`. Read the following guide on how to configure and use the Signal Generator: https://wiki.analog.com/university/tools/m2k/scopy/signalgenerator. Enter the settings menu for 

and select "Waveform." Configure the following settings:

`Signal Generator`	
Sine Wave	
Amplitude: $1V_{\text{p-p}}$ Frequency: 1 kHz	Offset: 0V Phase: 0 deg

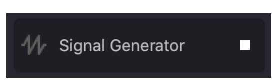
Open the `Spectrum Analyzer`. Read the following guide on how to configure and use the Spectrum Analyzer: https://wiki.analog.com/university/tools/m2k/scopy/spectrumanalyzer. Enter the settings menu for 

. Set Type to "Sample" and Window to "Hamming." Open the 

menu and configure the following settings:

`Spectrum Analyzer`	
Scale: Logarithmic	
Frequency	**Amplitude**
Start: 10Hz Stop: 100kHz	Top: 0 Bottom: -60 Scale/Div: 6 Units: dBFS Resolution BW: 6.10 Hz

Connect output W1 on the ADALM2000 directly to input CH1. (CH1+ → W1+, CH1- → W1-)

Click on the gray square next to the 

button to start outputting the waveform.

Then, in the `Spectrum Analyzer` window, hit the 

button to begin measuring. (Note: *The Spectrum Analyzer is rather CPU intensive so once you see the signal appear in the window, you can stop the measurement.*)

Note: If you run into performance issues, increase the Resolution BW.

1 pts

1.1 Paste a screenshot of your spectrum analyzer window in the box below. (Note: *If you have difficulties inserting your image into the PDF, simply append them as an extra page to the END of your lab packet and indicate this below.* ***Do NOT insert between pages.***)

1 pts

1.2 Explain why you only see one peak in the spectrum.

Since only one sinusoidal signal is present, there is only one frequency so it creates 1 peak.

Repeat the same process for a **square wave**:

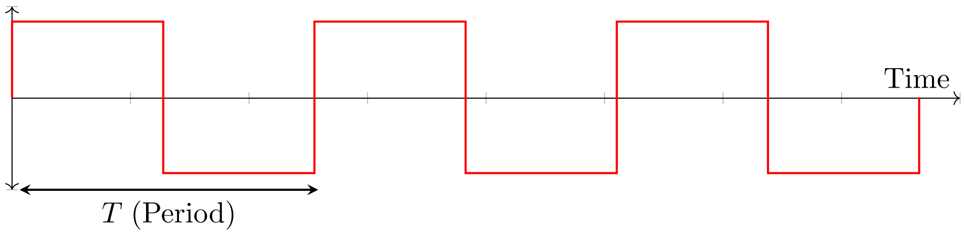


Figure 2: A Square Wave

1 pts

1.3 Paste a screenshot of your spectrum analyzer window in the box below. (Note: *If you have difficulties inserting your image into the PDF, simply append them as an extra page to the END of your lab packet and indicate this below.* ***Do NOT insert between pages.***)

1 pts

1.4 What is the frequency of the lowest harmonic in the spectrum, and how is it related to the fundamental frequency of 1 kHz?

3 kHz. It is the first odd multiple of 1 kHz, after 1 kHz itself, which is also present.

Repeat the same process for a **triangle wave**:

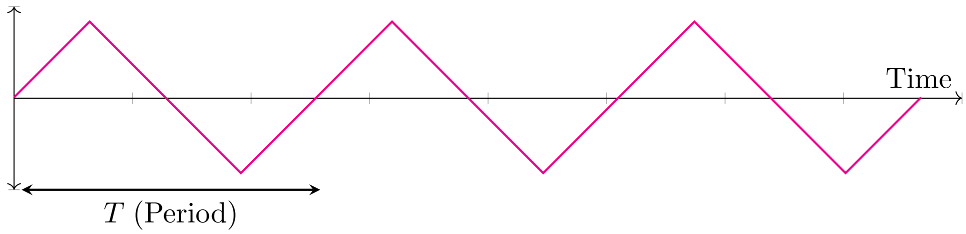


Figure 3: A Triangle Wave

1 pts

1.5 Paste a screenshot of your spectrum analyzer window in the box below. (Note: *If you have difficulties inserting your image into the PDF, simply append them as an extra page to the END of your lab packet and indicate this below.* ***Do NOT insert between pages.***)

1 pts

1.6 What is the frequency of the lowest harmonic in the spectrum, and how is it related to the fundamental frequency of 1 kHz?

3 kHz, it is $\frac{1}{3}$ of 1kHz

1 pts

1.7 Qualitatively, what is the difference between the triangle wave spectrum and the square wave spectrum?

The triangle wave contains the first odd multiple, while square wave has infinite peaks of odd multiples.

Repeat this process for the sum of two sine waves. You will use the Math function of the Scopy signal generator in order to define a signal mathematically. Use the following settings:

Signal Generator	
Math	
Record Length: 10 ms f(t): `cos(2*pi*300*t)+cos(2*pi*30000*t)`	Sample Rate: 1 Msps Noise: None

1 pts

1.8 Paste a screenshot of your spectrum analyzer window in the box below. (Note: *If you have difficulties inserting your image into the PDF, simply append them as an extra page to the END of your lab packet and indicate this below.* ***Do NOT insert between pages.***)

1 pts

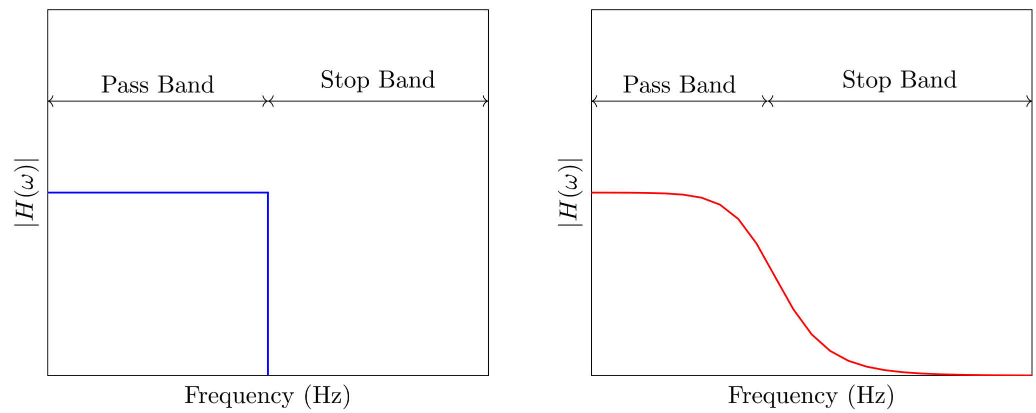
1.9 What are frequencies of these two sine waves, in Hz?

$f_1 =$ 300 Hz $f_2 =$ 30000 Hz

2. RC Filters

There are many types of filters that are used in electronic circuits. This lab covers the two most basic types: *High-pass* and *Low-pass*. As their names imply, High-pass filters allow all signals **above** a certain frequency, and Low-pass filters allow all signals **below** a certain frequency. The *passband* is the range of frequencies able to pass through the filter, and conversely the *stop band* is the range of frequencies that are filtered out and stopped by the filter.

Frequency responses of an ideal and a real Low-pass filter are shown below. The x-axis represents frequency and the y-axis represents gain (V_{out}/V_{in}, typically in decibels). In practice, analog circuits are incapable of creating a perfect ideal filter. Notice how the ideal filter passes all frequencies in the passband and removes all frequencies in the stop band, while the real filter attenuates some of the frequencies in the passband and allows some frequencies in the stop band.



(a) Ideal Low-pass Filter (b) Actual Low-pass Filter

The moment where the filter transitions from the pass band to the stop band is a called the *cutoff frequency* (f_c) For an ideal filter, it is the point where the gain changes from 0dB to $-\infty dB$. However for an actual first-order filter, the cutoff frequency is measured from what's called the -3dB point. This is the frequency where half the signal's energy aka -3dB) is attenuated by the filter. We can solve for this frequency with the following equation:

$$f_c = \frac{1}{2\pi RC}$$

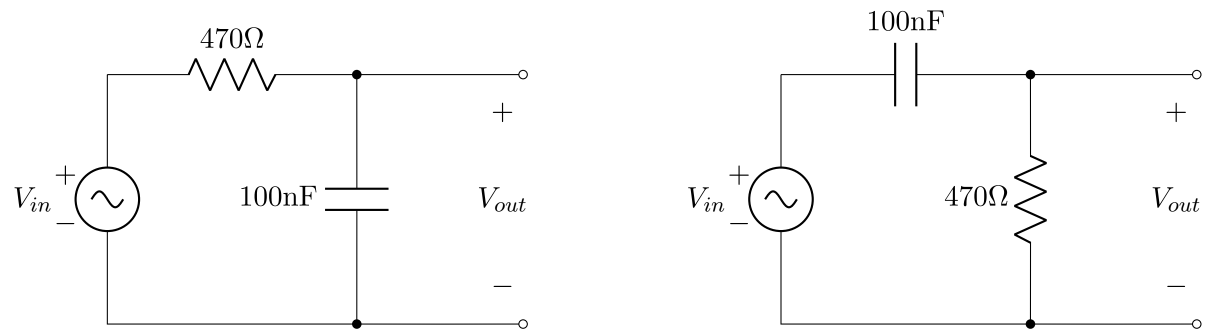
This equation works for both a first-order low-pass and high-pass filter.

RC Time Constant and Cut-off Frequency

The time constant (τ) is related to the cut-off frequency (f_c) as:

$$\tau = RC = \frac{1}{2\pi f_c}$$

Consider the two filter circuits below:



(a) Low-pass Filter (LPF) (b) High-pass Filter (HPF)

The capacitors are 100nF (labelled `104`). From the ADALM2000, W1 is the signal generator and should be connected across V_{in}, CH2 should measure across V_{out} and CH1 is a reference measurement and should be connected across V_{in}. The negative terminals for the signal generator and both probes are tied together.

2 pts

2.1 Calculate the cutoff frequency for both the first-order Low-pass and the High-pass filters. Set $R = 470\Omega$ and $C = 100$ nF for each filter.

$$\frac{1}{\tau} = \frac{1}{RC} = \frac{1}{47000} = \frac{1}{47000 \times 10^{-9}} = 21276.5 \times \frac{1}{2\pi} \text{ Hz}$$

LPF f_c = 3386 Hz HPF f_c = 3386 Hz

Now, let's measure some real filters. Begin by constructing the Low-pass filter on your breadboard.

In Scopy, open the `Network Analyzer`. Read the following guide on how to configure and use the Scopy Network Analyzer: https://wiki.analog.com/university/tools/m2k/scopy/networkanalyzer.

Configure the following settings:

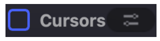
`Network Analyzer`			
Reference	**Response**	**Sweep**	**Display**
Channel 1 Amplitude: 1V Offset: 0V Settling Time: 0s	DC Filtering: Off Gain Mode: Auto Settling Time: 0s	Logarithmic Start: 10Hz Stop: 100kHz Samples Count: 50	Min. Magnitude: -30dB Min. Phase: -90deg Max. Magnitude: 0dB Max. Phase: 90deg

⚠ **Note the sample count! Change this value from the default!**
Higher sample rates may cause performance issues on slower computers.

Connect the ADALM2000 to your Low-pass Filter circuit. (wires 1/2 +/- refer to probes 1/2. W1 +/- refers to signal generator output 1)

Once your circuit is set up hit the 

button to start your measurement. The signal generator (W1) is sweeping from 10Hz to 100kHz with an amplitude of $1V_{pp}$. Probe 2, placed at V_{out}, is measuring the amplitude on the output of the filter with Probe 1 (at V_{in}) used as a reference. The difference in magnitude between the two probes is plotted in decibels (dB), and the difference in phase is plotted in degrees.

Let's use the cursors so we can easily measure the response of the filter. Enable the filter by clicking on the blue square labelled Cursors: 

Adjust the cursor settings such that the transparency is 100% and position the measurement window such that it's out of the way of your response curve.

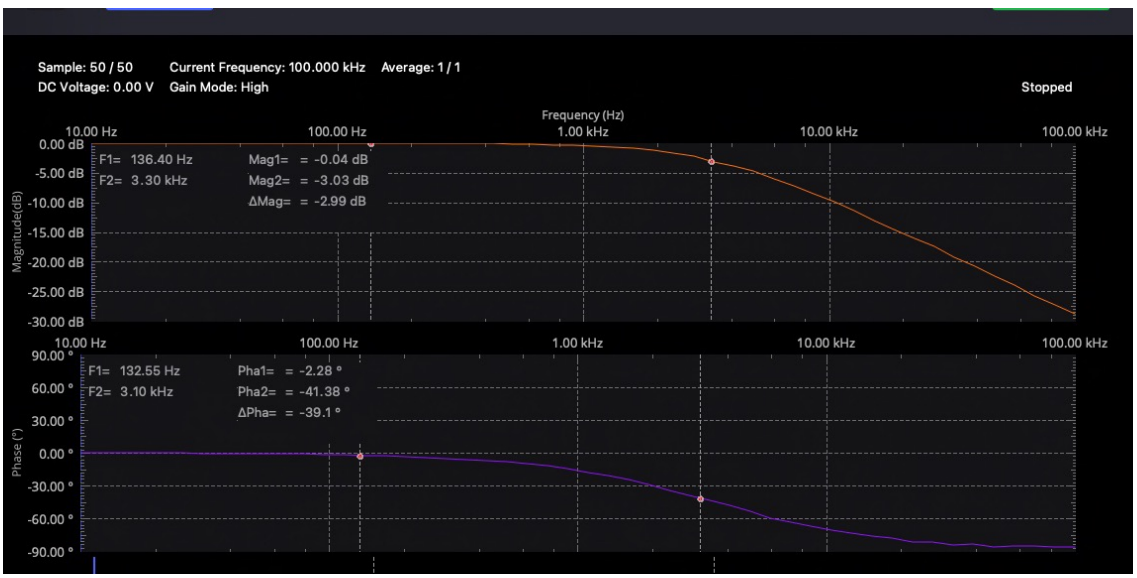
1 pts

2.2 Using the Network Analyzer plot, place one cursor such that it is in the pass band of your filter (i.e. at 0dB) and the other at ΔMag $= -3$dB. Use this to find the cutoff frequency.

LPF f_c = 3.3 k Hz

2 pts

2.3 Paste a screenshot of the Network Analyzer plot for the Low-pass filter below.
Make sure that your -3dB measurement window is visible in your screenshot.



Repeat this process for a High-pass Filter:

Reconfigure your RC circuit to make it into a High-pass Filter (HPF). Then, measure its frequency response again.

1 pts

2.4 Using the Network Analyzer plot, place one cursor such that it is in the pass band of your filter (i.e. at 0dB) and the other at $\Delta\text{Mag} = -3\text{dB}$. Use this to find the cutoff frequency.

HPF f_c = 3,4 K Hz

2 pts

2.5 Paste a screenshot of the Network Analyzer plot for the High-pass filter below.
Make sure that your -3dB measurement window is visible in your screenshot.

Now measure the response to a two-tone signal:

Apply the two-sine signal from Part 1 to the input of your RC High-pass filter using the Math function on the signal generator. You should not have to move any of your probes to do this as long as you use W1 as the output of your signal generator.

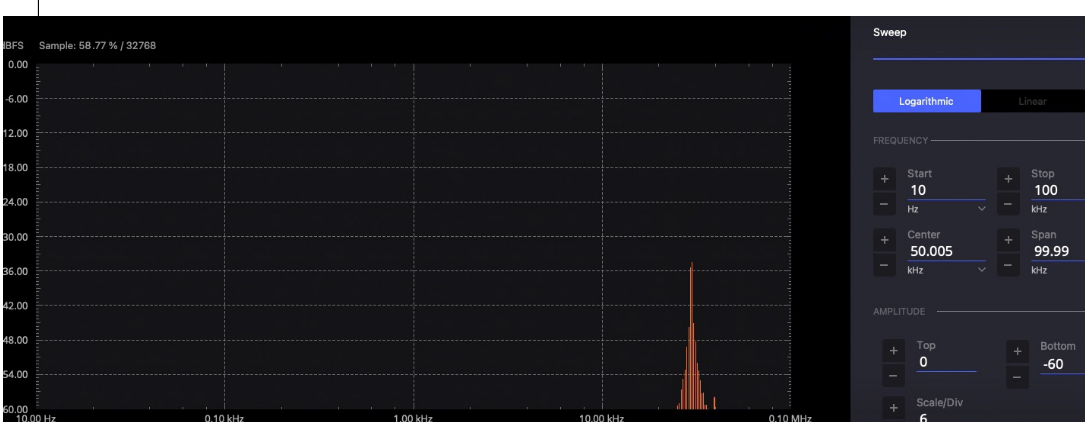
2 pts

2.6 Use the Oscilloscope to measure waveforms at both CH1 (V_{in}) and CH2 (V_{out}) and paste a screenshot below. **We recommend using a time base of 500 μsec/div.**

eup

2 pts

2.7 Use the Spectrum Analyzer to measure the spectrum of the highpass-filtered signal CH2 (V_{out}) and paste a screenshot below.



3. RL Filters

You have now measured the frequency responses of a real low-pass filter and a real high-pass filter. Each of these filters were realized with an RC circuit. It's important to know how to make equivalent filters using RL circuits instead.

The *cutoff frequency* f_c in the case of an RL circuit will use the L/R time constant:

$$f_c = \frac{1}{2\pi \frac{L}{R}}$$

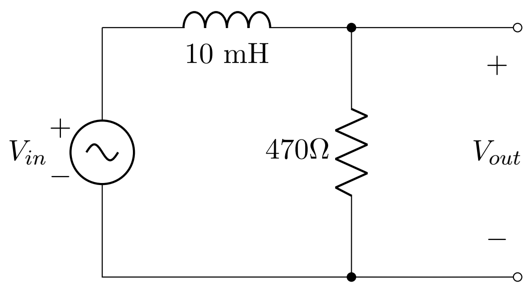
This equation works for both a first-order low-pass and a high-pass filter.

L/R Time Constant and Cut-off Frequency

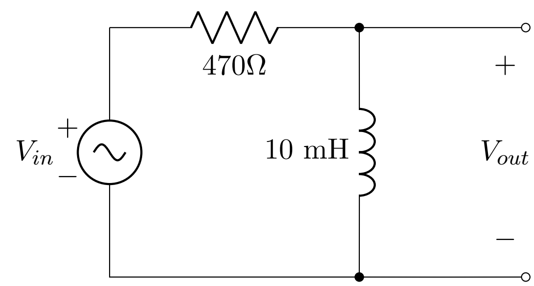
The time constant (τ) is related to the cut-off frequency (f_c) as:

$$\tau = \frac{L}{R} = \frac{1}{2\pi f_c}$$

Consider the following RL filter circuits:



(a) Low Pass Filter (LPF)



(b) High Pass Filter (HPF)

2 pts

3.1 Calculate the cutoff frequency for both the first-order low pass and the high pass filters. Set $R = 470\Omega$ and $L = 10$ mH for each filter.

$\frac{1}{\tau} = \frac{1}{\frac{L}{R}} = \frac{1}{\frac{10 mH}{470\Omega}} = \frac{470}{10 mH} = 0.047$ $\frac{0.047}{2\pi}$ τ

LPF $f_c =$ 7480 Hz HPF $f_c =$ 7480 Hz

Build the Low Pass Filter circuit with an inductor and resistor. Connect the ADALM2000 to your Low Pass Filter circuit, the same way you did in the previous section of this lab. Connect CH1 to V_{in}, CH2 to V_{out} and W1 to V_{in}.

Once your circuit is set up hit the 

button to start your measurement. The signal generator (W1) is sweeping from 10Hz to 100kHz with an amplitude of $1V_{pp}$. Probe 2, placed at V_{out}, is measuring the amplitude on the output of the filter with Probe 1 (at V_{in}) used as a reference. The difference in magnitude between the two probes is plotted in decibels (dB), and the difference in phase is plotted in degrees.

1 pts

3.2 Using the Network Analyzer plot, place one cursor such that it is in the pass band of your filter and the other such that $\Delta\text{Mag} = -3\text{dB}$. Use this to find the cutoff frequency.

LPF f_c = 6.84 Hz

2 pts

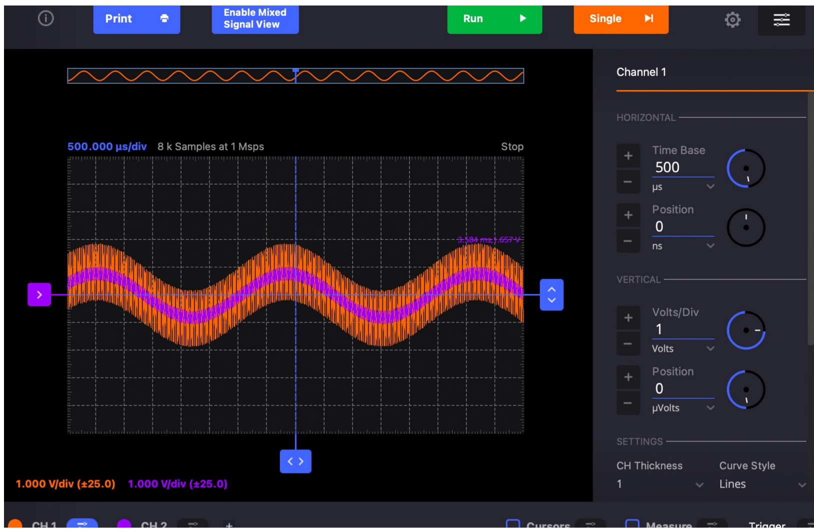
3.3 Paste a screenshot of the Network Analyzer plot for the low pass filter below.
Make sure that your -3dB measurement window is visible in your screenshot.

Now measure the response of the low-pass filter to a two-tone signal:

Apply the two-sine signal from Part 1 to the input of your RL low-pass filter using the Math function on the signal generator. You should not have to move any of your probes to do this as long as you use W1 as the output of your signal generator.

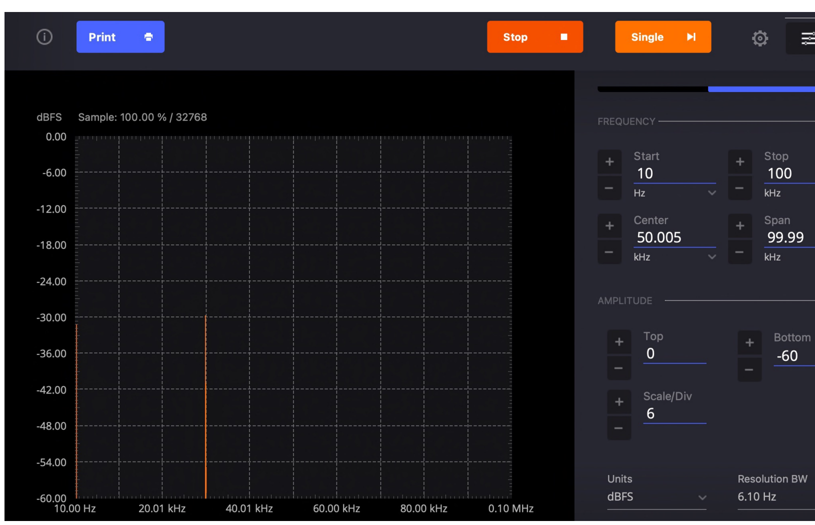
2 pts

3.4 Use the Oscilloscope to measure waveforms at both CH1 (V_{in}) and CH2 (V_{out}) and paste a screenshot below. **We recommend using a time base of 500 µsec/div.**



2 pts

3.5 Use the Spectrum Analyzer to measure the spectrum of the lowpass-filtered signal at CH2 (V_{out}) and paste a screenshot below.



Bonus Points: RL High-pass Filter

Reconfigure your RL circuit to make it into a High Pass Filter. Then, measure its frequency response again.

½ bonus

3.6 Using the Network Analyzer plot, place one cursor such that it is in the pass band of your filter (i.e. at 0dB) and the other at $\Delta\text{Mag} = -3\text{dB}$. Use this to find the cutoff frequency.

HPF $\boldsymbol{f_c}$ = Hz

½ bonus

3.7 Paste a screenshot of the Network Analyzer plot for the high pass filter below. (if you have trouble with this, attach the screenshot to a new page at the END of the handout and indicate below where to find it)

`Paste Screenshot Here`

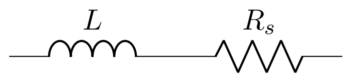
☐ I have appended the screenshot to the back of my lab writeup

1 bonus

3.8 In what ways does your measured frequency response deviate from the theoretical frequency response of the first-order high pass filters discussed in class? Don't forget about phase!

Bonus Points: Modeling an inductor

Because real inductors are made out of long coils of wire, they will have some resistance as well as inductance. This resistance is called **series resistance** and is modeled by putting a resistance R_s in series with the inductance L:



1 bonus

3.9 Measure the inductor's series resistance with your multimeter (the ohmmeter function measures DC resistance). In the space below, draw a modified schematic for the high pass filter that includes the inductor's series resistance. Label all the components in your schematic with their values.

2 bonus

3.10 Derive an expression for the frequency response of this high pass filter, then calculate its magnitude and phase angle at DC (i.e. its gain and phase shift). Compare your calculated results with the low-frequency end of the frequency response you measured in Question 3.7.