Nora Shao_L2A

September 26, 2023

1 ENPH259 Lab 2 - DC-DC Boost Prep: RC Circuits

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Teammates at Table: [redacted]

Student Number: [redacted]

Lab Section: L2A

[1]:
```
# @title
%%capture
from IPython.display import Image
from google.colab import drive
import os
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

drive.mount('/content/drive/')
path = 'drive/My Drive/UBC ENPH Y2/ENPH259/Lab2/'
file_name = 'Nora Shao_L2A.ipynb'

assert file_name in os.listdir(path)

def img_path(img_name):
  return path + img_name
```

2 Prelab

2.1 Prelab Q1

Description: From the values given in Figure 1, estimate the time constant for the circuit. If $V_{in}(t < 0) = 5$ V, what is $V_C(t = 0)$?

Solution: We have $\tau = RC$, where $R = 1M\Omega$ and $C = 500nF$, so

$$\tau = 1000000\Omega \times 500 \times 10^{-9}F,$$

which evaluates to $ = 0.5 $ s.

At $t = 0$, we have that $V_C(0) = 5$ V, since at $t < 0$, $**V_**in(t)$ is already 5 V.

2.2 Prelab Q2

Description: Sketch the expected waveforms of V_{in} and VC when the input is a square wave. If you would like to measure the time constant of the circuit using the square wave input, what is the frequency of the square wave you should use for V_{in}?

Solution: See Figure 2 for V_{in} and for V_C. To measure the time constant of the citcuit, we have several options, depending on how much of the charging and discharging of the circuit we want to see. Since $\tau = 0.5$s, and a capacitor fully charges or discharges in ~5 time constans, to get the full picture of this, we will let the period of the square wave be $T = 2 \times 5 \times 0.5$s, or $T = 5s$. Thus the frequency of the square wave should be $\frac{1}{T}$, which gives

$$f = 0.2Hz.$$

2.3 Prelab Q3

Description: If V_{in} is an AC signal, is the circuit in Figure 1 a low or high-pass filter when $V_C = V_{out}$? On either case, what is the 3 dB frequency?

Solution: Figure 1's circuit is a low-pass filter because the impedance of a capacitor is inversely proportional to the frequency of a signal, so the capacitor lets all high-frequency signals through to ground, while low-frequency signals are blocked by the capacitor continue to the output of the circuit. We have that

$$f_{3dB} = \frac{1}{2\pi RC},$$

which evaluates to give us

$$f_{3dB} = 0.3183Hz.$$

[2]:
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Image(filename = img_path('L2A_Prelab 1.png'))
```

[2]:

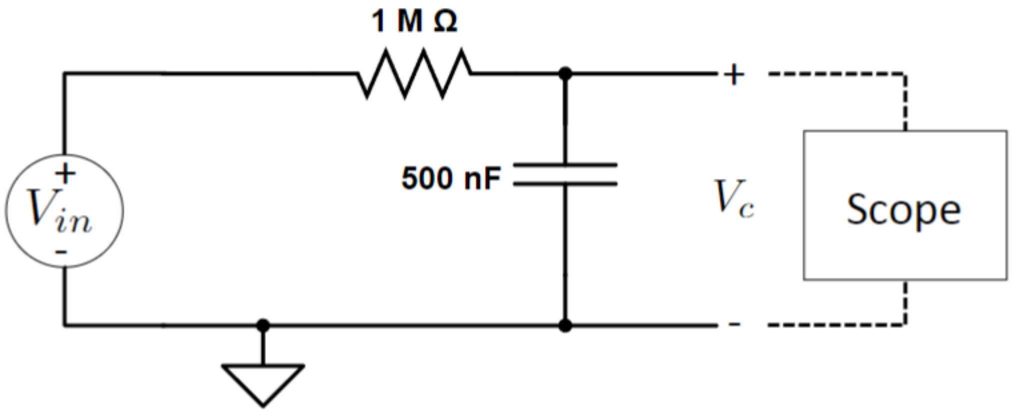

Figure 1: Simple RC circuit

[3]:
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# @title
Image(filename = img_path('L2A_Prelab 2.jpg'))
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[3]:

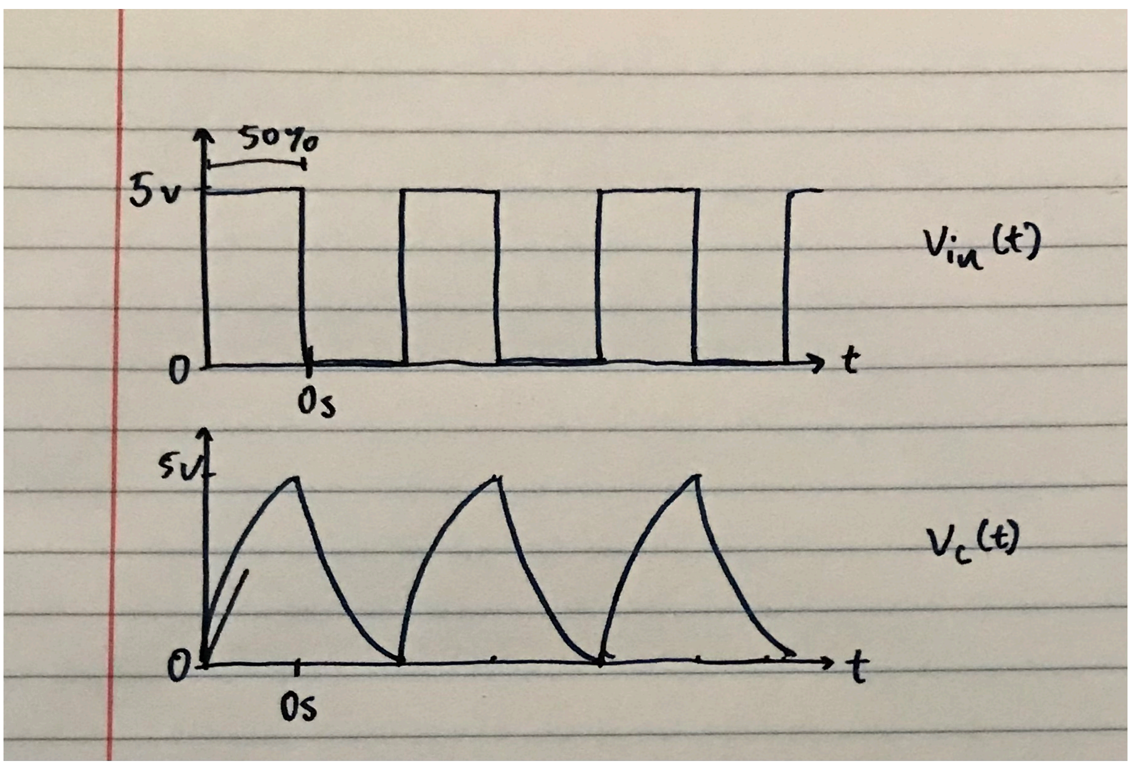

Figure 2: $V_{in}(t)$ and $V_C(t)$ for the circuit in Figure 1 over time

3 Troubleshooting

TS1: In 4.1 Task #1, I tried measuring the voltage across the capacitor with the positive and negative probes of the Channel 2 scope. While I could see the charging discharging shape on the graph, it was incredibly unstable and triggering it didn't work. The TA told me to try connecting the input to Channel 1. This stablized the graph, and we found that if we set the source to Channel 2 again, even if the BNC cable was connected to Channel 1, the graph destablized again, so it's a problem with Channel 2.

TS2: The graph acted up again, where it kept changing, although not as rapidly as before. I found out (with the help of the TA), that the frequency I had set the output square wave was far too low (200 mHz) and that meant the capacitor's charging and discharging had long periods in between that the scope was reading.

TS3: When determining the f_{3dB} frequency of the RC low-pass filter, I determined a resulting f_{3dB} frequency wildly off from my calculated value and the values my tablemates found. I checked the connection of all my inputs, ensuring the black probe of the Wavegen 1 cable was grounding the circuit, and switched the locations of the Scope + probes across the circuit.

I checked the capacitance of the capacitor again and made sure the colour code of the resistor was 100 $k\Omega$ by searching up the appropriate colour code and matching it

I changed the wavegen output to a stable 5 V and noticed that the voltage drop across the capacitor was signficantly higher than what made sense for the 100 $k\Omega$ resistor. I checked its colour code *again* and realized that I saw the colours wrong the first time and was using a 1 $k\Omega$ resistor instead of 100 $k\Omega$ resistor.

4 Experiment

4.1 Time Domain Experiment

4.1.1 Task 1: Measurement of Unknown R and C

We have to determine the capacitance and resistance of an unknown capacitor, C_U and, and resistor, R_U, respectively.

Resistance of R_U

We can utlize our knowledge of how the voltage drop over a resistor is proportional to its resistance to calculate R_U's resistance.

Procedure

- We will use a voltage divider with R_U and the 1 $k\Omega$ set up like the circuit in Figure 3 and with the setup in Figure 4.
  - I powered the circuit with the voltage supplies from the AD2 with the power wire attached to the V_{in} which I set to 5 V using the Supplies feature on WaveForms and the the GND wire connected to end of R_U, as visible in Figure 4.
  - I used the power probes from BNC cables connected to the Scope + and Scope - ports on the breakout board and the Voltmeter feature on the AD2 to measure the voltage across R_U.

Results - We measure 4.994 +/- 0.0005 V with the AD2 Voltmeter across the board and 4.178 +/- 0.0005 V across R_U.

- Instrument uncertainty: 4.994 V $\times$ $\frac{1}{2^{14}}$ $= 3.048 \times 10^{-4}$ or 4.178 V $\times$ $\frac{1}{2^{14}}$ $= 2.550 \times 10^{-4}$
- Measurement uncertainty: $\frac{0.0005}{\sqrt{3}} = 2.887$ V (since the Voltmeter display is digital)
- Net uncertainty $= \sqrt{(3.048 \times 10^{-4}\ V)^2 + (2.887 \times 10^{-4}\ V)^2} = 4.198 \times 10^{-4} V$ or $\sqrt{(2.550 \times 10^{-4}\ V)^2 + (2.887 \times 10^{-4}\ V)^2} = 3.852 \times 10^{-4} V$,
- **Our measured voltages:** $4.994 \pm 4 \times 10^{-4} V$ and $ 4.178 ±4 ×10^{-4} V$
- The DMM measured the actual resistance of the 1 $k\Omega$ resistor as 0.983 ± 0.0005 $k\Omega$.
  - We were told we could use the DMM for this measurement
  - Instrument uncertainty: 0.005 $\times$ 0.983 $k\Omega$ + 2 $\times$ 0.001 $k\Omega$ = 0.006915 $k\Omega$.
  - Measurement uncertainty: $\frac{0.0005k\Omega}{\sqrt{6}} = 0.0002041 k\Omega$
  - Net uncertainty $= \sqrt{(0.006915 k\Omega)^2 + (0.000204 k\Omega)^2} = 0.0069 k\Omega$
  - **Our measured resistance:** $0.983 \pm 0.007 k\Omega$.

Calculations: Since voltage drop is proportional to resistance of the resistor the drop is across, we have

$$\frac{R_U}{4.178V} = \frac{0.983k\Omega}{5V - 4.178V},$$

which evaluates to give us

$$R_U = \frac{0.983k\Omega \times 4.178V}{5V - 4.178V},$$

or

$$R_U = 4.996k\Omega.$$

Notes: Proper uncertainty will be propagated in the final lab. Accounting for uncertainty, we have we have

$$\frac{R_U}{4.178V} = \frac{0.983k\Omega}{4.994V - 4.17 \pm 0.0004V},$$

which evaluates to give us

$$R_U = \frac{0.983 \pm 0.007k\Omega \times 4.178 \pm 0.0004V}{4.994 \pm 0.0004V - 4.178 \pm 0.0004V},$$

or, using an online uncertainty propagation calculator (

$$R_U = 5.03 \pm 0.04k\Omega.$$

[4]:
```
Image(filename = img_path('L2A_voltage divider circuit.jpg'))
```

[4]:

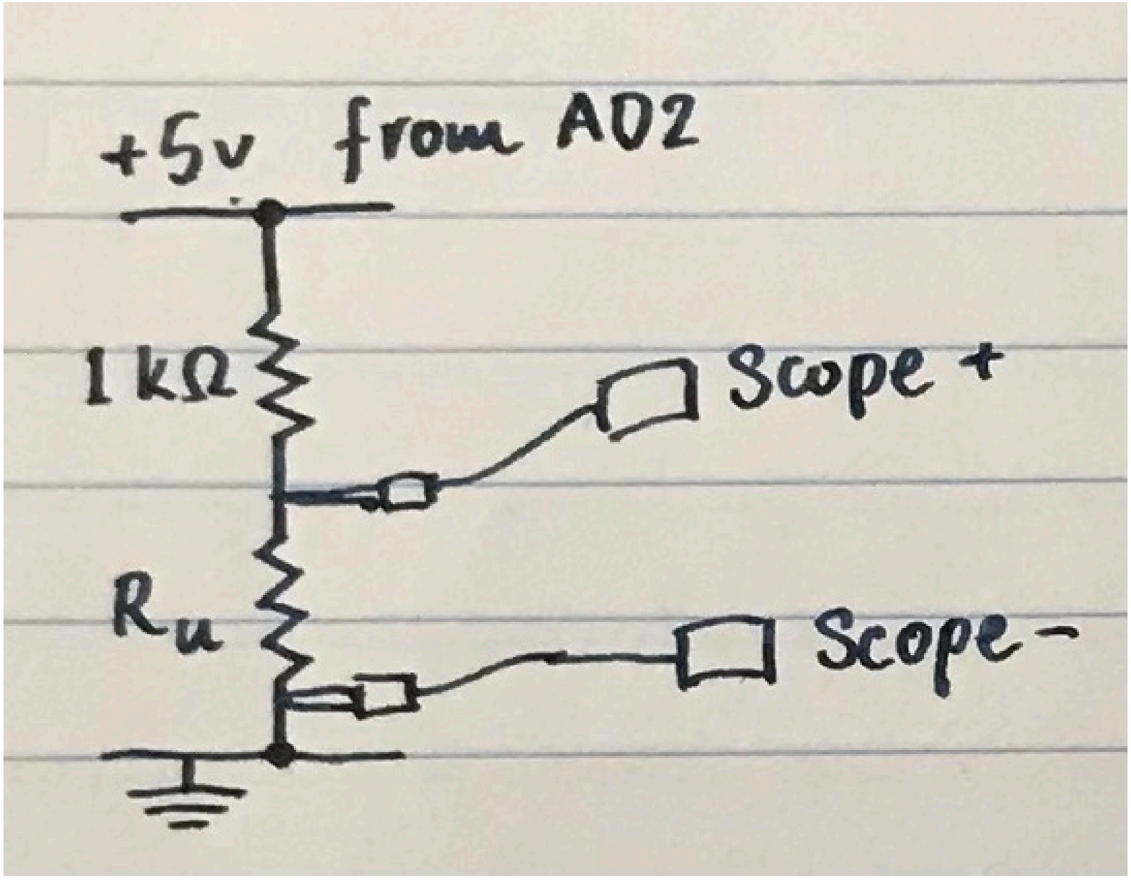

Figure 3: Voltage divider circuit used to find R_U

[5]:
```
Image(filename = img_path('L2A_Ru setup.jpg'))
```

[5]:

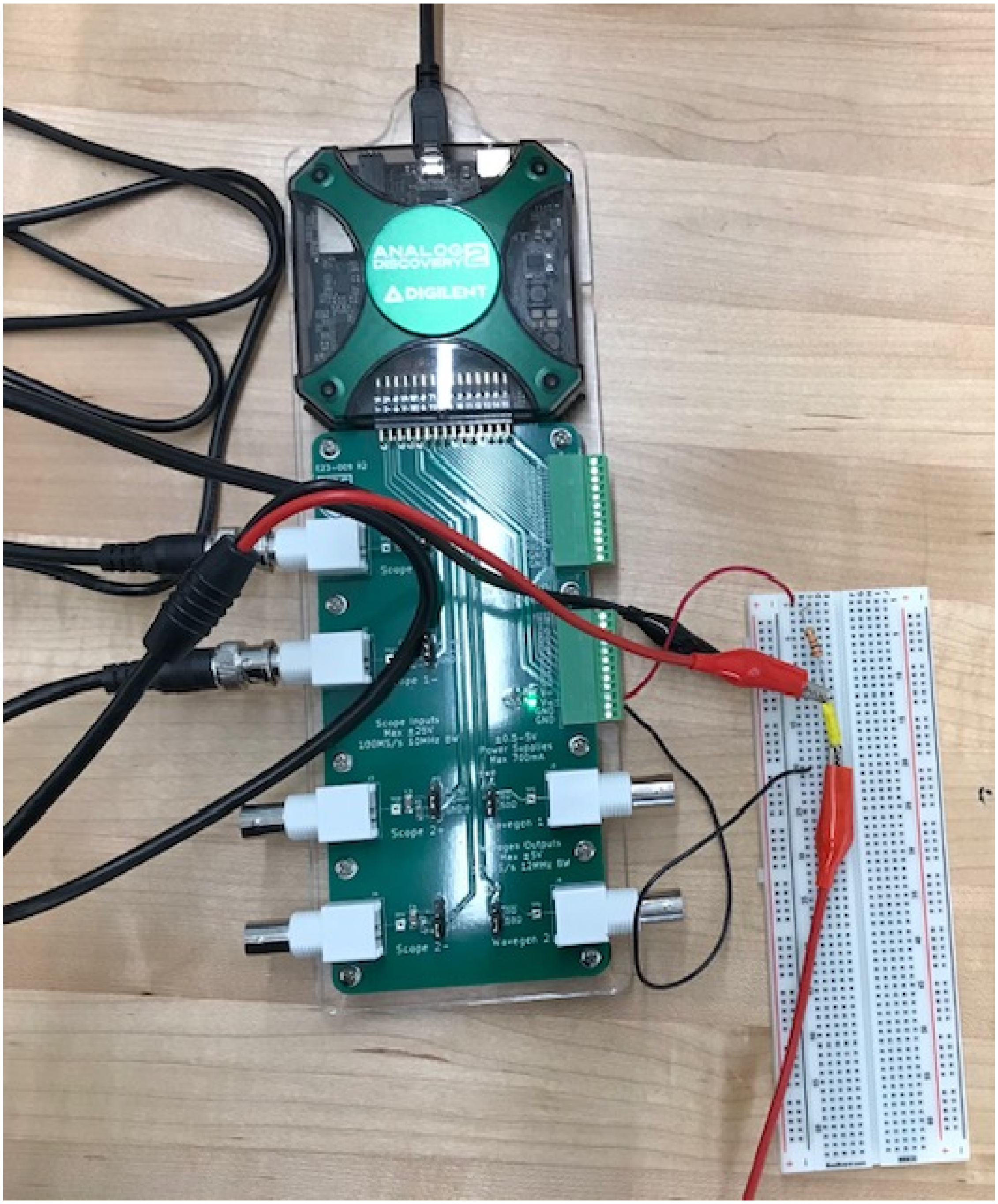

Figure 4: Setup of voltage divider circuit for R_U (pictured in yellow)

Capacitance of C_U: - We can use an RC circuit and look at the behaviour of the charging and discharging of the capacitor to determine the time constant, which depends on resistance and capacitance.

- We need the input to be a square wave to let the capacitor charge and discharge, but we can determine the frequency of the square wave through trial and error.

Procedure

- We set up a basic RC circuit like in Figure 5 and with the setup on the breadboard like Figure 6.
- I connected one wavegen output to the BNC cable, which acted as the square wave input
  - To start, I set up the square wave with a 1 V amplitude and 1 Hz frequency. The square wave had a 50% duty cycle to allow for equal charging and discharging time for the capacitor
- To measure the voltage across the capacitor, which changes accordingly to the charging and discharging of the capacitor, I added a BNC cable to the Channel 1 Scope (after using Channel 2, which didn't work, see **TS1**)
- Then I could see the charging and discharging shape but it kept moving rapidly, but I fixed that (see **TS2**)
- At an output of 250 Hz, the capcitor was almost fully charging and discharging, so I knew I needed a slightly longer period and the best frequency would be slightly lower.
- At 50 Hz, I could see the capacitor stablize after charging and discharging, so I am using this frequency for a better picture of the capacitor's behaviour.
- Since a capacitor charges ~0.632 of the way in one time constant, I will measure this 63.2% (the time it takes for the capacitor to charge to 63.2% of its maximum charged voltage)
- I'll use the y-cursors to find when the capacitor goes from -1 V to (-1 V + 0.632 * 2V)
  - We have that 2 * 0.632 V = 1.264, so I placed the bottom cursor at -1 V (the bottom of the capacitor's voltage) and the top cursor wherever the delta-Y value was closest to 1.264 V.
- Now I add the x-cursors where the y-cursors intersect with the charging-discharging graph and find delta-X for one time constant
  - I get **1.00 +/- 0.05 ms** as the time constant. The raw instrument uncertainty being the resolution of the graph since I used the cursors as an analog measurement
  - Visible in Figure 7, the resolution of the time scale on WaveForms is 0.05 ms, so we get an instrument uncertainty of 0.05 ms $\times$ 0.5s $\times \frac{1}{2^{14}} \approx 2 \times 10^{-12}$, which comes from a formula for the AD2's error the TA provided. This value is so small we really just have the measurement error as the primary uncertainty
  - Since we used the x and y cursors for an analog measurement, we have a measurement error of $\dfrac{0.05 \text{ ms}}{\sqrt{6}} \approx 0.02$ ms.

Notes: You can also export the data to calculate the time it takes for the voltage to increase of 0.632 of the full voltage more accurately, but that takes more time than it's really worth.

Uncertainty will be propagated in the final lab.

Calculations: We know that

$$\tau = RC,$$

so

$$C = \frac{\tau}{R}.$$

Plugging in our numbers, we have that

$$C = \frac{0.001s}{983\Omega},$$

which evaluates to

$$C = 1.017mF.$$

With uncertainty, we have

$$C = \frac{0.001 \pm 0.00002s}{983 \pm 7\Omega},$$

which propagates using the same online calculator to

$$C = 1.02 \pm 0.02 \text{ mF}.$$

[6]:
```
Image(filename = img_path('L2A_Cu circuit.jpg'))
```

[6]:

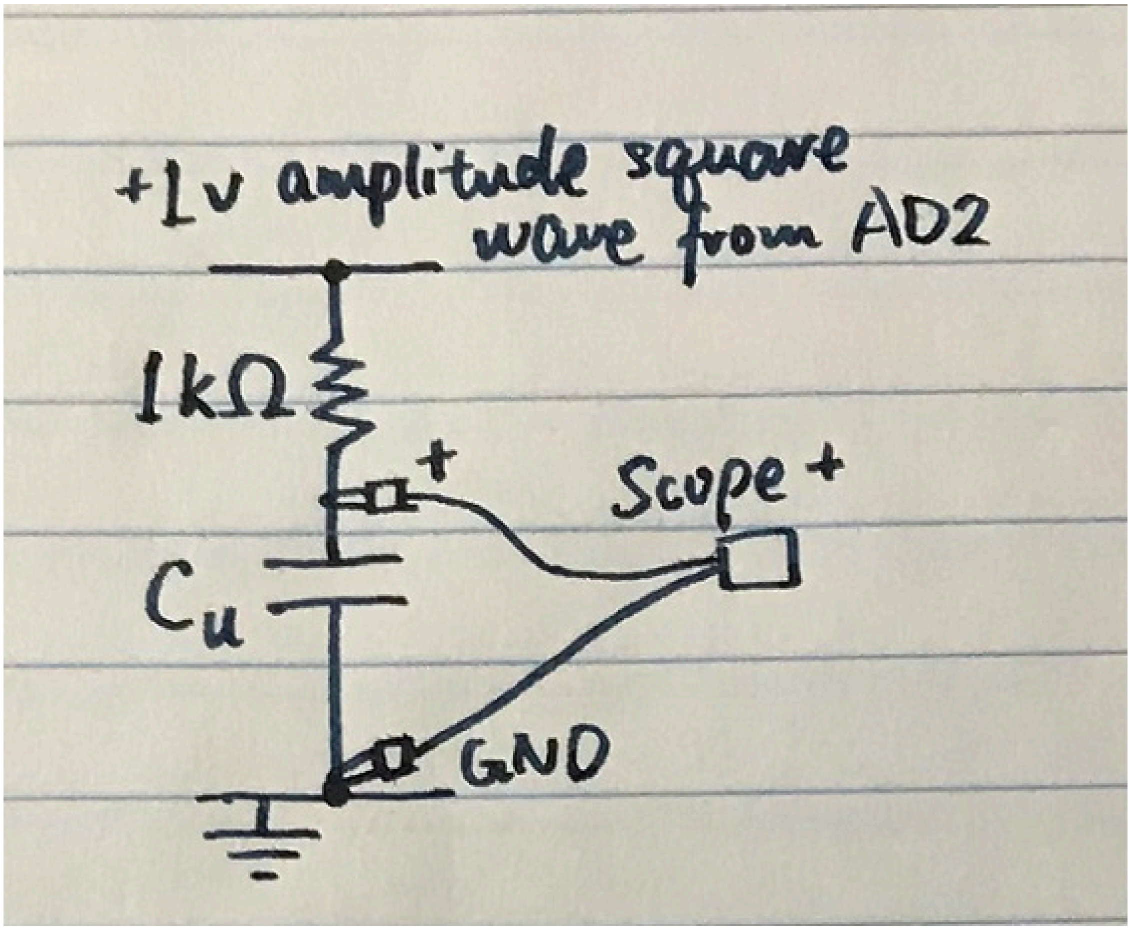

Figure 5: RC circuit schematic for determining C_U

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[7]: Image(filename = img_path('L2A_Cu setup.jpg'))
```

[7]:

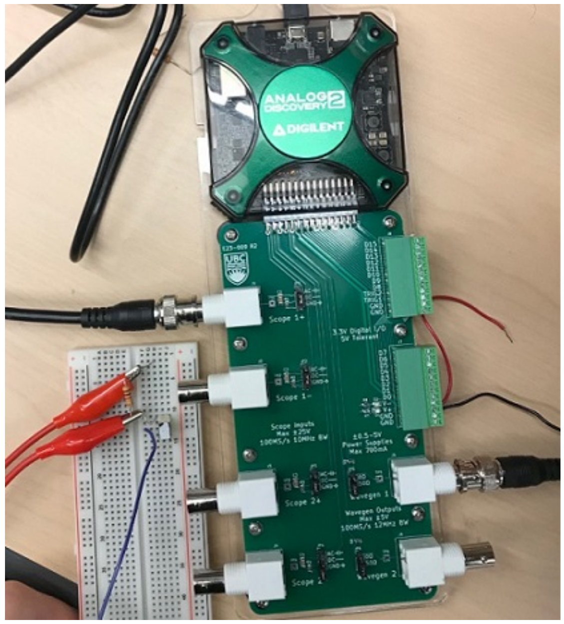

Figure 6: Setup of RC circuit for R_U

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[8]: Image(filename = img_path('L2A_Capacitance Cursors 3.png'))
```

[8]:

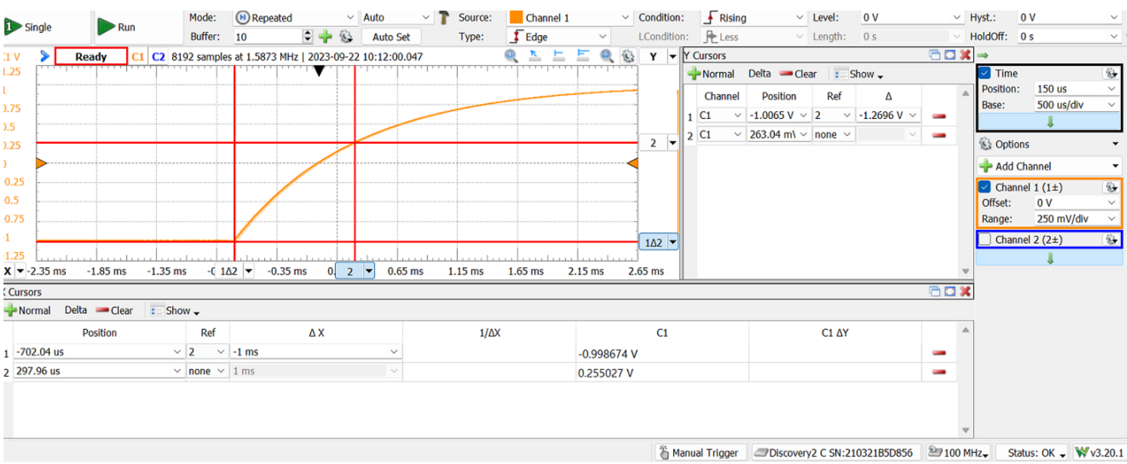

Figure 7: Measuring the time constant of RC circuit with cursors on the charging graph of the capacitor

4.2 Milestone

- Completed

4.3 Frequency Domain Measurements

4.3.1 Task 2: Measure the 3dB Cutoff of Simple RC Low-pass Filter

- Low-pass filters decrease the signal strength of an AC input depending on the frequency, and we are looking for a '3dB' frequency cutoff where the output signal strength is sufficiently lowered.

Procedure (IGNORE) - Setup:

- We only have 1000 nF capacitors, but we can construct a 500 nF capacitor from these but connecting two 1000 nF capacitors in series (because of how capacitors work)
- I have a 10 $k\Omega$ resistor in series with these two capacitors
- I measure the two capacitors to be 9967 nF and 9812 nF with the DMM
- We can use the y-cursors to measure the output signal amplitude
- Internet sources say that at the 3dB point of a low-pass filter, the resulting signal is at 70.7% of the input signal, so we can just trial and error our way across several frequencies for the input sine wave until the output amplitude is 0.707 * input voltage.
- Arbitrarily, I'll set the input voltage to 1 V, so we're looking for the frequency that gives an output amplitude of 0.707 V.
- Every time, I'm multiplying the input frequency by 5 and moving the y-cursor to the peak of the wave until the output amplitude decreases noticeably
  - At 10 kHz, the amplitude decreases significantly to ~0.75 V, so we proceed increasing the frequency more carefully from here
  - At 11.6 kHz, we get ~0.707 Hz
  - Any further precision unstablizes the graph too much

Measured f_{3dB}: 11.6 kHz

NOTE: This measured f_{3dB} is wrong but I will borrow a teammate's data to analyze after the lab. Disregard - I just redid the lab on my own after repeating the original procedure multiple times and figuring out I used the wrong resistor (more details in TS3).

Correct Procedure: - Setup:

- We only have 1000 nF capacitors, but we can construct a 500 nF capacitor from these but connecting two 1000 nF capacitors in series (because of how capacitors work)
- I have a 10 $k\Omega$ resistor in series with these two capacitors like in Figure 8, and with the setup in Figure 9.
- Internet sources say that at the 3dB point of a low-pass filter, the resulting signal is at 70.7% of the input signal, so we can just trial and error our way across several frequencies for the input sine wave until the output amplitude is 0.707 * input voltage.
- To avoid unnecessary calculations, I'll set the input voltage to 1 V, so we're looking for the frequency that gives an output amplitude of 0.707 V.

- The breakout board's Wavegen 1 outputs the sine wave to the circuit via the positive probe attached to the top of the resistor and the black probe grounding the circuit
  - Scope + reads the voltage across the capacitor with the black probe also grounding the circuit
- Measurements
  - I measure the two capacitors to be 996.7 nF and 981.2 nF with the DMM before setting up the low-pass filter, and the resistor to be 108.8 $k\Omega$.
  - I'll add the Measurements function on WaveForms for amplitude instead of using cursors for further accuracy
  - At 1 Hz, the output voltage is still around 1 V
  - At 2.88 Hz, we get an output voltage of ~0.707 V (visible in Figure 10), which is what we want

Measured f_{3dB}: 2.88 kHz

Calculations: The formula for f_{3dB} says

$$f_{3dB} = \frac{1}{2\pi RC}.$$

Thus, we have

$$f_{3dB} = \frac{1}{2\pi \times 108.8k\Omega \times (\frac{1}{9967nF} + \frac{1}{9812nF})^{-1}},$$

which evaluates to

$$f_{3dB} \approx 2.96Hz.$$

Note: I am not propagating error for this calculation because I only want a rough estimate of the expected f_{3dB}.

Our measured value of 2.88 Hz is close enough to 2.96 Hz that additional error can be attributed to the resistance and capacitance of the components changing based on temperature or contact with each other, as well as the scope's error.

[9]:
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Image(filename = img_path('L2A_f3db circuit.jpg'))
```

[9]:

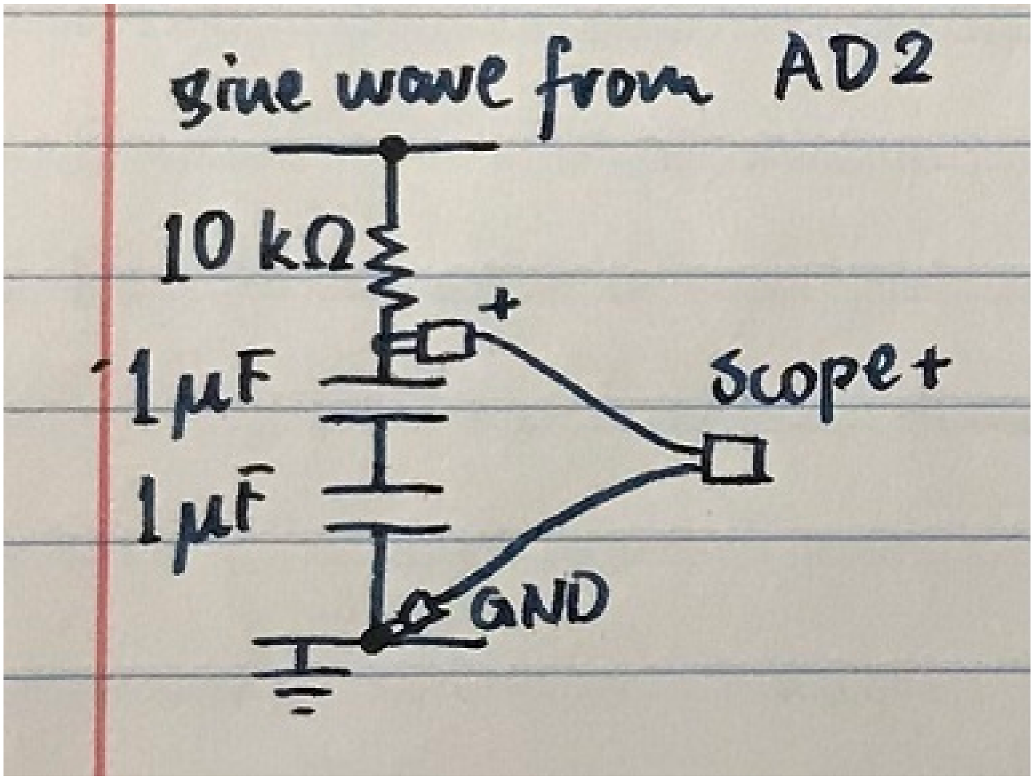

Figure 8: RC circuit for finding f_{3dB} of circuit

[10]:
```
Image(filename = img_path('L2A_f3db setup.jpg'))
```

[10]:

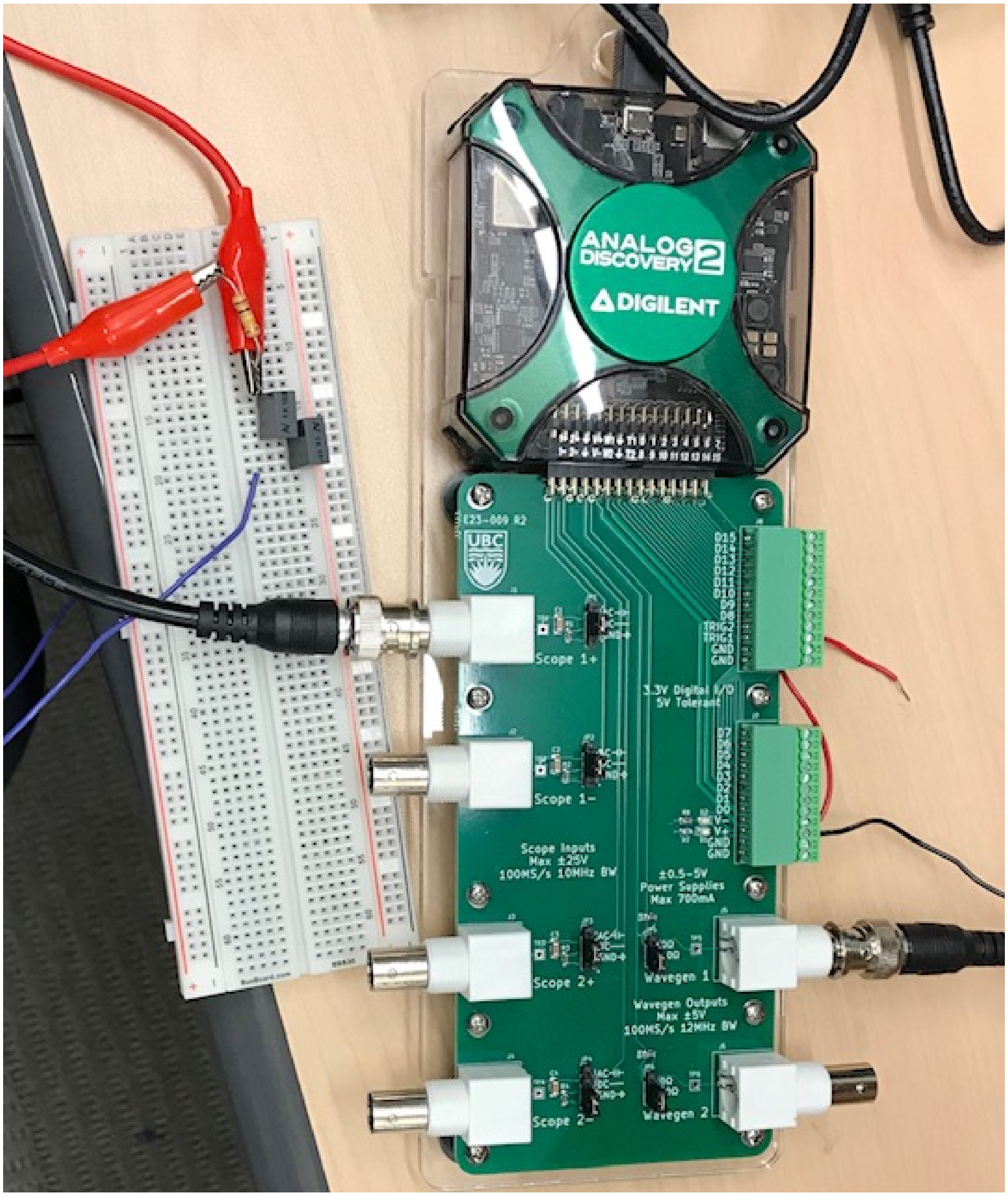

Figure 9: RC circuit setup on breadboard for determining f_{3dB}

[11]:
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Image(filename = img_path('L2A_f3dB Correct Measurement.png'))
```

[11]:

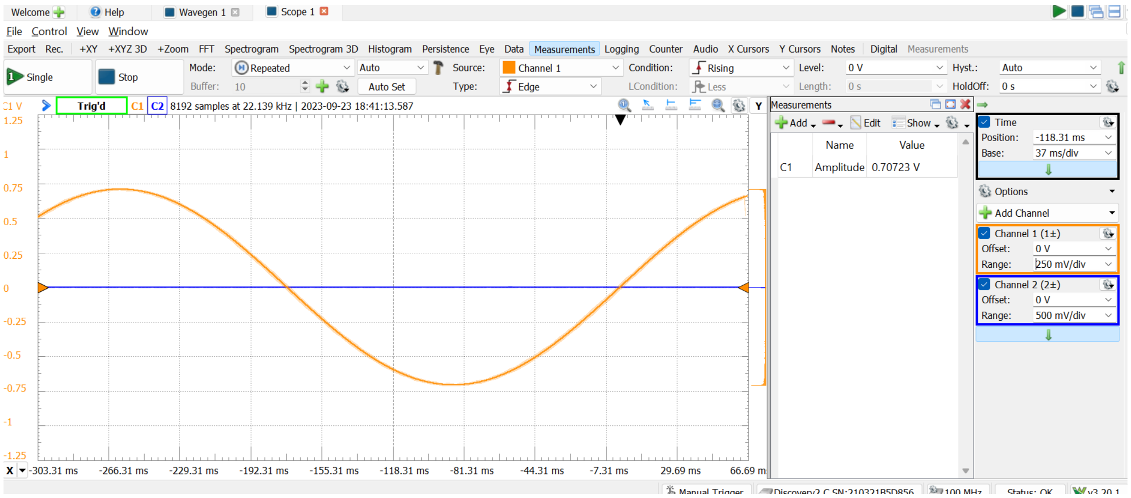

Figure 10: Resulting voltage across capacitor at 3dB cutoff

4.4 Task 3: Cleaning up Noisy Sine Wave

After importing the noisy sine wave, I notice that the frequency is roughly 100 Hz (according to WaveForms), so I'll let the f_{3dB} be close to that value. This way I can set up a low-pass filter with resistors and capacitors than 'cleans' up the noise from the signal and only lets the 'main' 100 Hz signal pass through. I'll proceed to calculate the desired RC value that outputs ~100 Hz.

Calculations:

$$100Hz \approx \frac{1}{2\pi RC},$$

so

$$RC = \frac{1}{200\pi},$$

or

$$RC = 0.00159s.$$

We have 0.000001 F capacitors, and 1 k Ω resistors, so we can set up a circuit with 1 $1k\Omega$ resistor in series with 2 $1k\Omega$ resistors in parallel.

Procedure: - I set up an RC circuit on the breadboard following the schematic in Figure 11. The result looked like the setup in Figure 12, but with one rather than two capacitors (I forgot to get a picture of the actual setup of the filter).

- The Wavegen 1 connector on the breakout board output the signal from the noisy sine wave file (which was imported into WaveForms), with the BNC cable's red probe attached to the top of the first resistor and the black probe attached to a wire connected to the ground of the circuit.
- I read the voltage across the capacitor with a cable connected to the AD2 breakout board's Scope + input, with the red probe attached to the end of one of the parallel resistors right above the capacitor, and the black probe attached to the grounding wire (adjacent to the Wavegen 1 connector's black probe).

Results: - The resulting output sine wave is depicted in Figure 14. It's significantly cleaner than the input signal see in Figure 11. As well, the amplitude has been lowered from the input 1 V to around 0.75 V, which makes sense, as low-pass filters decrease the strength of the signal by filtering out other frequencies.

- To ensure I reasonably optimized the filter, I tried removing the two parallel 1 $k\Omega$ resistors and just keeping one resistor, which outputted the wave seen in Figure 15. This graph is noticeably, albeit only slightly, noisier than the one in Figure 14, so we can understand that although with more time, a better filter could have been constructed for the noisy sine wave, the one already designed works decently well.

[12]:
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Image(filename = img_path('L2A_noisy sine wave.png'))
```

[12]:

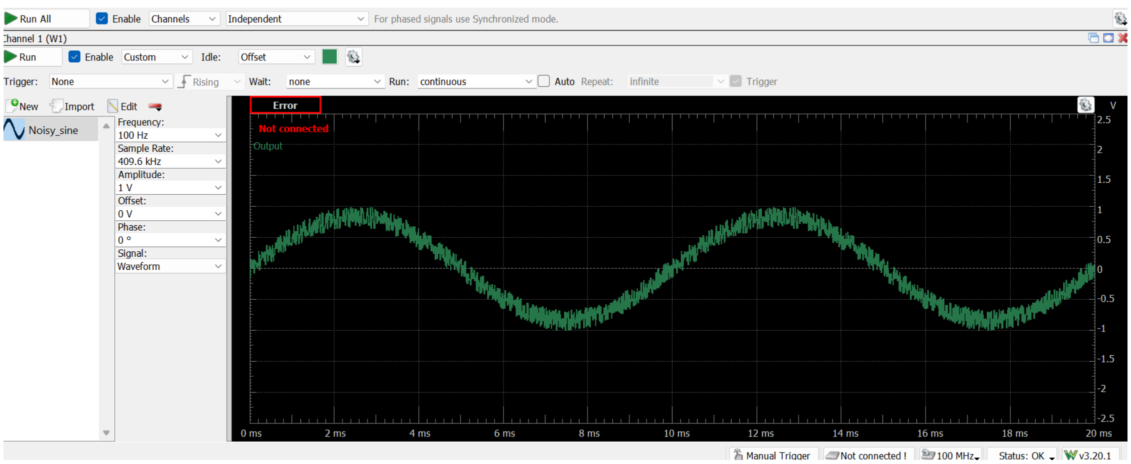

Figure 11: Noisy sine input signal that I cleaned up with low-pass filter

[13]:
```
Image(filename = img_path('L2A clean up circuit.jpg'))
```

[13]:

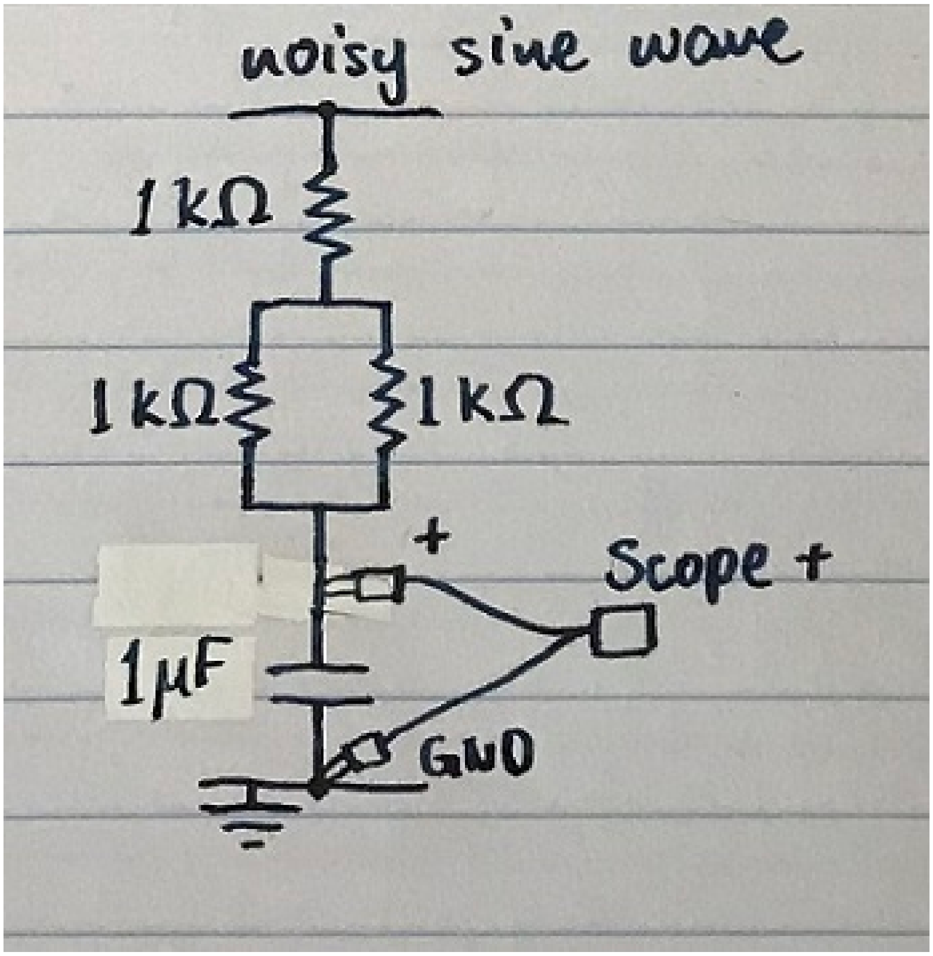

Figure 12: Circuit schematic of low-pass filter for cleaning up noisy sine wave

[14]:
```
Image(filename = img_path('L2A_clean up setup.jpg'))
```

[14]:

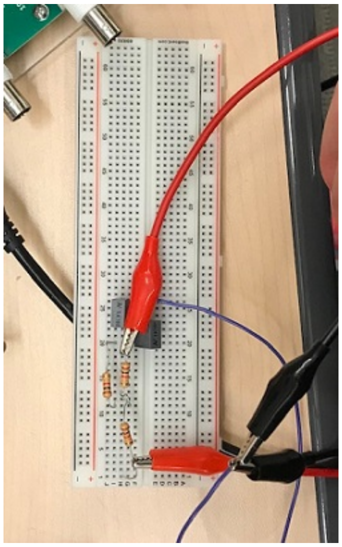

Figure 13: Breadboard setup of low-pass filter for cleaning up noisy sine wave

[15]:
```
Image(filename = img_path('L2A_clean sine wave.png'))
```

[15]:

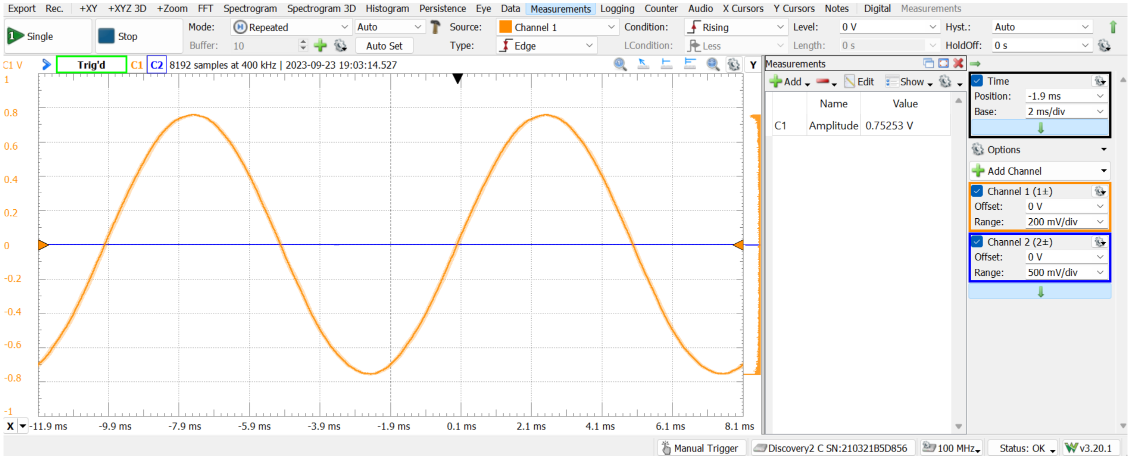

Figure 14: Cleaned up output sine wave

[16]:
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Image(filename = img_path('L2A_less clean sine wave.png'))
```

[16]:

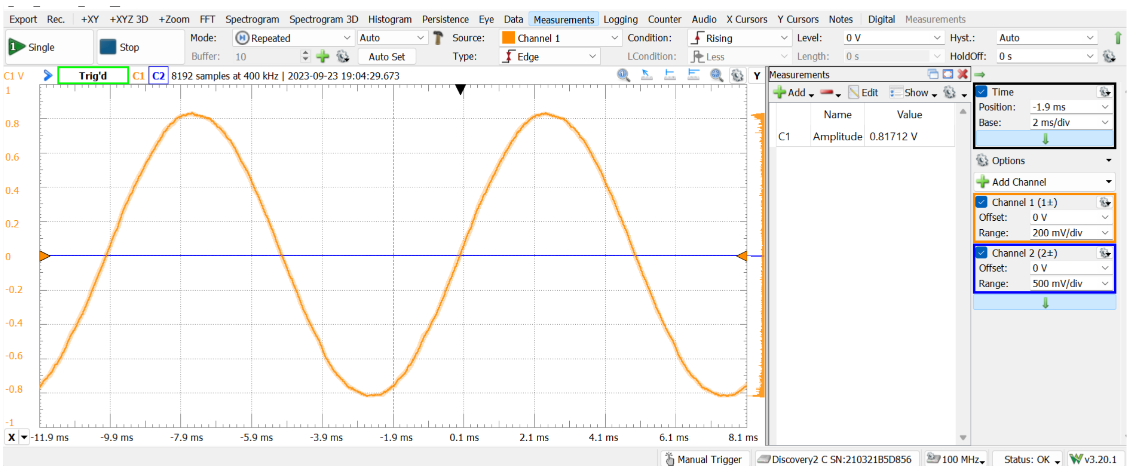

Figure 15: Slightly less cleaned up output sine wave

5 Conclusion

In this lab, we found the unknown resistance and capacitance of a resistor and capacitor just by measuring voltage across certain components, we used an Arbitrary Waveform Generator (AWG) and a scope to find the f_{3dB} of an RC low-pass filter, and cleaned up a noisy input sine wave with an RC low-pass filter as well.

I understood how a simple low-pass filter constructed from resistors and capacitors can clean up a noisy input signal due to the behaviour of capacitors towards voltages of different signals.

5.0.1 Measurement of unknown R and C

In this part of the lab, we had to measure the resistance and capacitance of an unknown resistor and capacitor without directly using a DMM on either.

To measure the resistance of the resistor, we built on the knowledge of voltage dividers we learned from Lab 1 and this lab's pre-lab to take advantage of the relationship of a resistor's resistance and its corresponding voltage drop to calculate R_U's resistance. We constructed a voltage divider with one know resistor and R_U and set up the AD2 to output a stable voltage. Measuring the voltage drop over R_U, we then calculated its resistance.

To measure C_U's capacitance, we used our knowledge of how capacitor's capacitance affect their charging and discharging behaviour to calculate its capacitance. We set up a simple RC circuit with the AD2 outputting a square wave, and measured the voltage over the capacitor. Using the X and Y cursors to find the time constant, we followed the time constant formula with the known resistor to calculate the capacitor's capacitance. The uncertainty was propagated from the cursors' analog time constant measurement and the resistor's digital measurement.

5.0.2 Measurement of Low-pass Filter's f_{3dB}

In this part of the lab, we determined the 3dB frequency of an RC low-pass filter by testing the signal outputs across a capacitor while varying the input signal's frequency.

While searching for the 3dB frequency, I observed different behaviour (amplitude changes) of the output voltage in the RC circuit depending on the input's frequency, which demonstrated how low-pass filters work based on the dependence of a capacitor's impedance on a voltage's frequency.

We used the formula

$$f_{3dB} = \frac{1}{2\pi RC}$$

to determine the expected f_{3dB} and compared it to the actual f_{3dB} we found via the AD2 scope. The actual value was close, but slightly lower than the expected value, even accounting for the circuit components' real specs.

5.0.3 Cleaning Up Noisy Sine Wave

In this part of the lab, we applied the knowledge of the behaviour of the output signal over a capacitor in an RC circuit's f_{3dB} we learned from the previous lab task to clean up a noisy sine wave input signal. I used the formula above the determine what RC value was necessary to give an f_{3dB} roughly equal to the main frequency of the noisy input signal, and used the resistors and capacitors I had to construct that low-pass filter. Since I wanted 100 Hz as f_{3dB} and had 1 $k\Omega$ and 100 $k\Omega$ resistors and 1 μF capacitors, I calculated the resistance I needed with a capacitance of 1 μF, the only capacitors I had, and used my knowledge of calculating total resistance of resistors together to use the 1 $k\Omega$ to add 1.5 $k\Omega$ resistance to the circuit.

By isolating the frequency in the noisy input sine wave signal we want (the primary frequency identified by WaveForms), which was 100 Hz, we minimized the other miscellaneous frequencies causing the noise.

This section of the lab offers a practical application of RC low-pass filters and an understanding of how noisy signals in real-life can be cleaned.

[ ]:
```
# @title
%%capture
!apt-get install texlive-xetex texlive-fonts-recommended
 ↪texlive-latex-recommended texlive-plain-generic pandoc
```

[ ]:
```
# @title
# Capture to prevent lots of output... Remove this if troubleshooting!
%%capture

pdf_file_name = file_name.split('.')[0]+'.pdf'  # Same as file_name with .ipynb
 ↪changed to .pdf
!rm $file_name
!rm $pdf_file_name

import os

full_path = os.path.join(path, file_name)
```

```
!cp  "$full_path" ./

!jupyter nbconvert "$file_name" --to pdf
```