Name: ________________________________

6.101 Introductory Analog Electronics Laboratory
Spring 2020

Laboratory No. 4 Report

Experiment 1: Differential Transistor Pair [Long-Tailed Pair]

Q 1.1 Without the schematic, explain how can you tell which input is the positive input?
The input is positive if you put an increasing voltage at its end, you get an increasing voltage at the output. For example, let's suppose we put a positively increasing voltage at the right transistor. This will increase the current running down it and cause the voltage drop across the 12k resistor to increase. Since Vout is just the 15V rail minus this voltage drop, the output voltage decreases. Therefore, the right side input is negative.

We can apply the same reasoning to the left side. We increase the input voltage there and the current running down the left transistor increases. Since current must be constant running down the Rx resistor, this means that the right side transistor current must decrease. With less current running down the 12k resistor at the output, our Vout increases. This makes the left input non-inverting.

For CMRR show both the numeric ratio and in dB. (This table is an excel object – double click)

$$cmrr = \left| \frac{A_{diff}}{A_{cm}} \right|$$

Table for Differential Amplifier Results				
Circuit	A_{cm}	A_{diff} Single-ended	Output Offset Voltage	CMRR
2N3904's 390 Ω R_E's 15kΩ Tail Resistor	0.39	10.5	21mV	**28.8dB** linear 27.5
2N3904's No R_E's 15kΩ Tail Resistor	0.42	80.1	160mV	**45.7dB** 193
LM394 390 Ω R_E's 15kΩ Tail Resistor	0.40	12.1	45mV	**29.6dB** 30
LM394 No R_E's 15kΩ Tail Resistor	0.41	84.8	17mV	**46.2dB** 204
2N3904's 390 Ω R_E's Current source	0.01	12.5	35mV	**62dB** 1259
2N3904's No R_E's Current source	0.03	82	93mV	**85dB** 17783
LM394 390 Ω R_E's Current source	0.01	12.6	40mV	**58dB** 794
LM394 No R_E's Current source	0.06	82.6	33mV	**85.5dB** 18836

Q 1.2 Explain in your write up which configurations and devices are the best with respect to CMRR, voltage gain, and low offset voltage.

Best CMRR „³ LM394 without RE and current source. Reason: the LM394 is well matched, and when we getrid of the RE¡¦s, we also eliminate another mismatch factor. Common mode is the measure of changes in output voltage as you put the same voltage into the two inputs. Changing voltage simultaneously on both inputs should not change the output, but since the transistors¡¦ biasing points are changing when you do this, any mismatch will reveal itself at the output. The current source helps with CMRR because it fixes the current running down the transistors regardless of any voltage changes that take place at the emitters. Notice that the tail current is determined by the bias voltage you set at the base of the current source transistor. In the case where you used the 15k Rx resistor, the voltage at the emitter of each transistor sets the current, so when you apply common mode voltage to the two transistor bases, you are essentially varying the emitter voltage (Vbe is about 0.6V fixed) and changing the tail current.

Best Voltage Gain „^{3} Any configuration without RE. As explained before, the RE basically reduces the effective current generator of the transistors.

Best Low Offset Voltage „^{3} any configuration with RE. Looking at the Vout vs Vin plot, you can see that with reduced differential gain, the differential amp is insensitive to offsets.

<u>Experiment 2: The Inverting Configuration.</u>

Q 2.1 What range of output-offset voltage can be achieved by adjusting the potentiometer over its entire range?

The measured output voltage that I got was 0.9mV. The input offset voltage can be modeled as an ideal voltage source at either V+ or V- terminals of the opamp. With the input and output grounded, the circuit looks like a non inverting amplifier with a gain of 2. Therefore, Vinput-offset=Vout/2=0.45mV.

I got a range of –2mV to 11.5mV when I adjust the pot.

Q 2.2 If an input coupling capacitor is inserted between the function generator and R1 what changes would need to be made to R1, R2 and why?

We do not need a coupling capacitor. We have already nulled out the input offset current and the DC potential of the function generator is 0V.

If you disconnect the offset potentiometer, you will notice that the output offset is approximately 5.5 times larger than that found when the amplifier was configured for a gain of 1 from the inverting input.

Q 2.3 Explain the 5.5 mathematically?

The output offset voltage can be calculated by $VO(1+R2R1)$, where VOS is the input offset voltage. In the initial condition, R2/R1 is 1. With R2=150k, R2/R1=10. So the ratio of the new output offset to the old is: $VO(1+10)VOS(1+1)$=11/2=5.5

When you had R1=R2=15k, you had a gain of –1 from the inverting input. However, since the offset voltage is modeled as a voltage source at the noninverting input, it sees a gain of 2 through the opamp. When R2=150K, the gain from the inverting input is –10, but it is 11 from the non-inverting terminal. Thus, the ratio of gain difference from the offset voltage point of view is just 11/2 = 5.5.

Q 2.4

Q 2.4 Why did we change R_3.?

We had to change the value of R3 because we changed R2. R3 = R1||R2.

Q 2.5 What is the ideal value of R_3 relative to the values of R_1 and R_2?

The ideal value of R3 should be the combination of resistors connected from the opamp's inverting input with a DC path to ground. In this case, it is the R1 and R2, which both have a DC path to ground and seem to be in parallel. So R3=R1||R2 ideally.

With the input amplitude set to the value at which the output voltage just starts to distort, calculate the maximum value of dv_{out}/dt on the output voltage.
Q 2.6 How does this value compare with the slew-rate value that is found in the LM741 spec sheet?

slew rate measured at 0.67V/us. Typical data sheet spec is 0.5 V/ us

Q 2.7 How do the saturation voltages with the load resistor differ from the test using the amplifier without a load resistance [infinite load impedance]?

The output waveform is not square because the opamp is slew rate limited. Slew rate is caused by the internal compensation cap that needs to be charged up and down. Thus, it takes the output a finite amount of time to charge up to a certain voltage. The slew rate I measured was 0.63 V/us.

Set the signal generator to produce a square wave input voltage. Adjust the amplitude and frequency of the input voltage until the output becomes a triangular wave.
Q 2.8 Why is the output waveform not a square wave?

The output waveform is not square because the opamp is slew rate limited. Slew rate is caused by the internal compensation cap that needs to be charged up and down. Thus, it takes the output a finite amount of time to charge up to a certain voltage. The slew rate I measured was 0.63 V/us.

Q 2.9 Measure the +5 supply voltage. For R1=5K what is the maximum output voltage? How does this compare to spec?

+5V: 4.9395V
Vout: 4.8278V
For a supply voltage of 5.0V, the datasheet lists a minimum output swing of 4.85V with a 5k load on the output. Although the measured maximum of V_{OUT} is lower than this, the +5V supply was nearly 100mV lower than it was supposed to be, so the amplifier is probably still in spec.

Experiment 3: Comparing the LF356 and the LM741 operational amplifiers.

Q 3.1 Measure the bandwidth of the amplifier built with an LF356 using a feedback R2 to 150 kΩ. How does this compare with your measurement with the value given in the spec sheet?

The bandwidth I measured of the LF365 with a gain of -10 is 595kHz compared to the LM741's 118kHz. A gain of 10 is 20dB in decibels, and looking at the spec sheet for the LF356, we see that 595kHz is within spec.

Q 3.2 How does the measured slew rate of the LF 356 compare with the value found in the spec sheet? How does the slew rate compare with the LM 741 slew rate?
Slew rate was measured to be 14.7V/us, which corresponds well with the data

sheet’s typical rating of 12V/us. It is much faster than the LM741..

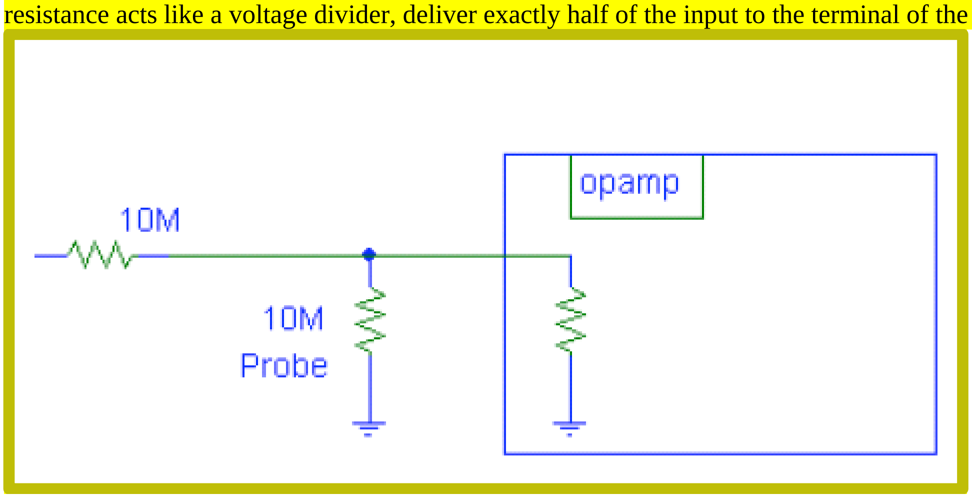
Construct the voltage follower [unity-gain buffer] of Figure 3[b]. Omit the resistor to ground.

Q 3.3 If you do not use a coupling capacitor, the circuit should work properly. Why?

lWithout the coupling cap, the circuit should work fine because the follower should output exactly what you put in, even DC voltages. Adding the coupling cap actually adds a problem at low frequencies. The cap acts like an open for DC signals and sothat your input signal never gets delivered to the opamp. At low frequencies, the input resistance of the opamp and the cap act like a HPF such that if you input a 1V, the opamp sees something less. It also poses severe offset problems

Q 3.4 Your scope probe has a resistance from tip to ground of 10 MΩ. What effect will your scope probe have if you use it to measure the input voltage (pin 3) to this op-amp?

With the scope probe measuring the input to the opamp, its 10MΩ is in parallel with the input impedance of the opamp. This lowers the effective input impedance. When the 10MΩ series resistor is in place, notice that the probe resistance acts like a voltage divider, deliver exactly half of the input to the terminal of the op-amp.



Show the Schmitt trigger output waveform; also show the capacitor charging and discharging voltage waveform

Q 3.5 How does the value of the hysteresis threshold voltage affect the frequency of oscillation?

Q 3.6 Find values of R_3 and C to produce an oscillation at approximately 1000 Hz. Measure the actual frequency using your scope. Then, increase the frequency to 100 kHz.

1000 Hz R3___________ C _______________

100 KHz R3___________ C _______________

1000 Hz: R3 = 10k C = 68nF f = 1.0414kHz
100 KHz: R3 = 10k C = 680pF f = 39.623kHz

Q 3.7 Sketch and show the wave shape at 100KHz and 1Khz. How does the wave shape at 100 kHz compare with the wave shape at 1 kHz? Why do you think this occurs?

This is probably happening because at 100kHz, the amplifier is trying to operate outside its slew-rate limit, and thus cannot produce a good square wave. The effects of slew-rate limitation can begin to be seen at the rising and falling edges of the 1kHz waveform, although its effects are more pronounced at 100kHz.

Q 3.8 LM311: How does the wave shape at 100 kHz compare with the wave shape at 1 kHz? What have we done to improve the waveform shape at 100 kHz?

At 100kHz, the output of the LM311 is much more “square” than the LF356 waveform. This is because the LM311 is a dedicated comparator—it has an open-collector output that is designed to drive the output all the way up to supply. Additionally, it has a typical response time of 115ns, much shorter than the period of a 100kHz signal.

Experiment 4: Integrators, filters, etc.

Q 4.1 What is the bandwidth of this filter?

For a LPF, the bandwidth is the same as the cutoff frequency, which is 1kHz in this case.

Q 4.2 For what frequencies does this circuit produce an output waveform that is the integral of the input? At what frequency does the output start to depart from the ideal waveform?

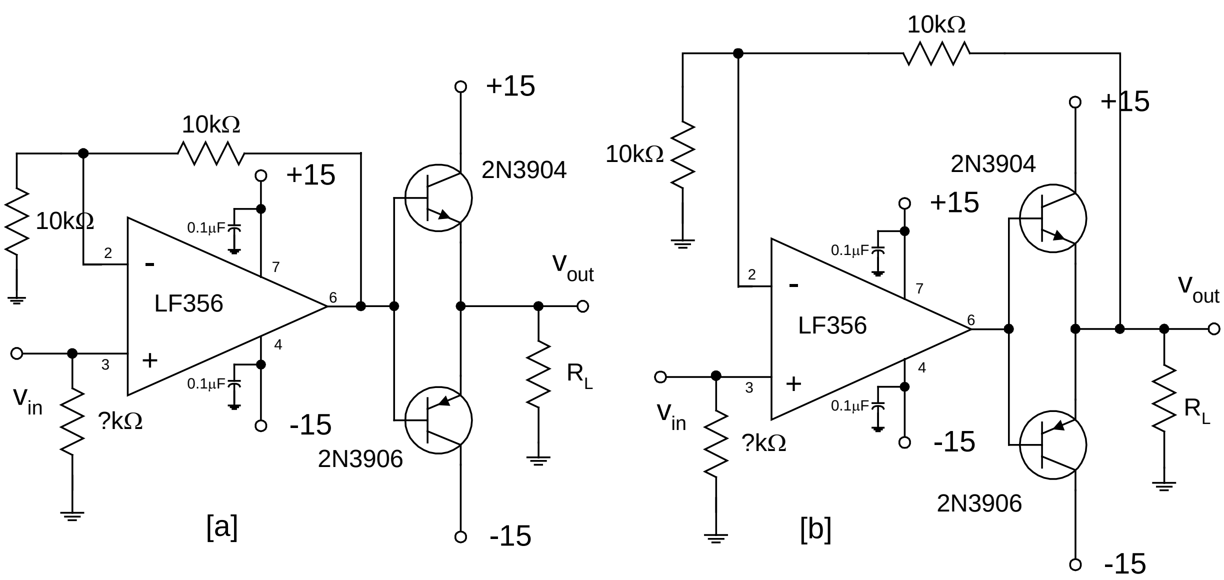
This circuit acts as an integrator when it is operating in the linear asymptotical region of the filter, or when f > 1kHz. However, at this point, the phase shift is only -45 degrees. The performance is greatest when the input frequency is at least a decade above the corner frequency, or f > 10kHz. The performance starts to degrade below 1kHz, as the filter begins to pass all frequencies through.

Q 4.3 For what frequencies should this differentiator produce an output waveform that is the derivative of the input?

It will act as a differentiator when it is operating well below the corner frequency, which is:
$12\pi RC \approx 11kHz$

Q 4.4 At what frequency does the performance of your differentiator begin to deteriorate?

About 5 kHz (by measurement).



Experiment 5: A few other op-amp applications

Q 5.1 Approximately at what frequency does this occur? Why does this circuit perform better than the simple rectifier?

The distortion is noticeable at 10kHz and significant by 50kHz. In the first circuit, when the input goes negative, the voltage across the diode is negative and the output of the op-amp is driven to saturation. When the output again becomes positive, the op-amp must recover from saturation, which takes time. In the second circuit, although the op-amp has to compensate for two diode drops, the op-amp's "recovery time" is lower because it is never driven to saturation: when the input is negative, no current flows through the diodes and the circuit operates as an inverting amplifier with gain 1+(R2/R1).

Q 5.2 What output voltage do you see from each of these circuits? Why?

From the first circuit, the output is 0. From the second circuit, there is a 1V p-p sine wave. The reason for this is that, in the first circuit, the amplifier is supplying a 1V p-p sine wave to the base of the push-pull output stage. However, for the transistors to turn on at all, the voltage V_{BE} must be >0.6V on each end of the signal—the input must be at least 1.2V p-p. In the second circuit, the feedback point for the op-amp is taken after the transistors, so the op-amp compensates for the V_{BE} of the output stage by "pre-distorting" the signal.

Q 5.3 How does the feedback used in the circuit of Figure 5[b] help this circuit to work?

The op amp works to ensure both of its inputs are as close to the same voltage as possible. So when the noninverting input begins to increase, the op-amp increases its output voltage until the output stage transistor is activated, at which point the output begins to track the input.

Q 5.4 What is the source of this distortion?

The distortion observed on the output of the first circuit is crossover distortion. It is caused because the output stage is only activated when the output of the amplifier is >0.6V or <-0.6V. This effectively "cuts out" the parts of the cycle in between peaks when the signal is too low to activate the output

Q 5.5 How does the configuration of Figure 5[b] greatly reduce the level of this distortion [look at the output of the LF356.]?

The configuration of 5[b] "pre-distorts" the input to the push-pull BJT pair, as described above.

Q 5.6 What is the minimum value of load resistor RL that can be used in the circuit of Figure 5[b] without exceeding the power dissipation capabilities of the output transistors?

The power dissipated in the transistor is the voltage across it times the current through it.

$$P = V_{ce}I = (15 - V_{out})\frac{V_{out}}{R}$$

To find the max power through the transistor, we must figure out the optimum combination of voltage and current that can produce the worse power dissipation. We can't just assume that this occurs when the voltage or current is max. We should differentiate the power expression and set it to zero.

$$0 = \frac{dP}{dV_{out}} = \frac{15}{R} - \frac{2V_{out}}{R} \Rightarrow V_{out} = 7.5$$

Plugging 7.5V back into the power equation, we find that R=282Ω.

Q 5.7 What is the maximum voltage and current that the op amp can supply to this load? Find this value on the op-amp spec sheet.

The opamp's max output voltage is determined by its current limit. If you put a very small resistor at the output, the voltage across that resistor V=IR is directly proportional to the current driving through it. If you can't source a high enough current, then you will not be able to output the rails. The LF356 is rated at 25mA so that the max Vout with a load resistor of 282Ω is 7.05V.

Experiment 6: Heart rate using Photoplethysmography (PPG)

Q 6.1 Submit a MATLAB plot of your data using plot(second, Volt)

Q 6.2 What is the sampling frequency of the oscilloscope (see CSV data)?

Q 6.3 What is peak to peak current in the photodiode?

For a transimpedance amplifier, the output voltage V_{OUT} is determined by the input current:

$V_{OUT}=R_F I_p \Rightarrow I_p=V_{OUT} R_F$

For R_F = 1.5M and V_{OUT} = 50mV_{p-p}, $I_p=0.05(1.5*10^{-6})\approx 33nA$.