

Lab 5: Building a Function Generator

Objectives

In this lab exercise you will build a function generator capable of generating square, triangle, and sine waves. The frequency and amplitude of these waves will be controlled through potentiometers. There will be some frequency analysis to aid in the understanding of Laplace transforms, Bode plots, and Fourier series. Finally, the function generator will be connected to the stereo amplifier constructed during Lab 3 in order to monitor the generated waveforms through a speaker.

Pre-Lab Instructions (10pts)

Part One: Square Wave Generator

1. Simulate the unstable multivibrator shown in Figure 1. The voltage source in the diagram is the PSpice part “VPULSE,” a voltage pulse needed to start the circuit oscillating. Note that when you actually build the circuit in lab, noise in the circuit will be enough to start oscillations. To view the output, set up a transient response with a runtime of about 15ms and a maximum step size (“step ceiling” in PSpice 9.1) of 5 μ s.

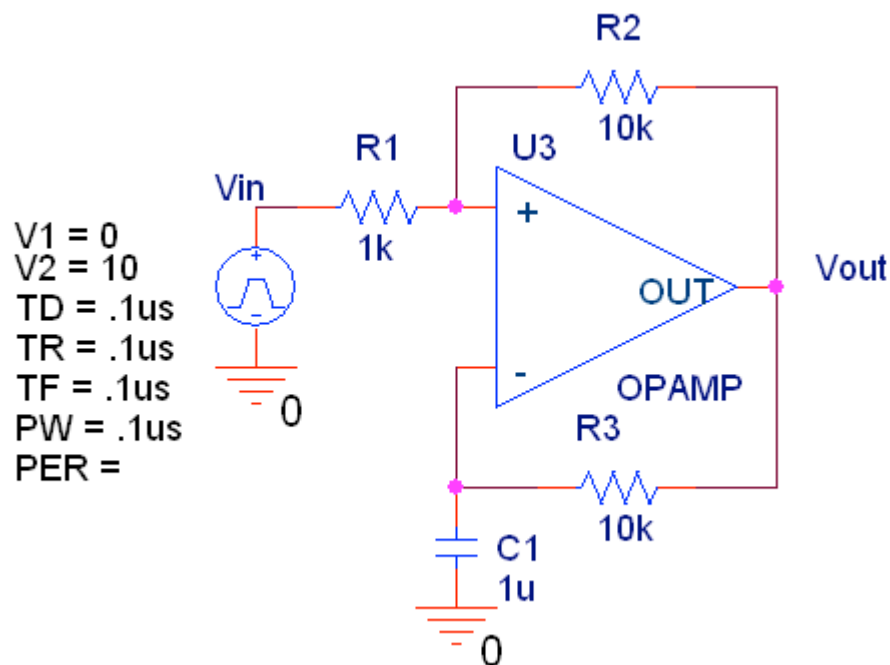


Figure 1: Unstable Multivibrator

2. The period of the output square wave can be calculated as:

$$T = 2R_3C_1 \ln\left(\frac{1+\beta}{1-\beta}\right)$$

where $\beta = R_1/(R_1 + R_2)$.

Examine the frequency of the output voltage for the following component values:

R_3	C_1	Frequency (Calculated)	Frequency (PSpice)
10K	1 μ F		
9K	1 μ F		
7K	1 μ F		
10K	2 μ F		
10K	3 μ F		

Table 1: Frequency Comparisons for Varying Resistances and Capacitances

To measure the frequency of the output waveform, measure the time it takes for the square wave to complete one full cycle, then take the reciprocal of this time.

Part Two: Integrator

1. Simulate the circuit shown in Figure 2. The voltage source is the part “VAC.”

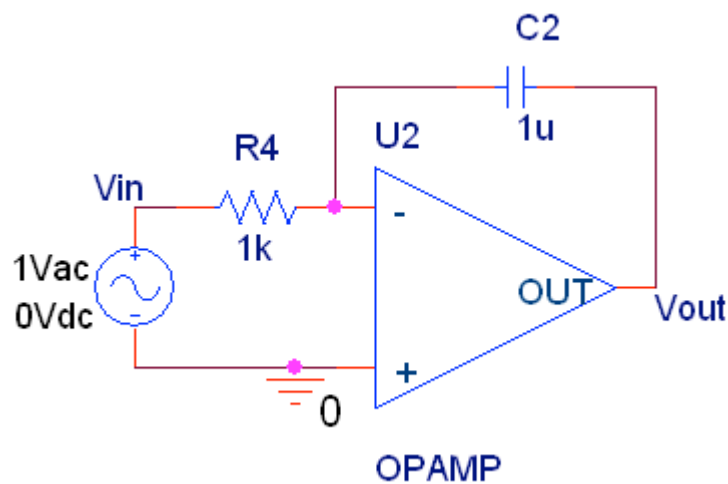


Figure 2: Integrator

2. Find the transfer function by hand, i.e., $\mathbf{V}_{\text{out}}(\mathbf{s})/\mathbf{V}_{\text{in}}(\mathbf{s})$. Later in the lab, the input of the integrator is going to be the output of the square-wave generator, either +15V or -15V, DC. For the sake of analysis, we can say that $v_{\text{in}}(t) = -15u(t)$ or $v_{\text{in}}(t) = 15u(t)$, depending on if the square-wave is at its minimum or maximum value.

If we take the input as $-15u(t)$, what will the output of the integrator be in both the frequency and time domains (hint: the integral of a constant)? What will the output be in both the frequency and time domains if the input is $+15u(t)$?

$$\mathbf{V}_{\text{out}}(\mathbf{s})/\mathbf{V}_{\text{in}}(\mathbf{s}) \quad \underline{\hspace{2cm}}$$

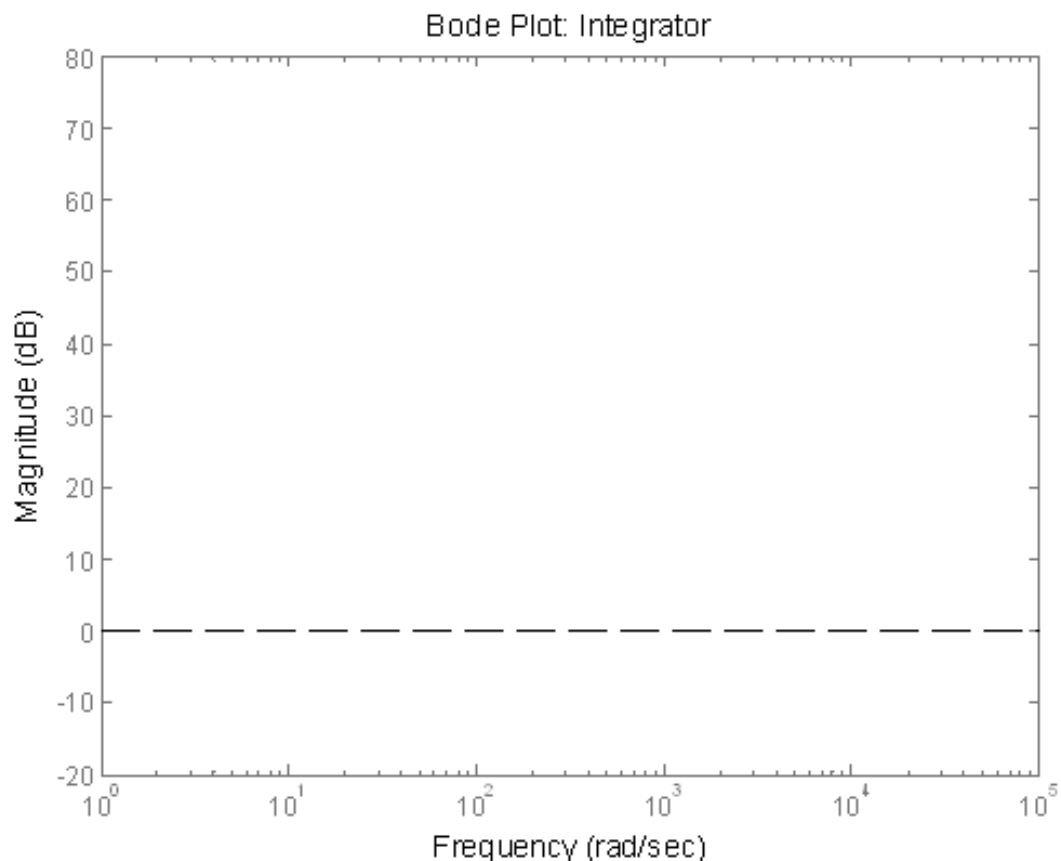
$$\mathbf{V}_{\text{out}}(\mathbf{s}) \quad (v_{\text{in}}(t) = -15u(t)) \quad \underline{\hspace{2cm}}$$

$$v_{\text{out}}(t) \quad (v_{\text{in}}(t) = -15u(t)) \quad \underline{\hspace{2cm}}$$

$$\mathbf{V}_{\text{out}}(\mathbf{s}) \quad (v_{\text{in}}(t) = +15u(t)) \quad \underline{\hspace{2cm}}$$

$$v_{\text{out}}(t) \quad (v_{\text{in}}(t) = +15u(t)) \quad \underline{\hspace{2cm}}$$

3. Sketch the asymptotic Bode plot of the transfer function of the integrator:



4. In PSpice, make a Bode plot of the transfer function by conducting an AC sweep on the input voltage. In the simulation profile for AC Sweep, set the start frequency to 1Hz, the end frequency to 100,000Hz, and the points per decade to 100. The sweep type should be logarithmic (“decade” in PSpice 9.1). Add a voltage marker to the output of the integrator. On the plot of the output voltage, change the trace to “20*LOG10(V(U2:OUT))” to get the gain in decibels (U2:OUT is the output node of the op-amp, which may be labeled differently in your circuit). Change the x-axis from Hz to rad/s by first selecting “Axis Setting” from the Plot menu, then clicking “Axis Variable” and changing “Frequency” to “2*pi*Frequency.”

Print out the Bode plot. (**NOTE: your name must appear in the filename of all circuit and waveform printouts!**)

How much does the gain (value plotted on the y-axis) change per decade (a factor of 10, e.g., between 100rad/s and 1000rad/s)?

dB/decade _____

Part Three: Low-Pass Filter

1. Simulate the circuit shown in Figure 3.

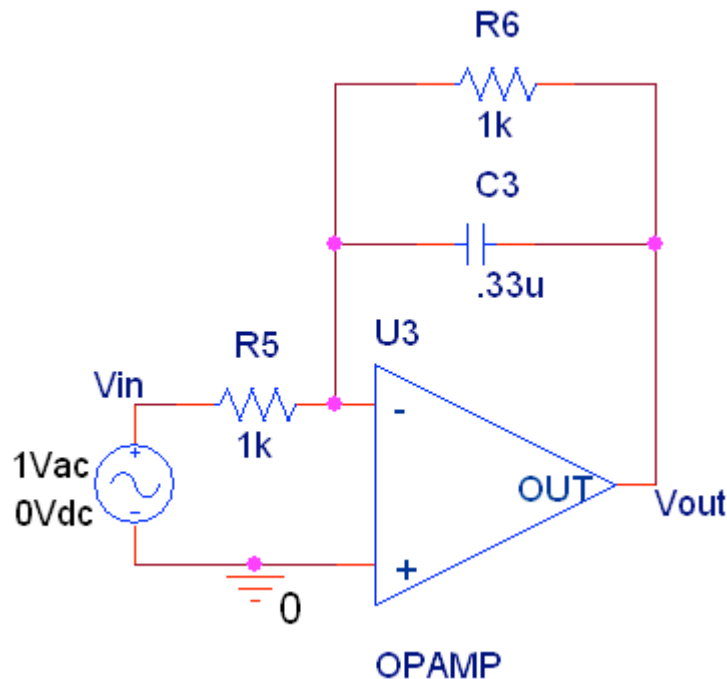
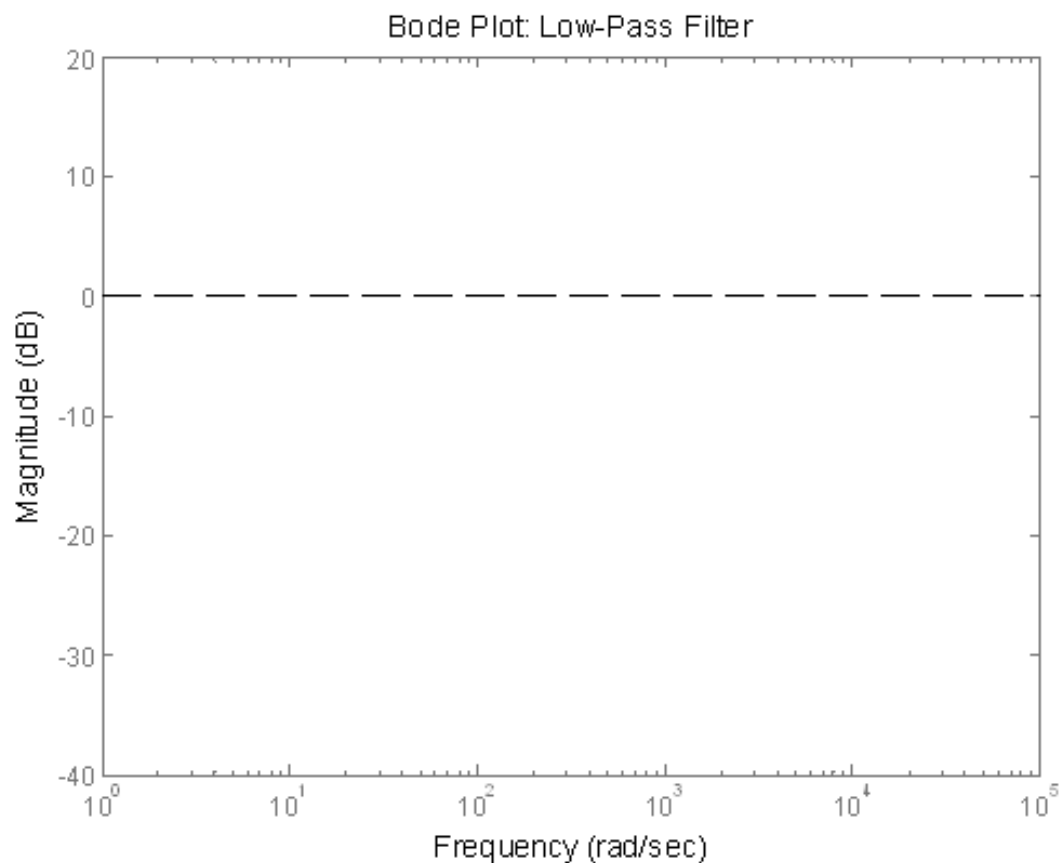


Figure 3: Low-Pass Filter

2. Find the transfer function by hand, i.e., $V_{out}(s)/V_{in}(s)$.

$V_{out}(s)/V_{in}(s)$ _____

3. Sketch the asymptotic Bode Plot of the transfer function of the low-pass filter:



4. The theory behind Fourier series is that any periodic function, $f(t)$, with period T , can be written as the sum of weighted sinusoids. The frequency of each sinusoid is a positive integer multiple of ω_0 , the frequency in rad/s of $f(t)$ ($\omega_0 = 2\pi/T$). Each sinusoid also has a coefficient multiplying it, determining how strongly that sine (or cosine) wave contributes to the function $f(t)$. Derive the coefficients (a_0 , a_n , and b_n) of the Fourier series representation of the following signal:

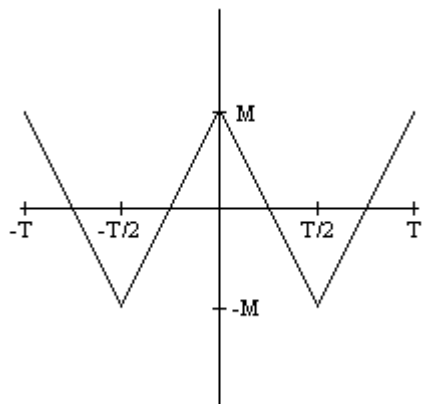


Figure 4: Triangle-Wave Input (to the Low-Pass Filter)

This calculation will need to be done on a separate page. Here is a hint to aid you in finding the coefficients: Is this function even or odd? For even functions, $b_n = 0$, meaning the function is comprised entirely of cosine waves. For odd functions, $a_n = 0$, meaning the function is comprised entirely of sine waves. If the function is even, it is recommended to double the integral over half the period to find a_n . If it is odd, use you can also double the integral over half the period to find b_n .

a_0 _____

a_n _____

b_n _____

5. For $M = 15V$ and $T = 3ms$, write down the first three non-zero terms in the Fourier series expansion of the triangle wave shown in Figure 4.

$f(t) =$

6. Make a Bode plot of the transfer function by conducting an AC sweep on the input voltage. In the simulation profile for AC Sweep, set the start frequency to 1Hz, the end frequency to 100,000Hz and the points per decade to 100. The sweep type should be logarithmic (“decade” in 9.1). Add a voltage marker to the output of the circuit. On the plot of the output voltage, change the trace to “20*LOG10(V(U3:OUT))” to get the gain in decibels (U3:OUT is the output node of the op-amp, which may be labeled differently in your circuit). Change the x-axis from Hz to rad/s by first selecting “Axis Setting” from the plot menu, then clicking “Axis Variable” and changing “Frequency” to “2*pi*Frequency.”

Print out the Bode plot. (**NOTE: your name must appear in the filename of all circuit and waveform printouts!**)

At what frequency (rad/s) does the Bode plot drop by 3dB from its constant value? This frequency is known as the “3dB point.” After the 3dB point, what is the rolloff (i.e., how much does the gain decrease per decade, say from 10kHz to 100kHz)?

3dB point (rad/s) _____

Rolloff (dB/decade) _____

Part Four: Function Generator

1. Cascade the three previous op-amp circuits to simulate the circuit shown in Figure 5. Print out the schematic for this circuit.

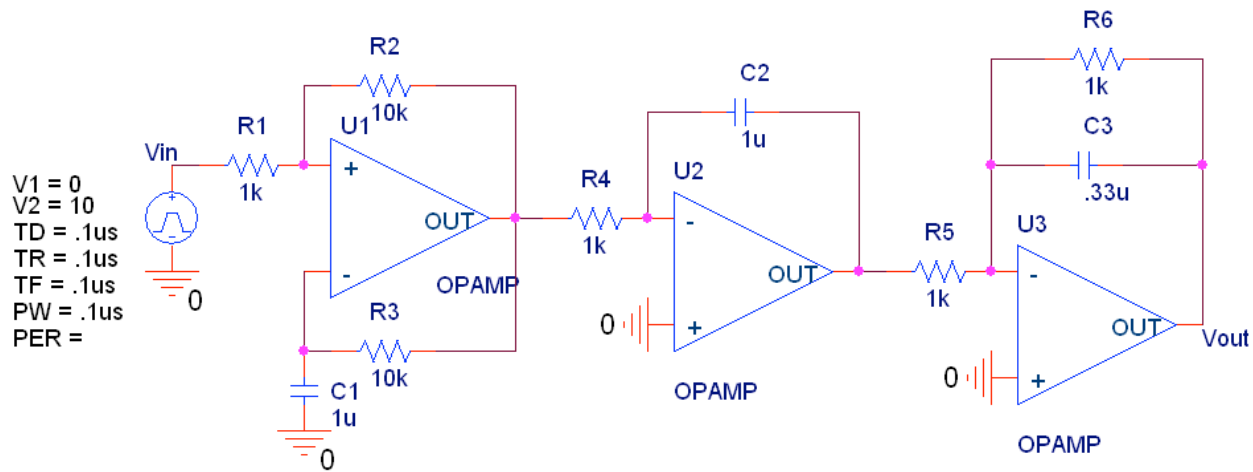


Figure 5: Function Generator

2. Using a transient analysis with the same parameters as in Part 1, plot the output of each op-amp (on the same plot). You can do this by placing voltage markers on the output of each op-amp, or by adding a trace and selecting the output nodes of the op-amps. Change R_3 to 7K and print the three waveforms again (on another plot).

3. Using the results from the previous sections, explain in a paragraph or two how this function generator works. Don't concern yourself with how the square wave is generated, but discuss how the triangle and sine waves are generated (sketching graphs of the outputs may be useful). Be sure to mention the role of the integrator, as well as the low-pass filter in relation to the Fourier series representation of the triangle wave.

4. Using the pin layout of the LM324 chip on the last page of this lab description, draw the necessary connections to each of the pins so that it resembles the schematic in Figure 8. Do not use op amp 4 from the LM324 chip. Instead, use op amp 1 from the last page for the U1 op amp in Figure 8, op amp 2 for the U2 stage, and op amp 3 for the U3 stage. Bring this drawing to lab and use it for the in lab connections.

Also comment on the following: Bode plots are useful in showing how the gain of a transfer function changes with the frequency of the input. Using this knowledge, respond to the question of why the amplitude of the triangle wave and the sine wave decrease in amplitude as R_3 is decreased from 10K to 7K. (Hint: Look at the equation on the top of page 2, and also the Bode plots of each op-amp stage.)

In-Lab Instructions (15pts)*Part One: Build the Function Generator*

1. Using one 324 op-amp chip (shown in Figure 7), wire the three stage op-amp circuit shown in Figure 8. The first op-amp stage generates a square wave. The second op-amp stage integrates the square wave to produce a triangle wave. The final op-amp stage is a low-pass filter, removing the higher frequency components of the triangle wave so that it closely resembles a sine wave with the same fundamental frequency. It is recommend you wire one stage at a time (starting with the square wave) and ensure the proper functionality of that stage before wiring subsequent stages.

The output of each op-amp is sent to one of the switches on the 4-Switch dual in-line package (DIP), which selects the output function when one turns on the appropriate switch.

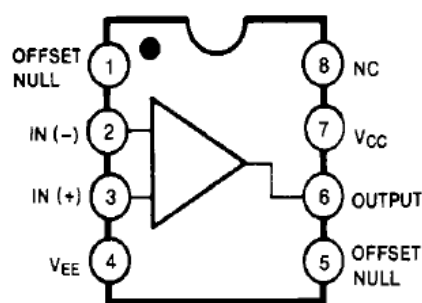


Figure 6: Pin Layout of the LM741 Op-Amp

$$V_{EE} = -15V$$

$$V_{CC} = 15V$$

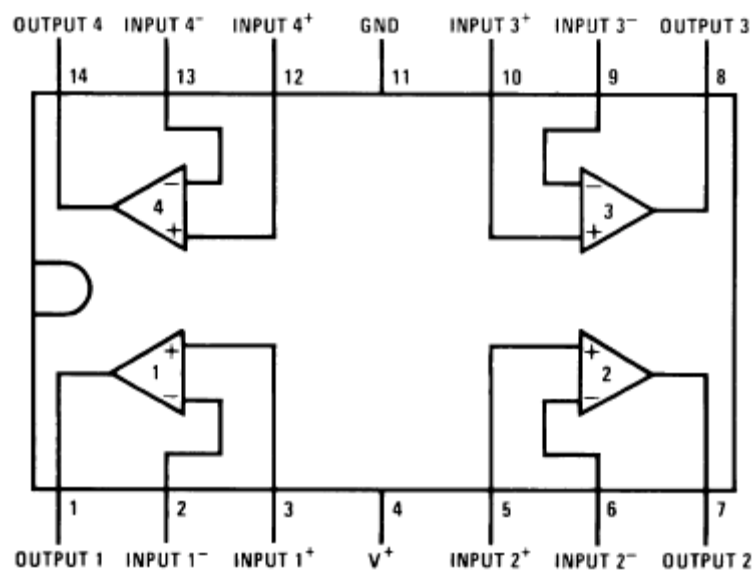


Figure 7: Pin Layout of the LM324 Op-Amp

$$V_+ = 15V$$

$$GND = -15V$$

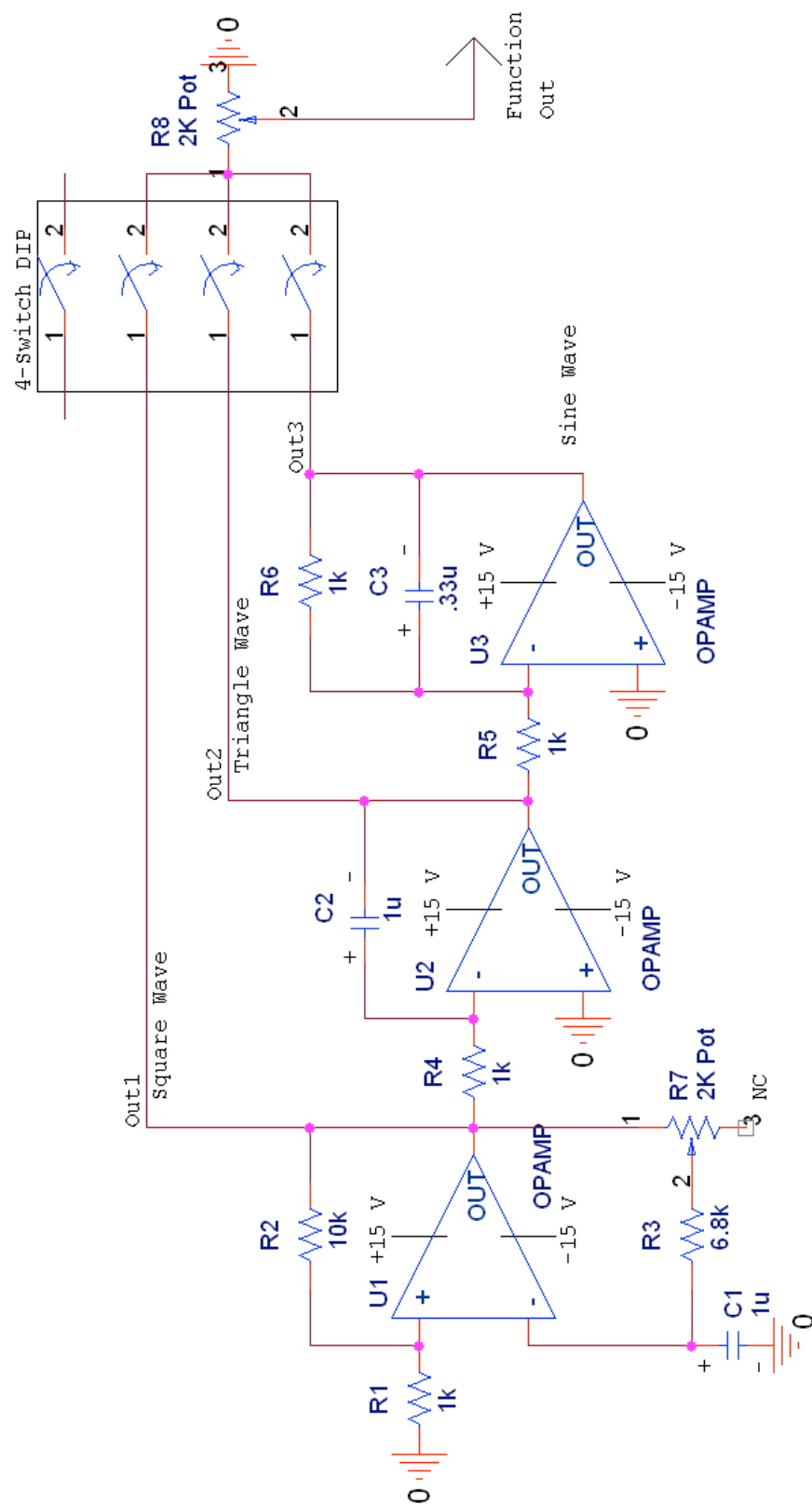


Figure 8: Circuit Diagram of the Function Generator

Part Two: Analyzing the Function Generator

1. Connect an oscilloscope probe to the point labeled “Function Out” in Figure 8. Select the output from the first op-amp (the square wave). You will now analyze the duty cycle of this square wave. Make sure that R8, the amplitude knob, is adjusted such that there is no resistance between the DIP-switch output and the oscilloscope probe (i.e. such that the amplitude of the output is at a maximum). Turn the knob on the potentiometer R7 all the way clockwise.

The duty cycle of a square wave is defined as:

$$\text{Duty Cycle} = 100\% \times \frac{\text{amount of time waveform is positive during one period}}{\text{duration of one period}}$$

For example, if a square wave has a period of 200ms and is positive for 50ms during each period, then the duty cycle is 25%.

Record what happens to the duty cycle as you adjust V_{CC} , the positive voltage supply to the op-amp.

V_{EE}	V_{CC}	Time Positive per Period	Period	Duty Cycle
-15V	15V			
-15V	10V			
-15V	5V			

Table 2: Effect of V_{CC} on Duty Cycle

What happens to the positive voltage level of the square wave as V_{CC} is decreased? What happens to the negative voltage level?

What do you think would happen if V_{EE} were changed from -15V to -10V? Record the duty cycle and the negative voltage level of the square wave to see if you are correct.

V_{EE}	V_{CC}	Time Positive per Period	Period	Duty Cycle
-10V	15V			

Table 3: Effect of V_{EE} on Duty Cycle

2. Return V_{CC} and V_{EE} to their respective maximum absolute values. Select the triangle wave output to be displayed on the oscilloscope. This waveform may not look quite like a triangle wave at its peaks, so adjust V_{CC} and V_{EE} until it looks as close to a triangle wave as you can get it. Change the switch to display the square wave and then the sine wave to convince yourself that the function generator is working properly. Record the values of V_{CC} and V_{EE} that are needed.

V_{CC} _____

V_{EE} _____

Show the TA that all three waveforms are being generated correctly before moving on.

TA initials _____

3. The potentiometer labeled R7 in Figure 8 controls the frequency of the square wave. Because the triangle and sine waves will have the same frequency as the square wave, this potentiometer is the frequency knob for the function generator. Fill in the following table for the maximum and minimum values of the resistance of the potentiometer, R7, between pins 1 and 2.

	Square Wave		Triangle Wave		Sine Wave	
R7 =	0K	2K	0K	2K	0K	2K
Voltage (p-p)						
Voltage (RMS)						
Frequency						

Table 4: Effect of R7 on Frequency and Output Voltage

In the pre-lab, it was stated that the frequency of the generated square wave is governed by the following equation:

$$T = 2(R_3 + R_7)C_1 \ln\left(\frac{1 + \beta}{1 - \beta}\right)$$

where $\beta = R_1 / (R_1 + R_2)$.

As R7 increases in the above equation, what should happen to the frequency? Do your results in the table above support your claim? Explain.

Part Three: Connecting the Function Generator to a Speaker

1. Using the maximum peak-to-peak voltage of the sine wave (from Table 4), design a voltage divider to reduce this voltage to 20mV peak-to-peak. Label the resistor values you choose in the figure below:

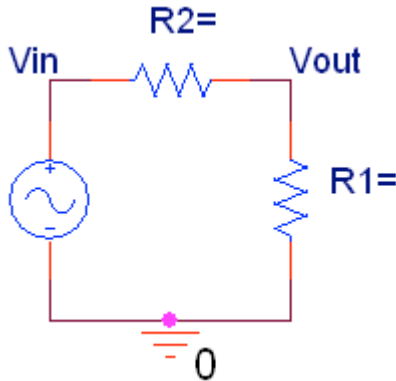


Figure 9: Voltage Divider to Reduce Function Generator Output to 20mV peak-to-peak

2. Connect the point labeled “Vout” in Figure 9 to one of the inputs of the stereo amplifier. Attach a speaker to the corresponding output channel, and play all three generated waveforms through the amplifier, varying the frequency (R7) and amplitude (R8) knobs to see how they affect the output signal you hear. Have the TA listen to all three outputs and initial below:

TA initials _____

When you have completed the lab, sign and print your names below and have the TA initial next to each name.

TA

Skills Assessment (5pts)

Everybody must demonstrate that he/she can perform certain lab skills, as described below.

Fill in your names in the spaces provided. A TA will initial the appropriate space when a skill has been successfully demonstrated.

	Name #1	Name #2
	_____	_____
1. Demonstrate how to change between high Z and 50 ohm modes on the function generator and explain its purpose.	_____	_____
2. Demonstrate how to trigger measured signals on different channels of the oscilloscope.	_____	_____
3. Demonstrate how to configure the channel coupling on the oscilloscope and explain its purpose.	_____	_____
4. Demonstrate how to obtain various measurements from a circuit using the multimeter.	_____	_____
5. Identify possible amplifier supply voltages from a series of waveform printouts.	_____	_____

