Results 1a:

We started first by getting familiarized with the test equipment at hand and to learn some of the limitations of the environment we are in. For this lab, we utilized three different pieces of equipment; the oscilloscope, the oscilloscope probes and the function generator. We tested the oscilloscope and its probes together utilizing the 'PROBE COMP' signal built into the oscilloscope. We further took this chance to explore the function of the gain setting on the probes and in the oscilloscope, and the results can be see as follows:

Probe Gain/Oscilloscope Gain	**Resulting Signal (Volts)**
1x/1x	2.53 V
1x/10x	25.3 V
10x/1x	256 mV
10x/10x	2.55 V

Table 1: This table shows the relationship between probe gain and oscilloscope gain on the resulting output signal form the 'PROBE COMP' port on the oscilloscope. Understanding this underlying relationship will help catch future errors due to accidental changes in gain settings.

We then followed up by testing the function generator, in order to get an understanding of the voltage frequency relationship for our given unit. The results are as follows:

Attenuation/Power Level	-20 dB/Max	-20 dB/Min	0 dB/Max	0 dB/Min
20 Hz	2.10 V	220 mV	22.8 V	2.00 V
200 Hz	2.24 V	220 mV	22.8 V	2.00 V
2 kHz	2.24 V	220 mV	22.8 V	2.00 V
20 kHz	2.22 V	220 mV	22.4 V	1.99 V

Table 2: This table shows the relationship between frequency, attenuation and power level on the resulting output signal from the function generator. All results were tabulated from the output of the oscilloscope with 1x/1x gain. We see stable output voltage across the tested frequency range with only the slightest hint of output voltage deviation at frequency extremes.

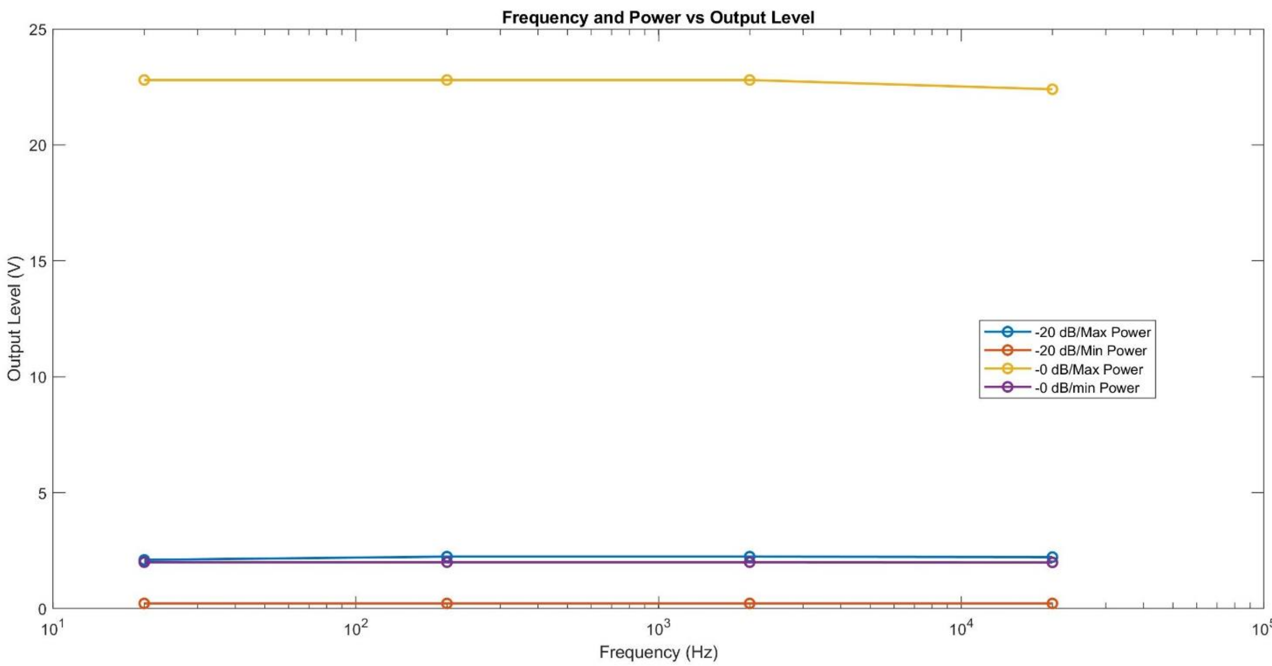

Figure 1: This figure visually explores the data exposed in Table 2. The X axis represents frequency in a log scale, while the Y axis shows output voltage. We can see two major things, first is that the -20dB/Max power setting and the 0dB/Min power setting result in essentially the same output, and second we see that aside from the slight dip in output voltage at the 0dB/Max power setting at 20 kHz, the output voltage is very stable.

Following the testing of the testing of the function generator, we moved onto testing the environment for noise. Using our oscilloscope probe, we managed to measure two major sources of noise. The first of which was a 20mV, 13.56 kHz switching frequency from our oscilloscope power supply. The second major source of noise we picked up was a 10mV, 60 Hz power line noise from touching the probe with our hands.

For next part of the lab, we went on to testing the two op-amps we would be using for the rest of the lab. Our first test was to calculate the differential gain (G_D) for each of the two op-amps provided, the INA137 and the INA118. To note, there was a 39 kOhm resistor attached to our INA118 setting its gain. The gain was calculated using the following formula: $G = \frac{V_{out}}{V_{in}}$ (1). The recorded and calculated results are as follows:

	Input Voltage (peak to peak)	Output Voltage (peak to peak)	Gain (G_D)
INA137	1.00 V	2.00 V	2.00
INA138	1.00 V	2.28 V	2.28

Table 3: This table shows the relationship between input and output voltage (peak to peak) and the corresponding gain calculated via equation (1) for both op-amps tested.

Once we calculated the differential gain for each op-amp we moved onto calculating the transfer function that describes the relationship between the external resistor and the gain of the op-amp. Utilizing the collected class data, we utilized the curve fitting toolbox in MATLAB to generate a regression line to best model the function that relates the resistor value to the gain. The best result I produced is follows:

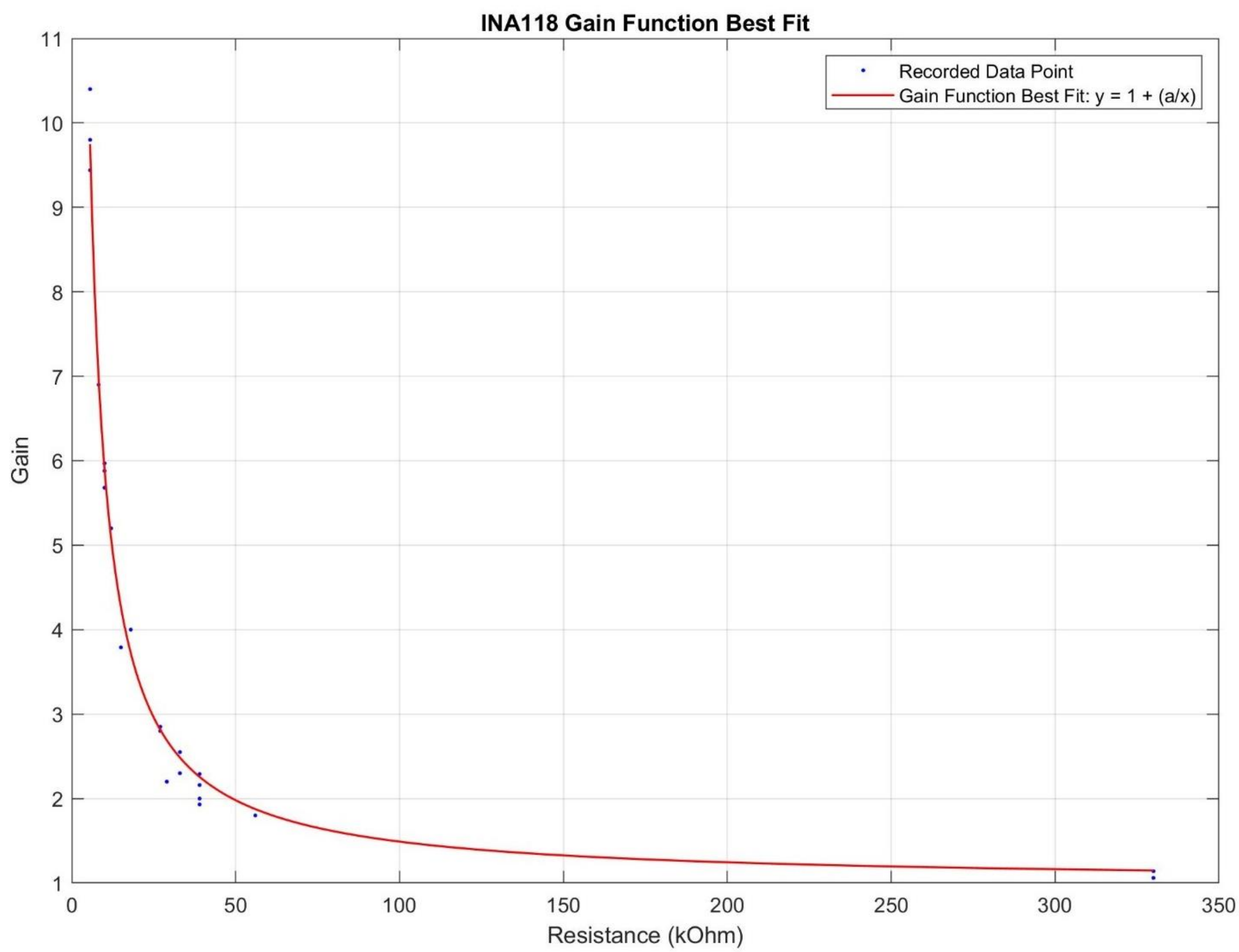

Figure 2: This figure shows the recorded data from the groups, in blue, and the calculated best fit line in red. The exact regression line that MATLAB produced is y = 1 + (48.99/x), where 48.99 refers to 48.99 kOhms. The regression model was programed to fit a custom equation in the form of y = 1 + (a/x). An equation of his form was used in the INA118's datasheet for calculating the gain for any resistance value provided.

Following this, we moved onto measuring the common mode gain (G_C) for each of the two op-amps under test. Common mode gain is calculated via equation (1), however, the op-amps are configured in common mode rejection mode. The results for the INA137 are as follows:

Frequency	Input Voltage (Peak to Peak)	Output Voltage (Peak to Peak)	Common Mode Gain (G_C)
10 Hz	1.00 V	36.8 mV	0.0368
10 kHz	1.00 V	38.4 mV	0.0384
10 MHz	1.00 V	48.0 mV	0.0480

Table 4: This table shows the relationship between frequency and common mode gain (G_C) for the INA137 op-amp. Common mode gain is calculated via equation (1).

The results for the INA118 are as follows:

Frequency	Input Voltage (Peak to Peak)	Output Voltage (Peak to Peak)	Common Mode Gain (G_C)
10 Hz	1.00 V	60.0 mV	0.0600
10 kHz	1.00 V	59.2 mV	0.0592

Table 5: This table shows the relationship between frequency and common mode gain (G_C) for the INA118 op-amp. Common mode gain is calculated via equation (1). We see lower overall common mode gain when compared to the INA137.

From this we can move to calculate the Common Mode Rejection Ratio. This can be found via

$$\mathrm{CMRR} = \frac{G_D}{G_C} \quad (2) \qquad \& \qquad \mathrm{CMRR(dB)} = 20\mathrm{Log}_{10}(\mathrm{CMRR}) \quad (3)$$

Thus, our CMRR results for the INA137 would be:

Frequency	CMRR	CMRR(dB)
10 Hz	54.3478	34.7036
10 kHz	52.0833	34.3339
10 MHz	41.6666	32.3957

Table 6: This table shows the relationship between frequency and CMRR/CMRR(dB) for the INA137 op-amp. CMRR is calculated via equation (2) and CMRR(dB) is calculated via equation (3).

Similarly, our CMRR results for the INA118 would be:

Frequency	CMRR	CMRR(dB)
10 Hz	38.0000	31.5956
10 kHz	38.5135	31.7122

Table 7: This table shows the relationship between frequency and CMRR/CMRR(dB) for the INA118 op-amp. CMRR is calculated via equation (2) and CMRR(dB) is calculated via equation (3). We see a uniform reduction in CMRR and CMRR(dB) when compared to the INA137.

Once we characterized the Common Mode Rejection Ratio, we moved onto finding the input impedance for our op-amps under test. We know that input impedance for the op-amp can be found via the formula:

$$\mathrm{V_{out}} = \mathrm{G} \cdot \mathrm{V_{in}} = \mathrm{G}\frac{\mathrm{R_i}}{\mathrm{R_i}+\mathrm{R_e}}\mathrm{V_{in}} \qquad (4)$$

Where G is the differential gain $\mathrm{G_D}$, $\mathrm{R_e}$ is the resistance of the decade resistor box, and $\mathrm{R_i}$ is our input impedance to solve for.

Thus, our results for the INA137 are:

	Input Voltage (Peak to Peak)	Output Voltage (Peak to Peak)	Frequency	Input Impedance (R_i)
INA137	1.08 V	800 mV	1.00 kHz	52941.2 Ohms
INA118	1.32 V	1.76 V	1.00 kHz	14.0845 MOhms

Table 7: This table shows the relationship between input and output voltage measured when the decade resistance box is used inline to test for the input impedance R_i of the op-amp. R_i was calculated using equation (4). We see that the INA118 has a much greater input impedance than the INA137.

Discussion 1a:

During the first part of this lab, we gained familiarity with the instruments and equipment we would be using for this lab. One of the most important pieces of equipment we used was the function generator. We saw earlier that the function generator maintains an essentially stable output voltage across the entirety of the frequency range we tested it over. This is desirable behavior as we would like the function generator to operate in a predictable, constant way Irregardless of what frequency we choose. This is so that we can change the frequency on the fly without having to worry about how the voltage might change, adding another variable to our results. In addition to getting acquainted with the function generator, we also got familiar with the oscilloscope. We used the oscilloscope to measure noise in and around our workbench and got some staggering results. We found relatively large noises of 10 to 20mv, with much larger occasional spikes. We found the two largest frequencies to be a relatively high 13.56 kHz noise and a comparatively lower 60 Hz noise. I believe the 13.56 kHz noise which was measured next to the power supply for the oscilloscope is a switching frequency used by the AC switch mode power supply to convert the 120 VAC powerline voltage to low voltage DC for the oscilloscope to use internally. The second major noise we picked up was 60 Hz, and it was found no matter where we checked. While the amplitude of the 60 Hz noise was slightly lower than the amplitude of the switching noise, we can see that the 60 Hz noise is another big source of noise due to how widespread it is. I believe that the 60 Hz noise is derived from the AC Line specification used in the USA, as it has a switching frequency of 60 Hz. This 60 Hz becomes pervasive as the wires in the wall act like antenna and radiate out fields that switch at thus 60 Hz frequency which we then pick up as noise.

For the next part of the lab, we calculated the gain of the two op-amps. However, it is interesting to note that the INA137 has no external resistor attached to set the gain, while the INA118 did have a resistor across two of its pins. From the data sheet however, we can see that if we have no resistor attached to the INA118 we get a default gain of 1, as the op-amp reverts to a unity gain follower configuration. This is contrasted with the gain of 2 we see in the INA137 without a gain setting resistor. Thus, we can see that the gain resistor bridges a path allowing for a voltage divider to be established inside the op-amp allowing for the op-amp to have variable gain within a range. This theory is confirmed by looking at the op-amp's schematic in the data sheet where we see that the external resistor R_G allows for a voltage path between the input buffer op-amps, thus establishing a voltage divider to set the gain with.

Following this section of the lab, we went on to find the common mode gain and used that to calculate the common mode rejection ratio (CMRR). In this section our results showed that the INA137 had a significantly higher CMRR than the INA138. However, looking at the product specifications in the data sheet tells a different story. The datasheet for the INA118 claims a CMR of 110dB minimum, while the INA137 datasheet claims a CMRR of ‘only’ 90dB. Thus, we should expect to see a better CMRR calculated for the INA118, however we do not see that. We also see an across the board massive reduction in real-world CMRR when compared to the datasheet values for both op-amps. I believe that this discrepancy is due to a multitude of sources. First and foremost is the fact that we are quite literally down in the noise. This is the case as we are not in fact amplifying a strong generated signal, but instead amplifying noise on the signal that is picked up between the two inputs of the op-amp. This poses a unique challenge as the voltage of the noise we are attempting to pick up and amplify is extremely low for the precision and class of equipment we have to measure the voltages. Another point of concern is the fact that there is a resistor in the direct feedback path of the INA118 op-amp, and in the configuration we had it in, the legs of the resistor can act as an antenna and pick up noise that shows up on one input but not the other, leading to inflated noise readings. Thus, I believe that with a different test methodology and higher precision equipment we can get CMRR figures that are much closer to the published values.

However, one benefit that the INA118, an instrumentation amplifier has over the INA137, a differential line amplifier is the input impedance. Going back to the data sheet, within the schematic, we can see that the INA118 internally is comprised of three op-amps. Two of which are used as non-inverting voltage followers to buffer the input of the final op-amp which is setup as a fixed gain output. This design is contrasted by the relatively simplistic INA137 which is comprised of a single op-amp with a 12 kOhm resistor on each input. These differences are further illustrated with the input impedance specifications listed in the datasheet, where the INA137 has ‘only’ 24 kOhms of impedance while the INA138 has 10^{10} Ohms, or 10 gigaohms of input impedance. However, once again like above, our actual measurements were off from the figures in the datasheet. For instance our input impedance value for the INA137 was calculated to be roughly equal to 52.94 kOhms, which is not much different from the datasheet value of 24 kOhms. However, our calculated input impedance for the INA118 is three orders of magnitude smaller than the given datasheet value of 10^{10} Ohms. I believe that the error in both measurements, can be attributed mainly to two sources, first of which being the decade resistance box. As we did not measure the exact resistance across the decade resistor box, and we do not know the tolerance of the resistors in the decade box we cannot be sure that the values we have chosen via the switches is correct. Thus we cannot know the exact resistance used and thus our formula cannot provide fully accurate values. The second main source of error is specifically for the INA118 reading, as when we tried to load down our INA118 op-amp, we got a signal that would oscillate between a low and high voltage state. This issue persisted across three different chips, two of which were fresh out of the package. This oscillation made it exceedingly difficult to get a accurate voltage measurement and further made the automatic calculation algorithms within the oscilloscope unable to provide us with a consistent output voltage. Thus, we had to use our best judgement for finding the output voltage and this is our largest source of error, which could explain a majority of the discrepancy found.

Finally to wrap things up, we can see that for op-amps, input impedance is quite an important property, especially for biological measurement devices. This is the case as the higher the input impedance is, less current flows and thus there is a smaller voltage drop, as voltage drop is proportional to current flow as per ohms law (V = IR). Thus, for biological systems we would like extremely large input impedance, as the current flows associated with biological systems are inherently minute, and thus even a small amount of current flowing due to a lower input impedance will lead to skewed measurements. This is also the reason why oscilloscopes have such high input impedances which are usually standardized at 10 MOhms. This large input impedance allows for the oscilloscope to probe signals without altering the flow of their current, preventing a voltage drop. This allows for more accurate readings, as a device that changes the signal it attempts to read is self-defeating, and essentially useless.