Operational Amplifiers: Basics and Design Aspects

A tutorial by Jonathan Ames

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Preface

The objective of this tutorial is to provide students with a means of better understanding the operational amplifier (op-amp). This comprehension is facilitated by first considering some of the fundamentals of op-amps, and from there using KCL circuit analysis to explore and develop common op-amp circuits. Next, some practical considerations are covered that view the op-amp from a real-world perspective which varies from the ideal. Finally, an op-amp circuit is actually constructed on a breadboard and oscilloscope prints are included to describe its operation and results. By reading through this tutorial a student should have a better understanding concerning operational amplifiers and how they are analyzed.

Chapter 1

1. Operational Amplifier (Op-Amp) Basics

1.1. Symbols and Schematic

Below is the symbol used to represent an operational amplifier. The two inputs are the inverting (V-) and non-inverting (V+) terminals, and the output is Vout. The supplies are discussed further in the pages ahead.

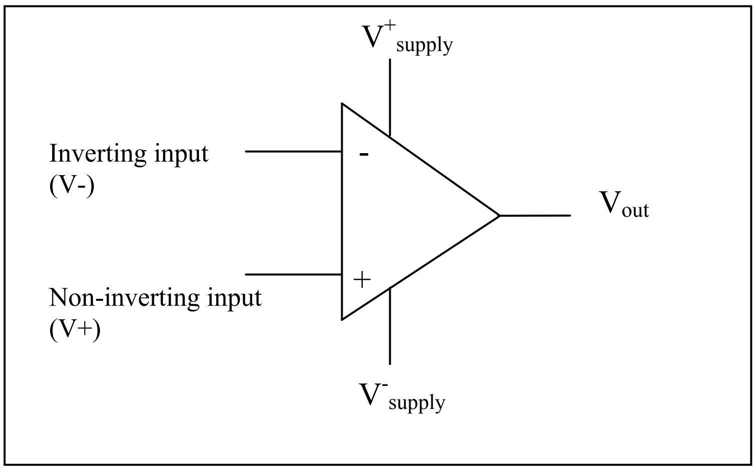


Figure 1. Op-amp Symbol

The op-amp can be thought of as a "black box" having two inputs and one output as seen in Figure 2 below:

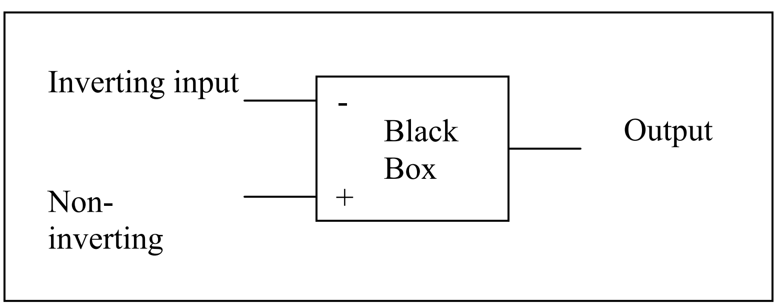


Figure 2. Block diagram of an operational amplifier

The op-amp can also be represented as a dependent voltage source (V_{dep}) as in Figure 3, having an output impedance (Z_{output}) and input impedance (Z_{input}). The input impedance is so high that no current can flow between the input terminals, but the output impedance is very low. The supply voltages provide the power necessary for the high gain and amplification and are viewed here as the dependent voltage source.

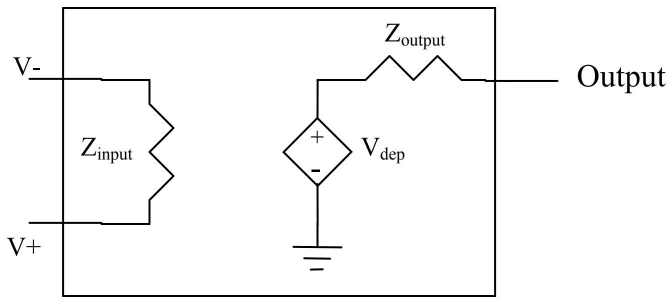


Figure 3. Equivalent view of an op-amp

The circuitry that makes up an op-amp consists of transistors, resistors, diodes, and a couple capacitors. In general, these components are combined to achieve within the op-amp two stages of differential amplifiers and a common-collector amplifier. [1]

In an effort to simplify the operational amplifier, one must not forget that the internal circuitry of an op-amp is more than just a “black box”. All operational amplifiers are integrated circuits (ICs), and Figure 4 illustrates the components that work together to achieve what we know to be an op-amp.

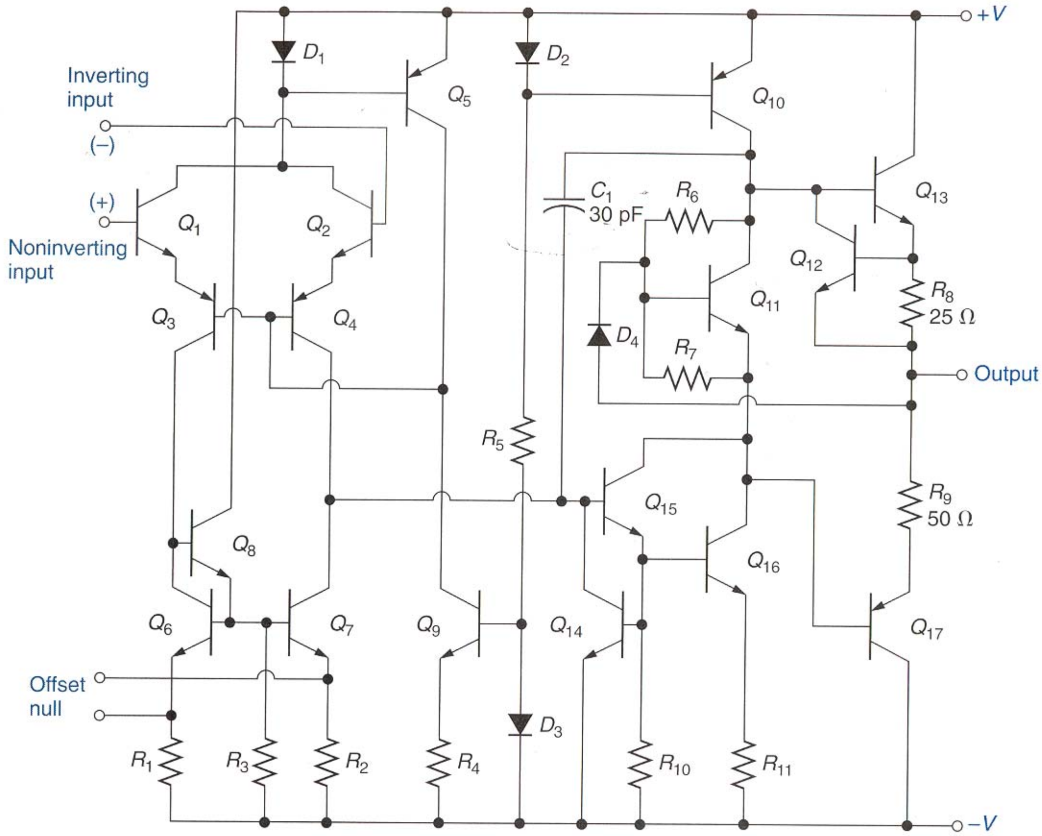


Figure 4. Internal circuitry of an op-amp [2]

1.2. Kirchhoff's Current Law applied to Op-amps

An operational amplifier circuit can be analyzed with the use of a well-accepted observation known as Kirchhoff's Current Law (KCL). KCL simply states that the currents entering a node are equal in magnitude to the currents leaving that same node. A node is any junction wherein two or more two-terminal components meet. Consider Figure 5 for clarification.

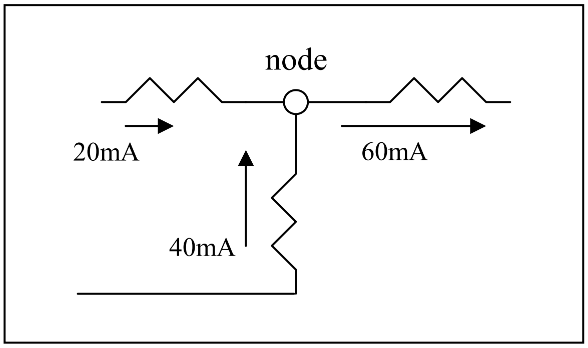


Figure 5. KCL defined

In this case, 20mA + 40mA = 60mA.

The principle of KCL is the heart of node voltage analysis. The purpose of node voltage analysis is to find the voltage value at a certain node(s). This is done by representing the currents entering and leaving the node by their Ohm's law equivalent (i.e. I=V/R). KCL and node voltage analysis apply to all electrical circuits including operational amplifiers. The following figure is a common non-inverting op-amp circuit that will be repeated later on in the tutorial.

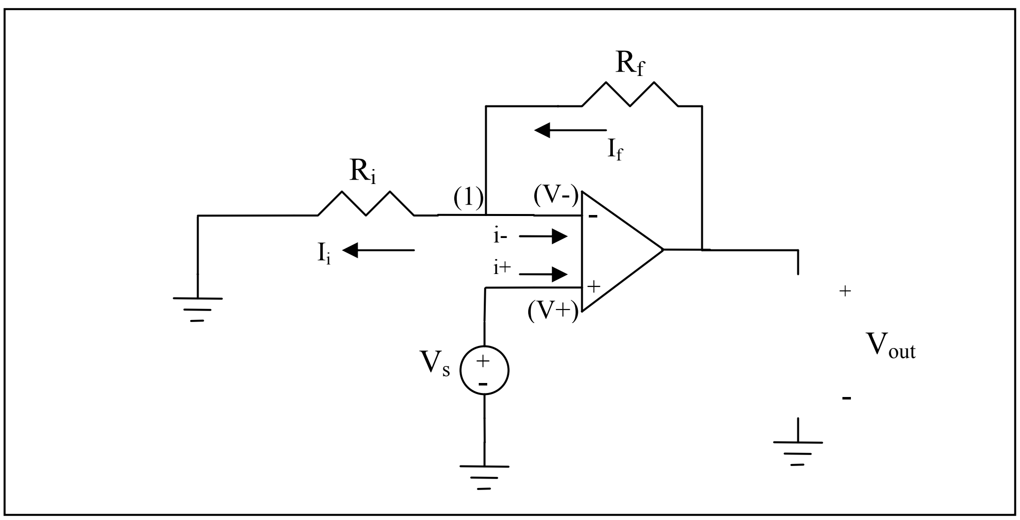


Figure 6. KCL and op-amps

The number (1) indicates the main node of significance. At this node, a current is assumed to leave the inverting terminal (V-) of the op-amp and go through R_i to ground. Another current is assumed to feed from the output back to the inverting input through resistor R_f. The third current (i-) feeds into the inverting terminal, but i- always equals zero. In fact, there are two important assumptions that concern op-amps when it comes to KCL circuit analysis:

Two very important assumptions:

1) $i- = i+ = 0$

2) $V+ = V-$

In Figure 6, i- equals zero, so If equals Ii. The voltage drops are across the resistor, so the voltage value of the side to which the current is flowing is subtracted from the side that the current is coming from (or the side of higher potential). See the equations below:

$$I_f = I_i$$

$$\frac{V_{out} - V-}{R_f} = \frac{(V-) - Gnd}{R_i}$$

The voltage source is connected directly to V+, so V+ = V_s = V- , and Gnd always equals zero.

$$\frac{V_{out} - V_s}{R_f} = \frac{V_s}{R_i}$$

$$V_{out} - V_s = V_s \frac{R_f}{R_i}$$

$$\frac{V_{out}}{V_s} - \frac{V_s}{V_s} = \frac{R_f}{R_i} \quad \Rightarrow \quad \frac{V_{out}}{V_s} = 1 + \frac{R_f}{R_i}$$

Simplifying further, we have determined the output voltage (Vout) to input voltage source (Vs) relationship. Op-amps can be accurately described by simply recognizing that i+ = i- = 0, and V+ = V- , and then correctly applying KCL. More examples of KCL circuit analysis are found in the pages ahead.

1.3. Input/Output Impedance

Two positive aspects of operational amplifiers are that they have a very high input impedance and a very low output impedance. A high input impedance is a good thing because the surrounding circuit in which the op-amp is a part sees the op-amp as having a large resistance, so nearly all of the voltage will be dropped across it, instead of, for example, it being dropped across the internal resistance of a preceding source. In relation, a low output impedance is like having a low internal resistance, so all of the output voltage leaving the op-amp will be dropped across the subsequent circuitry or load and not very much of it will be lost across the internal resistance of the op-amp. A reasonable output impedance value could be between 0-100 Ω, while an input impedance could be around 1 MΩ. [1,2]

The figure below illustrates the benefits of a high input impedance and a low output impedance by introducing an op-amp circuit called a voltage follower which will be revisited again later in the tutorial.

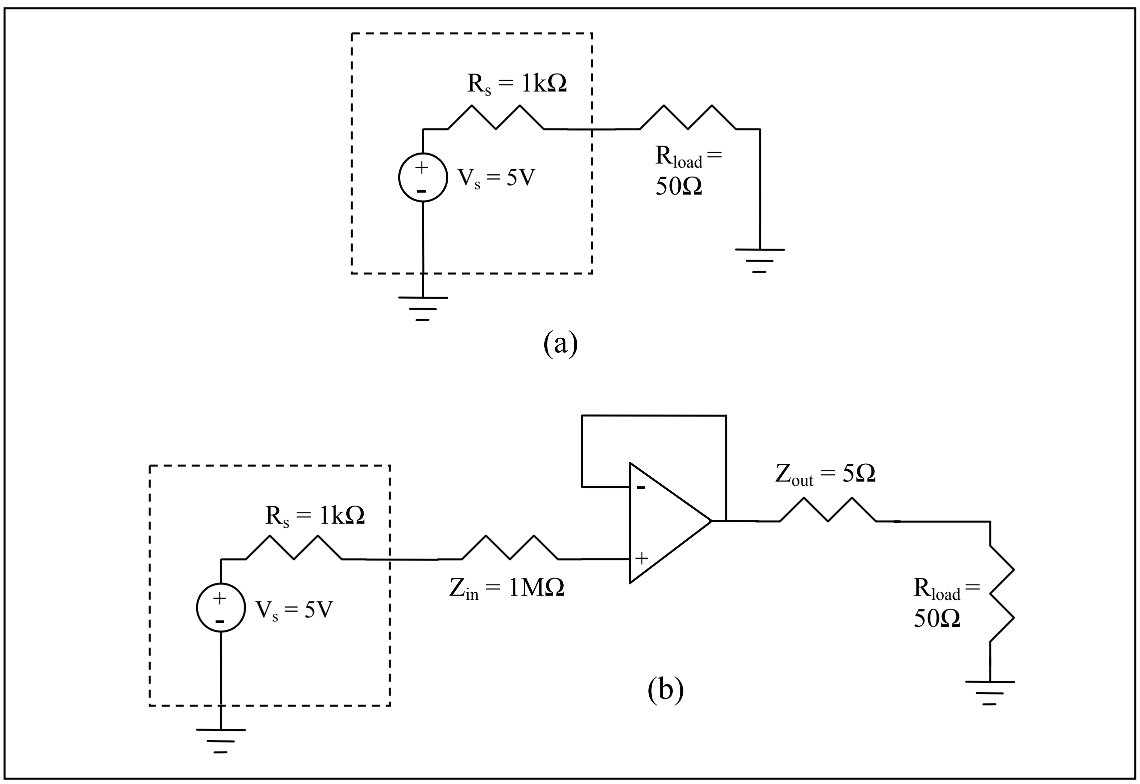


Figure 7. A simple voltage source and load with and without an op-amp voltage follower [1]

Example

Figure 7(a) shows a voltage source (5V) with an internal resistance (1kΩ) that is powering a load (50Ω). Using the voltage divider formula,

$$\left(\frac{50}{50+1k}\right)5V = 0.238V\ ,$$

only 0.238V actually gets dropped across the load while most of the voltage is dropped across the internal resistance (R_s). This is a waste of useable load voltage.

Now consider Figure 7(b) in which an op-amp is introduced with a high input impedance (Z_{in}) and low output impedance (Z_{out}). (Normally, input and output impedances are not represented this way.) The voltage source sees the high input impedance of the op-amp, so most of the voltage is dropped across this impedance rather than across the internal resistance of the source (R_s).

$$\left(\frac{1M\Omega}{1M\Omega + 1k\Omega}\right)5V = 4.995V$$

Now the op-amp acts as the source, so

$$\left(\frac{50}{50 + 5}\right)4.995V = 4.541V$$

Because of the op-amp, the load now drops a voltage of 4.541V, instead of a mere 0.238V. [1]

1.4. Supply voltages

Looking at the op-amp symbol, the V+supply and V-supply terminals are the dc supply voltages. The output of the op-amp is influenced by these supply voltages in three ways. First of all, even if the supply voltages are +10V, the output will never span the 20V range (+10V → -10V). Rather, depending on the resistance of the load that the op-amp is powering, the output will be 1V-2V shy of the supply voltage span. If the resistance of the load is greater than 10k then the output would max out between +9V and -9V, assuming the listed supply voltages are +10V. Otherwise, if the resistance of the load is between 2kΩ and 10kΩ then the output would max out between +8V and -8V, and even much less of a span for resistances of the load lower than 2kΩ. See the following two examples:

Example 1

Supply voltages = ±10V; resistance of the load = 20kΩ

<u>*Solution*</u>

Resistance of load > 10kΩ, so the output is ±9V

Example 2

Supply voltages = 12V and ground; resistance of the load = 5kΩ

Solution
2kΩ < Resistance of load < 10kΩ, so the output is 2V to 10V.

Second, the supply voltages are not always of the same value and of opposite polarity (i.e. + 5V). Instead, the max value could be +10V while the low value could be 0V (or grounded) and vice versa, similar to Example 2 above.

Finally, the output signal is clipped if it spans a larger voltage range than the supply voltages provide. For example, the output signal might have the potential to oscillate from -10V to +10V, but if the supply voltages are -5V and +5V, then the output will be clipped with a maximum value near +5V and a minimum value near -5V. [1-3]

1.5. Open/Closed Loop Gain, Positive/Negative Feedback

An especially notable characteristic of operational amplifiers is the very high gain achieved at the output. In general, gain is calculated as

$$V_{gain} = V_{out}/V_{in},$$

a ratio of the output voltage to the input voltage. An op-amp amplifies the difference between one input and the other, while neither individual input is itself amplified. The output is positive if the non-inverting input is more positive than the inverting input, and negative if the inverting input is more positive than the non-inverting input. The gain value of an op-amp can be as high as 200,000 when there is no physical connection between the output and either of the inputs. This is called open loop gain. However, if there is a connection between the output and the input, usually through a resistor, then a feedback network has been established, and the gain is now a closed loop gain. [1-4]

Contradiction?
KCL analysis strongly maintains that V+ = V- for any op-amp. Then, we are told that the difference between V+ and V- is what is amplified. Which is it? Are they equal or are they slightly different? In fact, both statements are true. *Internal* to the op-amp circuitry, V+ does equal V-, but *externally* the op-amp functions as a black box and amplifies the difference between the terminals.

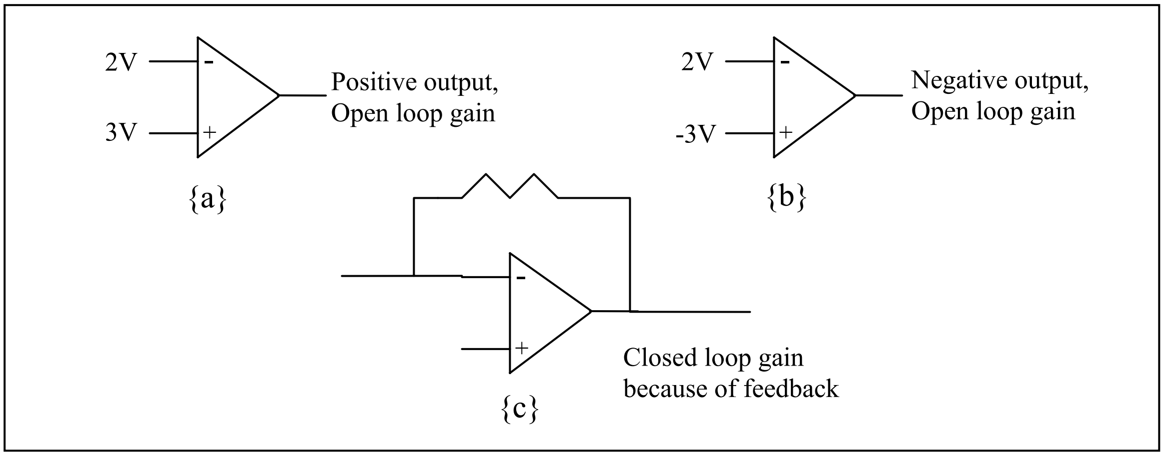


Figure 8. Gain and open/closed loops [2]

The feedback is either negative or positive, but usually negative feedback is used. Positive feedback occurs when some of the output feeds the input in a way that boosts the input value. Negative feedback exists when some of the output returns to the input, but it acts contrary to the input, in that it is of opposite polarity, and so diminishes the value of the input. When this input value is diminished then the difference between the inputs is also diminished. So, the voltage gain of a closed loop op-amp due to negative feedback is less than that of the open-loop gain. However, it is very helpful that the gain can now be calculated according to the resistors involved, whereas open loop gain cannot be easily calculated this way. Also, the bandwidth of the op-amp containing negative feedback is increased for both inverting and non-inverting amplifiers. Both of these types of amplifiers will be further discussed in the pages ahead. [1-4]

1.6. Frequency Response

The frequency response of the op-amp is pretty straight forward. Basically, as the operating frequency of the op-amp increases, the voltage gain decreases. Actually, it is only after the cutoff frequency is reached that the attenuation of voltage gain starts happening. The cutoff frequency is defined as the frequency at which the open loop gain equals 70.7% of its maximum gain, or, equivalently, down 3 dB from the maximum gain. All frequencies lower than the cutoff frequency, even 0 Hz, see the max gain because the op-amp is a dc amplifier. Gain bandwidth product is a simple formula that relates closed loop gain (Acl), bandwidth (cutoff frequency, fco), and unity-gain frequency, as such:

$$f_{unity} = (A_{cl})(f_{co})$$

Unity-gain frequency is the maximum frequency possible where the gain equals 1. Remember that a closed loop lowers the voltage gain, yet by lowering the voltage gain, higher operating frequencies are made available. So, depending on what is needed for the job, a certain degree of flexibility is available. A high gain, low frequency (or bandwidth) arrangement is possible, as is a low gain, high bandwidth configuration, as long as their product equals the unity-gain frequency. [1,2] See the figure below to better understand op-amp frequency response.

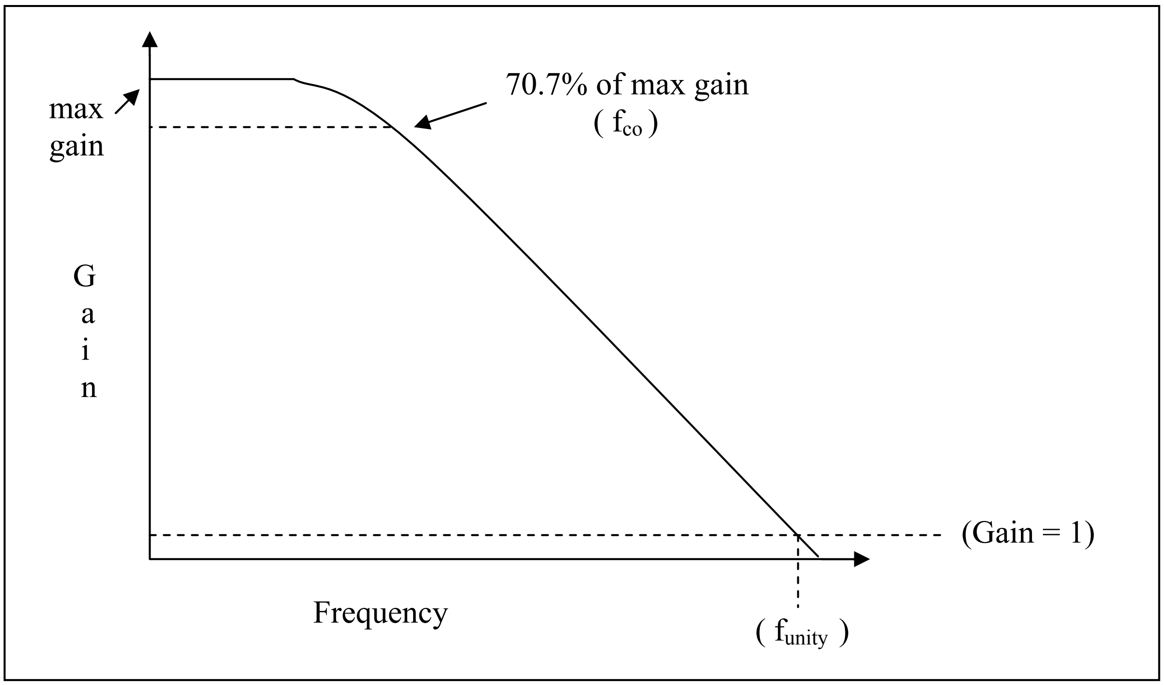


Figure 9. Gain and Frequency [1,2]

1.7. Basic Op-Amp Circuits

1.7.1. Inverting amplifier

The inverting amplifier makes use of negative feedback to the negative input terminal. The negative terminal also receives the source signal which is inverted at the output. Consider the circuit in Figure 10 (arrows indicate assumed current flow):

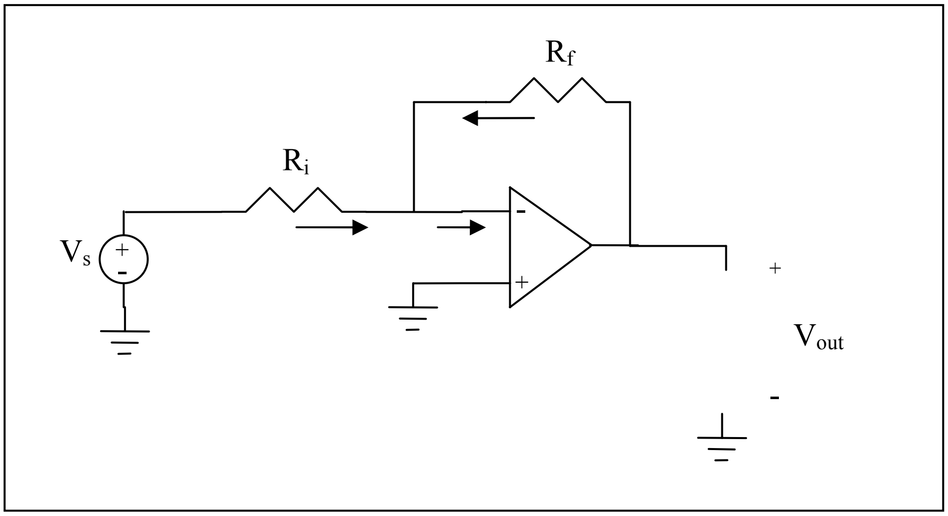


Figure 10 Inverting amplifier

Using KCL, the characteristics of the inverting amplifier can be described.

First, remember that V+ = V- , and that i+ = i- = 0

$$\frac{V_{out} - V-}{R_f} + \frac{V_s - V-}{R_i} = 0$$

Note: V- equals zero because V- = V+ = 0

$$\frac{V_{out}}{R_f} + \frac{V_s}{R_i} = 0 \quad \Rightarrow \quad \frac{V_{out}}{R_f} = \frac{-V_s}{R_i}$$

$$V_{out} = \frac{-V_s}{R_i} R_f = -Vs \frac{R_f}{R_i} \quad \Rightarrow \quad \frac{V_{out}}{V_s} = -\frac{R_f}{R_i}$$

1.7.2. Non-inverting amplifier

The non-inverting amplifier is very similar to the inverting amplifier except the signal is present at the non-inverting input and the output is of the same polarity as the input (i.e. the signal is not inverted).

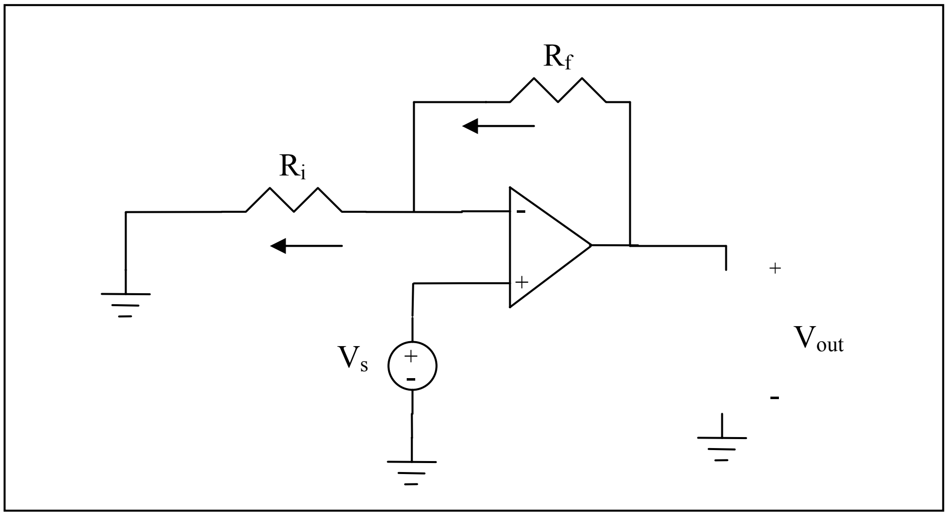


Figure 11 Non-inverting amplifier

Using KCL, the output can be related to the input and the resistors R_f and R_i.

Again, V+ = V- and i+ = i- = 0

$$\frac{V_{out} - V-}{R_f} = \frac{(V-) - Gnd}{R_i}$$

Note: V- = V+ = V_s, and Gnd always equals 0.

$$\frac{V_{out} - V_s}{R_f} = \frac{V_s}{R_i} \quad \Rightarrow \quad V_{out} - V_s = V_s \frac{R_f}{R_i}$$

$$\frac{V_{out}}{V_s} - \frac{V_s}{V_s} = \frac{R_f}{R_i} \quad \Rightarrow \quad \frac{V_{out}}{V_s} = 1 + \frac{R_f}{R_i}$$

1.7.3. Comparator

A comparator is a device that can be used to compare an input voltage to a reference voltage. The circuitry for comparators can vary in design and thereby vary in results. This configuration uses a voltage divider to create the reference voltage. [2]

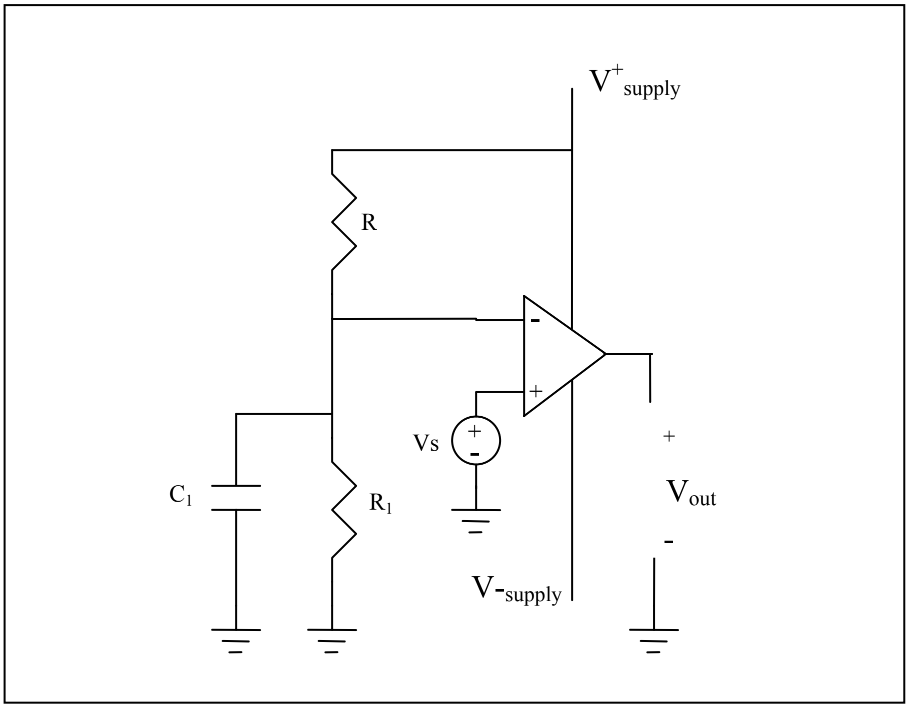


Figure 12 Comparator [2]

The inverting terminal of the op-amp is set at the reference voltage, which is:

$$\frac{R_1}{R+R_1}\left(V^{+}_{\sup ply}\right) = \text{ reference voltage}$$

When the input signal (V_s) at the non-inverting input is greater than the reference voltage at the inverting input then V_{out} will equal the positive supply (V^{+}_{supply}). Similarly, when V_s is less than the reference voltage, then V_{out} will equal the negative supply ($V-_{supply}$). $V-_{supply}$ could be grounded, in which case V_{out} would be 0V whenever V_s is less than the reference voltage. Since there is no negative feedback in this circuit, KCL cannot be used to describe the characteristics of the comparator. [2]

1.7.4. Voltage follower

Addressed earlier in the discussion on input and output impedance, the voltage follower (or buffer) is an op-amp circuit that has its inverting input connected directly to the output without a feedback resistor. Since the input always equals the output, the gain of a voltage follower equals one.

$$V_{gain} = \frac{V_{out}}{V_{in}} \quad (V_{out} = V_{in}, \text{ so gain is 1})$$

See Figure 13 and the following KCL analysis.

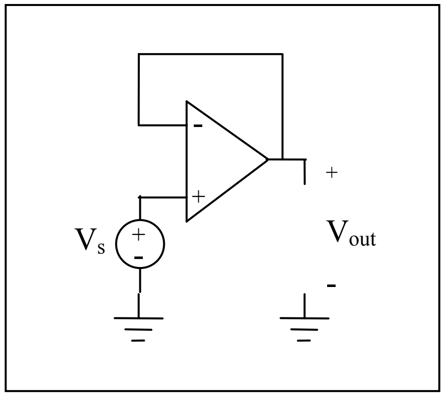


Figure 13 Voltage follower

Again, V+ = V-, and in this case V+ also equals the voltage source (V_s). Furthermore, the output (V_{out}) is equal to V-.

$$V- = V_{out}, \text{ and } V+ = V_s, \text{ therefore, } V_s = V_{out}$$

$$\frac{V_{out}}{V_s} = 1$$

The benefit of using a voltage follower is the high input impedance and low output impedance of the op-amp that allows almost all of the voltage from a previous source to be dropped across it. The op-amp can, in turn, feed the rest of the circuit with the higher desired voltage. See the section on input/output impedance for clarification. [1]

Chapter 2

2. Op-amp Circuits

2.1. Derived Op-Amp Circuits

2.1.1. Summation amplifier

The summation amplifier is an easily understood op-amp circuit that sums each of the inputs according the inverting amplifier output formula. In fact, the summation amplifier is very closely derived from the inverting amplifier. Only, instead of having a single voltage source (V_s) and resistor (R_i), multiple sources converge on the inverting input (V-), each having its own resistor (R_i). See the circuit below.

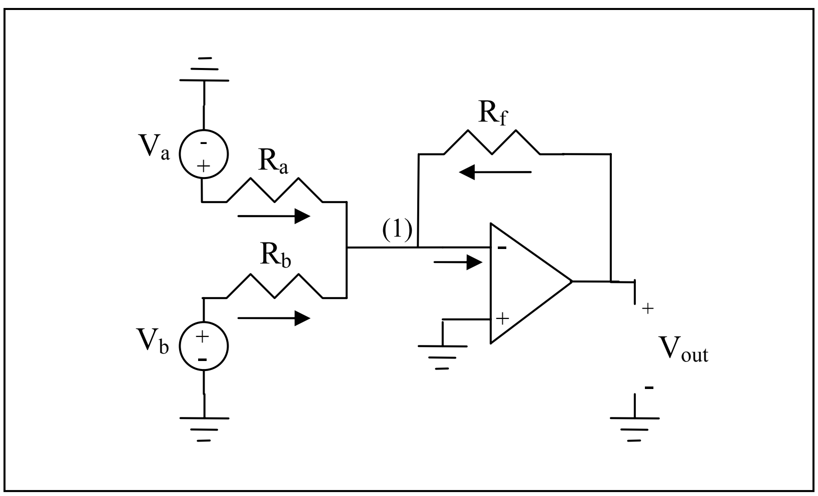


Figure 14 Summation amplifier [2]

KCL analysis for the summation amplifier goes like this at node (1):

$$I_{Ra} + I_{Rb} + I_{Rf} = i- = 0$$

$$\frac{V_a - V-}{R_a} + \frac{V_b - V-}{R_b} + \frac{V_{out} - V-}{R_f} = 0$$

V+ = 0 = V- , so

$$\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_{out}}{R_f} = 0$$

Output formula for summation amplifier ➔ $V_{out} = -R_f\left(\frac{V_a}{R_a} + \frac{V_b}{R_b}\right)$

This formula can be seen as simply adding together the outputs of multiple inverting amplifiers. To illustrate this point, it can be rewritten as:

$$V_{out} = -V_a\frac{R_f}{R_a} + (-V_b)\frac{R_f}{R_b}$$

Regardless of how it is written, this formula is good for input voltage sources with different values of R_a and R_b, as well as for cases where $R_a = R_b$. However, if $R_a = R_b = R_f$, then the output formula clearly becomes

$$V_{out} = -(V_a + V_b)$$

In this case, the summing amplifier is actually adding together the input voltage sources. Finally, note that the summation amplifier can sum as many input voltage sources as desired. [1,2]

2.1.2. Integration

The subject of calculus involves exercises in differentiation and integration of which most students struggle in varying degrees to understand. Well, the amazing versatility and value of the op-amp can be seen in its ability to perform integration and differentiation. Integrators and differentiators, as they are called, are very similar and their circuits are simple to draw. The use of a capacitor is what makes the complex mathematical process possible. Consider the integrator circuit of Figure 15:

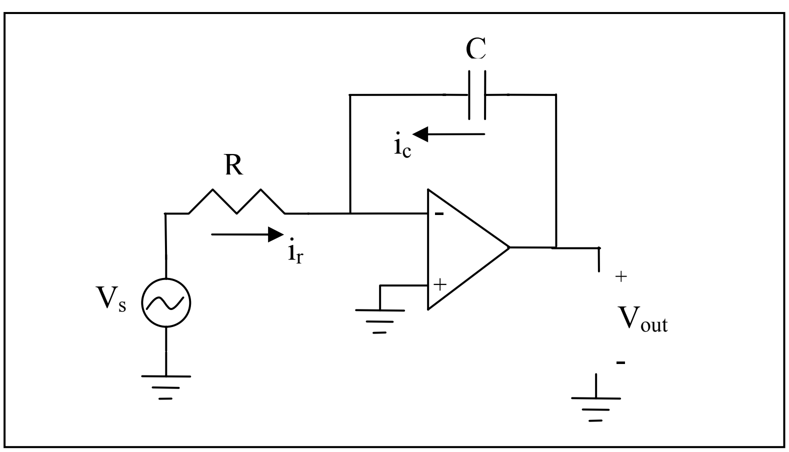


Figure 15 Integrator circuit

KCL analysis for the integrator can be accomplished by introducing the following formula for the current through the capacitor:

$$i_c = C\left(\frac{dV_c}{dt}\right)$$

The current flowing through the capacitor fluctuates as time passes, so the above formula is necessary to describe it. The KCL analysis looks like this:

$$i_r + i_c = 0$$

$$\frac{V_s - V-}{R} + C\frac{dV_c}{dt} = 0$$

V_c is the voltage across the capacitor, so $V_c = V_{out} - V-$, and

$$\frac{V_s - V-}{R} + C\frac{d(V_{out} - V-)}{dt} = 0$$

V- = 0, so

$$\frac{V_s}{R} + C\frac{dV_{out}}{dt} = 0$$

$$\frac{dV_{out}}{dt} = -\frac{1}{RC}V_s \quad \Rightarrow \quad V_{out} = -\frac{1}{RC}\int_{t_1}^{t_2} V_s dt$$

2.1.3. Differentiation

Differentiation is the counterpart to integration and by simply switching the location of the resistor (R) and capacitor (C), a differentiator circuit can be formed.

Since a capacitor does not allow dc current to pass through it, the voltage sources associated with the integrator and differentiator circuits are ac sources. See the circuit below.

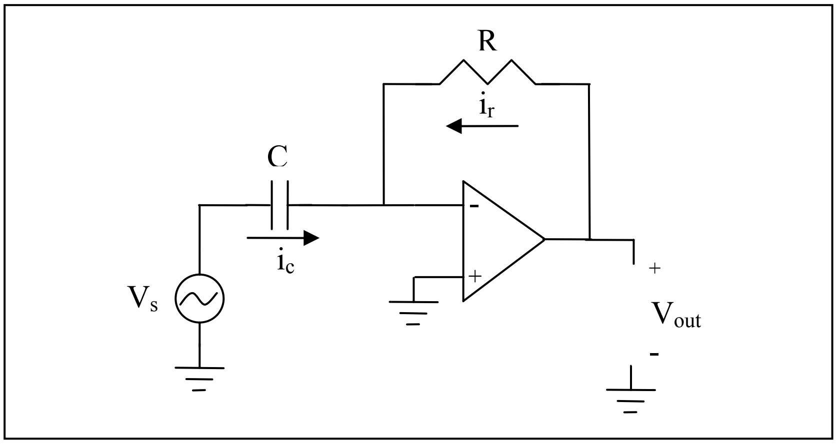


Figure 16 Differentiator circuit

The KCL analysis for a differentiator is naturally similar to the analysis of the integrator.

Once again, $i_c = C\left(\frac{dV_c}{dt}\right)$

$$i_r + i_c = 0$$

$$\frac{V_{out} - V-}{R} + C\frac{dV_c}{dt} = 0$$

V- = 0 and Vc = Vs – V-, so

$$\frac{V_{out}}{R} + C\frac{dV_s}{dt} = 0 \quad \Rightarrow \quad V_{out} = -RC\frac{dV_s}{dt}$$

2.1.4. Differential amplifier

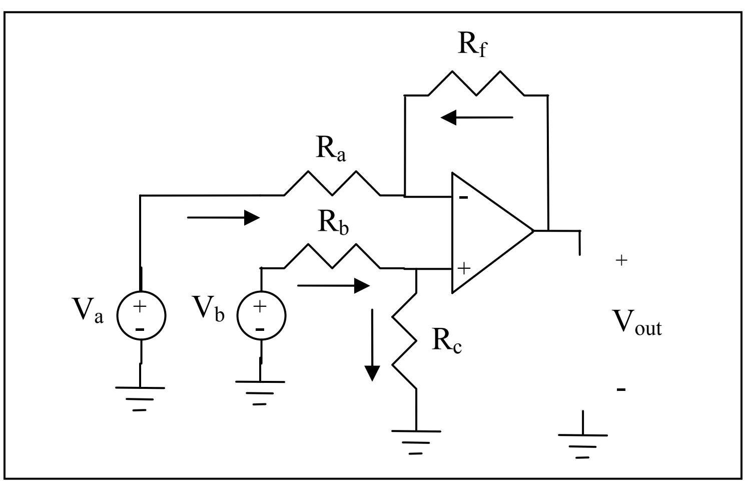


Figure 17 Differential amplifier [6]

The differential amplifier in the above figure can be analyzed according to KCL rules. Then, in order to demonstrate one of the more common concepts of a differential amplifier, the resistors will be related to each other as follows:

$$\frac{R_f}{R_a} = \frac{R_c}{R_b} = x$$

[6]

The two nodal equations are,

$$(1) \quad \frac{V_b - V+}{R_b} = \frac{V+}{R_c} \qquad \text{and} \qquad (2) \quad \frac{V_a - V-}{R_a} + \frac{V_{out} - V-}{R_f} = 0$$

Solve the first equation for V+, and solve the second equation (2) for V_{out} ,

$$V+ = \frac{V_b R_c}{R_b + R_c} \qquad \text{and} \qquad V_{out} = (V+)\left(1 + \frac{R_f}{R_a}\right) - V_a \frac{R_f}{R_a}$$

Insert the V+ equivalent into the equation for V_{out} ,

$$V_{out} = \frac{V_b R_c}{R_b + R_c}\left(1 + \frac{R_f}{R_a}\right) - V_a \frac{R_f}{R_a}$$

As previously mentioned, make R_c=R_b(x) , and R_f/R_a = x ,

$$V_{out} = \frac{V_b (R_b x)}{R_b + R_b x}(1 + x) - V_a(x) \quad \Rightarrow \quad V_{out} = V_b \frac{x}{(1 + x)}(1 + x) - V_a(x)$$

$$V_{out} = x(V_b - V_a)$$

With this differential amplifier, the difference between V_b and V_a is amplified by a gain of x. [6]

2.2. Applied Op-Amp Circuits

2.2.1. Audio amplifier

The audio amplifier below is composed of a transistor sector and an op-amp sector. Consider first the transistor whose collector voltage feeds the inverting input of the op-amp.

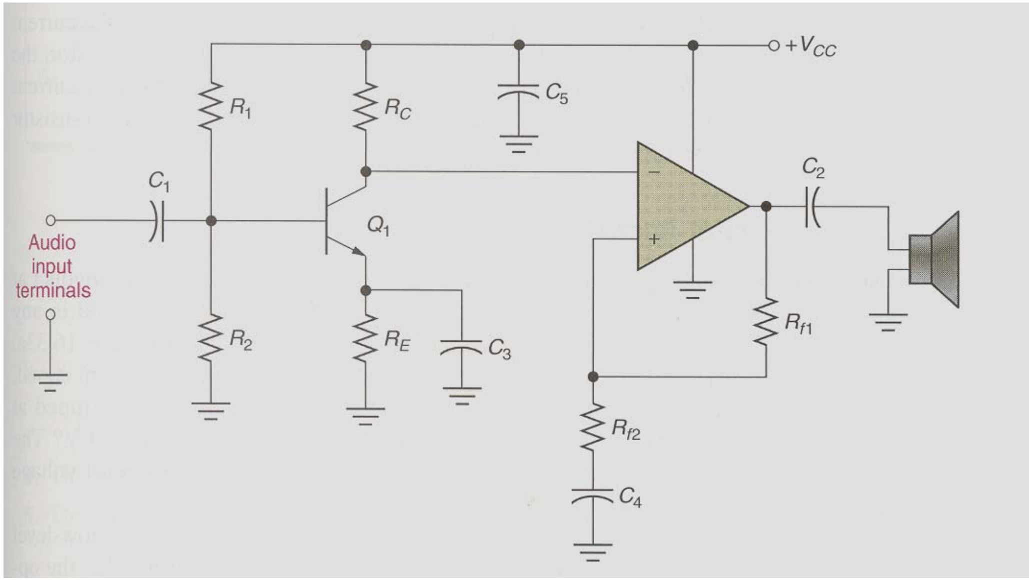


Figure 18 Audio amplifier [2]

The base of transistor Q_1 is biased with a voltage divider as follows:

$$\frac{R_2}{R_1 + R_2}\left(+V_{CC}\right) = V_{base}$$

The emitter voltage ($V_{emitter}$) is only a diode drop less than the base voltage V_{base} .

$$V_{emitter} = V_{base} - 0.7$$

The current through the emitter ($I_{emitter}$) is:

$$I_{emitter} = V_{emitter} / R_E \qquad \text{and} \qquad I_{emitter} \approx I_{collector}$$

The voltage of the collector ($V_{collector}$) is:

$$V_{collector} = +V_{CC} - V_{R_C} \qquad \text{and} \qquad V_{R_C} = \left(I_{collector}\right)\left(R_C\right)$$

The collector voltage ($V_{collector}$) feeds the inverting input of the op-amp, which is the second sector of the audio amplifier. KCL analysis of the op-amp proceeds as usual, assuming V+ = V- = $V_{collector}$, and i+ = i- = 0.

$$\frac{V_{out} - V+}{R_{f1}} = \frac{V+}{R_{f2}}$$

Solving for V_{out} and substituting $V_{collector}$ for V+, we get:

$$V_{out} = V_{collector}\left(\frac{R_{f1}}{R_{f2}} + 1\right) \qquad [1,2]$$

The advantage of using an audio amplifier that contains an op-amp is the expected high input impedance and low output impedance. Also, both the transistor amplifier and the op-amp work together in the amplification process to achieve a high gain. [2]

2.2.2. Instrumentation amplifier

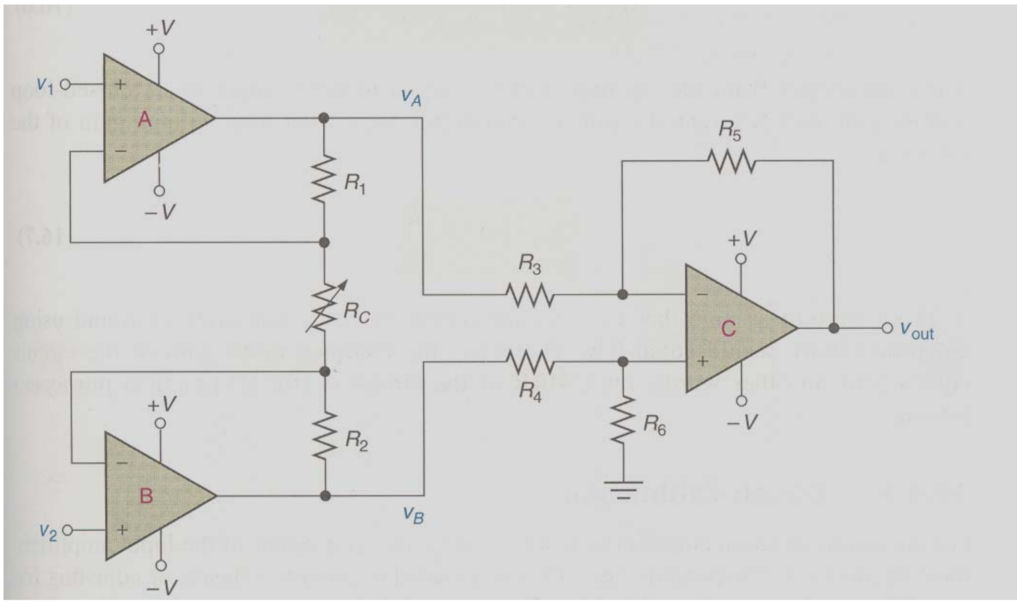


Figure 19 Instrumentation amplifier [2]

Instrumentation amplifiers are a combination of three op-amps that are typically grouped into two stages. The first two op-amps comprise the first stage and each is a non-inverting amplifier. The second stage is a differential amplifier that may or may not have unity gain. An instrumentation amplifier is beneficial for several reasons:

1. high input impedance, unlike the lower input impedance of a differential amplifier by itself
2. high CMRR (see the pages ahead for a better understanding of CMRR); the source internal resistances of v_1 and v_2 do not affect the total resistance on each input arm
3. good for smaller, insignificant input signals
4. gain of the non-inverting amplifiers (first stage) can be varied by the rheostat (R_C). [1-3]

Now consider the KCL analysis for the first stage of the instrumentation amplifier. It is helpful to redraw op-amps A and B and their corresponding circuitry for analysis.

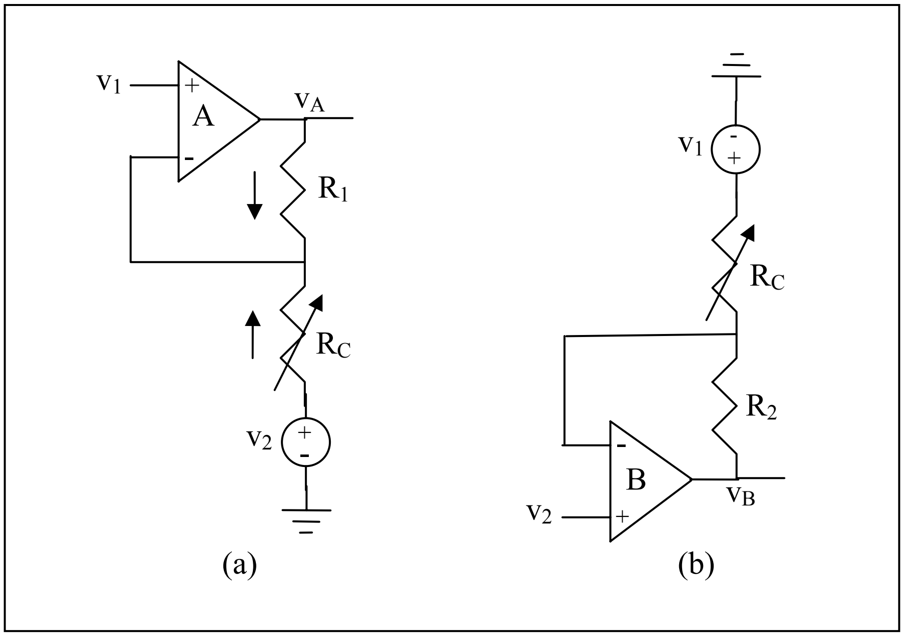


Figure 20 First stage of instrumentation amplifier redrawn for each op-amp

The KCL for op-amp A is as follows:

$$\frac{v_A - v_1}{R_1} + \frac{v_2 - v_1}{R_C} = 0$$

Solve for v_A,

$$v_A = v_1\left(1 + \frac{R_1}{R_C}\right) - \left(\frac{R_1}{R_C}\right)v_2$$

The KCL for op-amp B is as follows:

$$\frac{v_B - v_2}{R_2} + \frac{v_1 - v_2}{R_C} = 0$$

Solve for v_B,

$$v_B = v_2\left(1 + \frac{R_2}{R_C}\right) - v_1\left(\frac{R_2}{R_C}\right)$$

The values v_A and v_B are the two inputs into the differential amplifier. Refer back to the analysis of the differential amplifier and see that the output is one input minus the other, and this difference is multiplied by x, which is the gain. In the case of the instrumentation amplifier, the output is (v_A - v_B) if the differential amplifier has unity gain, or x($v_A - v_B$) if it has gain.

Either way, $v_A - v_B$ equals:

$$\left[v_1\left(1+\frac{R_1}{R_C}\right)-\left(\frac{R_1}{R_C}\right)v_2\right]-\left[v_2\left(1+\frac{R_2}{R_C}\right)-v_1\left(\frac{R_2}{R_C}\right)\right]$$

which equals,

$$v_1+v_1\frac{R_1}{R_C}-\frac{R_1}{R_C}v_2-v_2-\frac{R_2}{R_C}v_2+\frac{R_2}{R_C}v_1 \Rightarrow v1\left(1+\frac{R1}{RC}+\frac{R2}{RC}\right)-v2\left(1+\frac{R1}{RC}+\frac{R2}{RC}\right) \Rightarrow$$

$$\left(1+\frac{R_1}{R_C}+\frac{R_2}{R_C}\right)(v_1-v_2)$$

If R1 = R2, then $v_A-v_B=\left(1+\frac{2R}{R_C}\right)(v_1-v_2)$

Notice that the first stage has a gain of $\left(1+\frac{2R}{R_C}\right)$.

If the differential amplifier has a gain value (x), then the final output would be the product of the two gains multiplied by the difference between the two input voltages, or

$$\text{Final output} = (x)\left(1+\frac{2R}{R_C}\right)(v_1-v_2)$$

[1-3]

2.2.3. Precision full-wave rectifier

The precision full-wave rectifier receives an ac signal and produces a fully rectified output. The second op-amp (2) is a summation op-amp, and the first (1) is an inverting amplifier with two diodes (D_1 and D_2), which make the rectification possible. The first op-amp inverts the signal but does not amplify it.

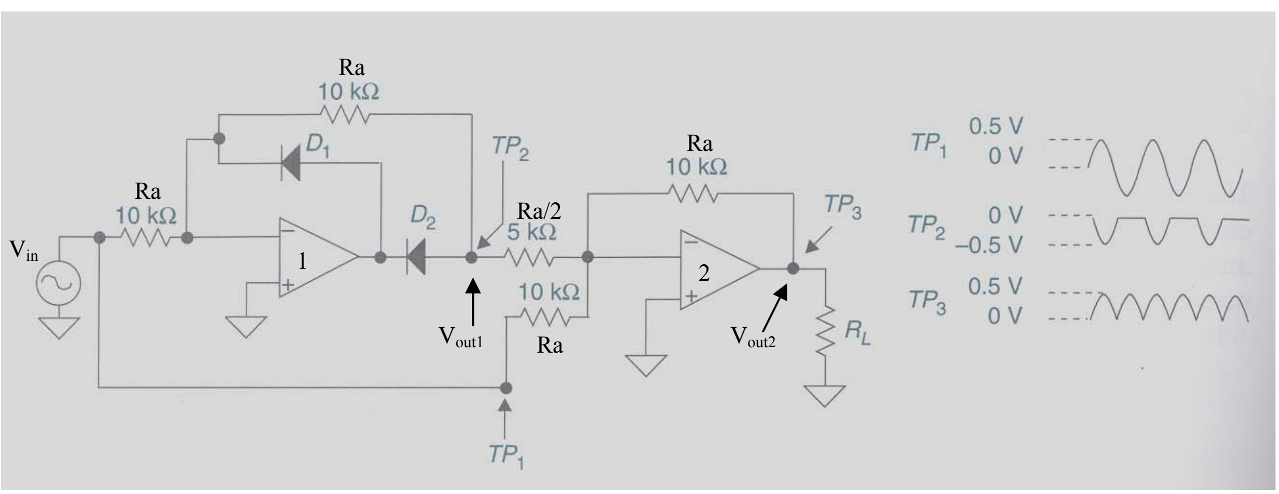


Figure 21 Precision rectifier (full-wave) [1]

The two conditions possible are a positive or negative alternation. On the positive alternation, the op-amp inverts the signal, producing a negative value that conducts through D_2 and the feedback loop. The output (V_{out1}) is –Vin. On the negative alternation, the op-amp again inverts the signal, and this time produces a positive value that does not conduct through D_2, so the output is zero. Instead, the positive signal feeds D_1 to avoid saturation. Using an op-amp along with diodes for rectification is an asset because without the op-amp, the typical 0.7V drop across a diode has to be taken into account. So, a small signal like 0.5V would not be rectified because the diode needs at least 0.7V to conduct. [1,3]

The KCL analysis for each op-amp in the precision full-wave rectifier is detailed below:

<u>Op-amp 1</u>

Positive alternation

$$\frac{V_{in} - V-}{R_a} + \frac{V_{out1} - V-}{R_a} = 0 \quad \Rightarrow \quad V_{out1} = -V_{in} \qquad \text{note: } V- = V+ = 0$$

Negative alternation: $V_{out1} = 0$

<u>Op-amp 2</u>

Positive alternation

$$\frac{-V_{in} - V-}{R_a/2} + \frac{V_{in} - V-}{R_a} + \frac{V_{out2} - V-}{R_a} = 0 \quad \Rightarrow \quad V_{out2} = V_{in}$$

Negative alternation

$$\frac{0 - V-}{R_a/2} + \frac{V_{in} - V-}{R_a} + \frac{V_{out2} - V-}{R_a} = 0 \quad \Rightarrow \quad V_{out2} = -V_{in}$$

note: V_{in} is negative, so $-(-V_{in}) = V_{in}$

It is helpful to consider the waveforms given in the figure (TP_{1-3}). [1,3]

2.2.4. Voltage-to-Current converter

The concept of the voltage-to-current converter may seem quite radical at first because, in general, everyone agrees that if a resistance increases then the current naturally decreases (I=V/R).

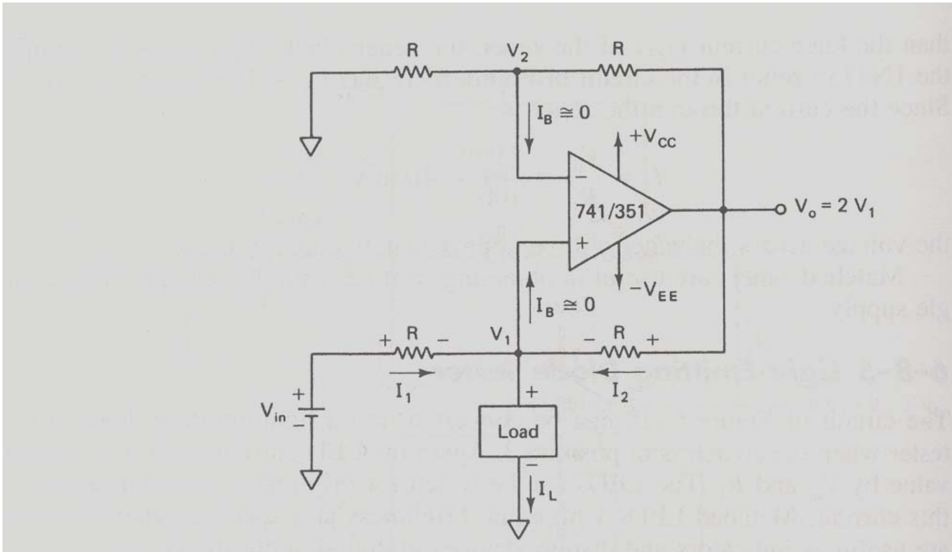


Figure 22 V-to-C converter [5]

But with the voltage to current converter, an increase or decrease in the load resistance has nothing to do with the amount of current flowing through it. The non-inverting input ($V+=V_1$ in the figure) will change with the load resistance, but the current through the load will change only according to V_{in} and/or R. See the KCL analysis below: [3,5]

$$\frac{V_{out} - V-}{R} = \frac{V-}{R} \quad \Rightarrow \quad V_{out} = 2V- = 2V+ = 2V_1$$

$$\frac{V_{in} - V+}{R} + \frac{V_{out} - V+}{R} = \frac{V+}{R_{load}}$$

Substituting 2V+ for V_{out} we get,

$$\frac{V_{in}}{R} = \frac{V+}{R_{load}} = I_{load}$$ [3,5]

Chapter 3

3. Op-Amp Practical Considerations

3.1. Input/Output Offset Voltage

Op-amps do not always perform practically as they should theoretically. For example, sometimes an output voltage exists when both inputs are grounded. This output voltage is called output offset voltage and it is caused by an input offset voltage. If one is known the other can be calculated,

$$V_{io} = \frac{V_{oo}}{A_v}$$

Imperfect transistors contained in the differential amplifier are responsible for the input offset voltage, which is usually no more than 2mV. The offset null pins on the IC op-amp can be used with a potentiometer to take care of V_{io} and V_{oo}. [1-3]

3.2. Input Bias Current / Input Offset Current

Similar to the offset voltages, there are currents flowing in or out of the inputs, and their average is known as input bias current, which may have a value of 80nA+. The currents on each input are not always equal and the difference between them is the input offset current. This is important because if the input bias currents are different, then the output voltage can be affected. So to keep the currents the same, each input needs to see the same resistance to ground, since identical currents will flow through identical resistances. [1-4]

3.3. Common Mode Rejection Ratio (CMRR)

The common mode rejection ratio (CMRR) is a ratio of the normal high gain that amplifies the difference of the signals on the inputs to the undesirable gain that amplifies a value when the signals are the same.

$$\text{CMRR} = A_{diff}/A_{cm}$$

If op-amps were perfect, then there would be zero amplification when the same signal, or common-mode signal, feeds each input. The common-mode signal may be noise, so obviously it is not a good thing to amplify this noise. An acceptable CMRR is in the 90's (dB), where

$$CMRR = 20 \log (A_{diff}/A_{cm}) \qquad \text{\{in decibels (dB)\}}$$

Still, the differential gain of an op-amp is much greater than the common-mode gain. See example,

> ***Example***
> To attain a CMRR of about 96dB, A_{diff} = 500, and A_{cm} = .008,
> *Solution*
> CMRR = 20 log (500/.008) = 95.9 dB

[1,2,4]

3.4. Output Short-Circuit Current

Op-amps do not output unlimited current because too much current flow could be damaging to the op-amp, particularly if a short circuit develops. Op-amps are made this way on purpose. An output short-circuit current of 25mA is a common value for an op-amp. It follows that a low resistance load does not drop the expected voltage.

> ***Example***
> Suppose a 200Ω load normally draws exactly 25mA. The voltage drop is as expected: V=IR = (25mA)(200Ω) = 5V.
> The problem arises when the load is perhaps only 25Ω. In this case, the lower resistance would be expected to allow a greater current flow, but the output short-circuit current has been reached. So, instead,
> V=IR = (25mA)(25Ω) = 0.625V

[1-4]

Chapter 4

4. Op-amp Circuit Design

In this section, we will explore how three op-amps can be used to create a circuit that produces an alarm/siren according to the schematic shown below. This circuit is by no means an original circuit by design or analysis. However, it was constructed using Multisim8 as well as on a breadboard, and oscilloscope "quick prints" are included.

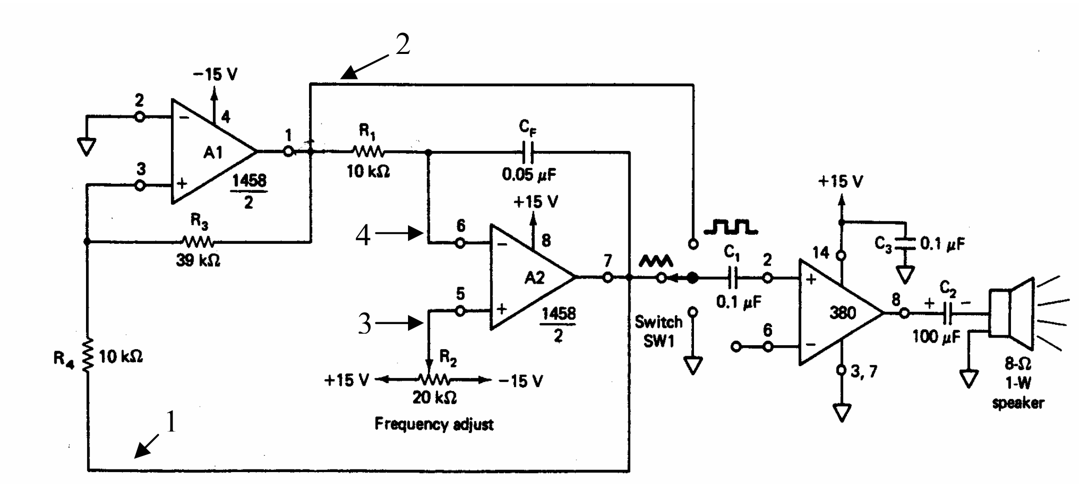


Figure 23 Siren schematic [5]

All three op-amps function in ways that have previously been mentioned or discussed.

<u>Op-amp 1 (A_1)</u>

The first op-amp is a *comparator* with a reference voltage of 0V (ground) at the inverting input. Either a triangular or a sawtooth wave from the output of A_2 is always feeding the non-inverting input of A_1. According to our previous discussion of comparators, if the input is more positive than the reference voltage then the output will be V^+_{supply}, and if the input is less than the reference voltage then the output will be $V-_{supply}$. So, when the triangular or sawtooth wave input rises above zero, the output will be V^+_{supply}, and when it falls back down below zero, the output is $V-_{supply}$. The result is a square wave, which is one of the input options to the third op-amp (labeled 380 in the schematic) as well as the input to the inverting input of A_2. [5]

<u>Op-amp 2 (A_2)</u>

The second op-amp is an *integrator* that holds to the output formula

$$V_{out} = \frac{-1}{RC} \int_{t1}^{t2} Vs \; dt$$

The non-inverting input is connected to a potentiometer, which when varied changes the output from a sawtooth wave that leans to the left to one that leans to the right. Within this transition naturally lies a triangular wave.

Op-amp 3 (380)

The third op-amp is an audio amplifier whose non-inverting input is fed by one of five different input categories:

1. square wave (but not always a perfect square wave)
2. sawtooth leaning to the left
3. triangular wave
4. sawtooth leaning to the right
5. ground (no output)

Multisim process and results

Once a project is chosen for experimentation and construction, the first step in the testing process is to assemble the components using a program called Multisim8. Multisim8 lets the user simulate the project by using virtual components that mimic their real-world counterparts. The program is especially useful if the project is an original design because the concept can be tested without having to purchase all of the components. If a component is damaged for any reason (maybe too much current), a new component is only a few “mouse clicks” away, so cost is minimized. The siren circuit is a previously designed and tested project, so gross design errors are improbable, but it is still good practice to achieve a functional simulation as part of the circuit design progression. Sometimes it is not possible to find the exact component in the Multisim8 component list, but usually a functional substitution can be found. For example, in the siren circuit, two 741 op-amps replaced the MC1458, and the LM380 amplifier was replaced by the MC33078D amplifier. Figure 24 shows the siren circuit assembled using Multisim8.

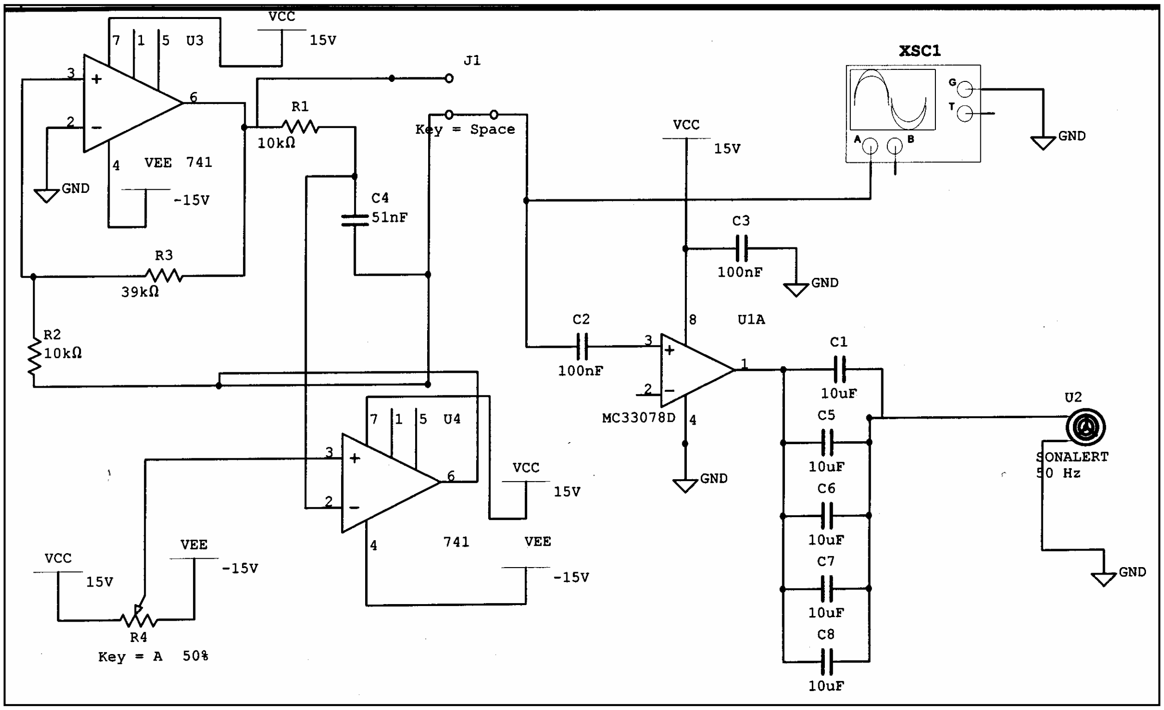
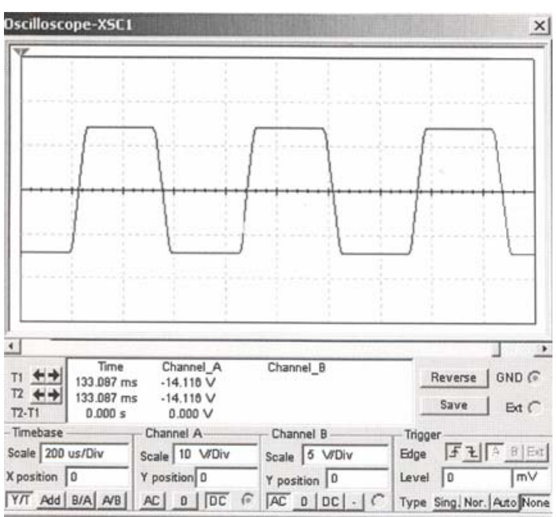
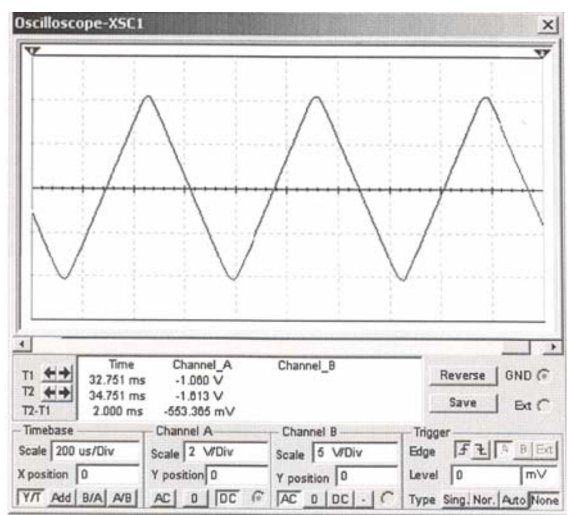


Figure 24 Siren circuit constructed using Multisim8

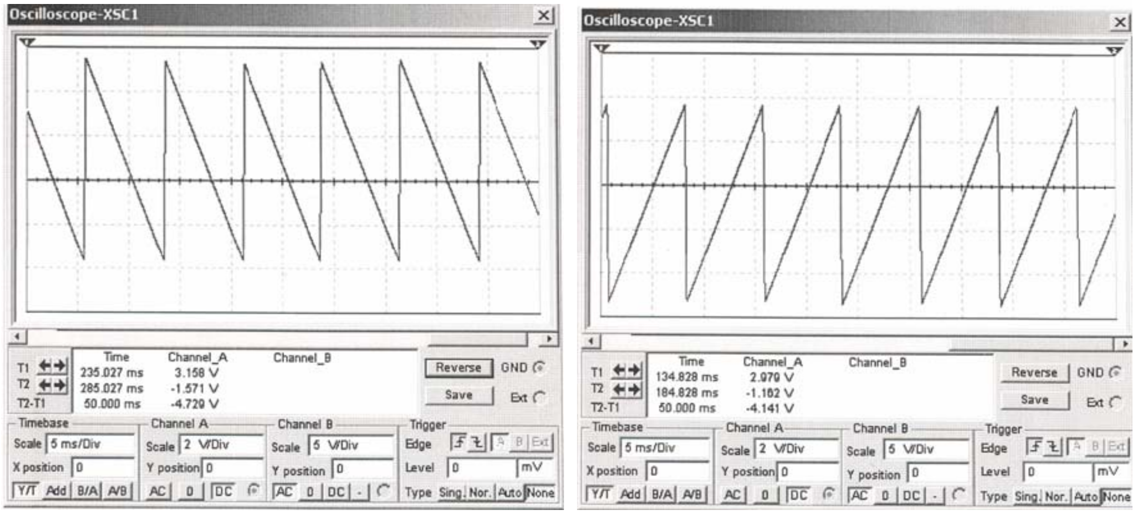
Notice that a virtual oscilloscope has been inserted at the input to the audio amplifier. It is possible to print the output of the instrument as is seen in Figure 25.



Square, R_4 at 50%



Triangular, R_4 at 50%



Sawtooth, R_4 at 5% Sawtooth, R_4 at 95%

Figure 25 Oscilloscope prints using Multisim8

Breadboarding process and results

The siren circuit was constructed on a breadboard and various oscilloscope prints were obtained at specific points throughout the circuit. Substitutions were made as needed for unavailable components, and it was necessary to focus on one op-amp stage at a time. Problems were encountered, but in the end the siren circuit functioned properly.

Substitutions

Because the listed op-amp integrated circuits were not readily available, two primary substitutions were made. First of all, the MC1458 dual op-amp was replaced by two separate 741 op-amps. Note that it is necessary to power *each* of these op-amps with their own $V^{+/-}$ supplies of +/-15V. The second substitution consisted of replacing the LM380 power audio amplifier with an LM386 low voltage audio power amplifier. Naturally, the pin numberings for the substituted ICs differ from those labeled in the figure. Also, the C_2 100uF capacitor was replaced with a 240uF capacitor (due to the IC substitution), and the speaker used had only a 0.1W rating. Finally, the inverting terminal of the LM386 was grounded.

Process

Life is good when the entire schematic, in terms of its components, is placed on the breadboard and the circuit functions as desired. However, more often than not, one will run into glitches and problems, and if the entire project is already breadboarded, it is difficult to know where to start troubleshooting. At this time, it is best to work with the individual sections or stages that make up the complete circuit. Such was the case with the siren. The following three steps led to a functional circuit:

1. Input a triangular wave from a function generator to the *comparator* (A_1) and achieve a square wave output.
2. Input a square wave from a function generator to the *integrator* (A_2) and achieve a triangular wave output.
3. Input a square wave and a triangular wave from a function generator to the *audio amplifier* and monitor the sound from the speaker.

Problems encountered

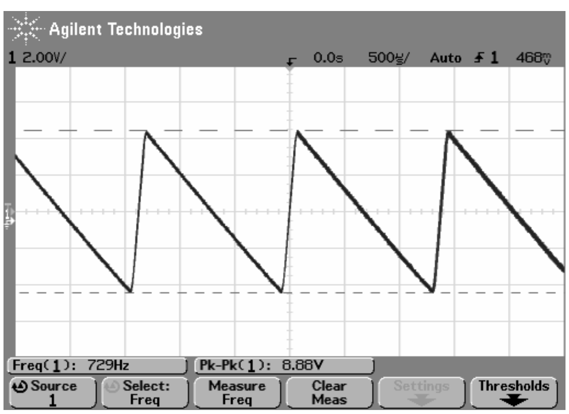
The comparator (A_1) functioned well when an artificial (from the function generator) triangular wave was fed to its non-inverting input. The output was the desired square wave. The integrator, however, did not perform well, and it was found that the chip was not functioning properly. The IC may have experienced improper voltages at one time or another, so it is important to remember to turn off the power supply any time wires or components are added to or taken away from the circuit. The third stage involved the audio amplifier. At first, a 10Ω resistor was used to simulate an 8Ω speaker, and an o-scope plotted the output, which was not a convincing wave shape. So, there was no audible sound to indicate proper performance. Once the speaker was added to the circuit the speaker resonated and the o-scope plotted a more likely wave shape. The problem was not the substitution of the resistor for the speaker; it was rather the method of measurement used, meaning it is important to apply the oscilloscope in parallel to the speaker (or resistor) and not in series with it. Finally, it is best to save o-scope files by using the "Quick Print" button rather than the "Save" button because the entire screen, including divisions, will be saved.

Oscilloscope prints

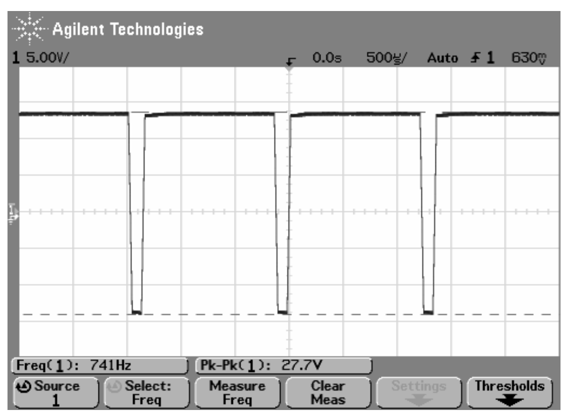
Multiple prints were made from the oscilloscope of the different waveforms found throughout the circuit at different potentiometer (R_2) settings. Notice that four points labeled 1-4 have been added to the figure along with their corresponding arrows. These four points represent where the o-scope readings were taken and will be referred to throughout this section. Point 1 is the output of A_2; point 2 is the output of A_1; point 3 is the non-inverting input value of A_2; and point 4 is the inverting input value of A_2. Note that point 3 will always have a dc value, and point 4 will sometimes have a dc value as well. R_2 was set at three different values and readings were taken at the four points for each pot value. The R_2 pot values were as follows:

- 1.05kΩ (a sawtooth wave leaning to the left); it was possible to obtain 0kΩ, but a signal was only present once 1.05kΩ was reached.
- 9.13kΩ (a close representation of a triangular wave)
- 17.89kΩ (a sawtooth wave leaning to the right); the potentiometer was in actuality about an 18kΩ pot instead of a 20kΩ pot.

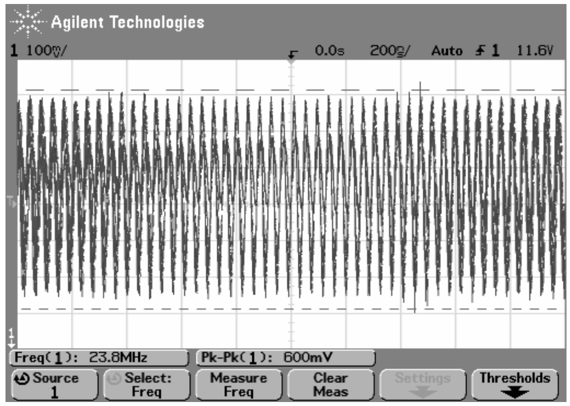
The following three sets of prints were taken before the first two op-amps (A_1 and A_2) were connected to the audio amplifier. The first set of prints was taken when R_2 equals 1.05kΩ. In this case, Point 3 equals 11.72V dc.



@ Point 1



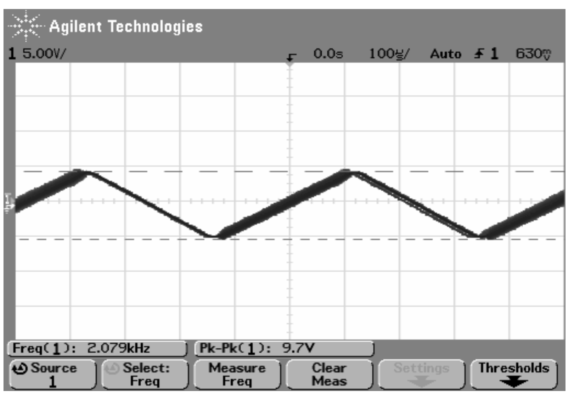
@ Point 2



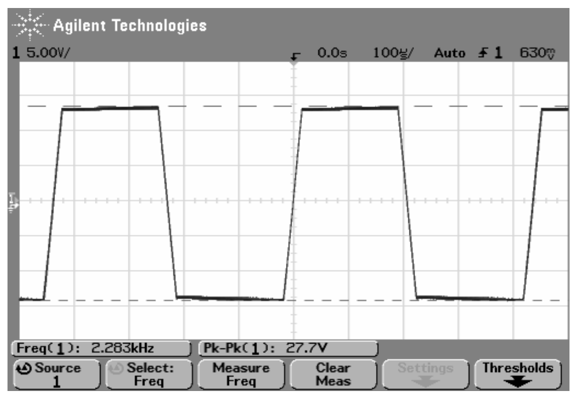
@ Point 4

Figure 26 O-scope prints taken at $R_2 = 1.05k\Omega$

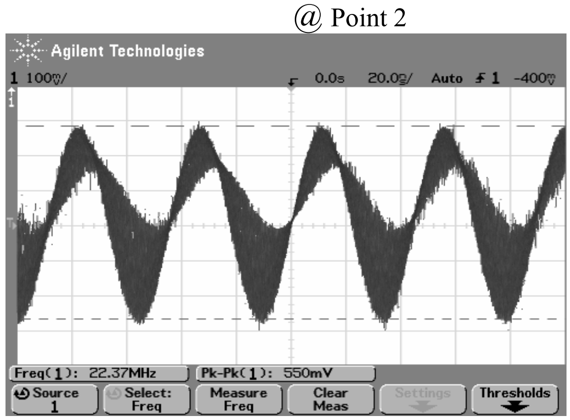
The second set of prints was taken when R_2 equals 9.13k. In this case, point 3 equals -0.3V dc. See figure 27 for the prints.



@ Point 1



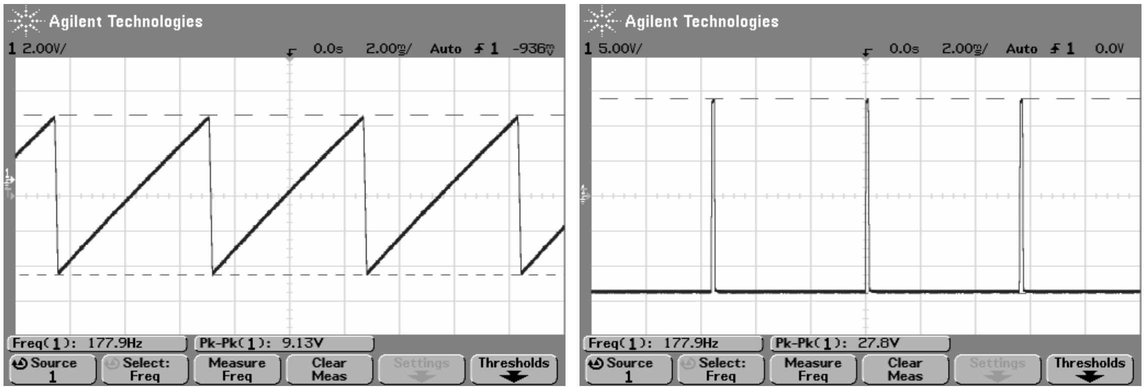
@ Point 2



@ Point 4

Figure 27 O-scope prints taken at $R_2 = 9.13k\Omega$

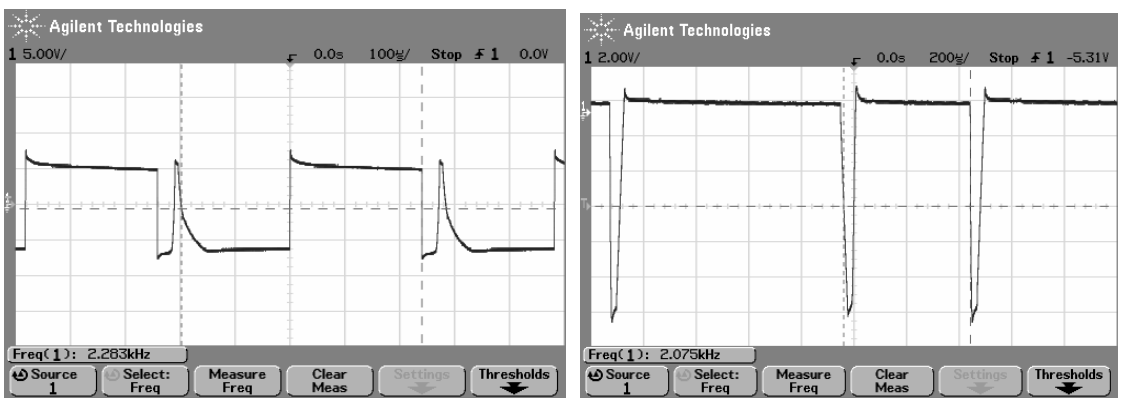
The third set of prints was taken when R_2 equals 17.89kΩ. In this case, point 3 equals -14.91V dc, and point 4 equals -12.94V dc.



@ Point 1 @ Point 2

Figure 28 O-scope prints taken at R2 = 17.89kΩ

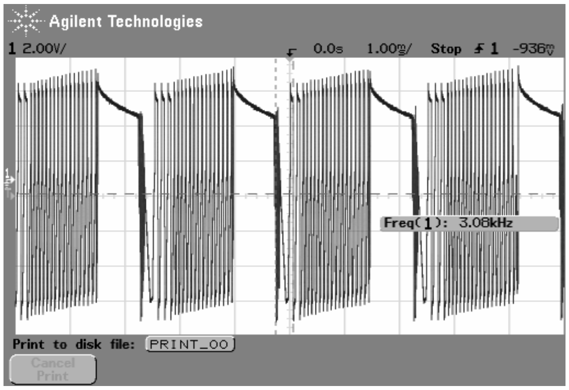
Remember, the above prints were acquired before the first two op-amps were connected to the audio amplifier. The two prints below represent the output from the LM386 audio amplifier when first a square wave and then a triangular wave, each from a function generator, serve as the inputs to the LM386.



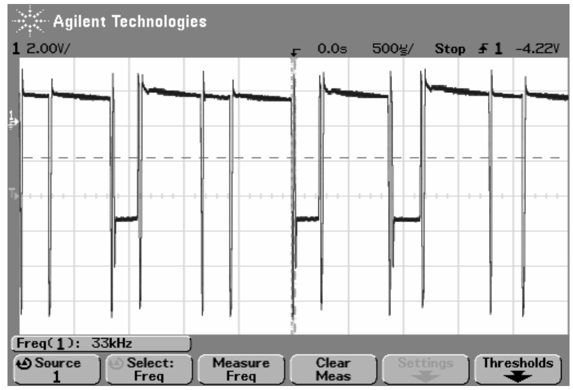
Output with square wave input Output with triangular wave input

Figure 29 Outputs with just a function generator, the LM386, and the speaker

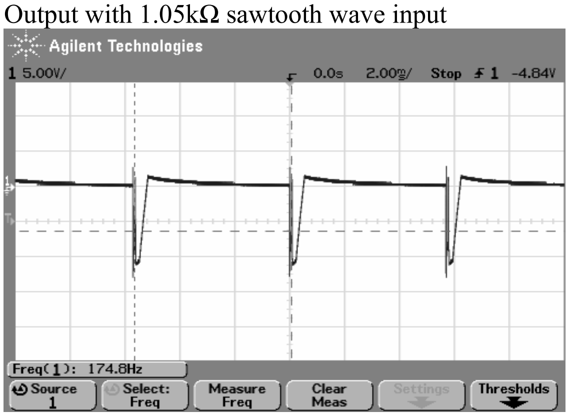
When A_1 and A_2 are connected to the LM386 to form a complete circuit, the following prints are obtained at the output (across the speaker). The previously listed five different input options for the LM386 were employed for these prints, except ground. As expected, the prints with the square wave and triangular wave inputs are similar to those found in the previous figure.



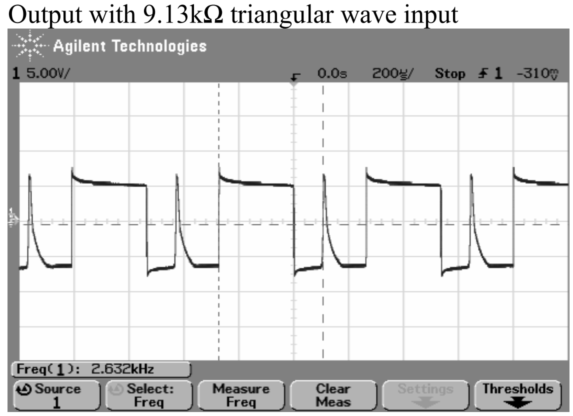
Output with 1.05kΩ sawtooth wave input



Output with 9.13kΩ triangular wave input



Output with 17.89kΩ sawtooth wave input



Output with 9.13kΩ square wave input

Figure 30 Output from the audio amplifier in the complete circuit

All three op-amps working together produce a circuit that functions as a siren. The oscilloscope prints represent the varying sound visually, and from an audible standpoint, when the pot is varied the siren output changes while connected to the output of A_2. [5]

5. Conclusions

Wrapped up in a small integrated circuit are transistors, resistors, diodes, and capacitors that are designed in a way that makes the operational amplifier a very useful electronic component. The triangular symbol with two inputs and one output can be analyzed using Kirchoff's Current Law and by remembering that V+ = V- , and i+ = i- = 0. Its high input impedance and low output impedance allow most of the voltage to be dropped across the load even if the load resistance is small. Furthermore, an op-amp's open loop gain, made possible by the supply voltages, is very large, but the closed loop gain with negative feedback is more knowable. And, generally the gain decreases in value as the frequency affecting the op-amp increases. An op-amp can be designed as an inverting or non-inverting amplifier, comparator, or voltage follower, and if a capacitor is included, then integration and differentiation is possible. Three op-amps grouped into two stages form an instrumentation amplifier, while an op-amp working with a couple diodes produces a rectifier. However, certain practical considerations should be realized when dealing with op-amps including offset voltages and output short-circuit current. Finally, op-amp circuit design is the same as for any other project when it comes to simulation and breadboarding. Multisim8 makes the simulation of a project, like the siren circuit, possible without having to purchase components or be concerned with cost factors. Breadboarding the siren circuit confirms its functionality, and oscilloscope prints illustrate the various waveforms. Sometimes it is best to work with the individual op-amps, especially if problems are encountered. Many other projects and designs are possible with operational amplifiers, and hopefully a tutorial such as this will enhance the understanding needed to make such projects succeed.

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