# Nora-Shao_L6A

November 1, 2023

## 1 Experiment 6 - Servo Motor Prep: Op Amp Basics

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**Teammates at Table:** [redacted]

**Student Number:** [redacted]

**Lab Section:** L6A

[35]:
```
# @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/Lab6/'
file_name = 'Nora-Shao_L6A.ipynb'

assert file_name in os.listdir(path)

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

### 1.1 Pre-lab

**Problem Description:** Assuming an ideal OpAmp, finish the derivation started in tutorial of the $\frac{V_{out}}{V_{in}}$ relation for the op-amp circuit shown in Fig. 2. If your input is a square wave of amplitude 200 mV and frequency 1 kHz, sketch the expected output (and note amplitude/frequency of waveform).

**Solution:**

In the tutorial, we proved that in the diagram in Figure 1, we have Equation 1:

$$V_{out} = -\frac{1}{RC}\int V_{in}\, dt.$$

We get this from the fact that the voltage inputs into the op amp should be as close to each other as possible. Since on input is connected to ground, the top input voltage should also be grounded. Thus we have $V_{in} = V_C$, and

$$\frac{V_{in}}{R} = i_C,$$

where $i_C$ is the current that goes from $V_{in}$ through the capacitor to $V_{out}$.

Since

$$-i_C = C\frac{dV_C}{dt} = C\frac{dV_{out}}{dt},$$

we have that

$$\frac{V_{in}}{R} = C\frac{dV_C}{dt}.$$

Integrating and rearranging, we get

$$V_{out} = -\frac{1}{RC}\int V_{in}\ dt.$$

However, we can't rearrange this equation to get a direct defined

$$\frac{V_{out}}{V_{in}}$$

value.

In Figure 2, I calculated the maximum value on $V_{out}$ using Equation 1. We get

$$V_{out,max} = -\frac{1}{10k\Omega \times 10nF}\int_0^{0.0005} V_{in}(t)dt.$$

We integrate to get

$$V_{out,max} = -1000000 \times 0.0005(-0.1V),$$

which evaluates to give us

$$V_{out,max} = 50V.$$

[36]:
```
Image(filename = img_path("L6A_integrator op amp diagram.png"))
```

[36]:

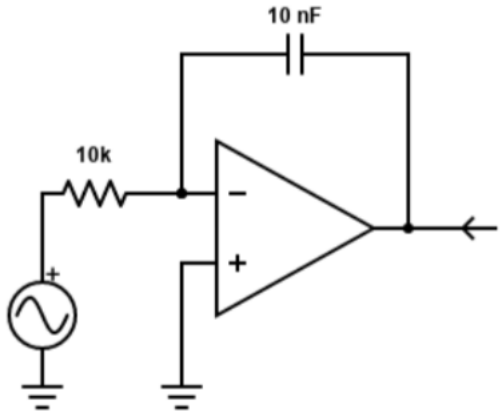

*Figure 1:* An op amp circuit where $V_{out}$ integrates the input voltage signal

[37]:
```
Image(filename = img_path("L6A_pre-lab.jpg"))
```

[37]:

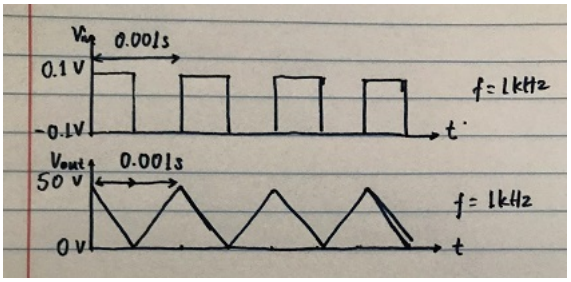


*Figure 2:* $V_{out}$ vs. $V_{in}$ for the op amp in Figure 1 against time

# 2 Experiment

## 2.1 Task #1: Getting cutoffs

**Procedure:**

- I follow the datasheet here for the lf411 op amp: https://www.ti.com/lit/ds/symlink/lf411.pdf?ts=1698422340978&ref_url=https%253A%252F%252Fsearch
- I connected wires to the op amp's $V_{CC}$ and $V_{CC}$ pins. Via WaveForms, I set $V_{CC}$ to 5 V and grounded the wire connected to $V_{CC-}$. I later realized this was incorrect in **TS1.**
- I grounded the op amp's ground terminal with the breakout board's gnd,
- I connected a wire to the op amp's negative input terminal, then used a BNC cable to attach this wire the the Wavegen 1 output of the AD2 breakout board. This would act as the input waveform seen in Figure 3
- Following the instructions, I selected a 100 kΩ resistor as $R_f$ and a 10 kΩ resistor as $R_g$
- I started the wavegen output on Waveforms with a configuration of a sine wave with a 1 kHz frequency and 200 mV amplitude
- Then I varied the amplitude until I saw the output signal being clipped

**Troubleshooting:**

**TS1:** I grounded $V_{CC-}$ when I should have input -5 V

[38]:
```
Image(filename = img_path("L6A_task 1 op amp circuit.jpg"))
```

[38]:

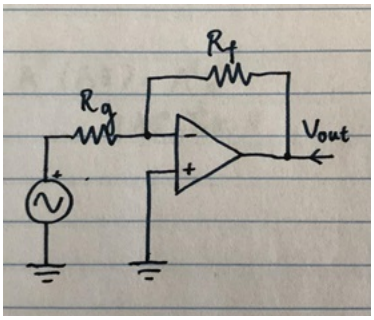


*Figure 3:* Inverting op amp circuit diagram

[39]:
```
Image(filename = img_path("L6A_task 1 bad setup.jpg"))
```

[39]:

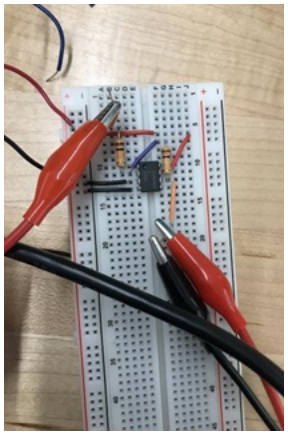

*Figure 4:* Incorrect inverting op amp breadboard setup

[40]:
```
Image(filename = img_path("L6A_task 1 good setup.jpg"))
```

[40]:

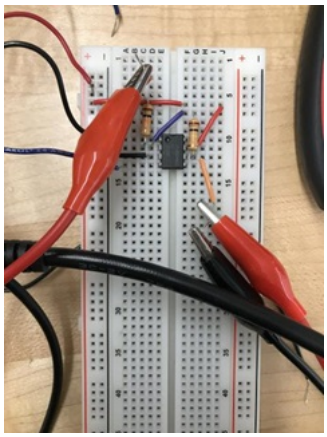

*Figure 5:* Working inverting op amp breadboard setup

**Results:**

In Figures 6 and 7, we get the output voltage from the op amp at an input sine wave of 200 and 500 mV, respectively. We can see that while the $V_{out}$ is behaving (mostly) ideally/regularly when our wavegen is outputting 200 mV, the output voltage of the 500 mV input is slightly cut off at the top and bottom. I varied the amplitude of the sine wave to determine around wave value the output started to saturate (be cut off), and at around an input sine wave with an amplitude of 370 mV, I observed that at any higher amplitude, the bottom of the output sine wave would start flattening out (a sign of the signal being cut off). And, the top of the output sine wave would start flattening out at an input wave with an amplitude of 370 mV.

**Understandings:**

$V_{out}$, the output signal, starts to be cut off because of the op amp's amplification limitations. Naturally, an op amp's output voltage is limited by its power supply, which I set with a minimum of -5 V and a maximum of 5 V. And since our op amp isn't ideal, the real cutoffs for the output voltage won't quite reach -5 or 5 V. Our results reflect this; since $\frac{R_f}{R_g} = 10$, and we observed that our maximum input voltage amplitude with no saturation is 370 mV, this suggests our max voltage amplitude is ~3.7 V, which is close enough to 5 V. Sources (https://web.stanford.edu/class/archive/engr/engr40m.1178/slides/opamps.pdf) suggest that $V_{out}$ actually saturates at voltage magnitudes between 1 to 2 V below the power supply, a range we're safely within.

Interesting, the op amp seems to be rated for different maximum vs. minimum output voltages. It seems to saturate at a lower magnitude when it comes to the minimum voltage, at ~ -3.5 V and an amplitude of 370 mV but at a higher magnitude when it comes to the maximum voltage, at ~4.3 V and an amplitude of 440 mV. These values bring us to the other oddity; there's a small vertical offset in $V_{out}$ that renders it unsymmetrical about the 0 V axis, hence the mismatched cut-off voltages/amplitudes. This offset is quite noticeable in Figures 7 through 9. While I can't find any Internet sources that explain this, it can likely just be attributed to the op amp's nonideal behaviour.

[41]:
```
Image(filename = img_path("L6A_task 1 200 mv amplitude sine.png"))
```

[41]:

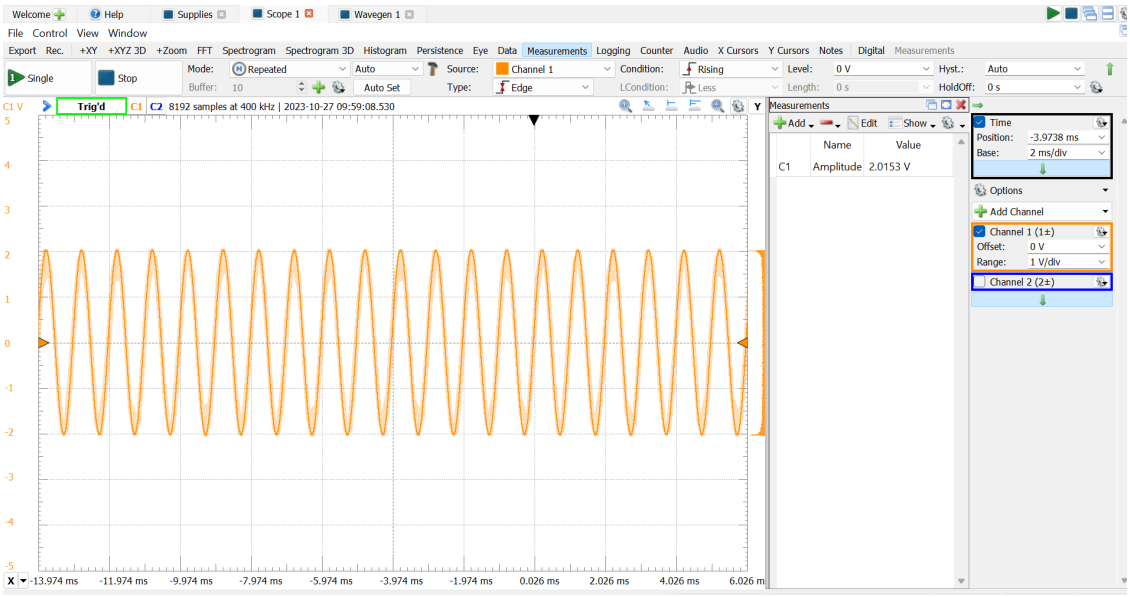


*Figure 6:* Op amp $V_{out}$ with a 200 mV amplitude $Vin$

[42]:
```
Image(filename = img_path("L6A_task 1 500 mv amplitude sine.png"))
```

[42]:

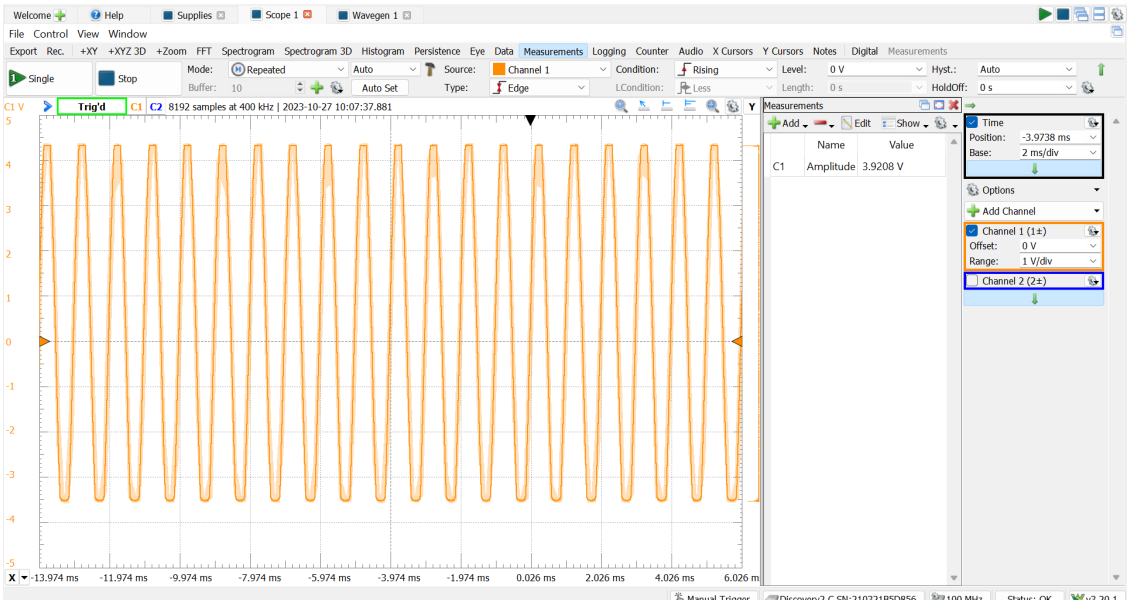


*Figure 7:* Op amp $V_{out}$ with a 500 mV amplitude $Vin$ (op amp saturation observed)

[43]:
```
Image(filename = img_path("L6A_task 1 top cutoff (440 mV).png"))
```

[43]:

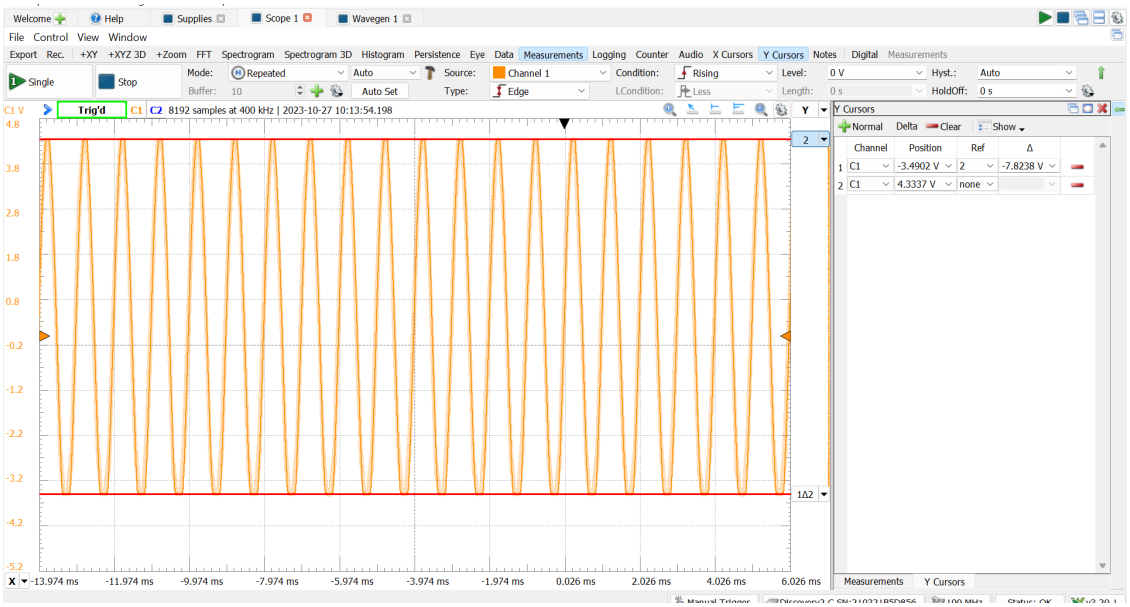


*Figure 8:* Op amp $V_{out}$ with a 440 mV amplitude $Vin$ (op amp max voltage saturation observed)

[44]:
```
Image(filename = img_path("L6A_task 1 bottom cutoff (370 mV).png"))
```

[44]:

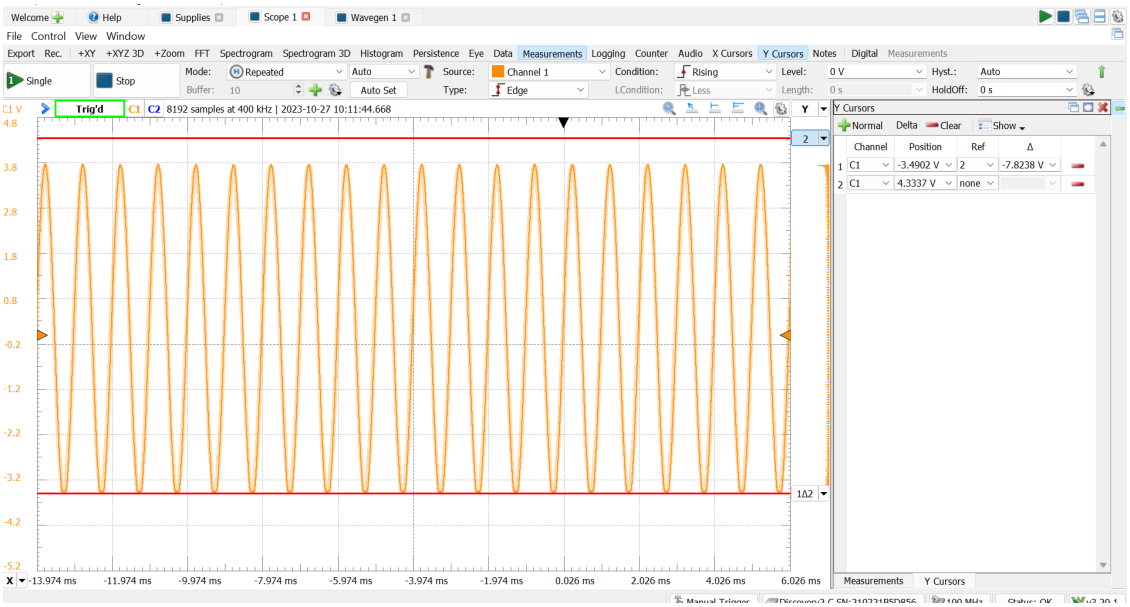


*Figure 9:* Op amp $V_{out}$ with a 370 mV amplitude $Vin$ (op amp minimum voltage saturation observed)

## 2.2 Task 1: Varying Resistance for Different Gains

Varying resistance values

- The setup stays the same (Figure 3's circuit)
- I added a BNC cable from the breakout board's Scope 2+ input to the input of the Wavegen 1 into the invertering terminal of the breakout board to measure the input signal as well. Figure 5 shows the setup with the additional cable
- I measured the gain of the original setup (Figure 1's) by using WaveForms's measurement feature to measure the amplitudes of the input and output voltages and dividing them.
  - We expect the gain to be 10
- First, I switched out $R_f$ for a 51 $k\Omega$ resistor
  - This gives us the configuration in Figure 3 with $R_g = 10k\Omega$ and $R_f = 51k\Omega$ and an expected gain of 5.1
- Then, I switched out $R_g$ from 10 $k\Omega$ to 100 $\Omega$.
  - This gives us the configuration in Figure 3 with $R_g = 100\Omega$ and $R_f = 100k\Omega$ and an expected gain of 1000
  - For this, I had to adjust the input voltage amplitude to 3 mV, since at anything higher, the op amp saturates and output voltage is clipped

[45]:
```
Image(filename = img_path("L6A_better gain og 200 mv.png"))
```

[45]:

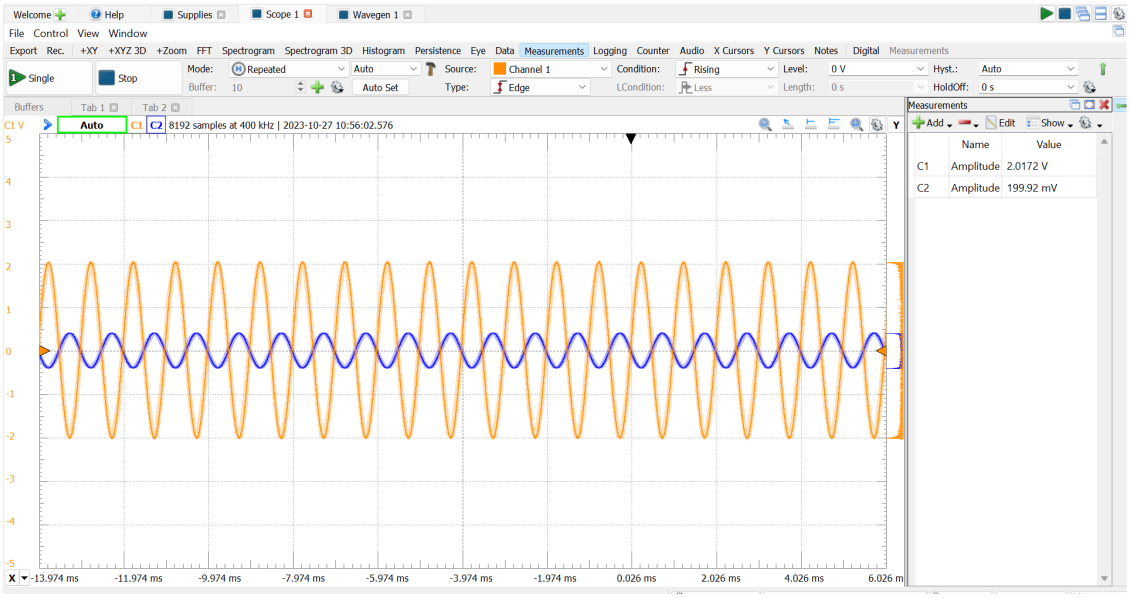


*Figure 10:* $V_{in}$ (blue) vs. $V_{out}$ (orange) of op amp with expected gain of 10 and input amplitude 200 mV

[46]:
```
Image(filename = img_path("L6A_gain 51 k resistor.png"))
```

[46]:

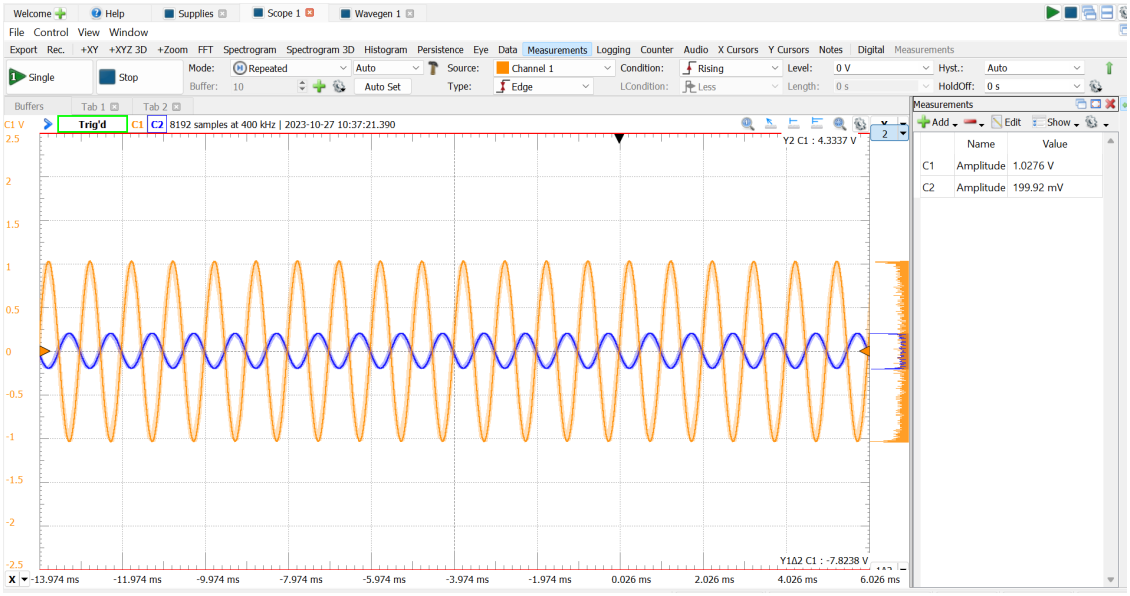


*Figure 11:* $V_{in}$ (blue) vs. $V_{out}$ (orange) of op amp with expected gain of 5.1 and input amplitude 200 mV

[47]:
```
Image(filename = img_path("L6A_gain rg 100 ohm resistor.png"))
```

[47]:

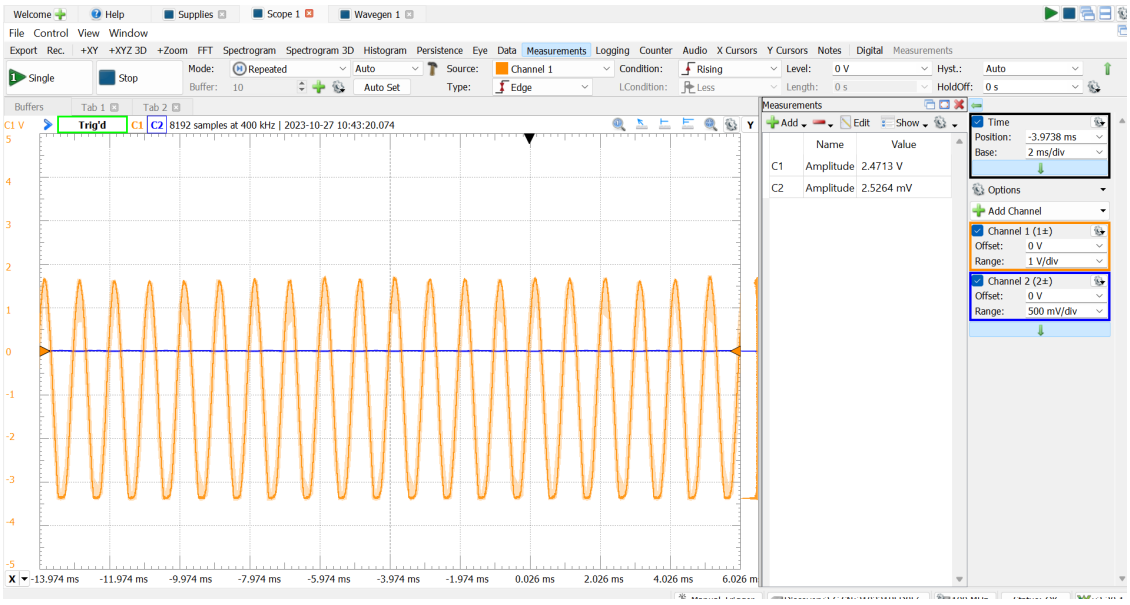


*Figure 12:* $V_{in}$ (blue) vs. $V_{out}$ (orange) of op amp with expected gain of 1000 and input amplitude 3 mV

**Results:**

I measured the gains of three different resistor configurations for our inverting op amp, with expected gains of 10, 5.1, and 1000, visible respectively in Figures 10, 11, and 12.

In Figure 10, with an input voltage of amplitude ~200 mV and output voltage of ~2 V, we get a gain across the op amp of $\frac{2.0172V}{0.19992V} \approx 10.1$

In Figure 11, with an input voltage of amplitude of ~200 mV and output voltage of ~1 V, we get a gain across the op amp of $\frac{1.0276V}{0.19992V} \approx 5.1$.

In Figure 12, with an input voltage amplitude of ~2.5 mV and output voltage amplitude of ~2.5 V, we get a gain across the op amp of $\frac{2.4713V}{0.0025264V} \approx 978$.

**Understandings:**

For the significantly most part, our results are what we expected. With a configuration of $R_g = 10$ kΩ and $R_f = 100$ kΩ, we get a gain of 10.1, which is close enough to the expected gain of 10. The small difference can easily be attributed to the resistors not having exactly accurate resistances and the fluctuations of the WaveForms readings.

The unreliability of exact amplitude measurements can be further demonstrated by Figure 3, where I set the input signal to have an amplitude of 3 mV, but we see an input amplitude of 2.5 mV.

As well, with the gain factor of 1000, I did see the op amp saturate (obviously) with larger input signal amplitudes. With the 200 mV input, over half of the output signal was clipped, which is also expected, since the op amp can't output 20 V.

### 2.3 Task #2

**Procedure:**

- I set up the circuit in Figure 13 on the breadboard. The finished setup in in Figure 14.
- With the potentiometer, I input the -5 V into the top leg, grounded the bottom, and treated the middle leg as the output.
- Initially, my output was just a sine wave with an offset of -6 V, but I realized my error and fixed this in the #TS below.
- I used a screw to twist the knob of the potentiometer until the output signal rose to an offset of 2 V.

**Troubleshooting:**

**TS:** I realized that the reason my $V_{out}$ was at -6 V for whatever reason is that the wire powering the op amp at $V_{CC+}$ wasn't even plugged into the breadboard. After connecting it back to the $V_{CC}+$ terminal, I had the $V_{out}$ I wanted, seen in Figure 15.

[48]:
```
Image(filename = img_path("L6A_task 2 summing op amp circuit.jpg"))
```

[48]:

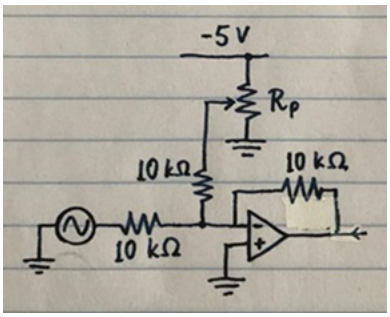


*Figure 13:* Circuit diagram for an inverting summing op amp using a potentiometer to adjust one input voltage

[49]:
```
Image(filename = img_path("L6A_task 2 summing op amp setup.jpg"))
```

[49]:

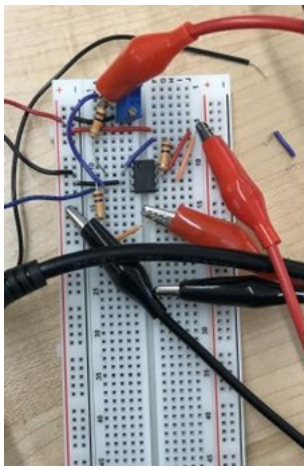

*Figure 14:* Breadboard setup of a working summing op amp with a potentiometer controlling one voltage input channel

**Results:** In Figure 15, we see our $V_{out}$ from the input signal and the -2 V input from one of the input voltages. $V_{out}$ is a sine wave with the same characteristices of the other input voltage signal, with an amplitude of ~100 mV, and the -2 V offset from the first input voltage brings it up to give $V_{out}$ an offset of 2 V.

**Understandings:**

The op amp sums the two input voltages with no scaling when all three resistors have the same value. We can prove this mathematically; say we have two input voltages $V_1$ and $V_2$, and all resistors are of value $R$. We know that the current from both input voltages must go through the resistor ($R_f$ in Figure 3) to $V_{out}$, so we get $i_1 + i_2 = i_f$, where $i_f$ is the current that runs through $R_f$.

Then we have

$$\frac{V_1}{R} + \frac{V_2}{R} = -\frac{V_{out}}{R},$$

and thus

$$V_{out} = -V_1 - V_2.$$

I used the potentiometer as a voltage divider to bring the -5 V source to -2 V. The potentiometer is rated as a 10 kΩ resistor, but how I understand is that I can treat it as two separate resistors in series that always total to 10 kΩ. However, twisting the knob changes the output voltage because it changes the resistance of the two 'sides' of the resistor.

[50]:
```
Image(filename = img_path("L6A_working summing op amp.png"))
```

[50]:

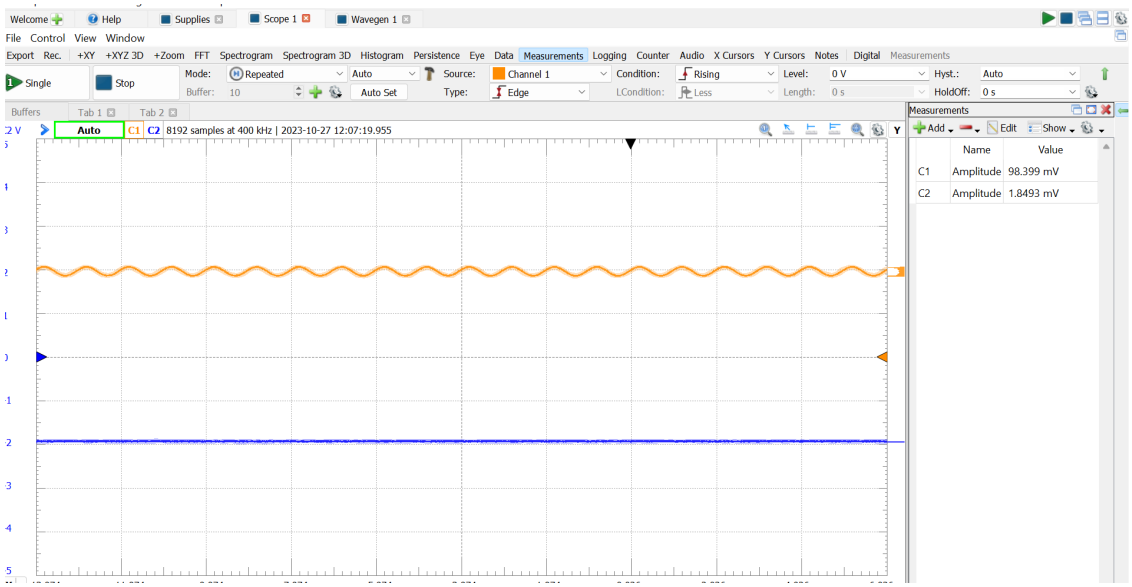


*Figure 15:* $V_{out}$ (orange) of an inverting summing op amp summing one input of -2 V and the other a 100 mV amplitude sine wave with no offset

## 2.4 Task #3

Integrating op amp

**Procedure:**

- I set up the circuit Figure 2 depicts on the breadboard. Figure 16a shows the finished setup for the first part
- For the wave input into the op amp, I plugged one end of a wire into the breadboard on the same column as the 10 kΩ resistor, and attached the other end to the red probe of a BNC cable connected to the AD2 breakout board's Wavegen 1 output

  - I also attached the red probe of a BNC cable connected to the AD2 breakout board's Scope 2+ input to this wire just to read the input

- To read $V_{out}$ from the op amp, I plugged on end of a wire into the breadboard on the same column as the op amp chip's $V_{out}$ terminal and attached a BNC cable's red probe to the unconnected end of the wire. Then I connected the BNC cable to the breakout board's Scope 1+ input.
- After turning on the supply voltages (still with $V_{CC}$ as 5 V and $V_{CC-}$ as -5 V), I configured the input signal as a square wave with a frequency of 1 kHz and 200 mV amplitude.
- Then I added an offset to the input wave of -1 mV
- Then I added a 100 kΩ resistor in parallel across the capacitor. This setup is shown in Figure 16b

**Troubleshooting:**

**TS:** When I applied the -1 mV offset to the input signal, I found that virtually nothing was affected in the output signal, which I decided was odd since the lab instructions implied something would change. After examining my circuit, I found I was using a 1 nF capacitor instead of a 10 nF capacitor, so I replaced it with a 10 nF capacitor.

Figures 17 and 18 show our results for the integrating op amp and integrating op amp with a -1 mV offset in the input signal when I was using a 1 nF capacitor.

After I replaced it correctly with the 10 nF capacitor, I had the results in Figure 19 and 20, a triangle wave with a negative offset, but the -1 mV offset for the input changed virtually nothing. Oddly enough, even though I didn't change anything, when I disconnected everything, then came back, I found that applying -1 mV offset to the input wave brought the output triangle wave to have a significant positive offset. Below, I discuss why we get this.

[51]:
```
Image(filename = img_path("L6A_task 3 setup.jpg"))
```

[51]:

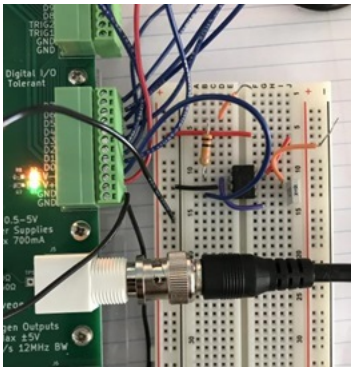

*Figure 16a:* Set-up of integrating op amp on breadboard

[52]:
```
Image(filename = img_path("L6A_task 3 lossy setup.jpg"))
```

[52]:

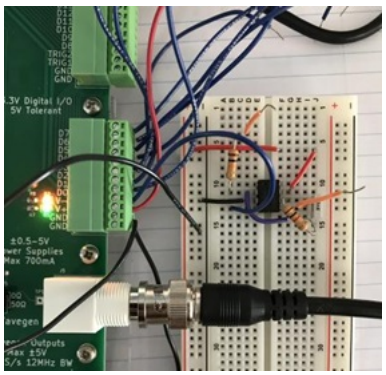

*Figure 16b:* Set-up of lossy integrating op amp (with 100 kΩ$ on breadboard)

**Results:**

Initially, I had issues with my results (explained in the troubleshooting section), which I noticed because the -1 mV offset in the input voltage virtually didn't affect my output noticeably at all. After I actually fixed my circuit, we get the outputs in Figures 22 and 23. Interestingly, adding the 100 kΩ resistor in parallel across the capacitor almost completely shut off $V_{out}$, albeit with a small signal that just reflected the input square wave but inverted. This is visible in Figure 24.

**Understandings:**

Qualitatively, we get exactly what we expected in the pre-lab, hence the similarity between Figure 22 and my Figure 2. However, I seem to have done the calculations incorrectly.

We have

$$V_{out} = -\frac{1}{RC}\int V_{in}\ dt.$$

CH1 in the figures shows $V_{out}$ and CH2 is the input signal. Again, since the non-inverting input of the op amp is grounded, we can treat the inverting input node as a virtual ground. We see $V_{out}$ rising like a ramp in the negative period of the input signal and vice versa in the positive period of the input signal because the positive period charges the capacitor, increasing the voltage across it. And, since the 'higher voltage' side of the capacitor is connected to virtual ground, the $V_{out}$ we see is becoming proportionally *more* negative. The opposite occurs on the input signal's off period, where the current through the capacitor is effectively reversed, and it charges 'in the other direction' (aka discharges), which increases $V_{out}$. Effectively, the output voltage of the op amp is the voltage across the capacitor, but reversed. The capacitor stops charging at the saturation point of the op amp since $V_{out} = V_C$, which cannot exceed the op amp's output capacity.

When I applied a -1 mV offset to the input signal, the output immediate rose to have a positive offset. This occurs because the op amp *integrates* the input signal, so even though the offset to the input I applied is small, the effect is compounded by the integration. The capacitor is continually kept partly charged by the input signal. To understand why even though we added a negative offset, the output voltage became more positive, see above. The same principle applies where the

output voltage 'turns around' at the saturation point of the op amp (which roughly reflects the saturation points we determined in Task 1)

The reason we see the constant offset of ~-3 V even with no input voltage offset across the capacitor can likely still attributed to the op amp's unideal behaviour (https://www.youtube.com/watch?v=SWvsS2MoWzo&ab_channel=InderjitSinghDhanjal), where we don't get exactly symmetrical on and off periods of the input signal, so that minute difference is integrated significantly to the max point until the output signal saturates the op amp.

When I added the resistor in parallel with the capacitor, $V_{out}$ became the input square wave but with a significant decrease in strength and inverted. This wasn't what I expected, as I figured the resistor in parallel with the capacitor would just slow its charging down until you could see the exponential curve of it charging and discharging, but it does make sense for the amplitude to be significantly smaller than previously as the resistor makes it so the capacitor can't charge fully.

[53]:
```
Image(filename = img_path("L6A_task 3 bad first part.png"))
```

[53]:

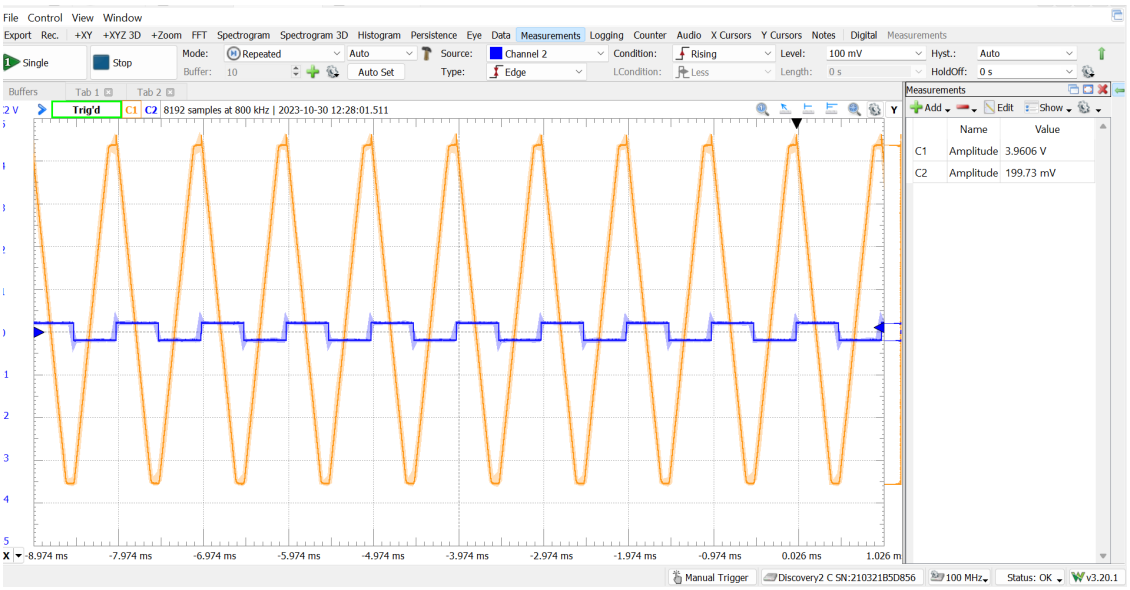


*Figure 17:* $V_{in}$ (blue) vs. $V_{out}$ (orange) for 1 nF capacitor integrating op amp

[54]:
```
Image(filename = img_path("L6A_task 3 bad offset.png"))
```

[54]:

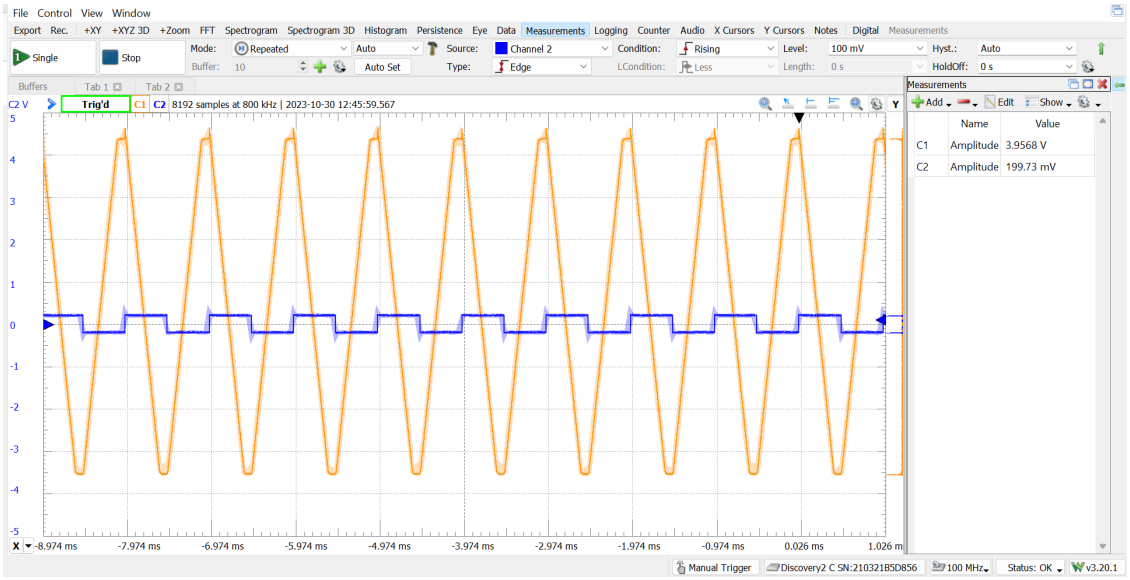


*Figure 18:* $V_{in}$ (blue) vs $V_{out}$ (orange) of integrating op amp with -1 mV

[55]:
```
Image(filename = img_path("L6A_good task 3 first part.png"))
```

[55]:

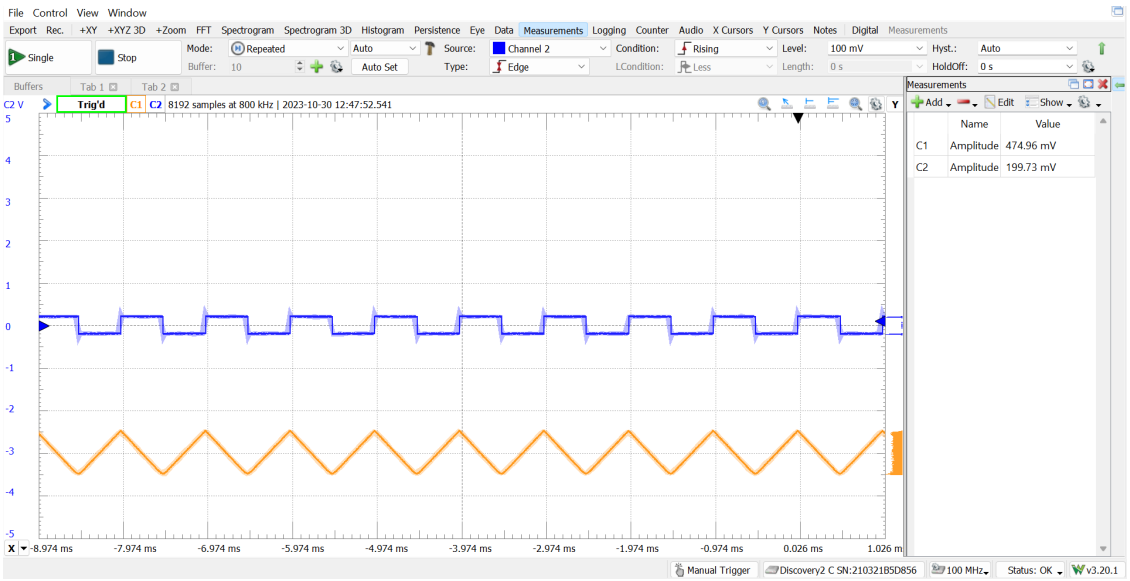


*Figure 19:* 'Fixed' $V_{in}$ (blue) vs. $V_{out}$ (orange) of integrating op amp (initial)

[56]:
```
Image(filename = img_path("L6A_task 3 offset.png"))
```

[56]:

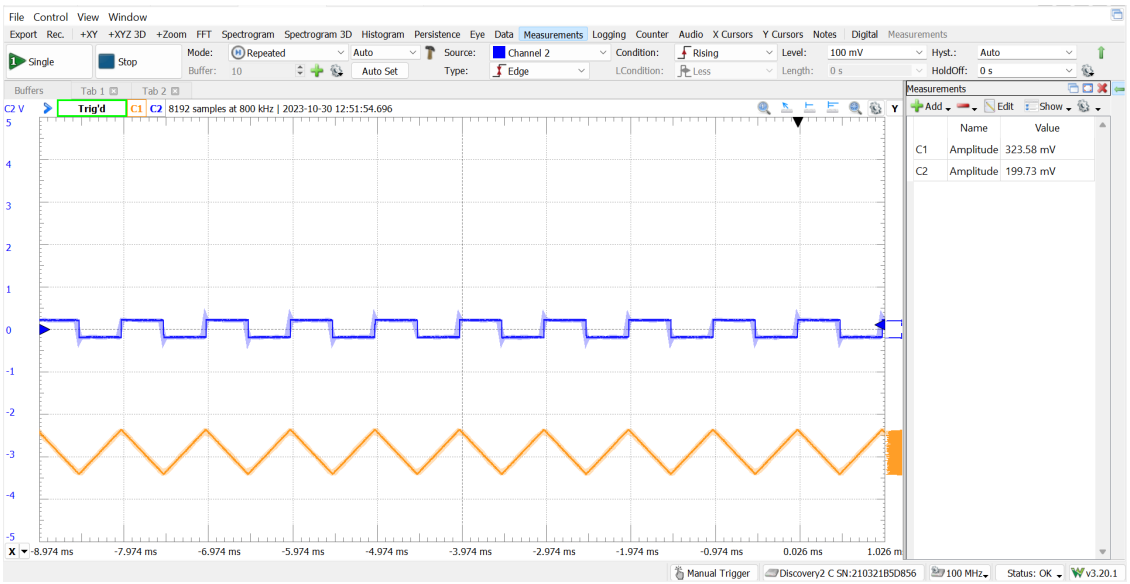


*Figure 20:* 'Fixed' $V_{in}$ (blue) vs. $V_{out}$ (orange) with -1 mV (initial)

[57]:
```
Image(filename = img_path("L6A_task 3 lossy.png"))
```

[57]:


*Figure 21:* 'Fixed' $V_{in}$ vs $V_{out}$ of lossy integrator op amp (initial)

[58]:
```
Image(filename = img_path("L6A_task 3 no offset.png"))
```

[58]:

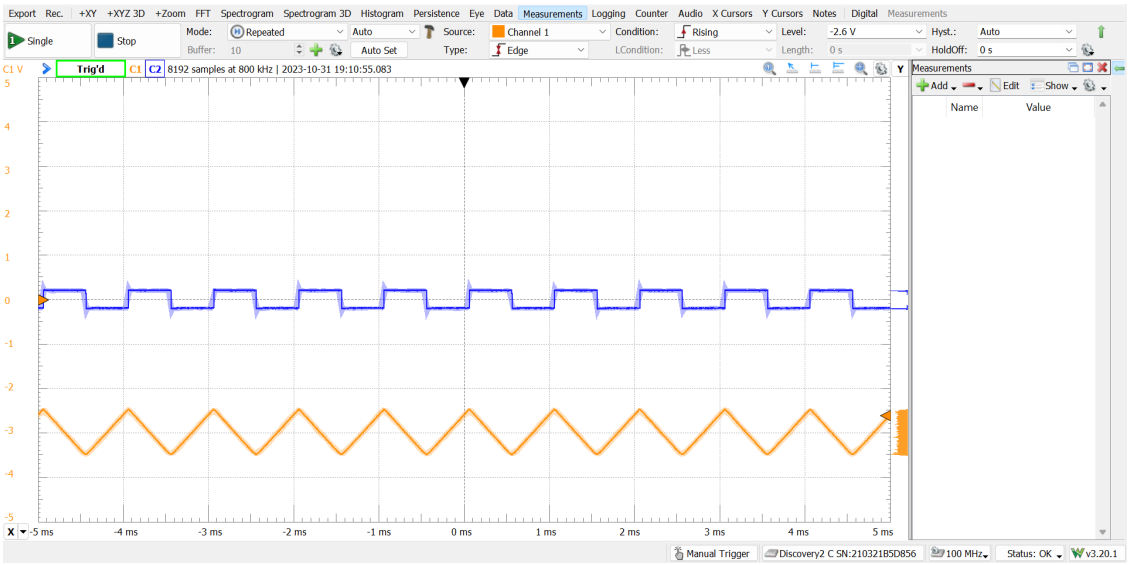


*Figure 22:* Actually fixed $V_{in}$ (blue) vs. $V_{out}$ of integrator op amp with no input offset

[59]:
```
Image(filename = img_path("L6A_task 3 offset is actually cursed.png"))
```

[59]:

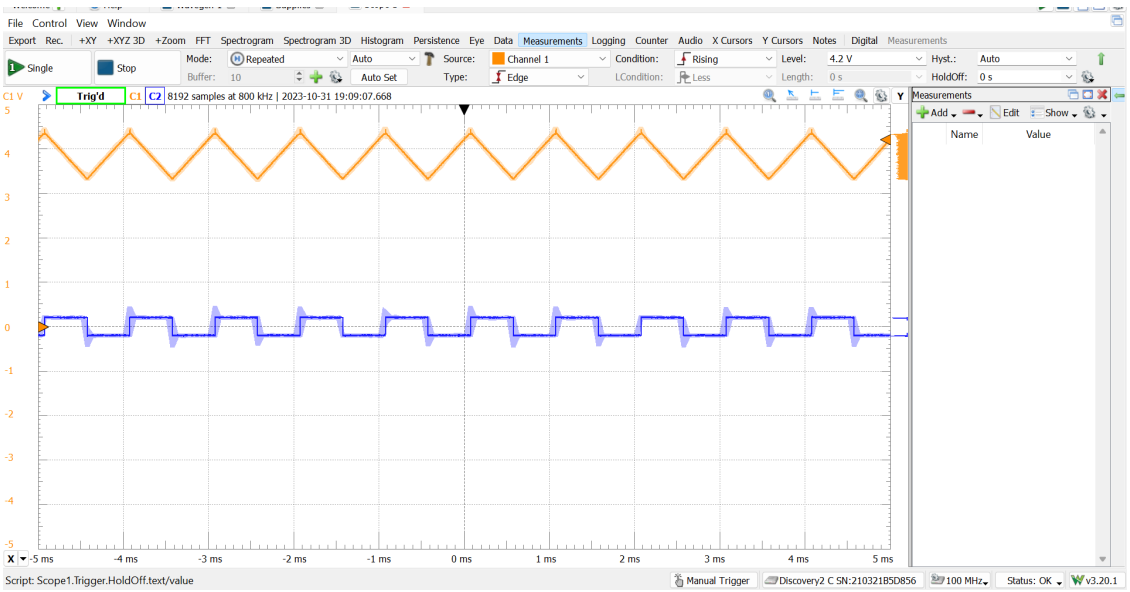


*Figure 23:* Actually fixed $V_{in}$ vs $V_{out}$ of integrator op amp with -1 mV offset in input signal

[60]:
```
Image(filename = img_path("L6A_task 3 actual lossy op amp.png"))
```

[60]:

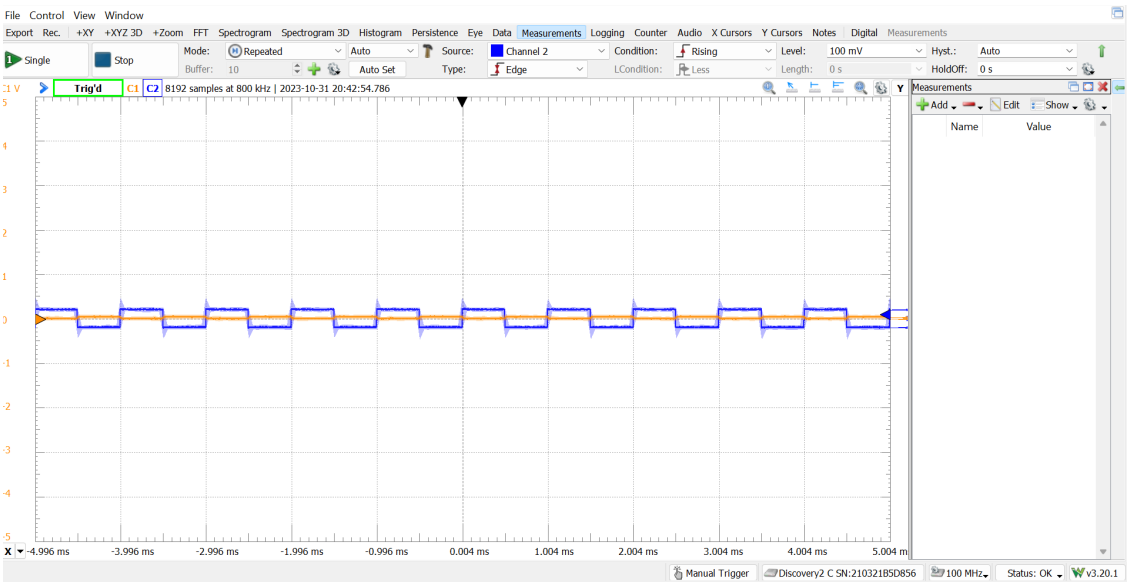


*Figure 24:* $V_{out}$ (orange) vs. $V_{in}$ (blue) of integrating op amp with a resistor in parallel with capacitor

# 3 Conclusion

### 3.0.1 Task 1

The first part of the lab introduced us to basic op amp operation.

We confirmed our theoretical understanding of how a basic inverting op amp works; we found that the output voltage could indeed be determined based on the input voltage and the two resistors either are connected to. We theorized this using the golden rules of op amp, that $V_{out} = \frac{R_f}{R_g} V_{in}$, but we actually varied the resistance values and $V_{in}$ to confirm this calculation.

Most importantly, we understood how while ideal op amps have infinite gain, their output voltages are ultimately still limited by the op amp's supply voltages. Moreover, real op amps further deviate from their theoretical counterparts' behaviour because their voltage output doesn't even go all the way to either $V_{CC+}$ or $V_{CC-}$, rather are limited somewhere around 1 to 2 V in magnitude less than either supply voltages.

### 3.0.2 Task 2

Here, we performed a summing operation with our op amps, summing the two input voltages with no scaling. We applied our understanding of circuits and the golden rules of op amps to design a configuration with three resistors that could do this.

This was also our first time using a potentiometer. The exercise of using a potentiometer expanded on our understanding of voltage dividers, as I learned to use the potentiometer by essentially treating it as one. It also showed us how useful slightly more sophisticated components can be, as

we just had to 'tune' the resistance of the potentiometer to get transform a set input voltage to the output voltage we wanted.

### 3.0.3 Task 3

In the final part of the lab, we performed another mathematical operation on $V_{in}$ using the op amp. We used the charging and discharging behaviour of a capacitor to integrate the input voltage, and found that even the smallest input voltage would integrate to a significant $V_{out}$. Hence, why the -1 mV offset in $V_{in}$ caused such a dramatic output difference between Figures 22 and 23/ We confirmed the behaviour of the op amp we expected in Figure 2, which we derived based on our understanding of integration and the operation of an op amp with a capacitor. Although my calculations were incorrect, the qualitative behaviour of the op amp indeed makes sense.

There was quite a bit of troubleshooting involved, as the specifications of the components signficantly affected the behaviour of my circuit. Using 1 nF capacitors instead of a 10 nF capacitor skewed my results significantly (the incorrect ones in Figures 17 and 18).

As well, we understood how adding a resistor in parallel with the capacitor could actually be more useful. Although the result in Figure 24 is not what I expected based on my understanding of how op amps work, and I'm not entirely sure it's correct, it does make sense to me how making sure the capacitor can't charge to the point of the op amp's saturation is more useful in attenuating input voltages.

[61]:
```
# @title
%%capture
!apt-get install texlive-xetex texlive-fonts-recommended␣
  ↪texlive-latex-recommended texlive-plain-generic pandoc
```

[62]:
```
# @title
# Capture to prevent lots of output... Remove this if troubleshooting!


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
```

```
rm: cannot remove 'Nora-Shao_L6A.pdf': No such file or directory
[NbConvertApp] Converting notebook Nora-Shao_L6A.ipynb to pdf
[NbConvertApp] Support files will be in Nora-Shao_L6A_files/
[NbConvertApp] Making directory ./Nora-Shao_L6A_files
[NbConvertApp] Making directory ./Nora-Shao_L6A_files
```