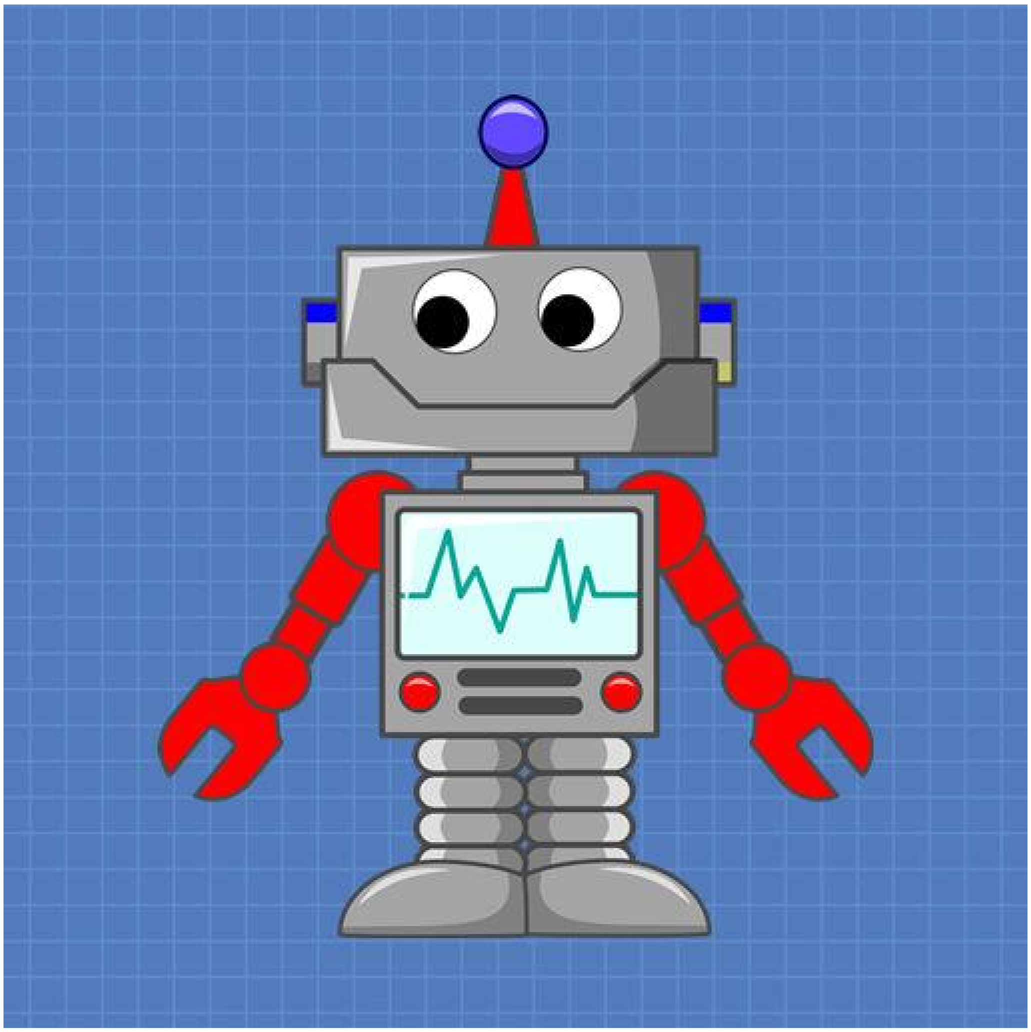
Operational Amplifiers



DroneBot Workshop Tutorial

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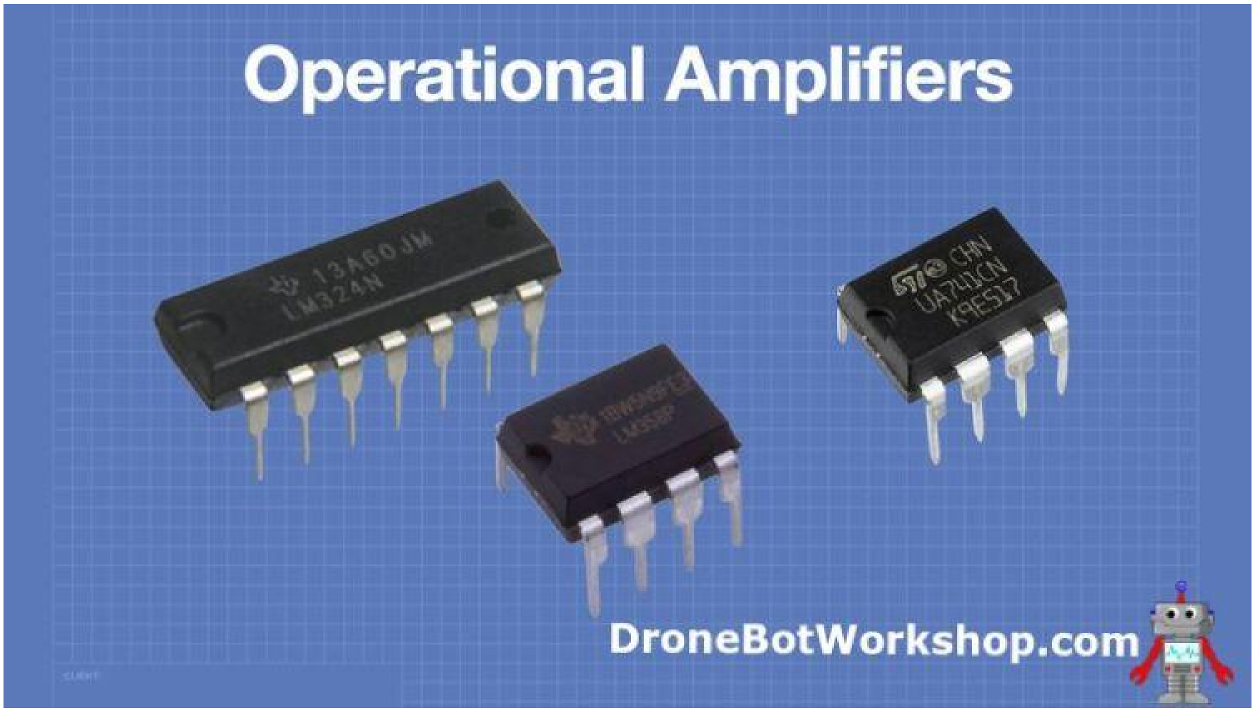
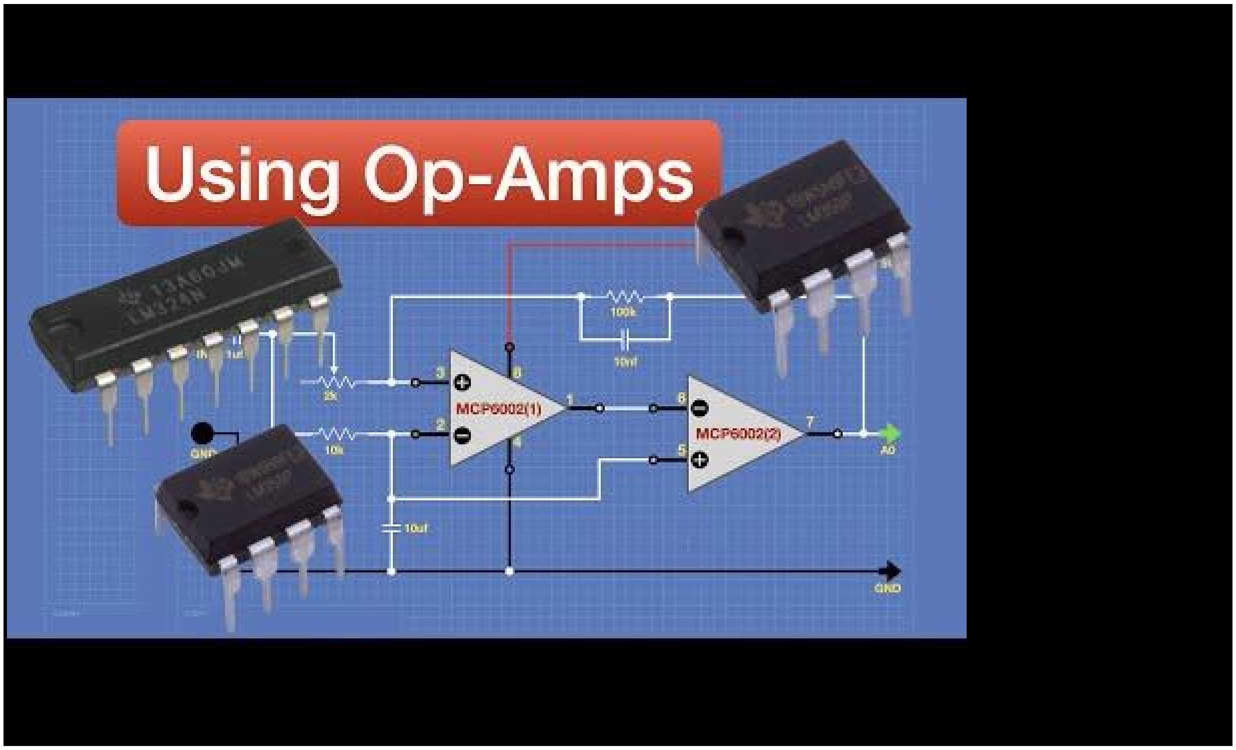
Today we will look at one of the fundamental “Building Blocks” of analog electronics, the Operational Amplifier, commonly referred to as an “Op-Amp”.



Let’s see how these devices work and how we can use them in our designs.

Introduction

With most of the focus these days on microcontrollers and digital electronics, we tend to forget what an important role analog electronics play in modern designs. All the home entertainment and communications devices we cherish contain analog components, and there are still thousands of “analog-only” devices in use today.



One of the most important analog components is the operational amplifier or Op-Amp. This device permeates analog electronic designs due to its low cost, high performance, and, most of all, its versatility. Op-Amps can be configured so many different ways, and it is not uncommon for them to make up the bulk of an analog design

Today we will explore how Op-Amps work and how to use them in several basic configurations. We'll also build a couple of projects, and we'll even make use of an op-amp with an Arduino.

Let's get operational!

Operational Amplifiers

Operational amplifiers, commonly known as *Op-Amps*, are versatile electronic components widely used in analog circuits.

An Op-Amp is a high-gain differential amplifier that amplifies the difference between two input voltages. It consists of an inverting input (labeled with a minus sign), a non-inverting input (labeled with a plus sign), and an output.

The basic function of an Op-Amp is to amplify the difference between the two input signals and make the resulting voltage available at the output. Due to their high gain, Op-Amps are often employed in applications such as audio and signal amplification, filtering, and mathematical operations. They find use in a wide variety of products.

One of the most common applications of operational amplifiers is in building amplifiers or filters. Op-Amps can be configured to amplify, filter, phase-shift, or attenuate an analog signal when used with external components such as resistors and capacitors.

Op-Amps can also be used as comparators or integrators. In these modes, operational amplifiers can be used to interface analog signals to digital ones.

Today we will look at some common operational amplifier chips and see how to use them in several classic configurations.

History of the Operational Amplifier

Op-Amps have a long history, as they were originally developed for use in Analog Computers. Yes, there were computers that were not digital but analog! They used voltages to represent numbers and were incredibly fast.

Analog computers were widely used in various scientific, engineering, and military applications during their heyday, particularly from the 1940s to the 1960s. They excelled in solving differential equations, simulating dynamic systems, and performing real-time computations in control systems. Some notable applications of analog computers included aircraft flight simulators, artillery trajectory calculations, and the simulation of chemical processes.

Operational Amplifiers were a key component in Analog Computers; in fact, the name ”operational” refers to their ability to perform many mathematical operations.

The invention of the operational amplifier can be traced back to the early 20th century when the concept of a high-gain, direct-coupled amplifier was introduced. The foundations of modern op-amps were laid by Karl D. Swartzel Jr. in 1941 while working at Bell Labs. He created a device known as the “K2-W,” designed for analog computers and mathematical modeling during World War II.

This early op-amp was built using vacuum tubes. The K2-W was an essential component in developing the electronic analog computer, as it allowed for complex mathematical operations and simulations.

The evolution of op-amps took a significant leap forward in the 1960s with the introduction of the transistor, a revolutionary semiconductor device that replaced vacuum tubes. Transistors offer numerous advantages, such as reduced size, lower power consumption, and increased reliability.

In 1963, Robert J. Widlar, an American engineer, designed the first integrated circuit (IC) operational amplifier, the uA702. This invention marked the beginning of the modern op-amp era. It combined several discrete transistors, diodes, and other components into a single IC, making the device more compact, efficient, and cost-effective.

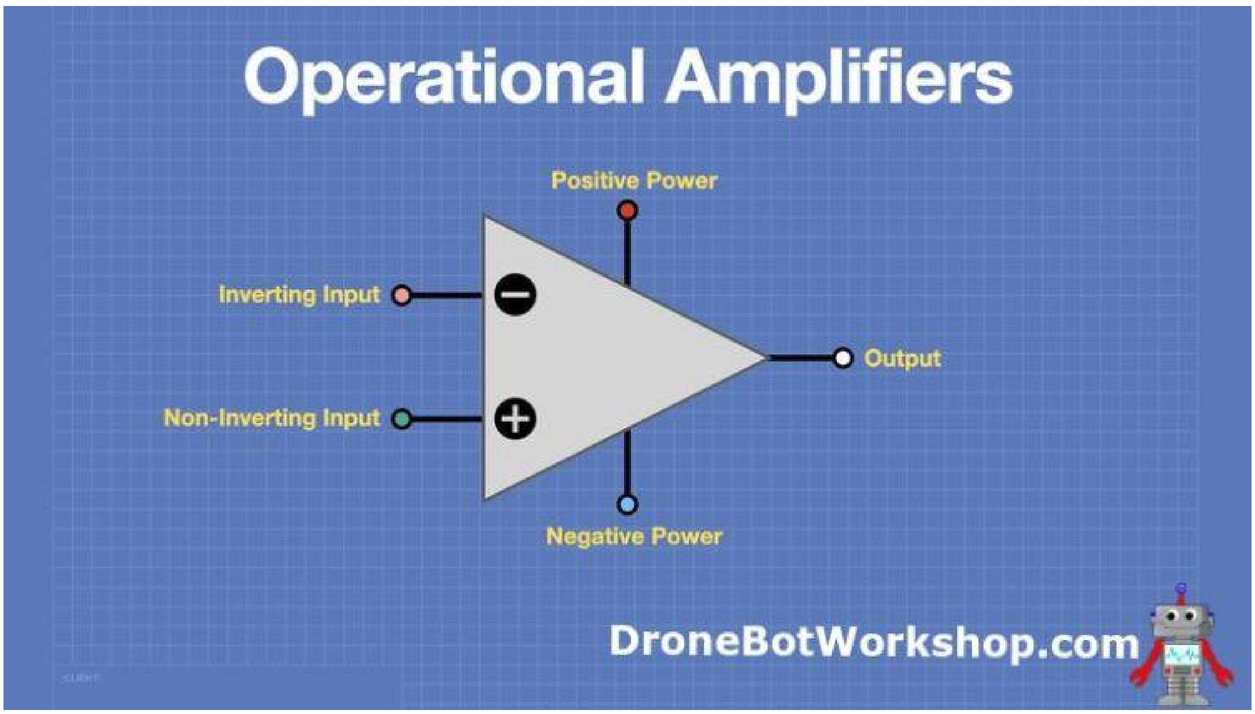
Today, op-amps are available in various forms, such as bipolar, CMOS, and BiCMOS technologies, each offering unique advantages for specific applications.

How Op-Amps Work

As mentioned earlier, Operational Amplifiers are high-gain differential amplifiers. They can be used in many different configurations.

OP-Amp Schematic Symbol

In schematic diagrams, an op-amp is represented by a triangle, with the output at the tip, as shown here.



The op-amp requires both a positive and negative supply voltage. Many modern op-amps are capable of operating on a single positive supply voltage.

There are two inputs on an op-amp:

- Inverting or Negative – A signal applied here will be inverted when output.

- Non-Inverting or Positive – A signal applied here will not be inverted when output.

Some op-amps also have a pin to null the output voltage.

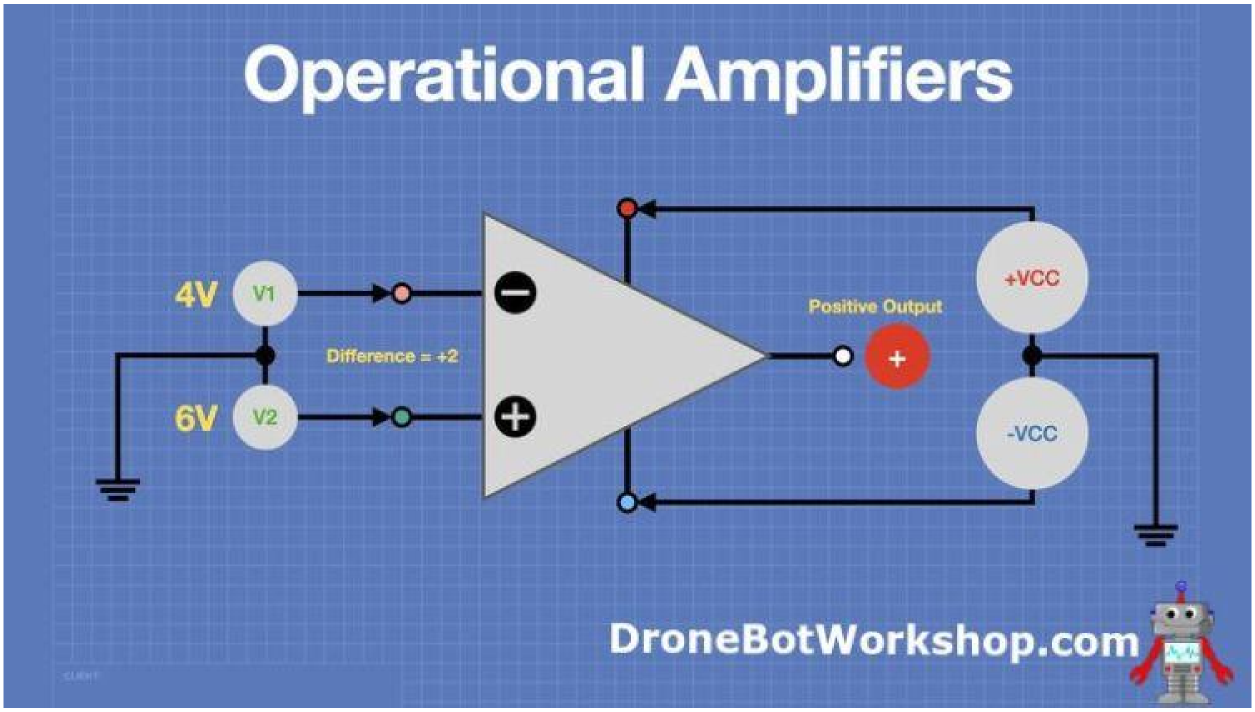
Note that there is no actual convention for drawing the inputs on op-amps, and you may just as well see the non-inverting input drawn above the inverting one. Always pay close attention to the diagram!

Differential Amplifier

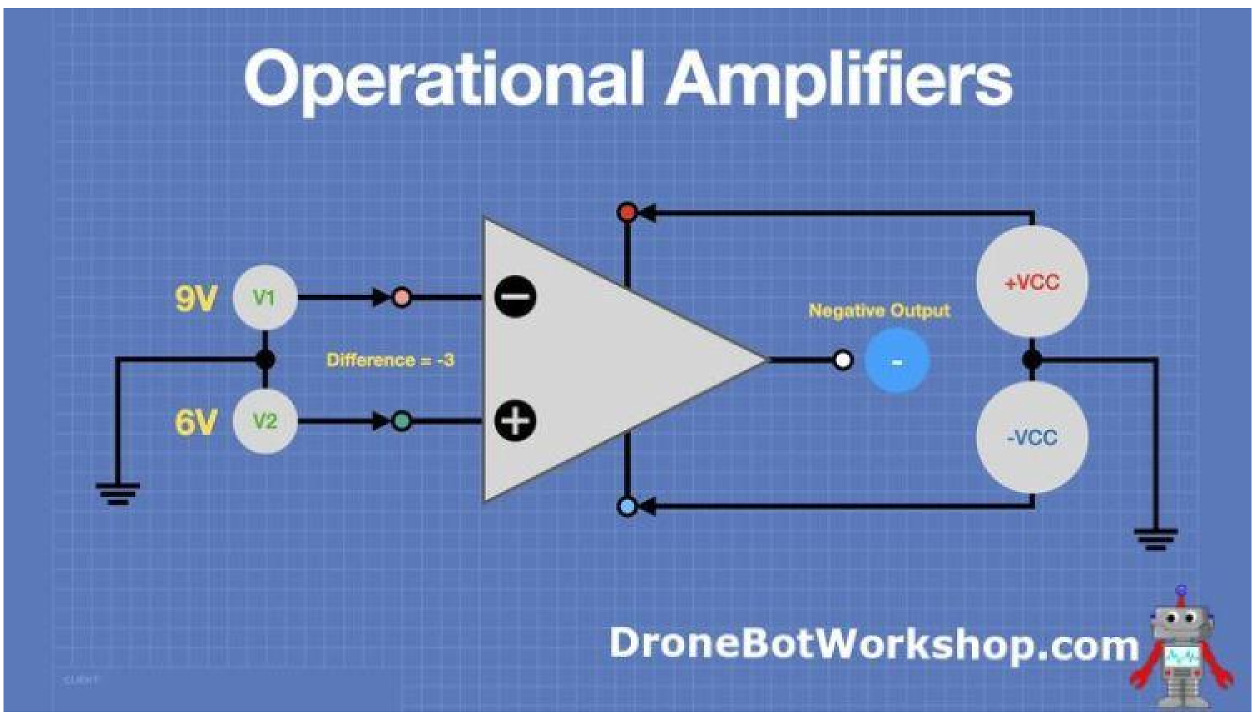
As already noted, the op-amp is a *differential amplifier*, its output is regulated by the *difference* between its two input pins. The greater the difference, the greater the output, and the output can swing both positive and negative with respect to the reference point (i.e, ground).

To observe this, let's take a typical op-amp and power it up with a dual power supply, which has equal positive and negative voltages and a common ground connection.

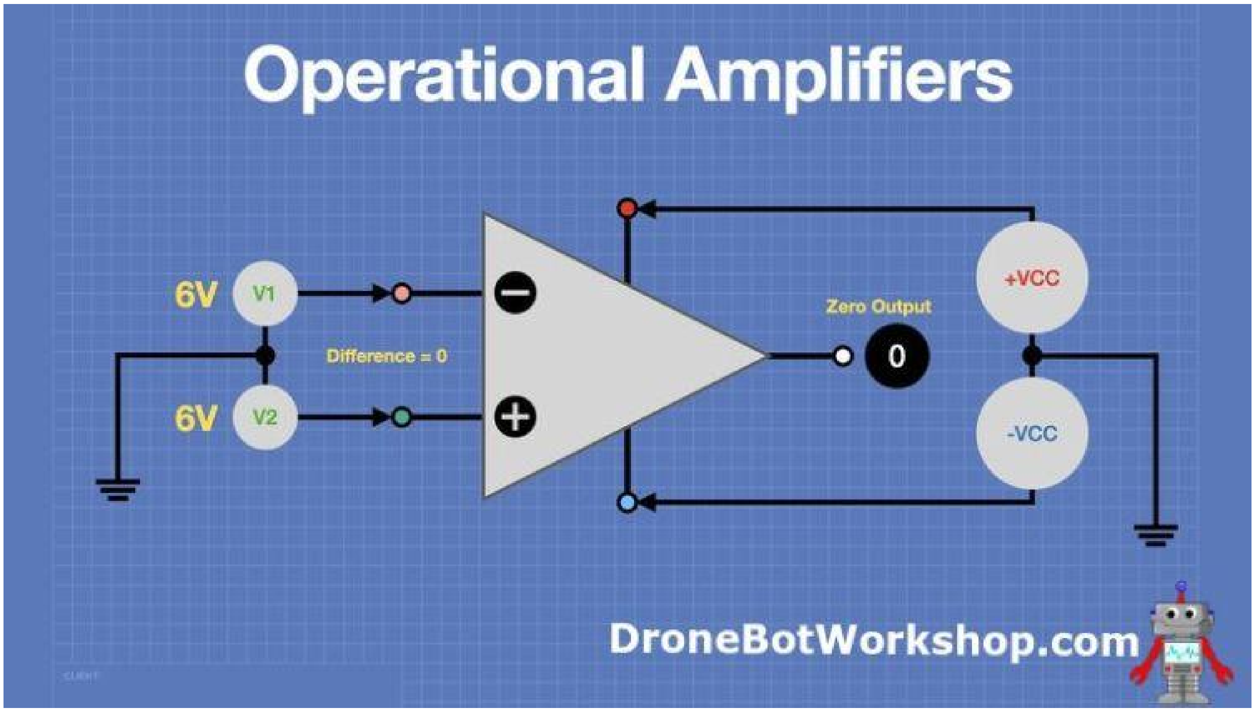
We will then feed two voltages into the two op-amp inputs, each voltage is referenced to the same ground connection used by the power supply.



Now if we feed a higher voltage into the non-inverting input than we do into the inverting one, the output will be positive, as the difference between the voltages is positive.



Conversely, if we now feed more voltage into the inverting input, the difference will be negative, and so will the output.



And if both input voltages are equal, the output will be zero, as there is no difference between the inputs.

Keep in mind that when I refer to "ground," I'm actually talking about the reference point, which in normal dual-power supply designs is ground. However, in a single-supply design, the reference point is often a voltage halfway between the positive voltage and ground.

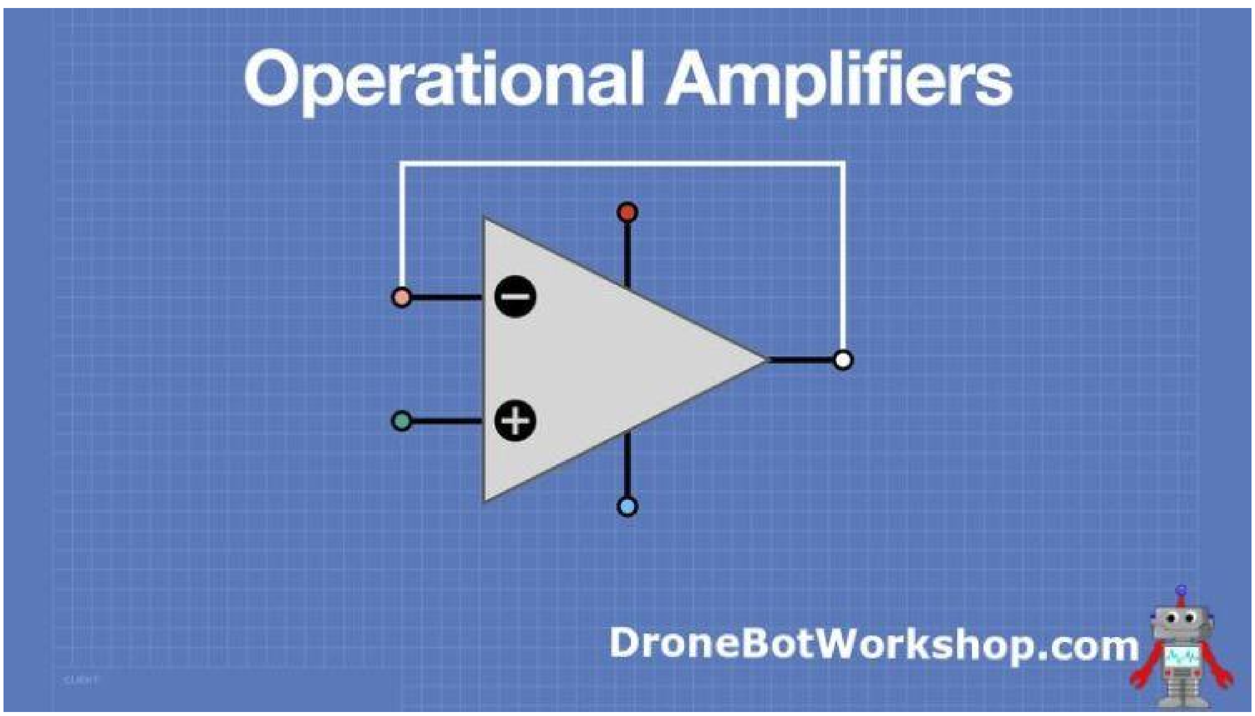
Setting the Gain

By definition, an op-amp is an amplifier, and an amplifier has gain. The amount of gain determines how much the signal is amplified; a gain of two doubles the output, while a gain of 10 is ten times higher.

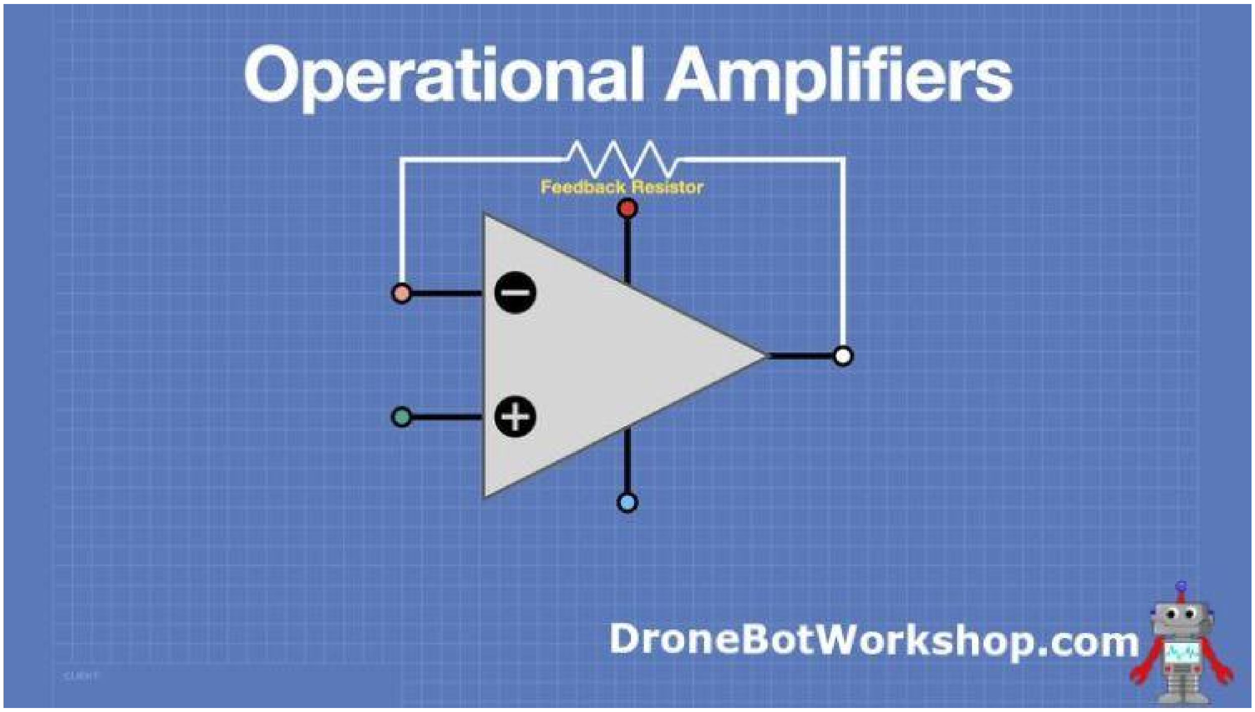
Of course, you can't keep amplifying a signal indefinitely, as eventually, you will reach the maximum voltage the op-amp can output. This is usually just a little less than the supply voltage.

Without any external connections, an op-amp has a very high gain, often over 100,000 times the input. This is far too much gain for most applications, so we need a way to control it.

The most common method of controlling gain is to use feedback, sending some of the output signal back to the input. This is commonly done with the inverting input, creating what is referred to as "negative feedback". Unlike an Amazon review, negative feedback is actually a good thing!



If we connect the output directly to the inverting input, as shown above, we will reduce the gain to 1. An amplifier with a gain of 1 has essentially no amplification, its output is the same as its input. This is a valid configuration, which we will discuss in a moment.



If we want a gain of more than 1 but less than 100,000, we can use a resistor to regulate it. The higher the resistor value, the higher the gain. The resistor used here is called a "*feedback resistor*," as it controls the feedback loop.

Important Op-Amp Specifications

There are literally thousands of op-amps on the market now, each one with a specific set of specifications. Almost every one of these op-amps has an extensive specification sheet, usually available on the Internet.

Aside from the physical specifications, such as package and temperature ratings, the spec sheet contains a number of electrical and electronic specifications. Knowing how to interpret these can assist you in selecting the correct op-amp for your application.

Here are a few specs that are worth knowing:

Open Loop Gain

The open loop gain refers to the amplification factor when the op-amp is used without external feedback. It is typically very high, often in the range of 100,000 to 1,000,000 times (measured in V/V or dimensionless), and is given by the ratio of the output voltage to the input voltage.

Since the open loop gain can be somewhat unpredictable, feedback is often employed to stabilize and fine-tune the amplification process.

Input Impedance

The input impedance of an op-amp is a measure of how easily it allows an input signal to flow into it, and it’s expressed in ohms (Ω). A high input impedance is desirable because it means that the op-amp won’t “load down” the signal source, allowing it to pass through with minimal loss or distortion

Output Impedance

The output impedance is an indication of how effortlessly the op-amp can send the amplified signal to the next component in the circuit. This is measured in ohms (Ω). A lower output impedance is preferred, as it ensures that the op-amp can deliver the amplified signal effectively without any significant loss or distortion.

Gain-Bandwidth Product

The Gain-Bandwidth Product (GBP) is an important characteristic that shows the connection between the op-amp's amplification factor and its ability to handle different frequencies. This is expressed in hertz (Hz).

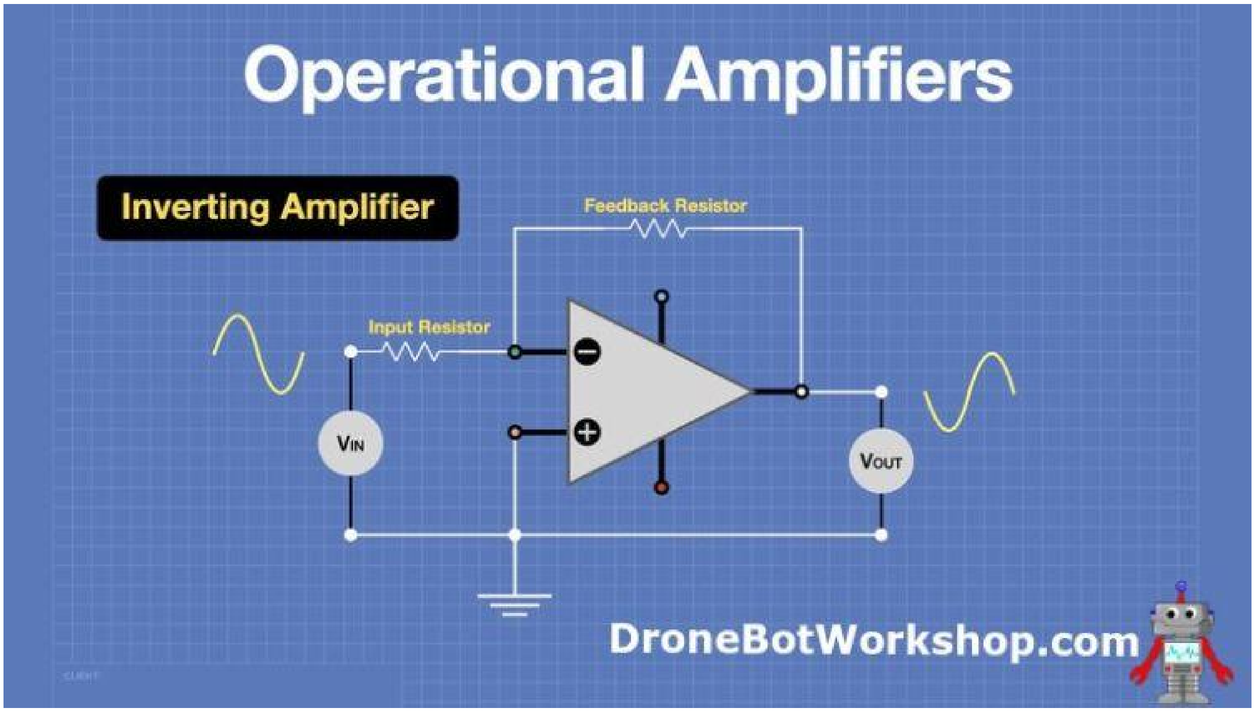
Offset Voltage

The offset voltage is a tiny voltage difference that exists between the op-amp's input terminals even when the output should be zero. This voltage difference is expressed in microvolts (μV) or millivolts (mV) and arises from slight manufacturing inconsistencies.

Common Op-Amp Configurations

Inverting Amplifier

In this configuration, the input signal is applied to the inverting (-) input terminal, while the non-inverting (+) input terminal is connected to ground.

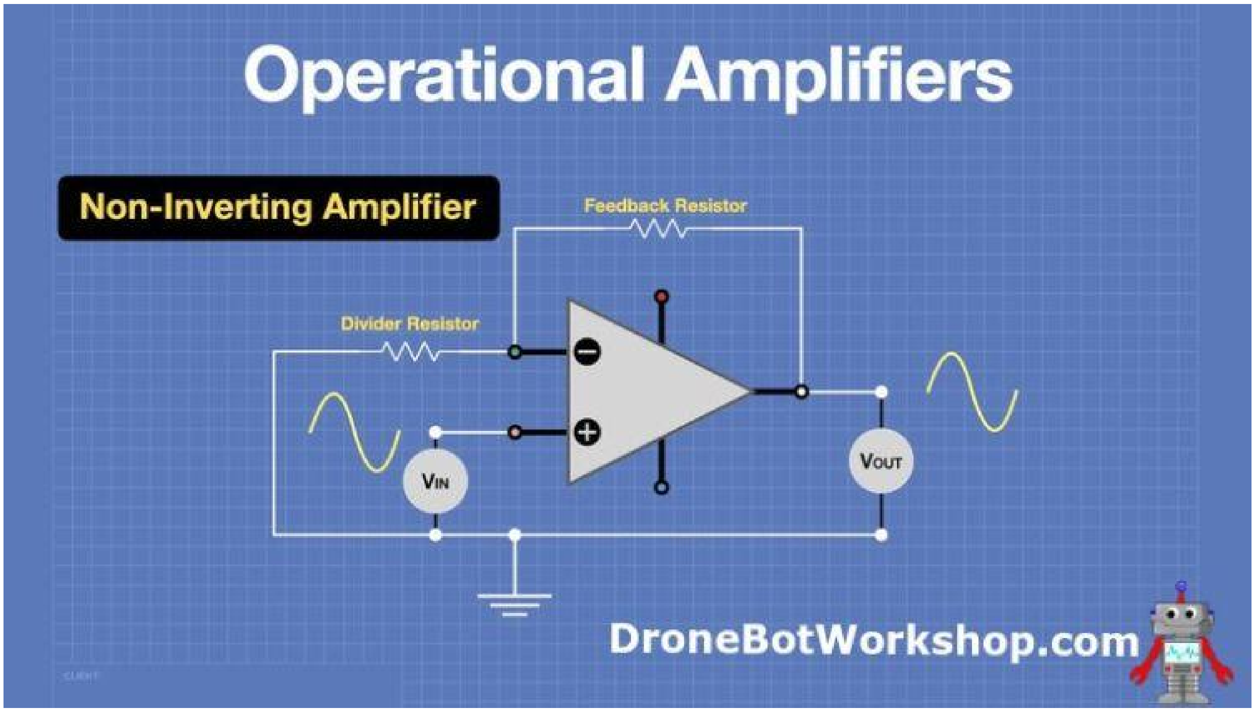


A key component, the feedback resistor, is connected between the output and the inverting input, and an input resistor is connected between the input signal and the inverting input. The ratio of these resistors determines the gain of the amplifier.

In an inverting amplifier, the output signal is amplified and has the opposite polarity of the input signal, making it a useful tool for various signal processing applications.

Non-Inverting Amplifier

In this configuration, the input signal is fed into the non-inverting (+) input, while the inverting (-) input is connected to both a feedback resistor and a divider resistor. The divider resistor links the inverting input to ground, and the feedback resistor connects the output back to the inverting input.

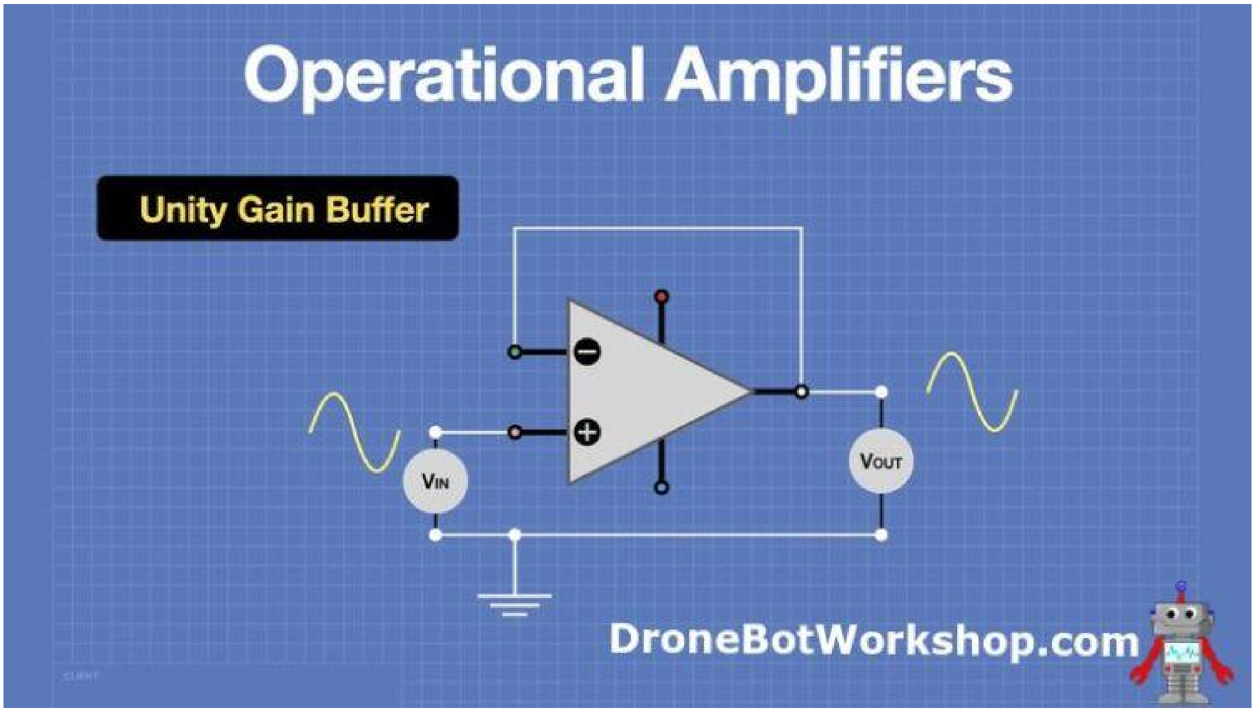


The gain of the non-inverting amplifier depends on the ratio of these resistors.

The output signal of a non-inverting amplifier is amplified and retains the same polarity as the input signal.

Unity Gain Buffer

A Unity Gain Buffer is an amplifier with a gain of 1, meaning that the output signal has the same amplitude as the input signal.

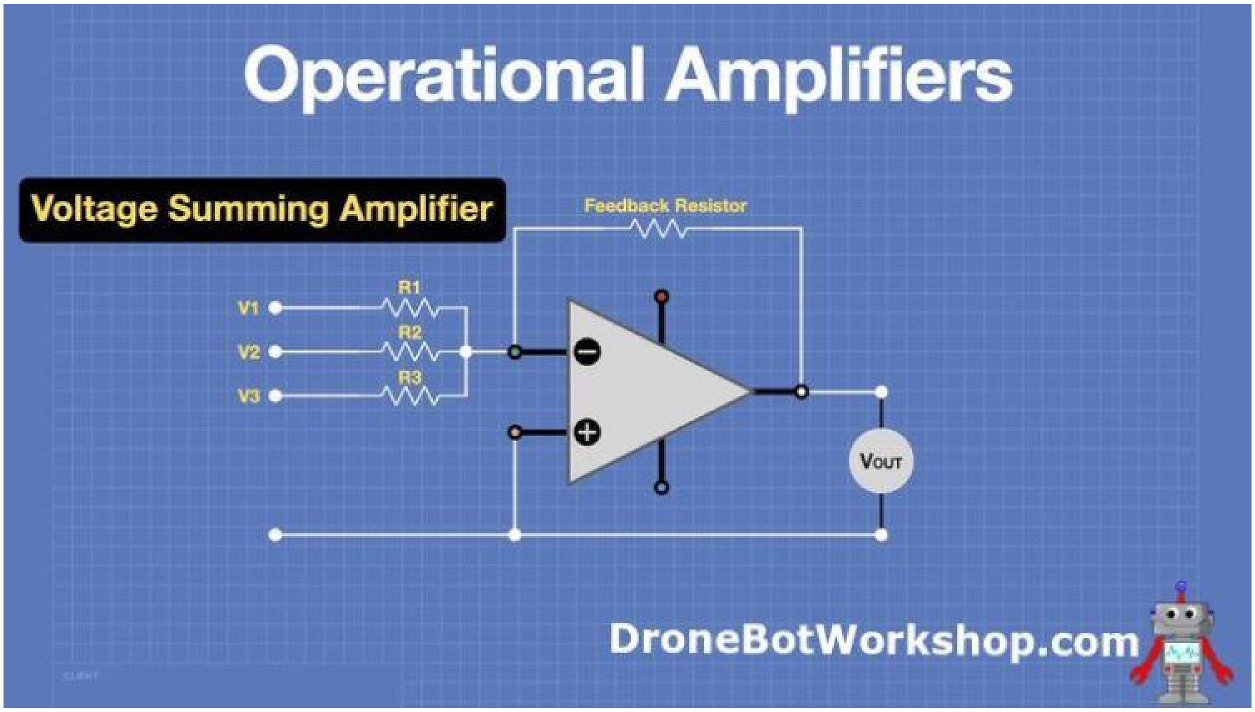


In this setup, the input signal is connected directly to the non-inverting (+) input terminal, while the output of the op-amp is directly connected back to the inverting (-) input terminal, creating a feedback loop.

The primary function of a unity gain buffer is to provide impedance matching or isolation between circuits, preventing the input signal source from being affected by the load connected to the output

Voltage Summing Amplifier

An operational amplifier can be configured as a voltage summing amplifier, which combines multiple input signals into a single output signal.

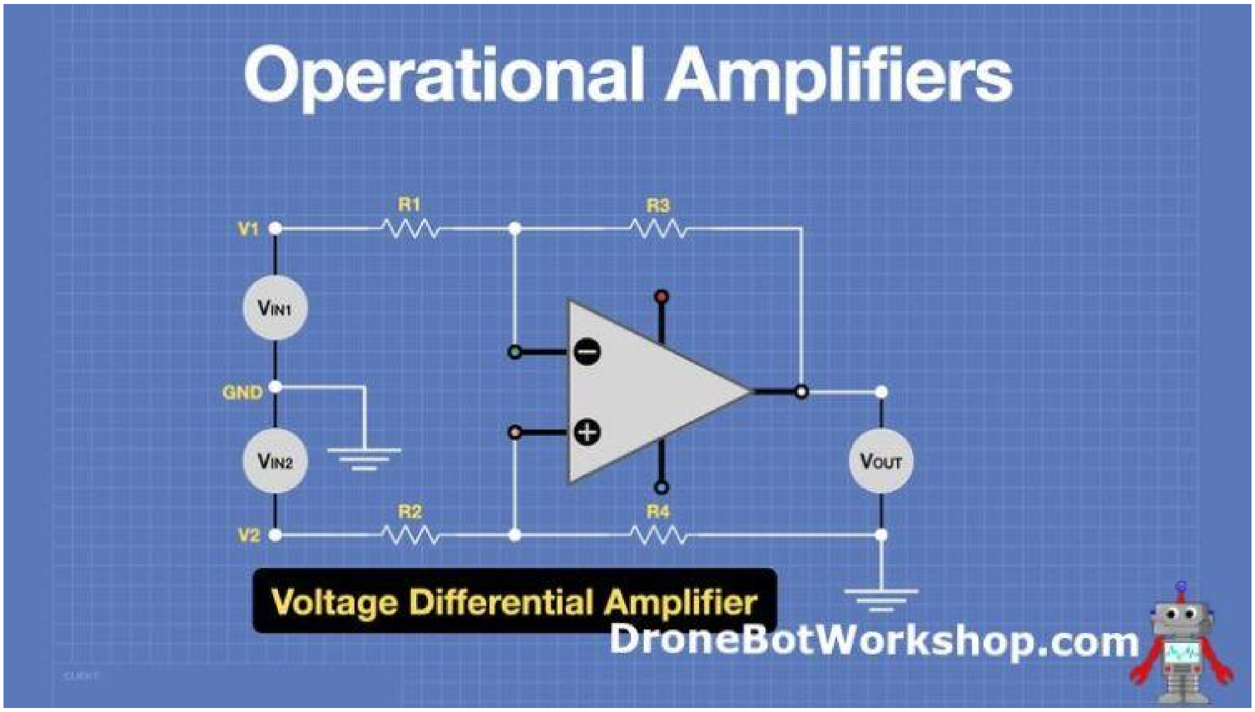


In this setup, the op-amp is arranged as an inverting amplifier, with each input signal connected to the inverting (-) input terminal through individual input resistors (R1, R2, R3, etc.). A feedback resistor is connected between the output and the inverting input. The non-inverting (+) input terminal is connected to ground.

The output signal's voltage is a weighted sum of the input signals, determined by the ratio of the feedback resistor to each input resistor (Rf/R1, Rf/R2, Rf/R3, etc.). The voltage summing amplifier is useful in various applications, including audio mixing and analog-to-digital conversion.

Voltage Differential Amplifier

You can also configure an op-amp as a voltage differential amplifier, which amplifies the difference between two input signals.



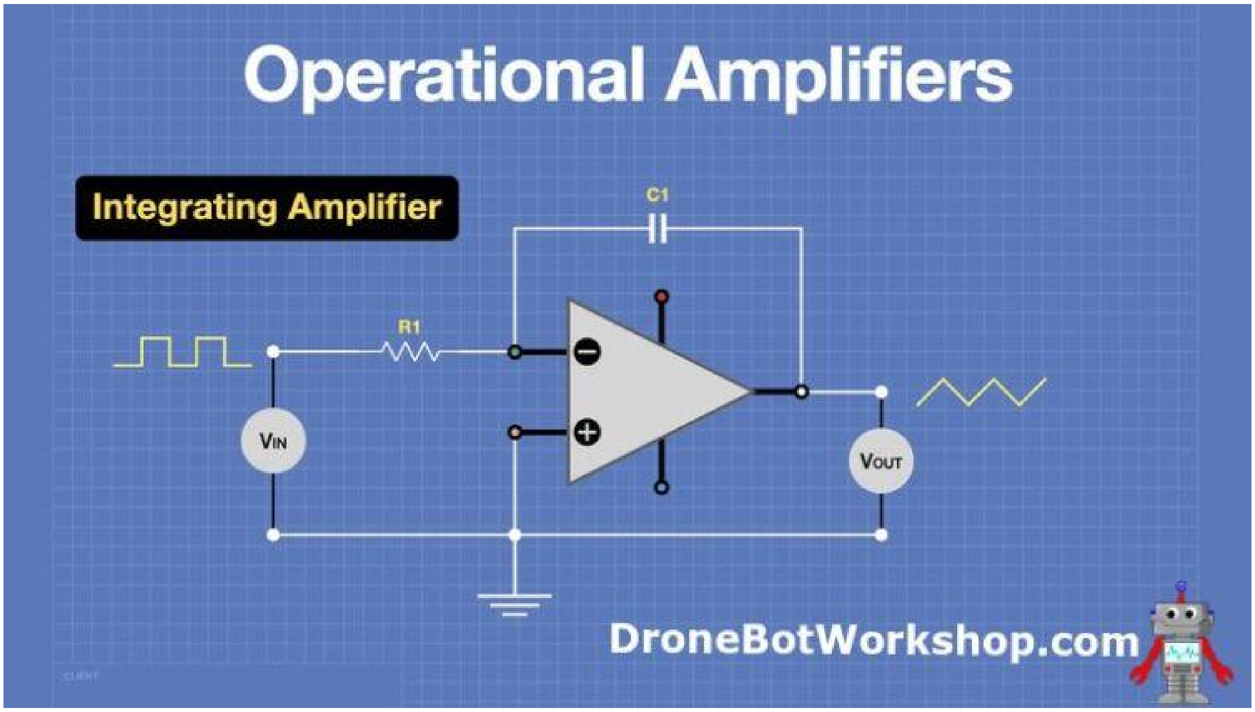
In this setup, both the inverting (-) and non-inverting (+) input terminals receive input signals. Two pairs of resistors, R1 and R3, and R2 and R4, are used to set up a balanced gain for each input signal. The resistors are connected in such a way that R1 links the inverting input to the first input signal, R3 connects the inverting input to the output, R2 connects the non-inverting input to the second input signal, and R4 links the non-inverting input to ground.

The output signal's voltage is the amplified difference between the two input signals, with the gain determined by the ratio of resistors (R3/R1 = R4/R2).

Voltage differential amplifiers are useful in various applications, such as measuring the difference between two sensor signals or removing common-mode noise.

Integrating Amplifier

Another op-amp configuration that stems back to its analog computer past is an integrating amplifier. This configuration produces an output signal that is the time integral of the input signal.



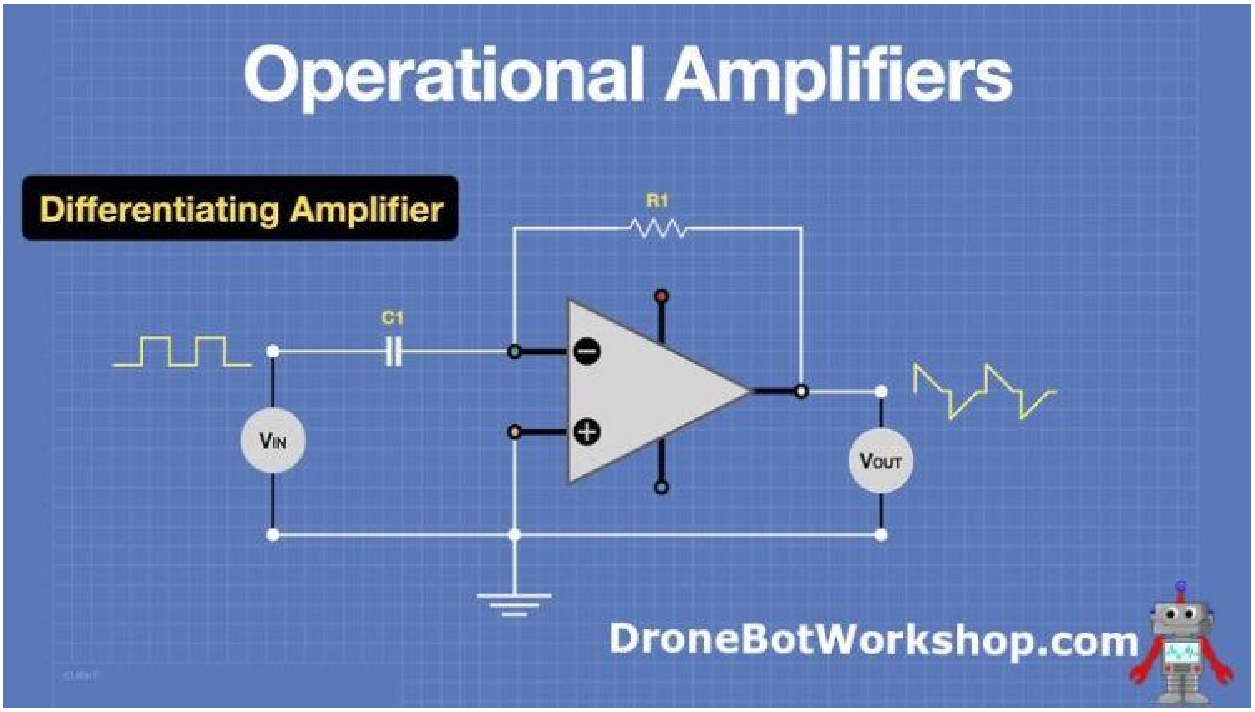
The op-amp is arranged as an inverting amplifier, with the input signal connected to the inverting (-) input terminal through an input resistor (R1). Instead of a feedback resistor, a capacitor (C1) is connected between the output and the inverting input, while the non-inverting (+) input terminal is connected to ground.

The output signal's voltage is proportional to the integral of the input signal, with the integration time constant determined by the product of the input resistor and the capacitor (R1*C1).

Integrating amplifiers are useful in various applications, such as converting a square wave into a triangular wave or filtering high-frequency noise.

Differentiating Amplifier

An op-amp can be configured as a differentiating amplifier, which generates an output signal that is the time derivative of the input signal.

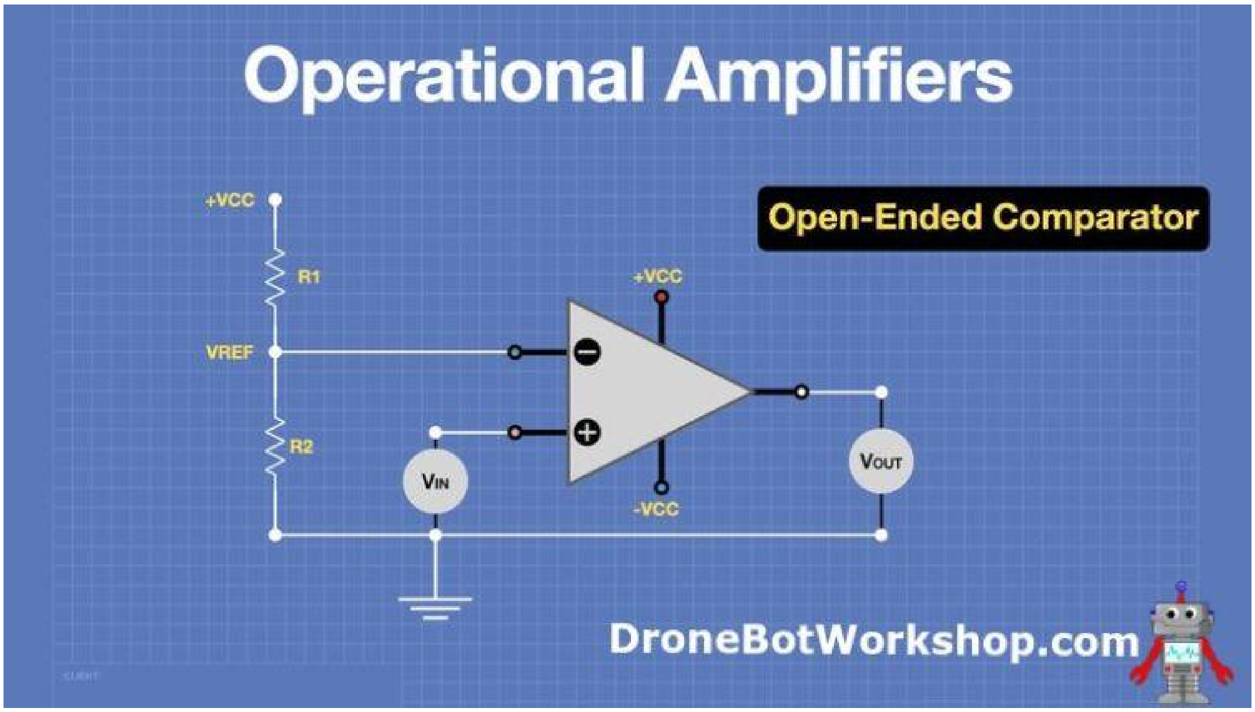


In this setup, the op-amp is arranged as an inverting amplifier, but with a capacitor (C1) connected to the inverting (-) input terminal in place of the input resistor and the input signal connected to the capacitor. A feedback resistor (R1) is connected between the output and the inverting input, while the non-inverting (+) input terminal is connected to ground.

The output signal's voltage is proportional to the derivative of the input signal, with the *differentiation time constant* determined by the product of the feedback resistor and the capacitor (R1*C1). Differentiating amplifiers are useful in various applications, such as detecting edges in a waveform or enhancing high-frequency components of a signal.

Open-Ended Comparator

A comparator is a circuit that compares two input voltages and generates an output signal based on the voltage difference.



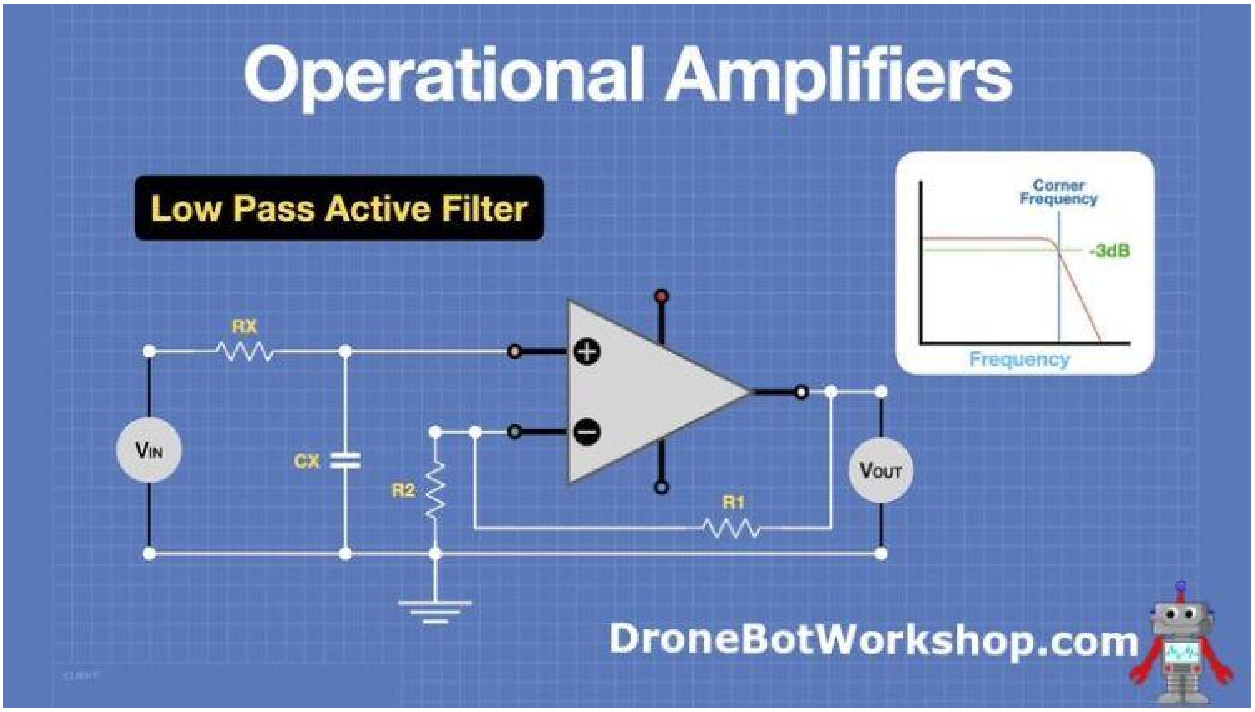
In this configuration, the non-inverting (+) input receives a reference voltage, while the inverting (-) input gets the input voltage to be compared. We are using a couple of resistors (R1 & R2) to establish the reference voltage.

If the input voltage is higher than the reference voltage, the output will be HIGH, close to the positive supply voltage. However, if the input voltage is lower than the reference voltage, the output will be LOW, near the negative supply voltage.

Comparators are used in many applications, such as threshold detection or converting an analog signal into a digital output.

Low Pass Active Filter

A low pass active filter allows low-frequency signals to pass through while attenuating higher-frequency signals.



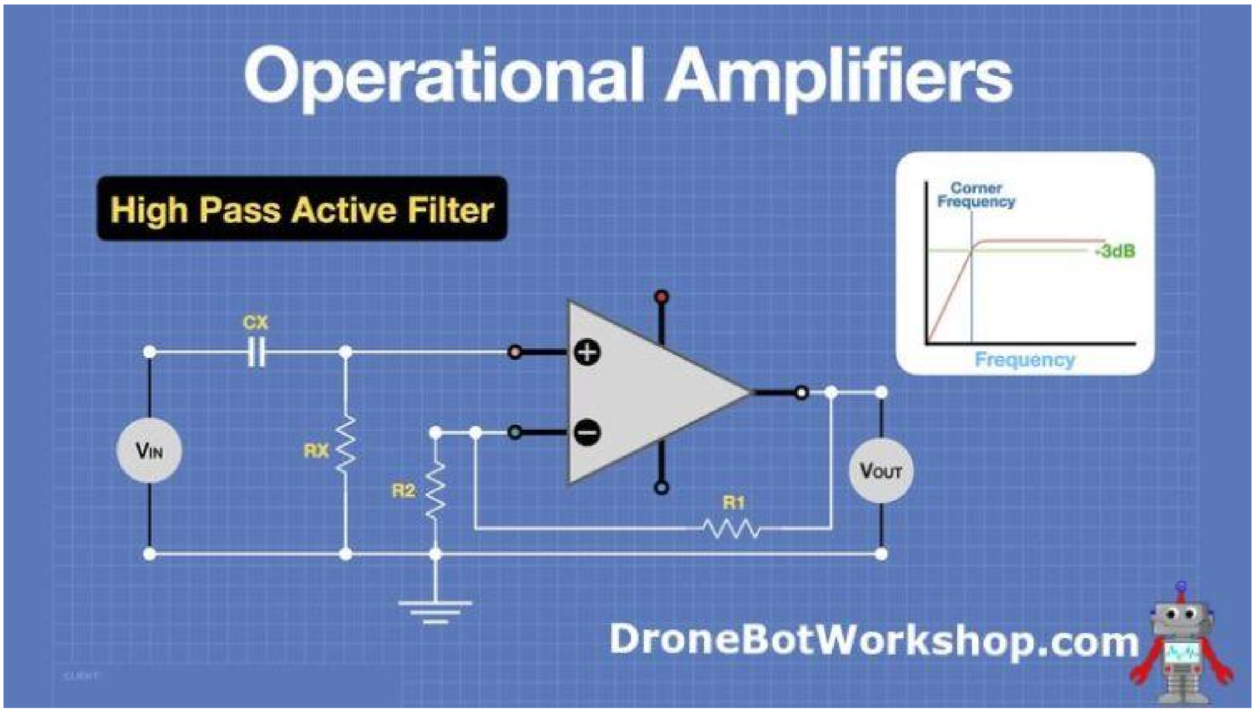
In this configuration, the op-amp is arranged as an inverting amplifier, with an input resistor (RX) connecting the input signal to the inverting (-) input terminal. A capacitor (CX) is connected between the non-inverting input and ground. A feedback network composed of a resistor (R1) is connected between the output and the inverting input.

The output signal's voltage is affected by both the gain and the filtering, with the cutoff frequency determined by the values of RX and CX.

Low pass active filters are useful in various applications, such as audio systems for bass enhancement or removing high-frequency noise from a signal.

High Pass Active Filter

A high pass active filter allows high-frequency signals to pass through while attenuating lower-frequency signals. In other words, this is the opposite of a low pass filter.



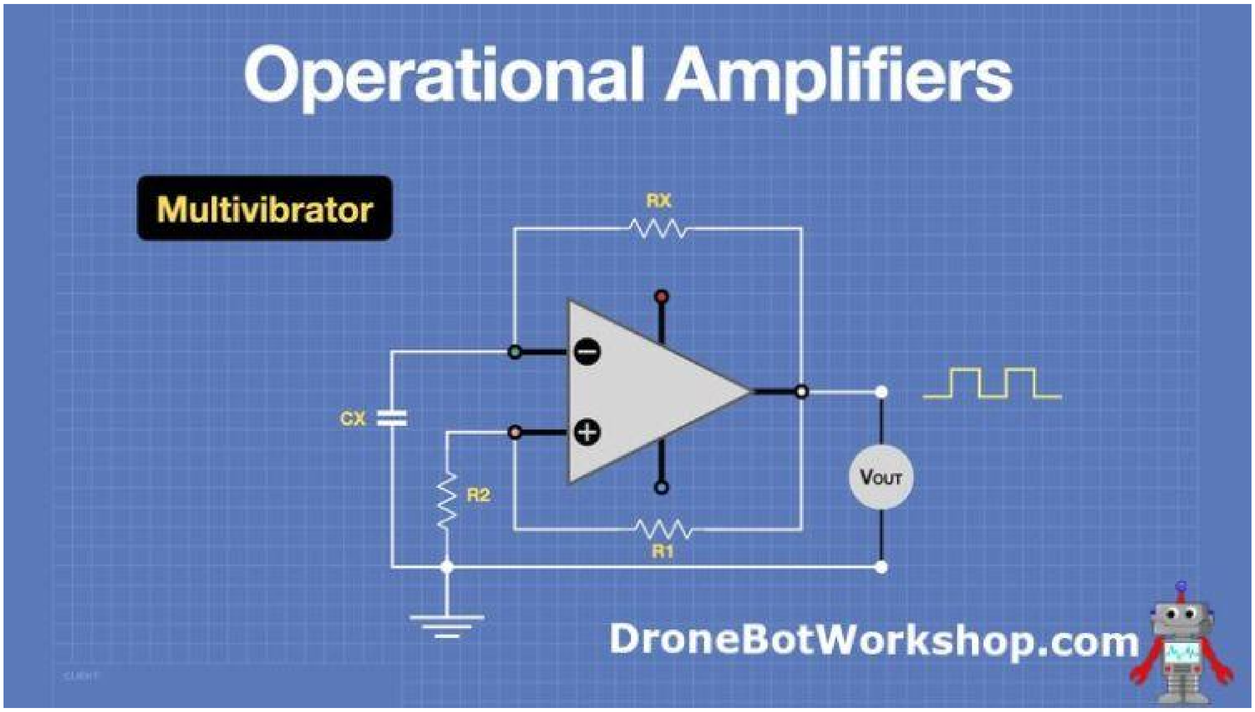
Once again the op-amp is arranged as an inverting amplifier, with the input signal connected to the inverting (-) input terminal through a capacitor (CX). A resistor (RX) is connected between the non-inverting input and ground. A feedback network composed of a resistor (R1) is connected between the output and the inverting input.

Once again, the output signal's voltage is affected by both the gain and the filtering, with the cutoff frequency determined by the values of RX and CX.

High pass active filters are useful in various applications, such as audio systems for treble enhancement or removing low-frequency noise from a signal.

Multivibrator

A multivibrator is an electronic circuit that generates oscillating waveforms without an external input signal. In the arrangement shown here, a square wave will be generated.



To create a multivibrator, the op-amp is arranged as a comparator, with a positive feedback network composed of resistors R1 and R2 connected between the output and the non-inverting (+) input terminal. The inverting (-) input terminal is connected to a capacitor (CX) and a resistor (RX) that form a time-delay network.

The output signal's waveform alternates between high and low voltage levels, creating a square wave output. The oscillation frequency, as well as the pulse width, is determined by the values of R1, R2, RX, and CX.

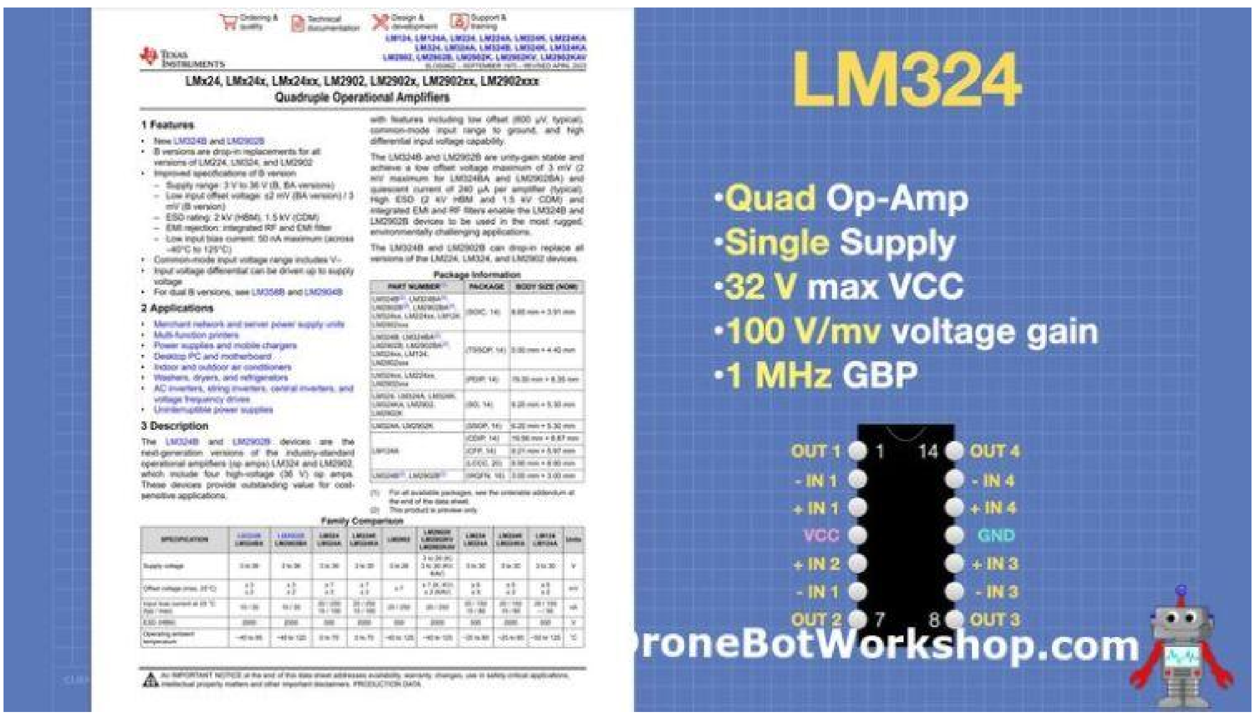
Multivibrators are useful in various applications, such as generating clock signals or creating simple electronic sound effects.

Popular Operational Amplifiers

If you check out the websites of large distributors like DigiKey and Mouser, you'll find hundreds of operational amplifiers in stock. There may be a semiconductor chip shortage, but it hasn't affected classic components like op-amps!

With so many choices, selecting an op-amp for your project can be difficult. Here is a list of some popular operational amplifier chips to help you narrow down your selection:

LM324



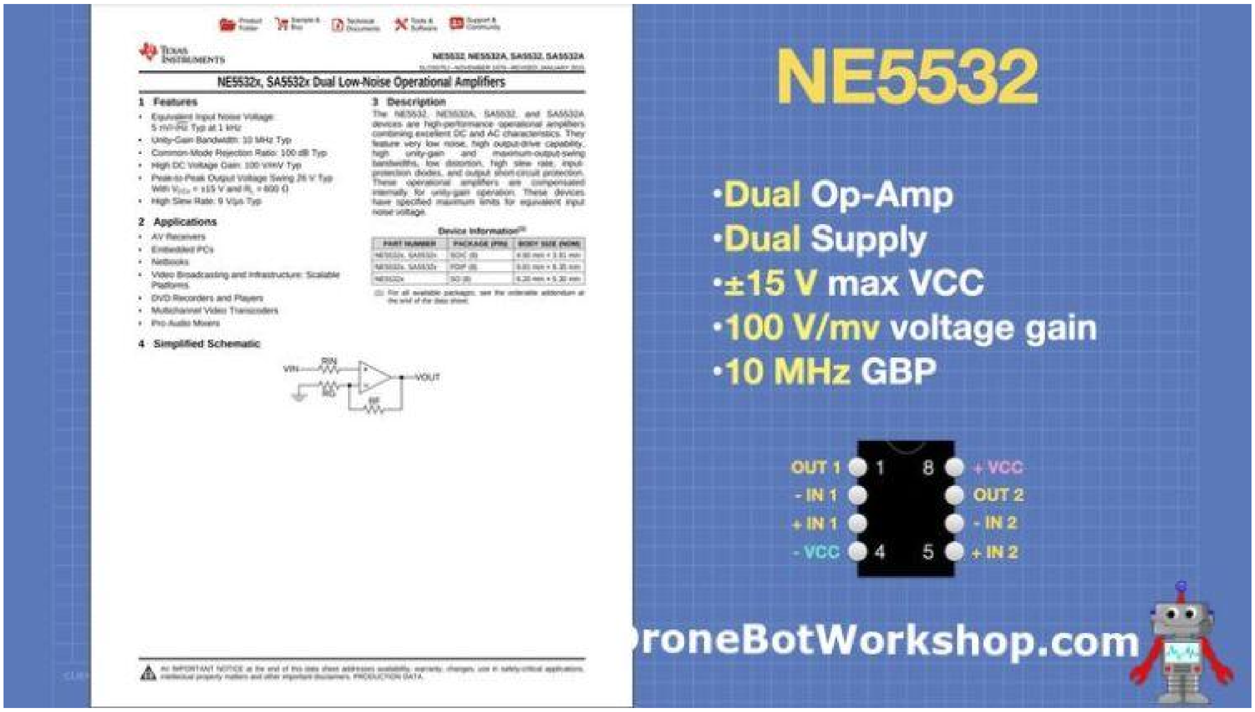
- **Quad op-amp:** The LM324 is a quad operational amplifier, meaning it contains four separate op-amps in a single integrated circuit (IC).
- **Low power consumption:** The LM324 has a low power consumption, making it suitable for battery-powered and energy-efficient applications.
- **Wide supply voltage range:** The LM324 can operate from a single supply voltage as low as 3V and up to 32V, or with a dual supply voltage of ±16V.

- **Internally frequency compensated**: It has internal frequency compensation, which eliminates the need for external components for stable operation.
- **Large output voltage swing:** The LM324 has a large output voltage swing, nearly reaching the supply rails, which is useful in applications where a wide dynamic range is required.
- **Low input bias current:** The op-amp has a low input bias current, reducing errors caused by input offset voltage in high-impedance circuits.
- **Input common-mode voltage range:** The LM324 has a wide input common-mode voltage range, which includes ground, making it suitable for single-supply applications.
- **Short-circuit-protected outputs:** The outputs of the LM324 are short-circuit-protected, providing increased reliability in the event of a fault condition.
- **High gain and wide bandwidth:** The LM324 has a high open-loop voltage gain and a wide bandwidth, making it suitable for a variety of applications.
- **Low input offset voltage:** The op-amp has a low input offset voltage, which minimizes errors in high-gain applications.

The LM324 operational amplifier is a versatile and widely used component in various electronic applications, such as signal conditioning, filtering, analog-to-digital conversion, instrumentation, and control systems.

Its low power consumption, wide supply voltage range, and internal frequency compensation make it an attractive choice for battery-powered devices, while its high gain, wide bandwidth, and large output voltage swing allow for use in a range of analog signal processing tasks.

NE5532



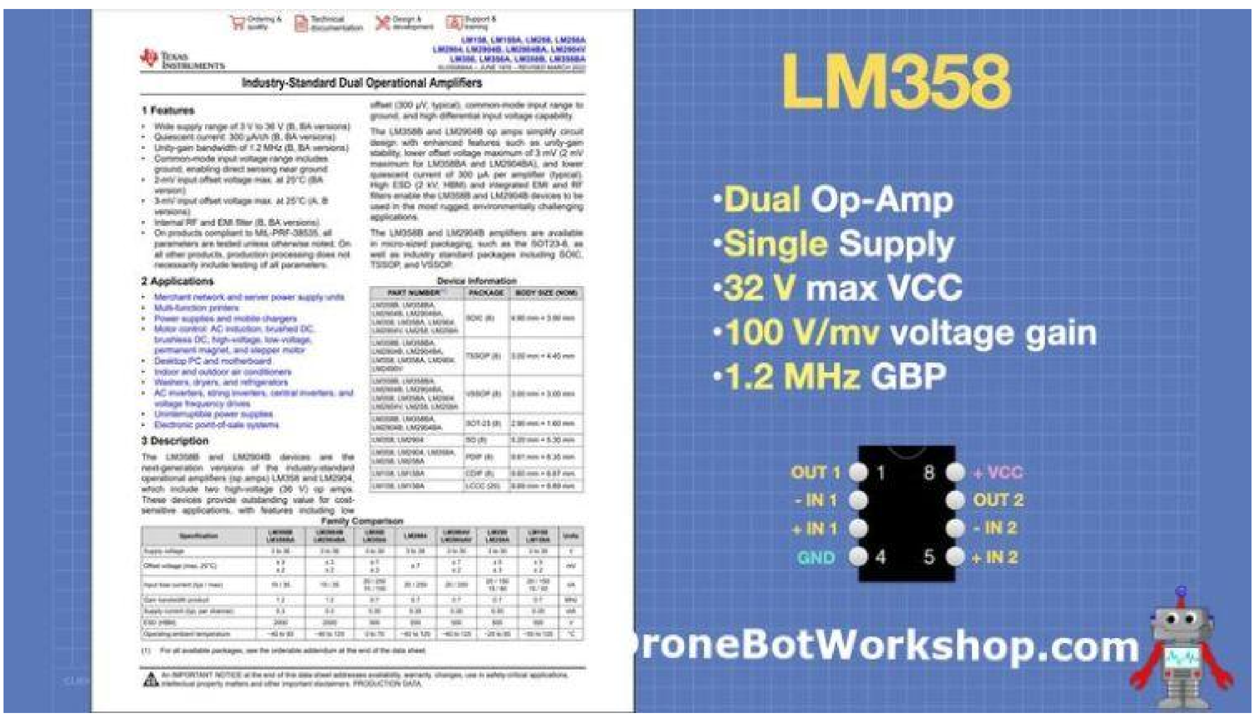
- **Dual op-amp:** The NE5532 is a dual operational amplifier, consisting of two separate op-amps within a single integrated circuit (IC).
- **High-performance:** The NE5532 is a high-performance op-amp, designed for low noise, low distortion, and high slew rate applications.
- **Wide supply voltage range:** It can operate with a supply voltage range from ±5V to ±15V, allowing for a variety of applications.
- **Low noise:** The NE5532 has a low input noise voltage and current, making it suitable for audio, instrumentation, and other noise-sensitive applications.
- **High slew rate:** With a high slew rate of 9V/μs, the NE5532 can handle fast-changing signals, making it ideal for high-frequency applications.
- **High input impedance:** The op-amp features high input impedance, which reduces loading effects and is beneficial for high-impedance signal sources.
- **Low total harmonic distortion (THD):** The NE5532 has low THD, making it suitable for high-fidelity audio applications and other applications that require low distortion.
- **Wide bandwidth:** The NE5532 has a wide bandwidth, typically around 10MHz, allowing it to handle a wide range of frequencies.
- **High open-loop voltage gain:** With a high open-loop voltage gain, the NE5532 is ideal for precision applications requiring high gain.
- **Short-circuit protection:** The outputs of the NE5532 are short-circuit-protected, providing increased reliability in the event of a fault condition.

- **Internally compensated:** The NE5532 is internally compensated, which simplifies circuit design by eliminating the need for external compensation components.

The NE5532 operational amplifier is widely used in high-performance audio, instrumentation, and control systems, thanks to its low noise, low distortion, and high slew rate characteristics.

Its wide supply voltage range, high input impedance, and short-circuit protection make it suitable for a variety of applications, including audio preamplifiers, active filters, and signal conditioning circuits.

LM358P



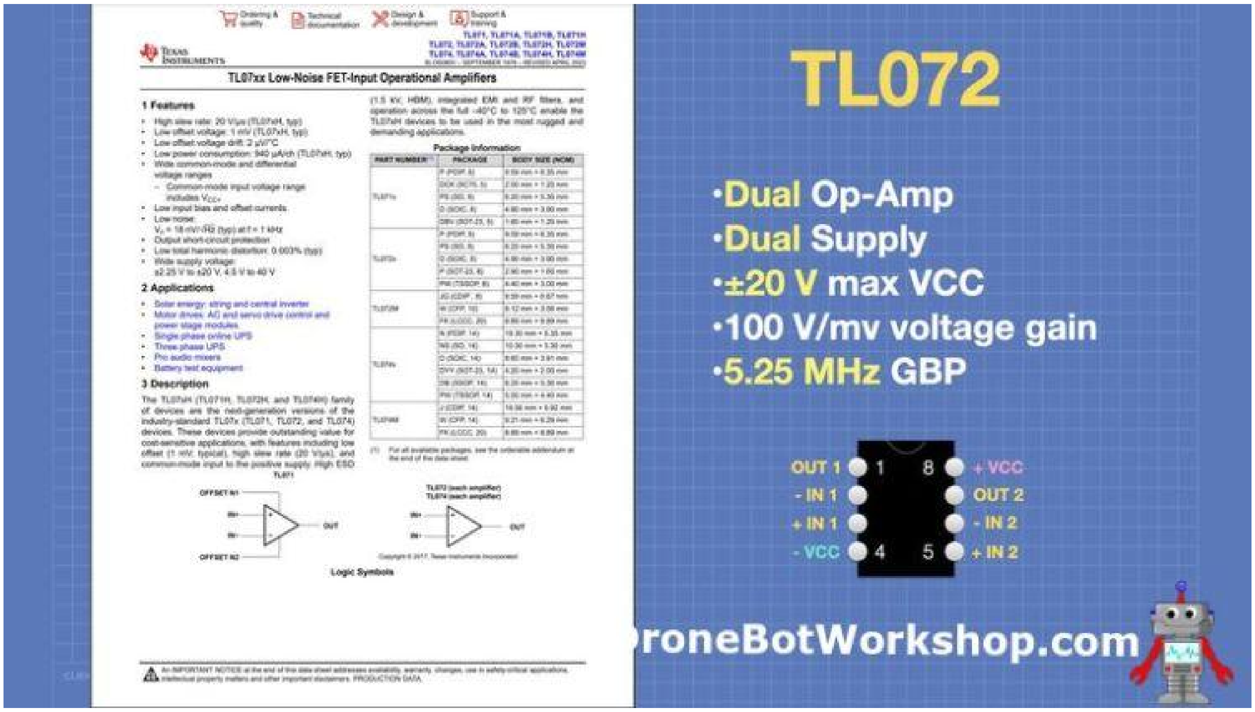
- **Dual op-amp:** The LM358 is a dual operational amplifier, consisting of two separate op-amps within a single integrated circuit (IC).

- **Low power consumption:** The LM358 has a low power consumption, making it suitable for battery-powered and energy-efficient applications.
- **Single-supply operation:** The LM358 can operate from a single supply voltage, with a range from 3V to 32V, simplifying power supply requirements.
- **Wide Input common-mode voltage range:** The LM358 has a wide input common-mode voltage range, which includes ground, making it suitable for single-supply applications.
- **Large output voltage swing:** The LM358 has a large output voltage swing, nearly reaching the supply rails, which is useful in applications requiring a wide dynamic range.
- **Low input offset voltage:** The op-amp has a low input offset voltage, which minimizes errors in high-gain applications.
- **High input impedance:** The LM358 features high input impedance, which reduces loading effects and is beneficial for high-impedance signal sources.
- **Internally frequency compensated:** It has internal frequency compensation, which eliminates the need for external components for stable operation.
- **Wide bandwidth:** The LM358 has a wide bandwidth, typically around 1MHz, allowing it to handle a wide range of frequencies.
- **Short-circuit-protected outputs:** The outputs of the LM358 are short-circuit-protected, providing increased reliability in the event of a fault condition.
- **Low cost:** The LM358 is a low-cost op-amp, making it an attractive choice for a variety of applications where cost is a concern.

The LM358 operational amplifier is a versatile component used in a wide range of applications, such as signal conditioning, filtering, analog-to-digital conversion, instrumentation, and control systems.

Its low power consumption, single-supply operation, and wide input common-mode voltage range make it suitable for battery-powered devices and applications with limited power supplies.

TL072



- **Dual op-amp:** The TL072 is a dual operational amplifier, consisting of two separate op-amps within a single integrated circuit (IC).
- **Low noise:** The TL072 is a low-noise op-amp, making it suitable for audio, instrumentation, and other noise-sensitive applications.
- **JFET input:** It features JFET (Junction Field-Effect Transistor) input stages, which provide high input impedance and low input bias current.
- **Wide supply voltage range**: The TL072 can operate with a supply voltage range from ±4V to ±18V, allowing for a variety of applications.
- **Wide bandwidth:** The TL072 has a wide bandwidth, typically around 3MHz, allowing it to handle a wide range of frequencies.
- **High slew rate:** With a high slew rate of 13V/µs, the TL072 can handle fast-changing signals, making it ideal for high-frequency applications.
- **Low harmonic distortion:** The TL072 has low total harmonic distortion (THD), making it suitable for high-fidelity audio applications and other applications requiring low distortion.
- **Internally compensated:** The TL072 is internally compensated, which simplifies circuit design by eliminating the need for external compensation components.
- **High input impedance:** The op-amp features high input impedance, which reduces loading effects and is beneficial for high-impedance signal sources.
- **Low input offset voltage:** The TL072 has a low input offset voltage, which minimizes errors in high-gain applications.

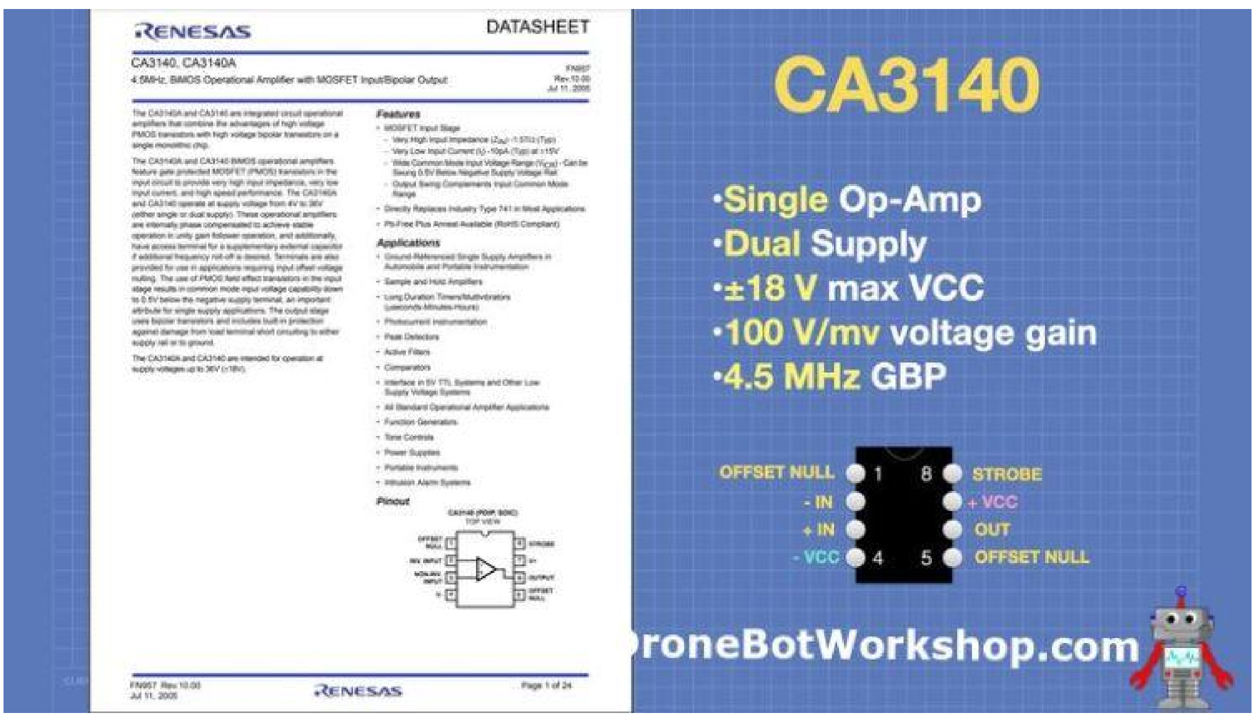
- **Short-circuit-protected outputs:** The outputs of the TL072 are short-circuit-protected, providing increased reliability in the event of a fault condition.

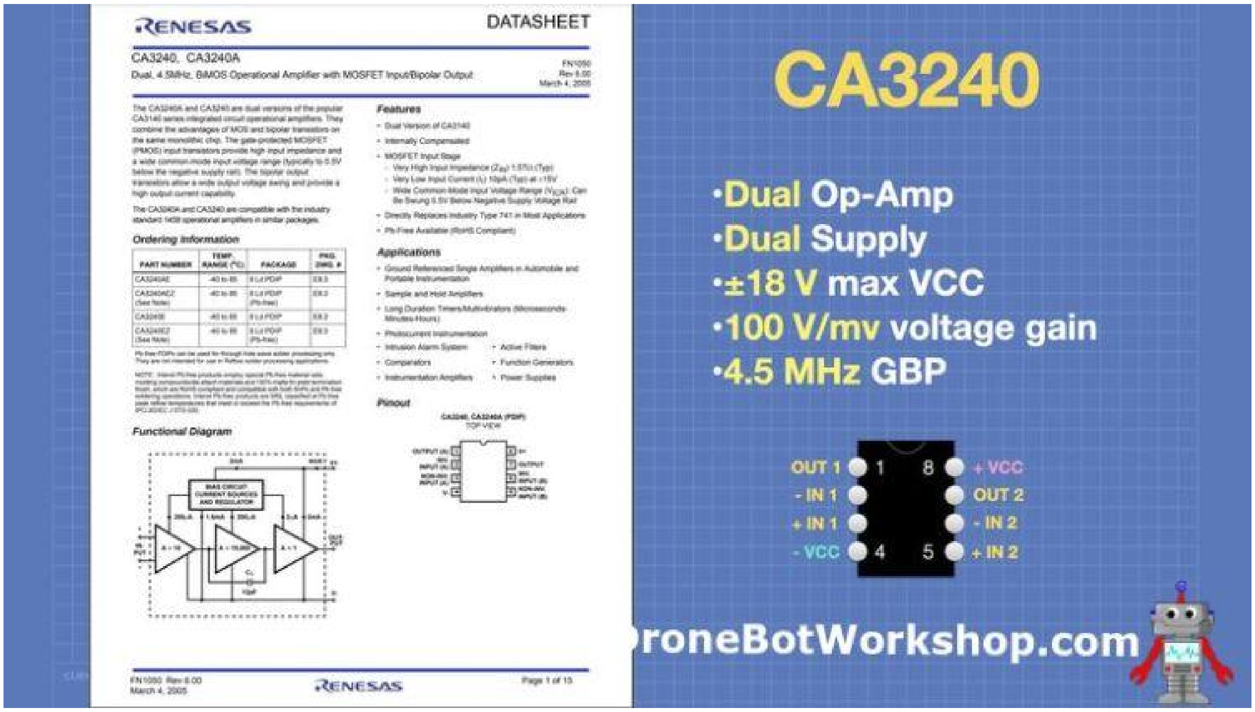
The TL072 operational amplifier is widely used in audio, instrumentation, and control systems due to its low noise, JFET input stages, and high slew rate characteristics.

Its wide supply voltage range, high input impedance, and short-circuit protection make it suitable for various applications, including audio preamplifiers, active filters, and signal conditioning circuits.

The TL072's low harmonic distortion, wide bandwidth, and high slew rate ensure excellent performance in precision analog signal processing tasks.

CA3140EZ & CA3240EZ





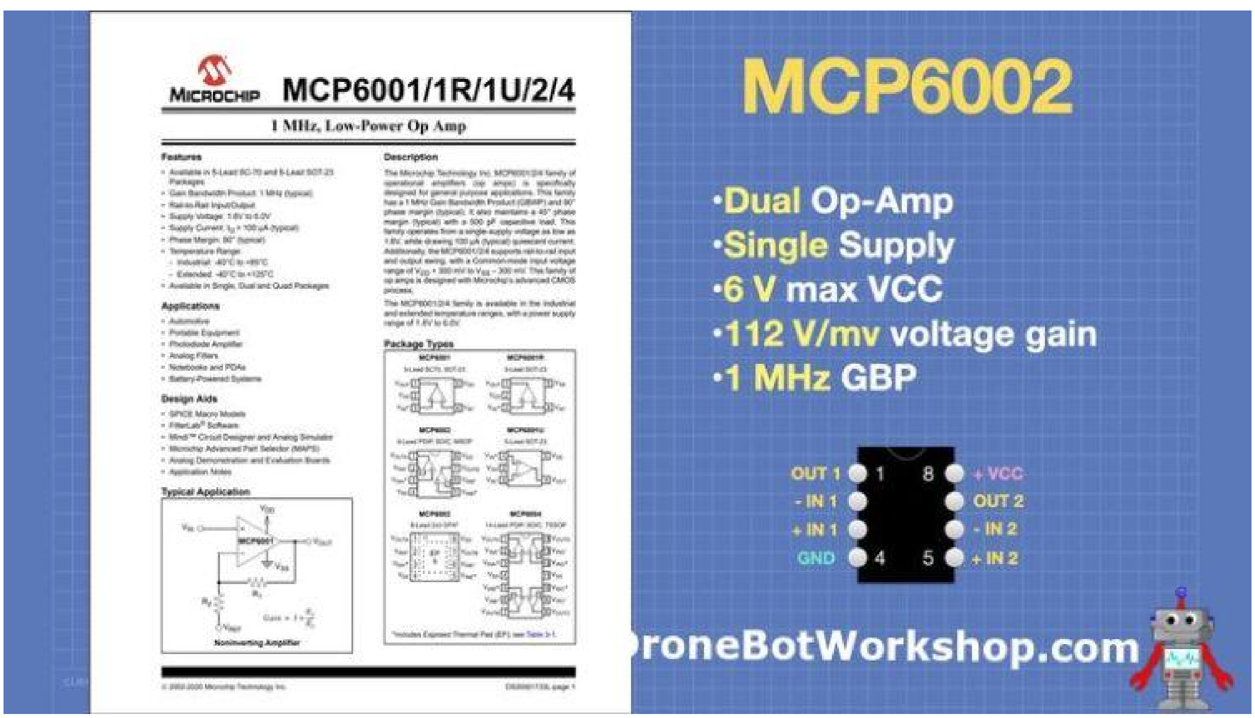
- **Single op-amp (CA3140):** The CA3140 is a single operational amplifier integrated into one circuit (IC).
- **Dual op-amp (CA3240):** The CA3240 is a dual operational amplifier, consisting of two separate op-amps within a single integrated circuit (IC).
- **MOSFET input:** The CA3140 & CA3240 feature a MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) input stage, providing high input impedance and low input bias current.
- **Wide supply voltage range:** The CA3140 & CA3240 can operate with a supply voltage range from ±4V to ±16V, allowing for a variety of applications.
- **Low input current**: The op-amps have very low input bias and offset currents, making them suitable for high-impedance input sources.
- **Wide bandwidth:** The CA3140 & CA3240 have a wide bandwidth, typically around 4.5MHz, allowing them to handle a wide range of frequencies.
- **High slew rate:** With a high slew rate of 9V/µs, the CA3140 & CA3240 can handle fast-changing signals, making them ideal for high-frequency applications.
- **Low input offset voltage:** The CA3140 & CA3240 have a low input offset voltage, which minimizes errors in high-gain applications.
- **Internally compensated:** The CA3140 & CA3240 are internally compensated, which simplifies circuit design by eliminating the need for external compensation components.

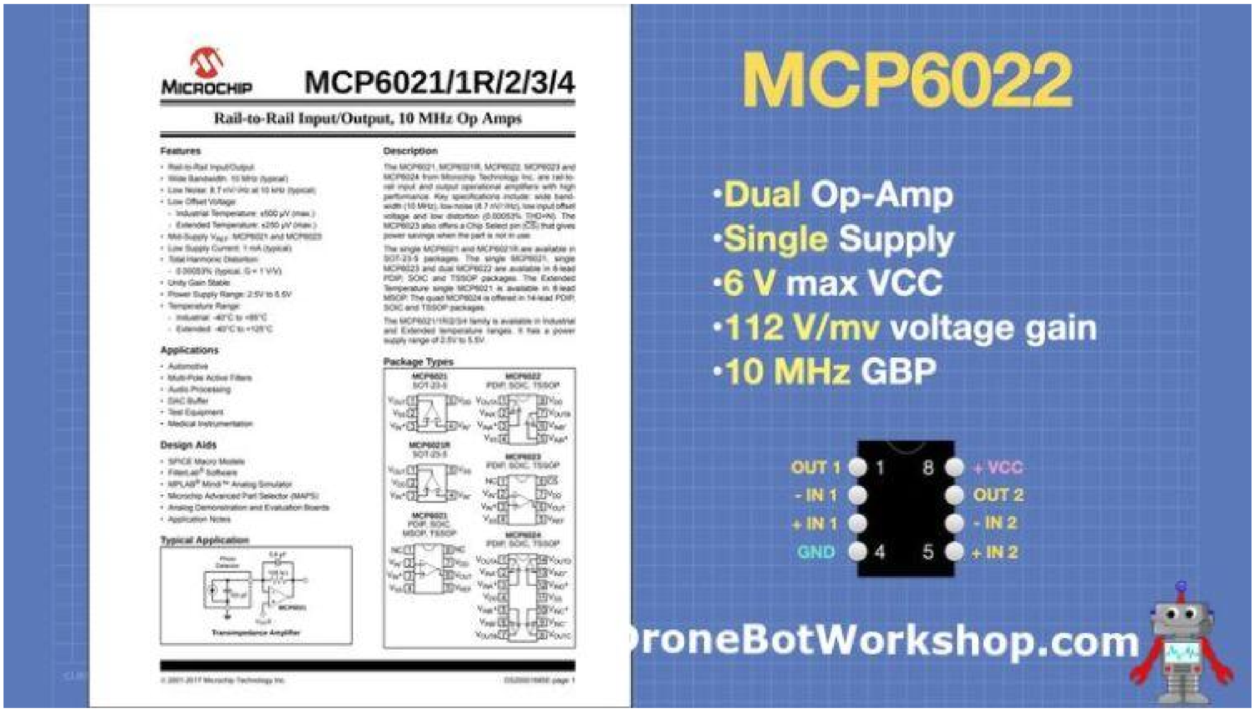
- **High open-loop voltage gain:** The op-amps feature a high open-loop voltage gain, making it ideal for precision applications requiring high gain.
- **Short-circuit-protected outputs:** The outputs of the CA3140 & CA3240 are short-circuit-protected, providing increased reliability in the event of a fault condition.
- **Wide common-mode input voltage range:** The CA3140 & CA3240 have a wide common-mode input voltage range, including ground, making them suitable for single-supply applications.

The CA3140 & CA3240 operational amplifiers are well-suited for various applications, including instrumentation, control systems, and signal conditioning, due to their MOSFET input stages, wide bandwidth, and high slew rate characteristics.

Their wide supply voltage range, high input impedance, and low input current make them ideal for high-impedance input sources and single-supply applications.

MCP6022 & MCP6002





- **Dual op-amp:** The MCP6002 & MCP6022 are dual operational amplifiers, consisting of two separate op-amps within a single integrated circuit (IC).
- **Low power consumption:** The MCP6002 & MCP6022 have low power consumption, making them suitable for battery-powered and energy-efficient applications.
- **Rail-to-rail output:** The MCP6002 & MCP6022 feature rail-to-rail output, which allows for a larger output voltage swing, nearly reaching the supply rails.
- **Single-supply operation:** The MCP6002 & MCP6022 can operate from a single supply voltage from 1.8V to 6V, simplifying power supply requirements.
- **Wide bandwidth:** The MCP6002 has a wide bandwidth, typically around 1MHz, and the MCP6022 has a 10MHz bandwidth.
- **Low input offset voltage:** The op-amps have a low input offset voltage, which minimizes errors in high-gain applications.
- **High input impedance:** The MCP6002 & MCP6022 feature high input impedance, which reduces loading effects and is beneficial for high-impedance signal sources.
- **Low input bias current:** The MCP6002 & MCP6022 have a low input bias current, reducing errors caused by input offset voltage in high-impedance circuits.

- **Wide temperature range:** The MCP6002 & MCP6022 can operate over a wide temperature range, typically from -40°C to +125°C, making them suitable for various environments.
- **CMOS technology:** The op-amp is designed using CMOS (Complementary Metal-Oxide-Semiconductor) technology, offering low power consumption and high noise immunity.
- **Short-circuit-protected outputs**: The outputs of the MCP6002 are short-circuit-protected, providing increased reliability in the event of a fault condition.

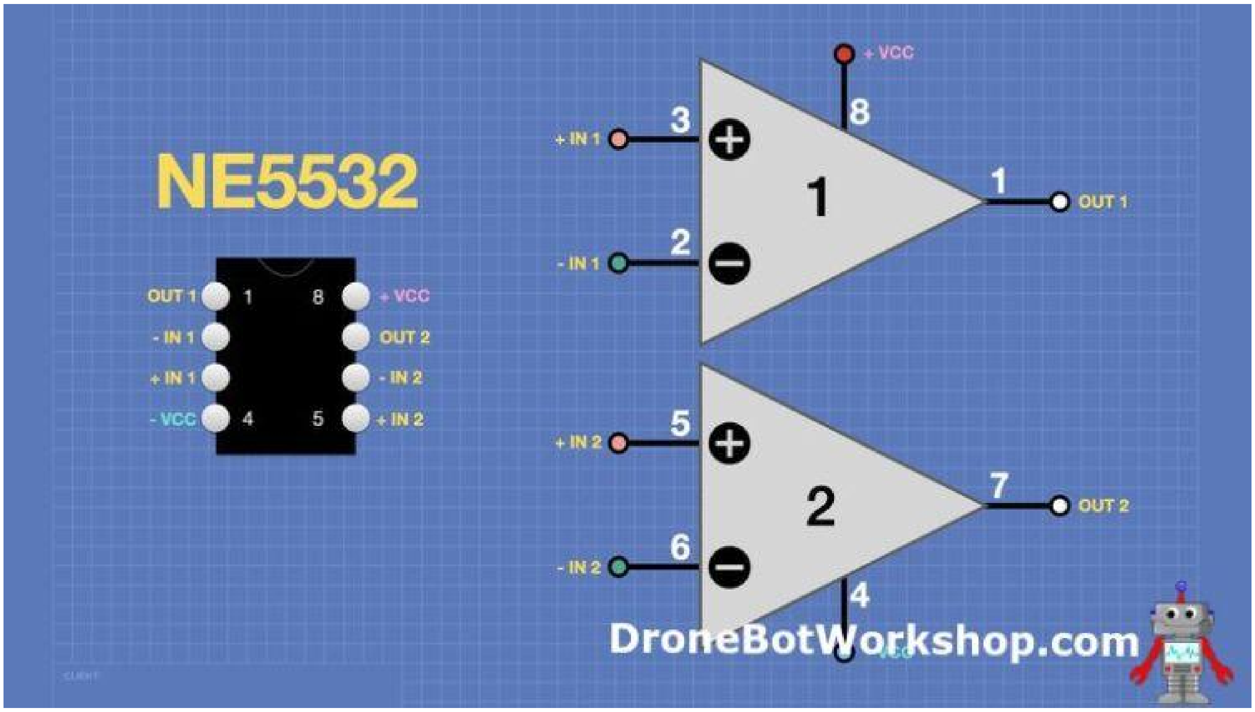
The MCP6002 & MCP6022 operational amplifiers are versatile components used in various applications, such as signal conditioning, filtering, analog-to-digital conversion, instrumentation, and control systems.

Their low power consumption, single-supply operation, and rail-to-rail output make them suitable for battery-powered devices and applications with limited power supplies. They are perfect for use with both 3.3 and 5-volt logic.

Op-Amp Basic Circuits

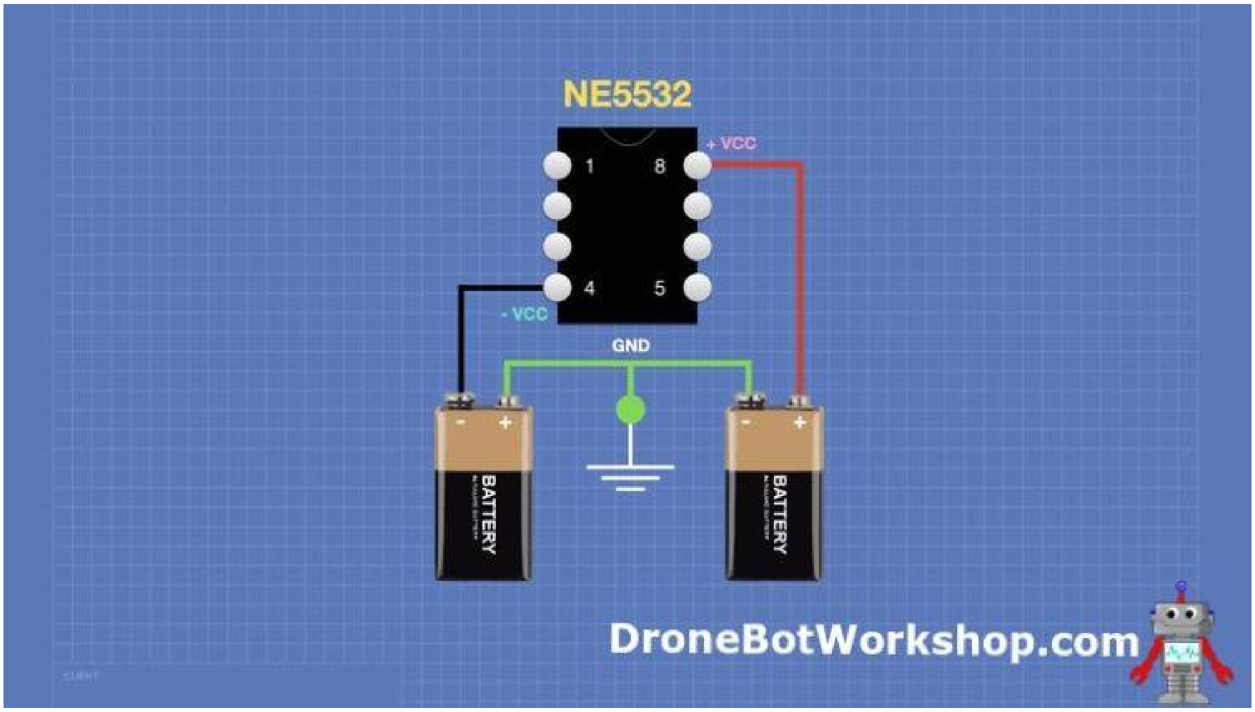
Let’s get the solderless breadboard out and experiment with some basic Op-Amp configurations.

For these experiments, we will be using the NE5532 Dual Op-Amp. It’s a standard, dual-supply voltage operational amplifier, so you need a bipolar power supply to get everything to work.



A very simple method of supplying power to the NE5532 is with two 9-volt batteries. This is the method I'm using in the video accompanying this article.

The power connection to the NE5532 is shown here. There are three power supply connections:

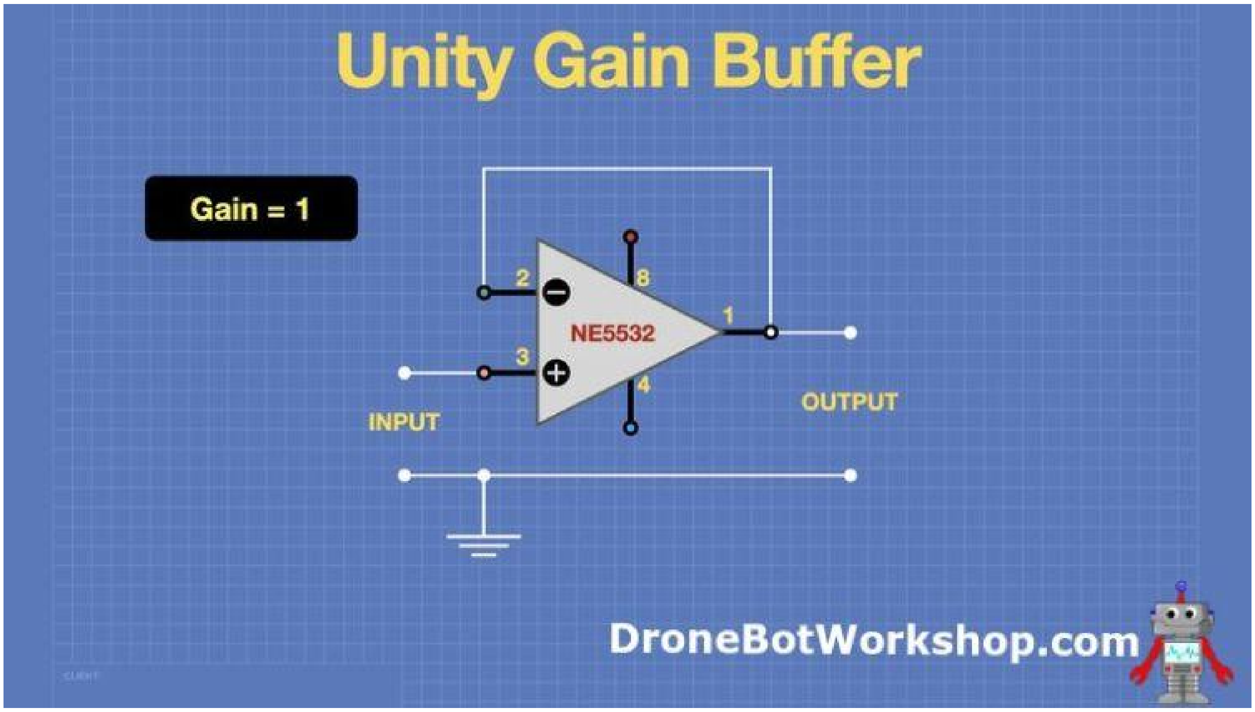


- Positive 9 volts
- Ground
- Negative 9 volts

The Ground is the connection between the returns of both the positive and negative batteries. Note that the NE5532, like all op-amps, does not have a ground connection pin.

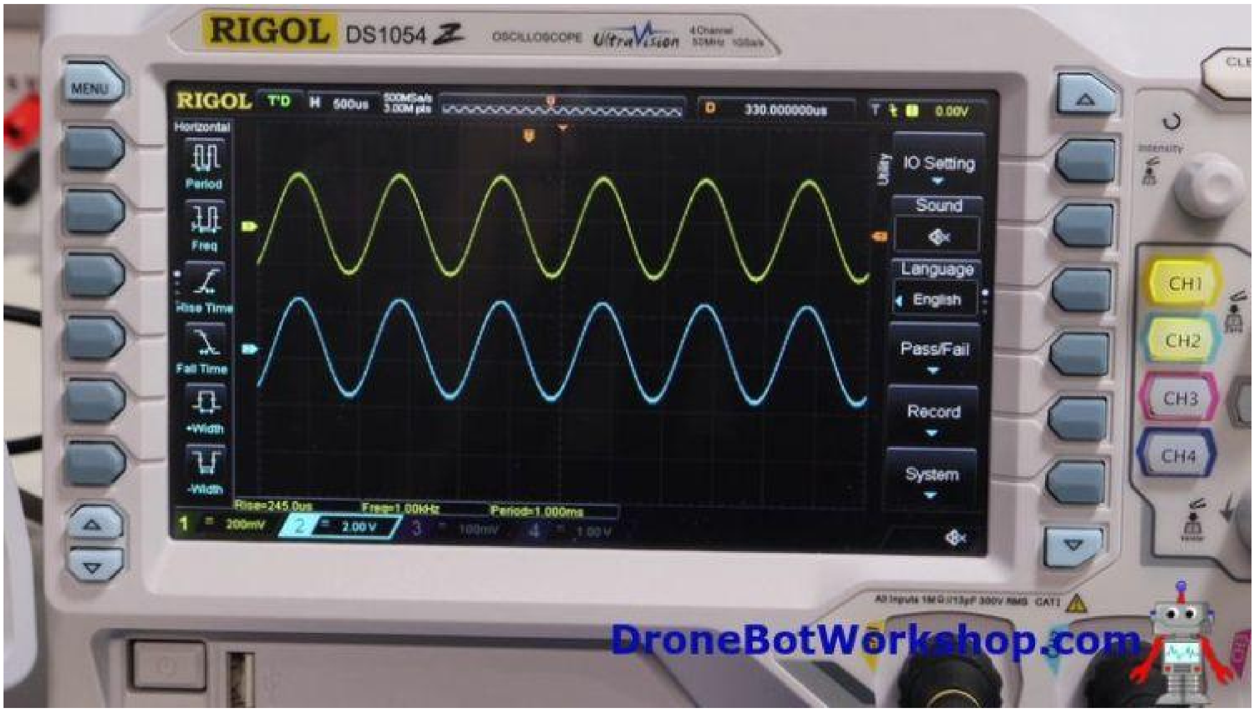
Voltage Follower (Buffer)

This is the simplest experiment of them all, as it literally requires only one component – the operational amplifier itself.



In this arrangement, the output of the op-amp is fed back to the inverting input. This keeps the gain of the amplifier at 1, which means no gain (or loss) at all.

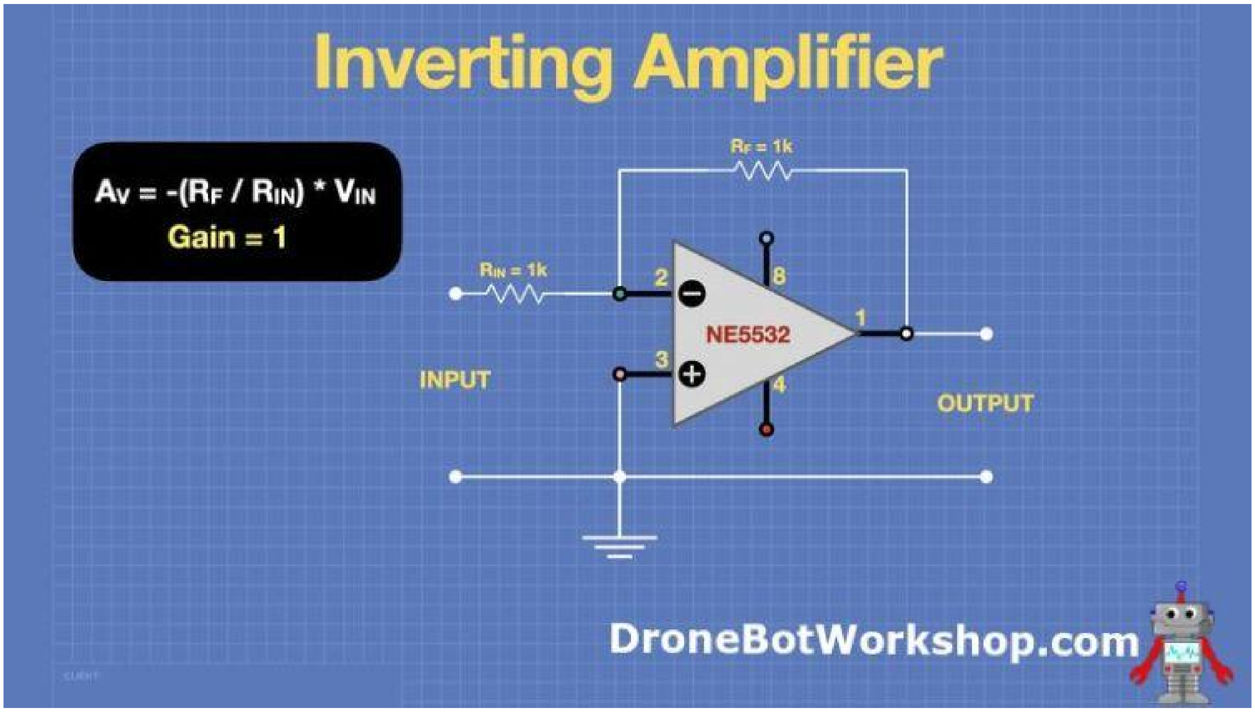
Buffers are used throughout analog designs, and the op-amp's high input impedance and low output impedance make it ideal for this purpose.



If you wire this up and feed it a signal, you should observe the same signal on the output. Here is the buffer illustrated on an oscilloscope. The sine wave is at 1kHz, and the top waveform is the input. Note that the output is identical to the input.

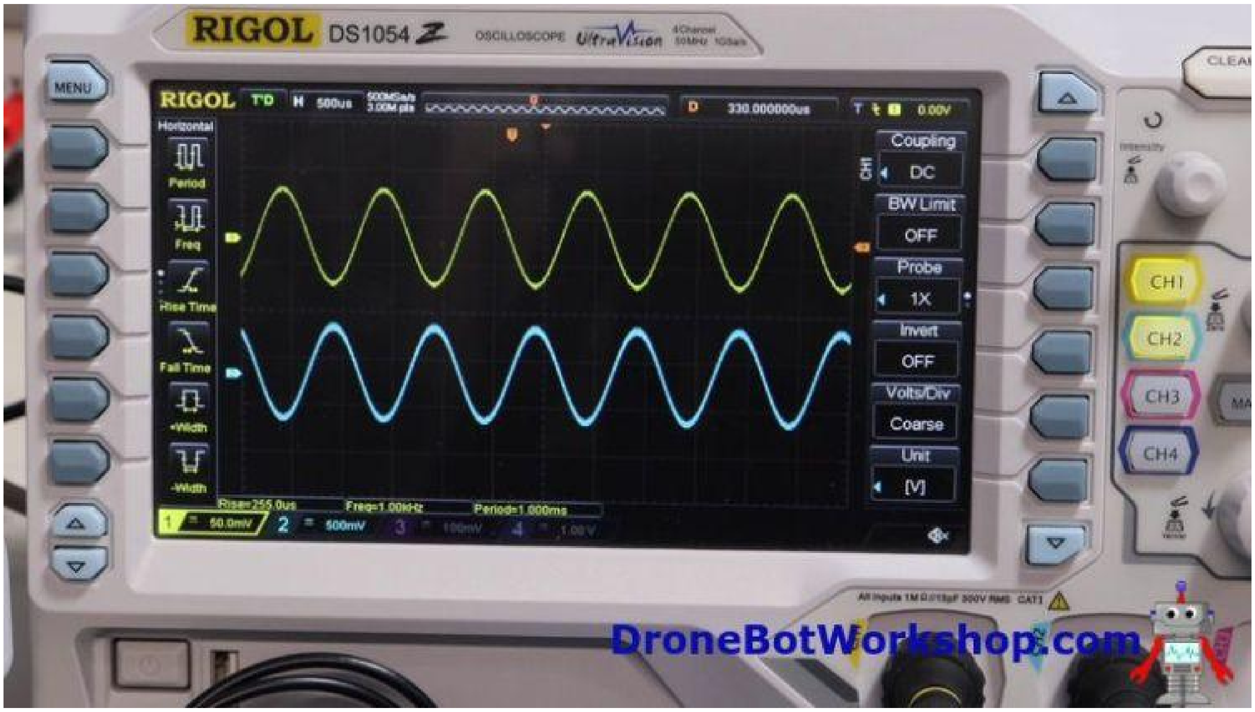
Inverting Amplifier

Next on the list is the inverting amplifier. This is a very common application, and it is often used in audio designs.



The gain of the inverting amplifier is determined by the ratio of RF (the feedback resistor) and RIN (the input resistor). With the two 1k resistors shown, the gain will be 1.

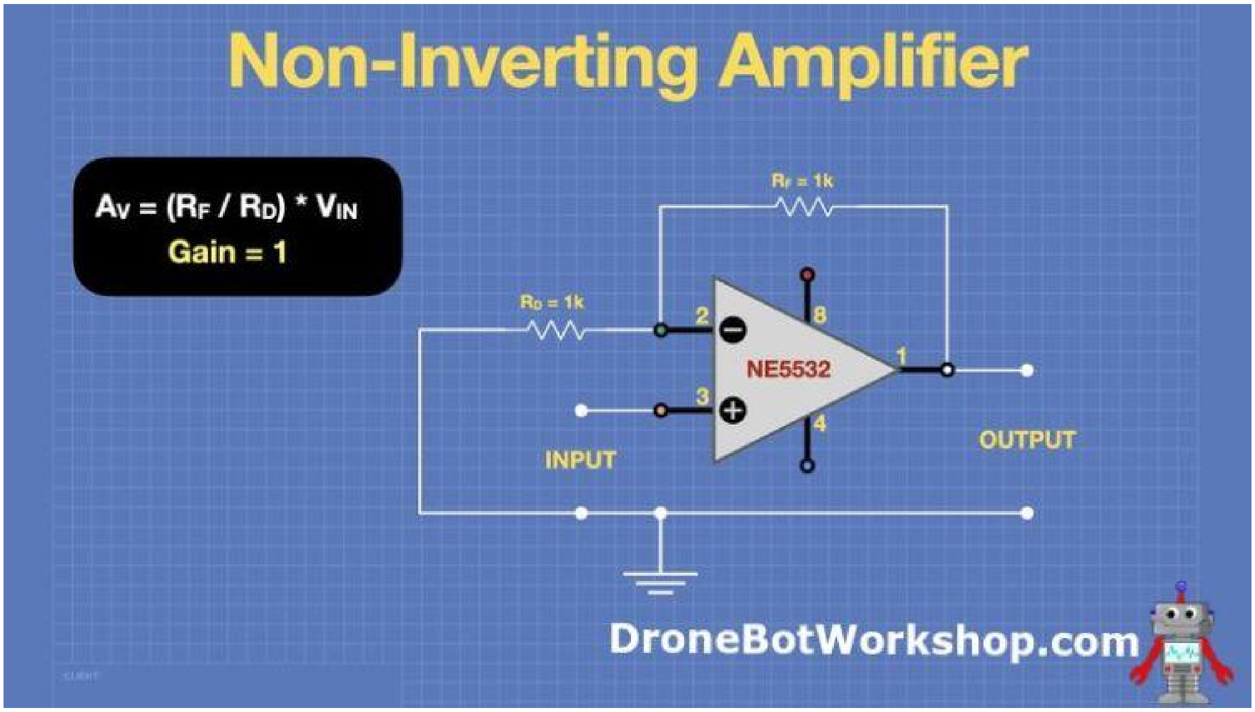
You could change RF to be a potentiometer to make a variable gain amplifier. A 20k pot would be ideal here.



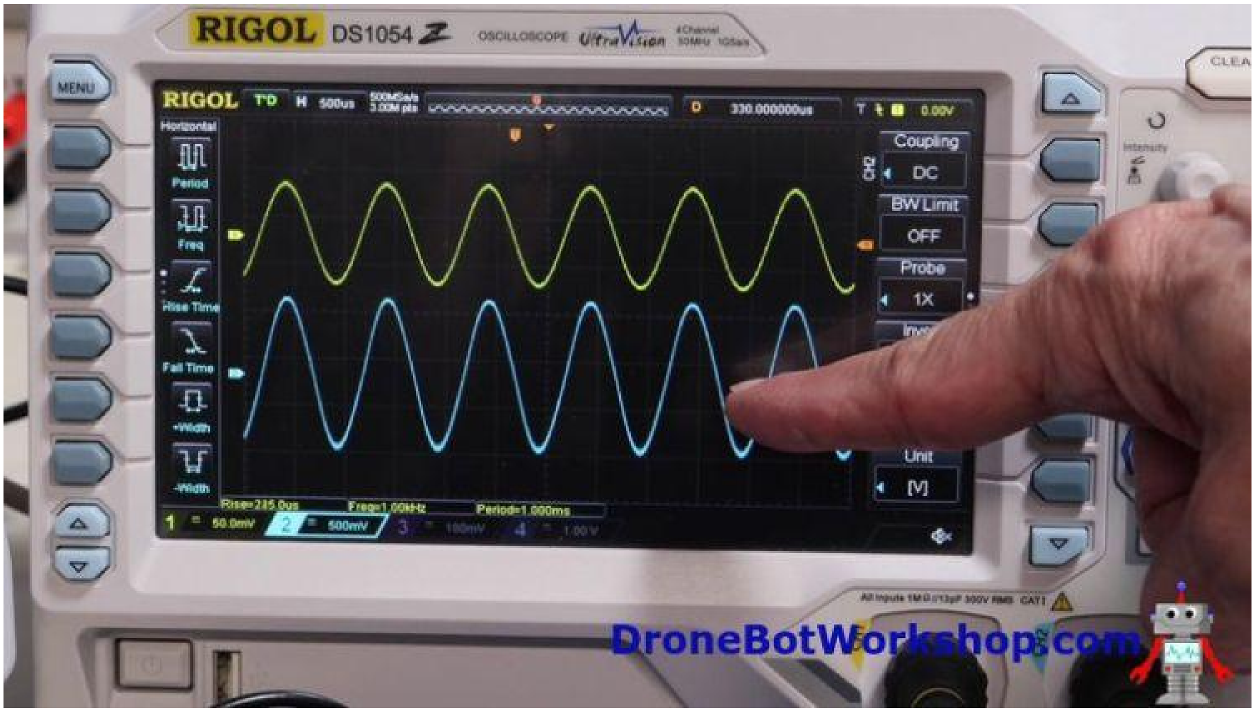
The oscilloscope shows the input (yellow) and output (blue). Note that the output is inverted from the input.

Non-Inverting Amplifier

You can also swap inputs on the Op-Amp to create a non-inverting amplifier.



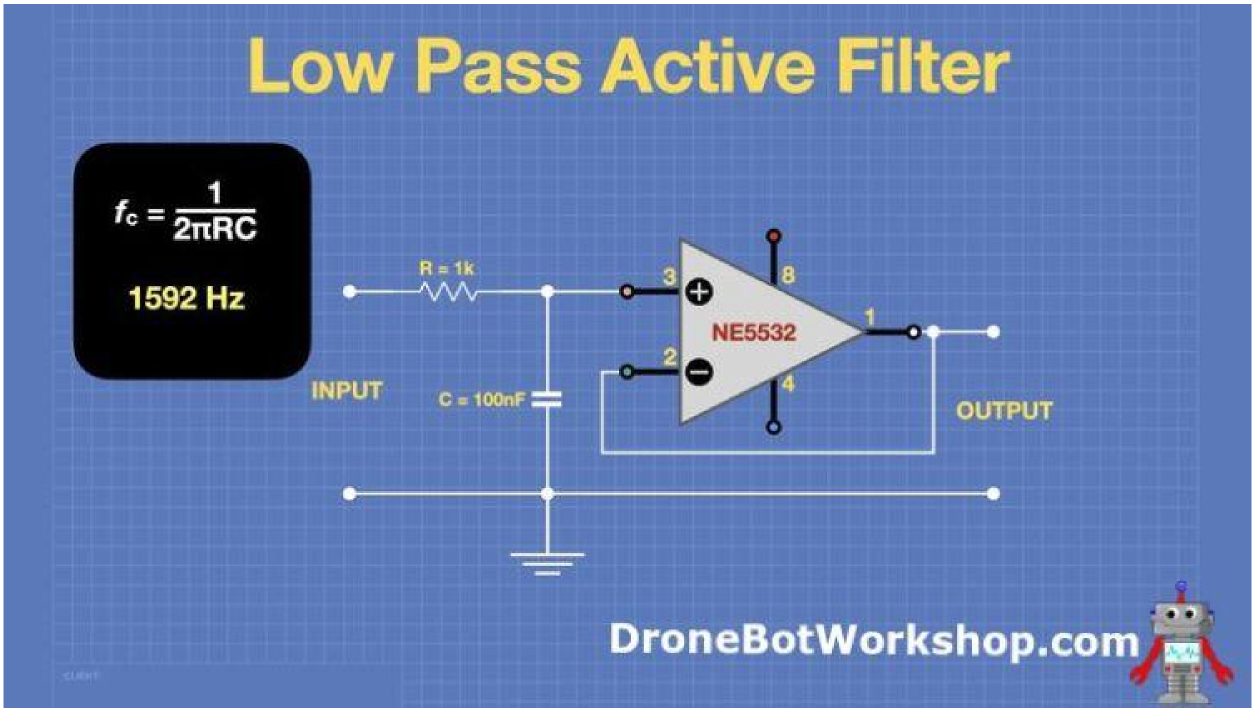
Once again, the gain is determined by the ratio of two resistors, RF and RD. In this case, the feedback loop goes back to the inverting input while the signal is fed into the non-inverting input.



As the scope trace shows, the input and output are in phase.

Low-Pass Filter

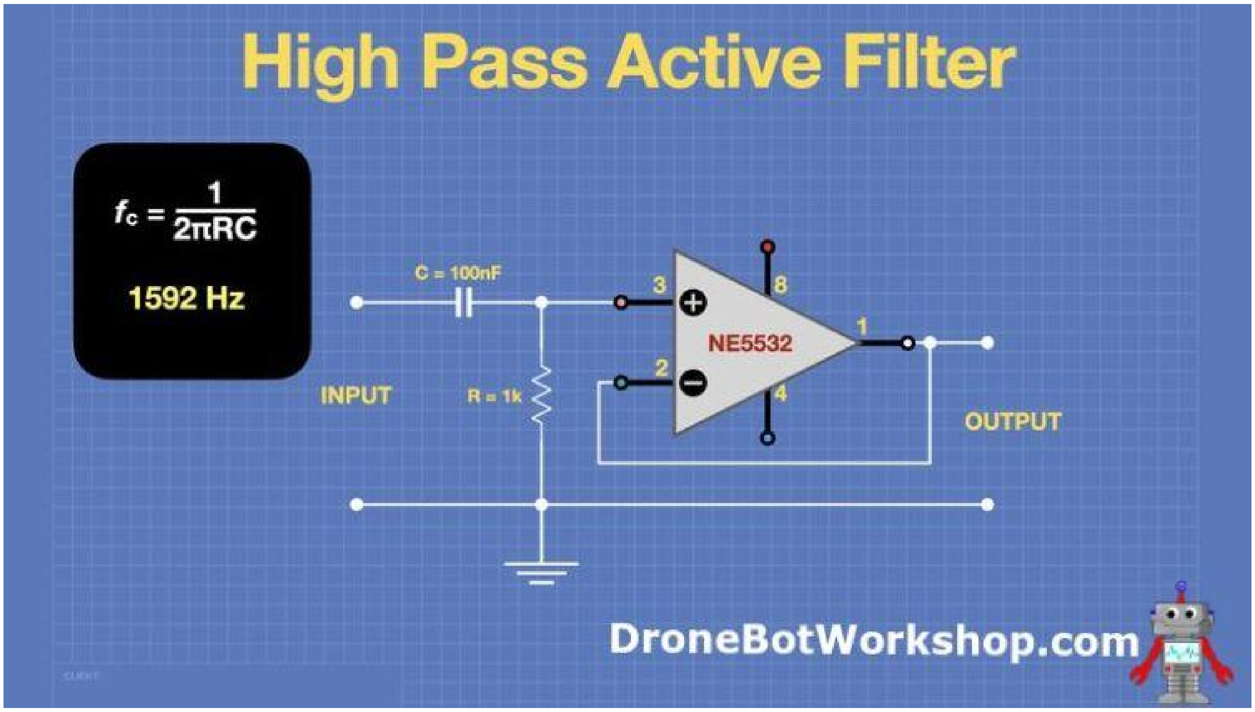
In the next experiment, we will build a low-pass filter using the NE5532 op-amp.



As you recall, the low pass filter allows lower frequencies to pass while attenuating the higher ones. This filter has an attenuation of 3dB per octave, so every time the frequency doubles, the signal is reduced by 3 decibels.

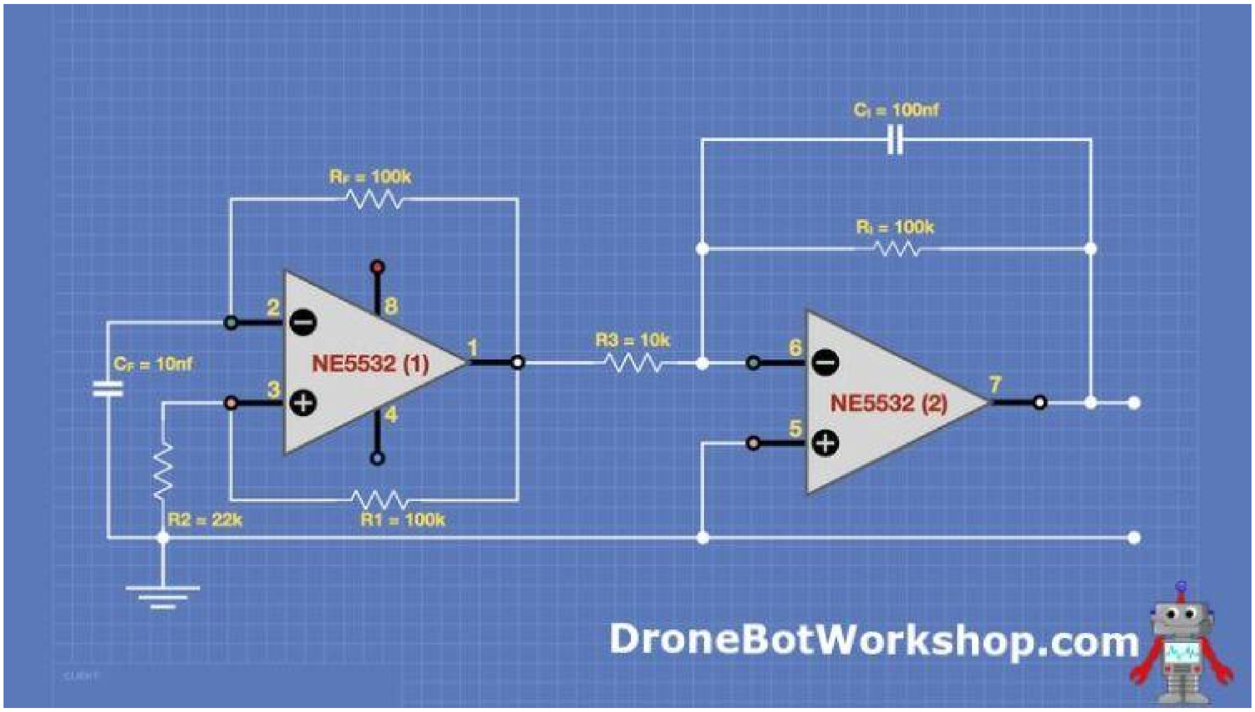
High-Pass Filter

We can construct a high-pass filter by flipping around the resistor and capacitor. This filter has the opposite properties to those of a low-pass filter; in a high-pass filter, the lower frequencies are attenuated while the higher ones pass through.



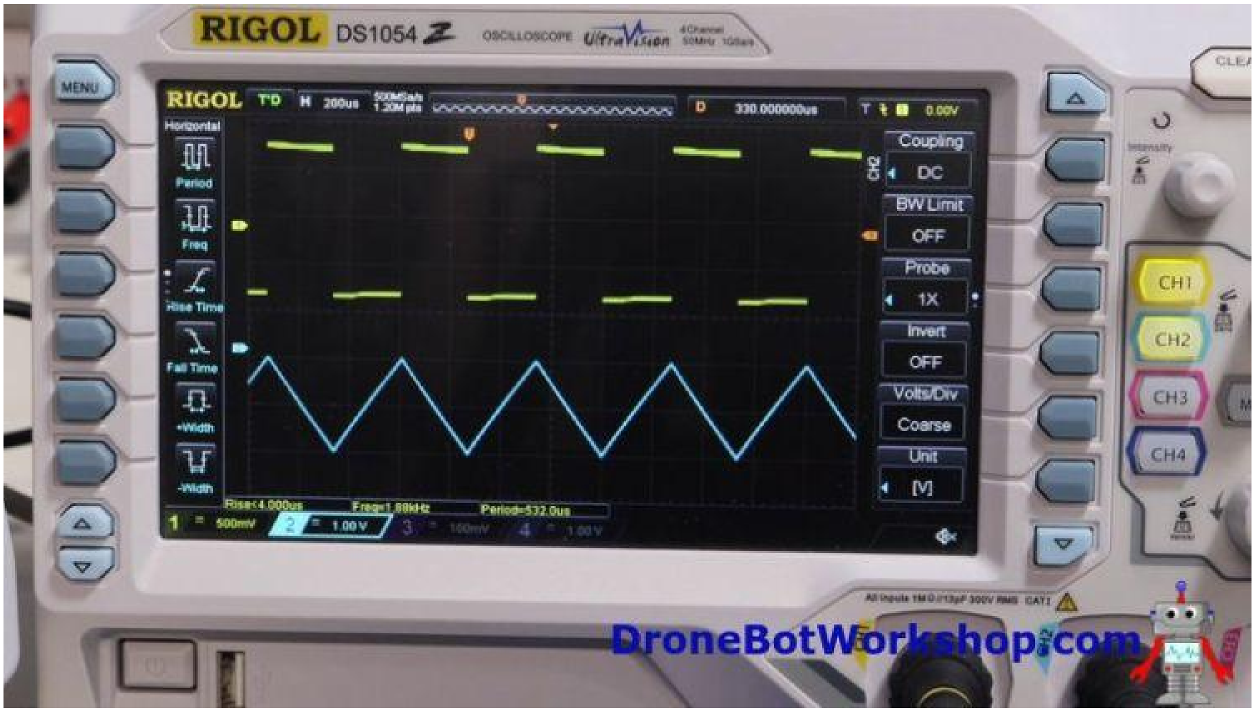
Square & Triangle Wave Generator

The final experiment we will perform with the NE5532 is actually two circuits, so we'll use both op-amps in the package.



The first circuit is a multivibrator that will produce a square wave. You can change the wave frequency by altering the value of the resistor and capacitor.

The second circuit is an integrator, which will turn the square wave into a triangle wave.



Op-Amps with Microcontrollers

While operational amplifiers are analog components, they can also be used with microcontrollers. There are a couple of ways of using Op-Amps to expand your project:

- **As a Comparator** – Using the Op-Amp in a comparator configuration, with its output fed into a digital input on the microcontroller.
- **With the ADC** – Most microcontrollers have a built-in ADC (Analog to Digital Converter). You can use an Op-Amp to amplify or condition the input to the ADC.

We will experiment with the second method.

Using an Op-Amp with the Arduino Analog Input

The analog-to-digital converter, or ADC, on the Arduino Uno is a 10-bit unit, so it has a resolution of 1024 discrete points that it can measure.

By default, the Arduino Uno ADC measures voltages in the range of 0 to 5 volts DC; that maximum voltage is equal to the supply voltage the Uno uses. You can set the voltage threshold to a different voltage by applying a reference voltage (5 volts or less) to the *AREF* or Analog Reference pin.

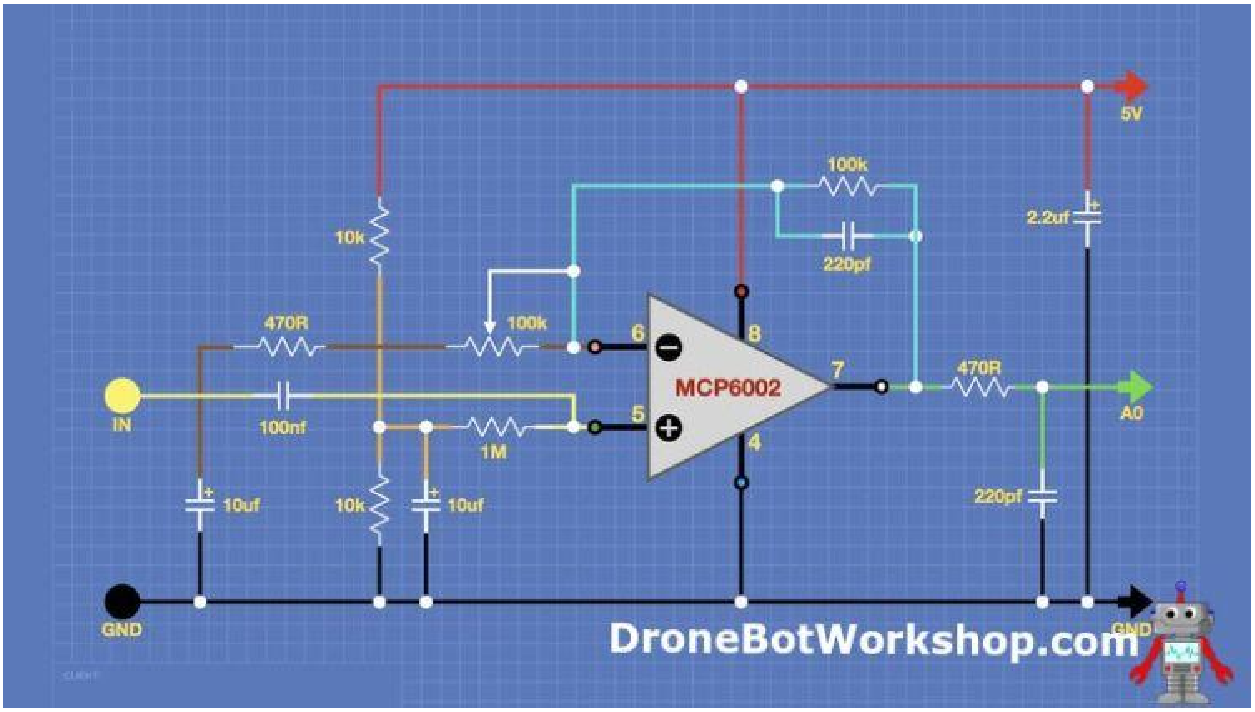
If you need to measure a voltage significantly less than 5 volts (or the voltage applied to the AREF pin), then you will sacrifice a lot of accuracy, as you won't be using the full 10-bit range of the ADC. For example, with a 5-volt reference and an input that never exceeds 2.5 volts, you would only have your reading spread over 512 points instead of 1024.

A solution for this, or for measuring very low (or negative) voltages with the Arduino ADC is to use an Op-Amp to amplify the signal first.

A great choice for this is the MCP6002, which we looked at earlier. It is a single-supply Op-Amp with a maximum VCC of only 6 volts, so it is well suited to both 3.3-volt and 5-volt microcontrollers.

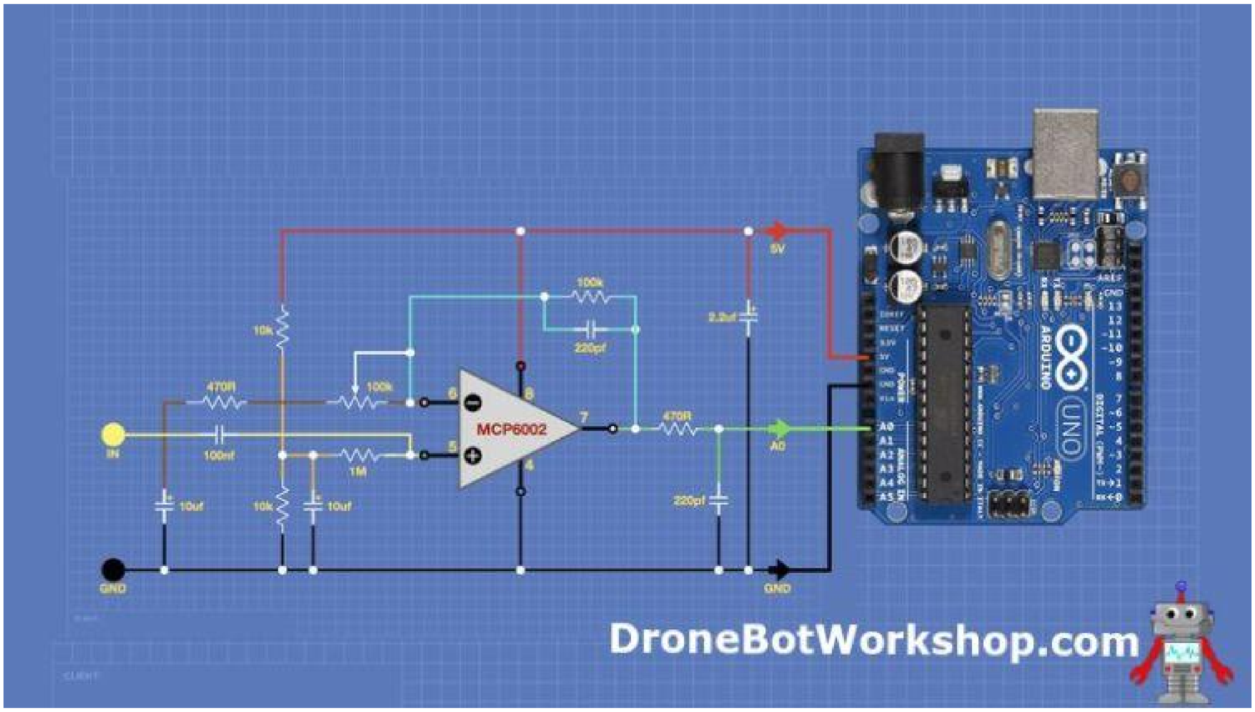
Op-Amp Hookup

The amplifier is a classic, non-inverting design. The gain is set by both the feedback resistor and the 100k potentiometer.



The input of the amplifier has a 100nf capacitor to block DC voltages so that it can be used with audio signals. You can eliminate the capacitor if you want to allow DC voltages to pass through.

The output of the amplifier is fed into one of the analog inputs on the Arduino. I used the first one, analog input A0.



The 5-volt Arduino Uno power pin powers the whole thing. There is a 2.2uf filter capacitor across the power supply, it should be located as physically close to the MCP6002's power supply pins as possible.

Of course, the MCP6002 has two op-amps, so you could build two circuits and use them with multiple analog inputs.

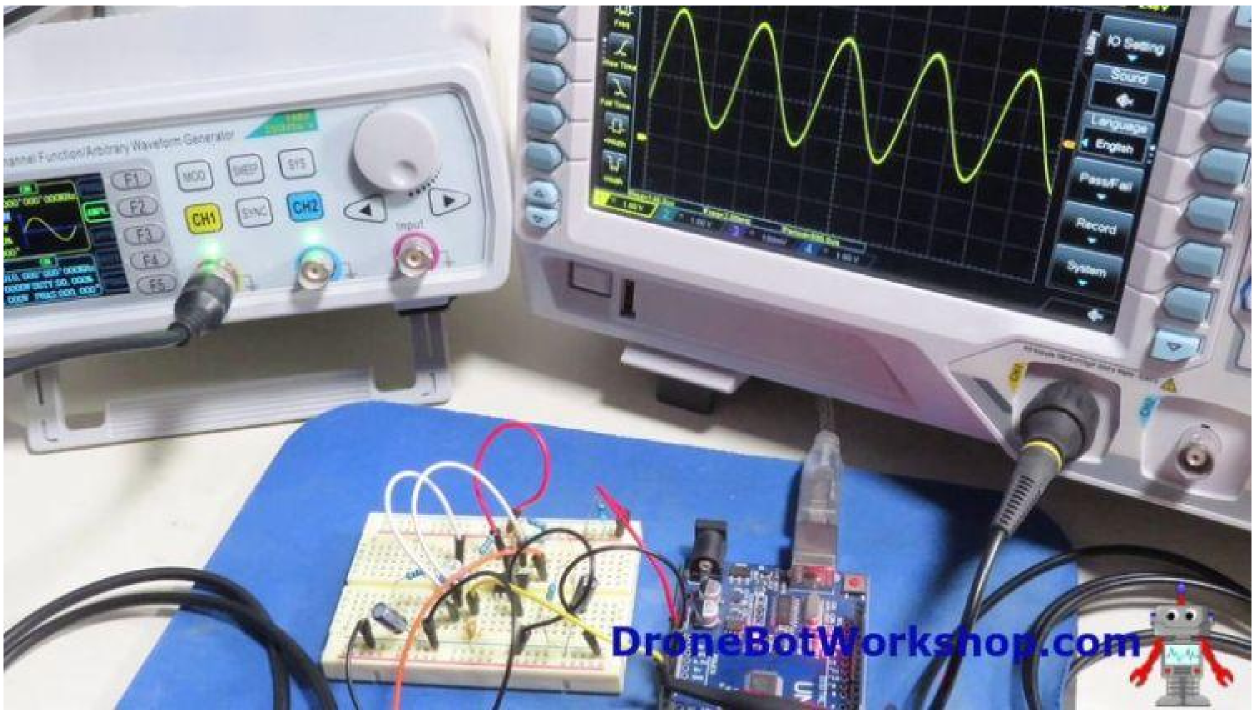
Arduino Sketch and Test

The sketch for this demonstration really couldn't be any simpler, as all we need to do is to read the ADC pin A0 input, write it to the serial plotter and then do it all over again. Here is a quick sketch I threw together:

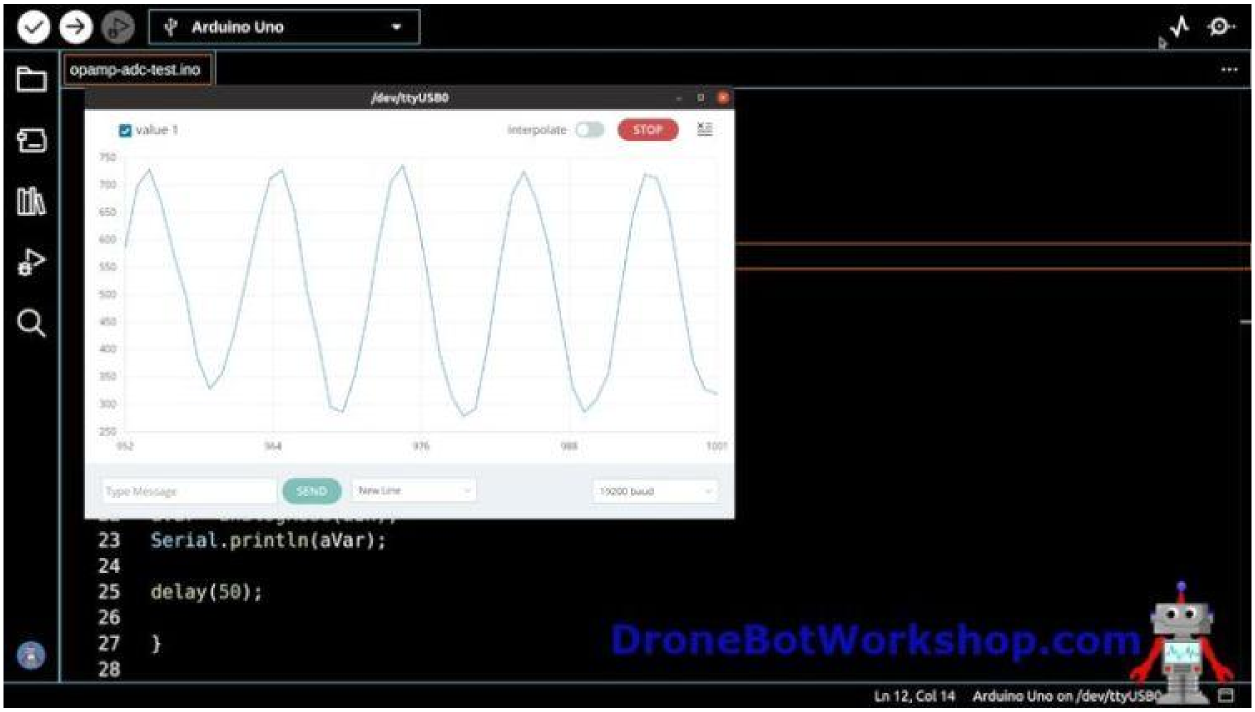
```
/*
  Arduino Op-Amp ADC Test
  opamp-adc-test.ino
  Demonstrates Op-Amp with ADC

  2023 DroneBot Workshop
  https://dronebotworkshop.com
*/

int aIn = A0;
int aVar = 0;

void setup() {

  Serial.begin(19200);

}

void loop() {

aVar =analogRead(aIn);
Serial.println(aVar);

delay(50);

}
```

I’m using a 2KHz sine wave from my waveform generator at 0.1 volts for the demo, so I chose the delay time in the sketch to suit this. If you use a different frequency, you could try changing the delay time for a better display.

The result on my serial plotter looks a bit like a sine wave, and it is at a much higher level than the Arduino would be able to define without amplification.



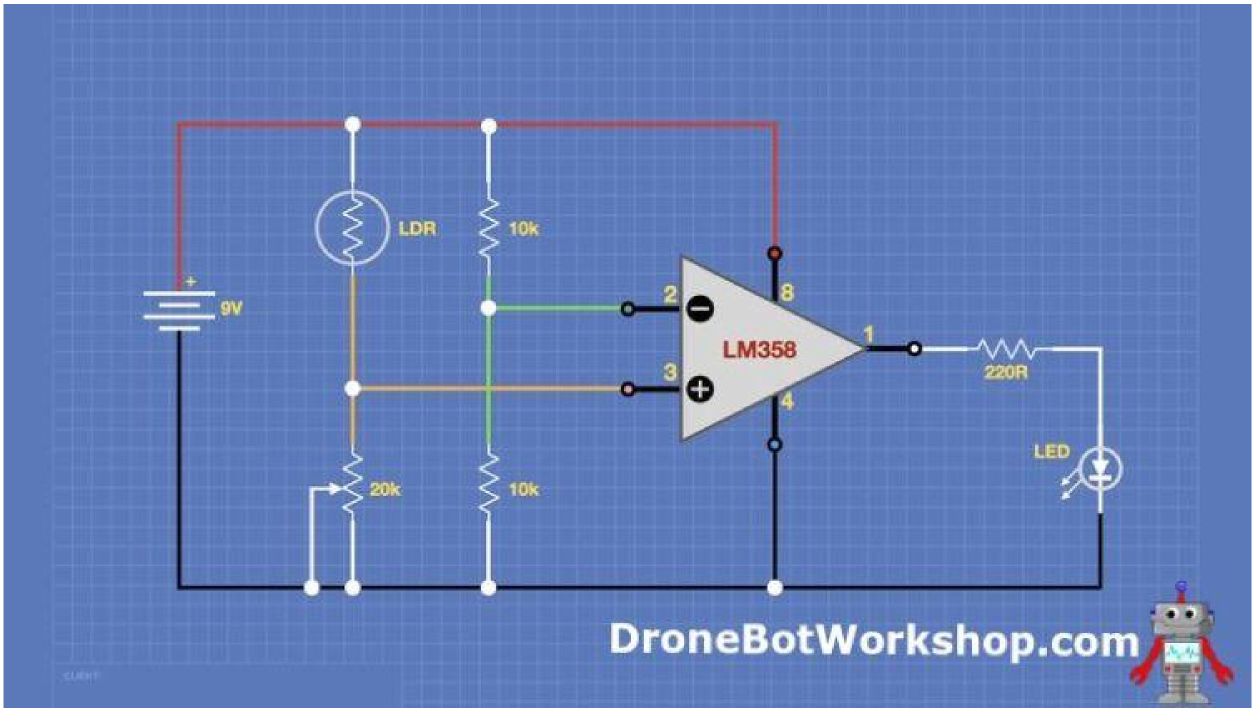
You can adjust the value of the feedback resistor and other components to suit your needs.



Light-Sensitive Switch

A light-triggered electronic switch is something that you might build with an Arduino, but it is a lot easier (and a lot cheaper) to use an op-amp.

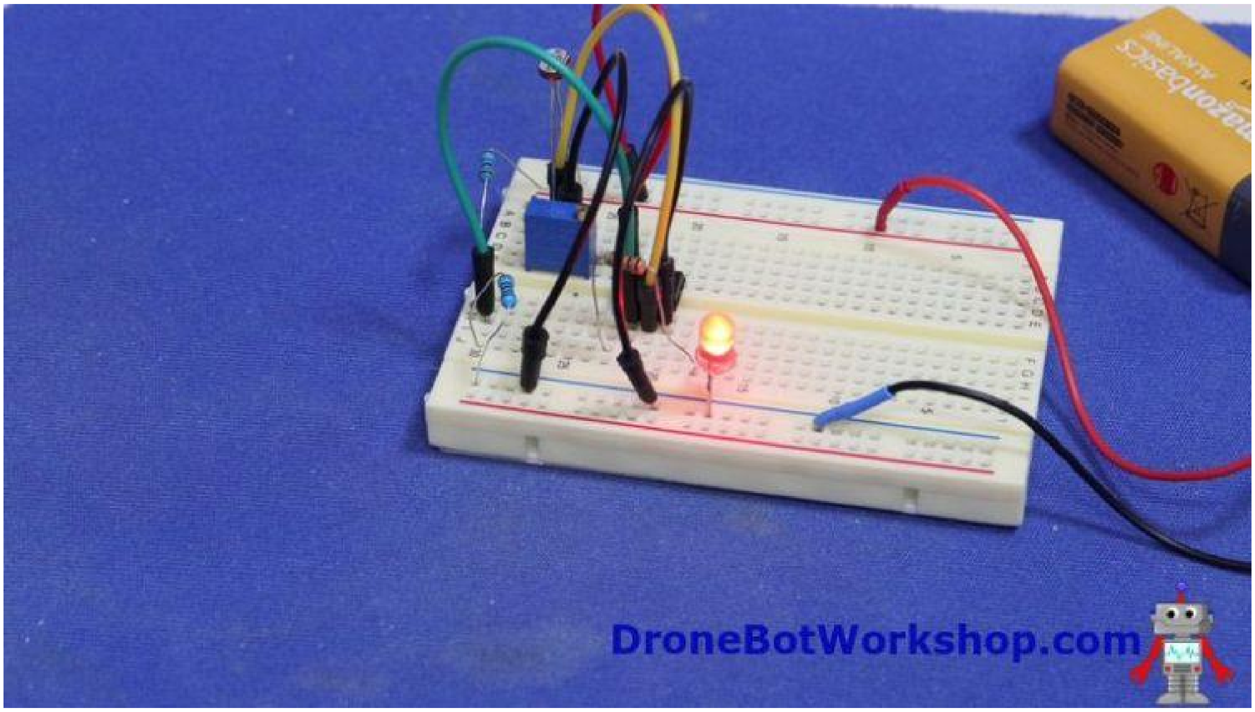
This is a simple circuit that just triggers an LED. Of course, it's just an example, and you could replace the LED with a transistor and a relay if you wanted to control something else.



The circuit is essentially a comparator, comparing a voltage reference with a voltage divider formed by a potentiometer and a photo-resistor. The resistance of the photo-resistor will change as it is exposed to light. You can adjust the potentiometer to set the trip point of the comparator.

As shown, the LED will light in the presence of light and will be extinguished when you block light to the photo-resistor.

You can reverse the operation by connecting the LED to the 9-volt positive supply, be sure to connect the anode side of the LED to the 9-volts and the cathode to the 220-ohm resistor. Now, the LED will light when the photo-resistor is blocked.



Pretty simple and a lot cheaper than an Arduino. Plus no code to write!

Single to Dual Power Supply

As you have undoubtedly noticed, operational amplifiers often require dual power supplies, that is, power supplies with both a positive and negative output referenced to ground.

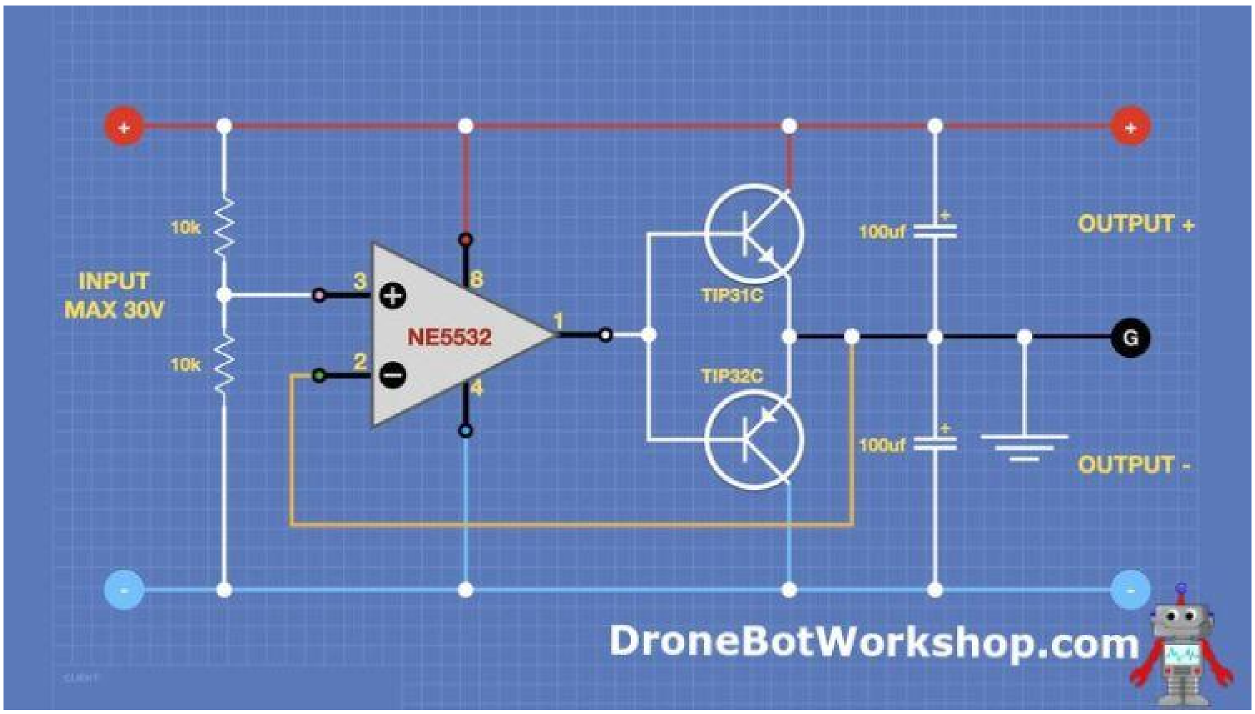
This can often be a problem, as dual power supplies are not as common as single ones. If you want to perform breadboard experiments with op-amps, it can be inconvenient to always rely on batteries. But the expense of a new power supply is usually not in the budget.

In this final example, I'll show you how to split a power supply into two components with a common reference. This can convert a single power supply to a dual one for just a few dollars worth of components.

And, of course, the circuit is based upon an op-amp!

Dual Voltage Hookup

This is a pretty basic circuit, and you can use a wide variety of components to build it. As illustrated, it will handle currents of up to 3 amperes.



The design is based around an NE 5532 op-amp, but any dual power supply op-amp could be used. The power requirements of the op-amp will limit the maximum input voltage, as the NE5532 has a +15 and -15 volt supply; this means the input cannot exceed 30 volts.

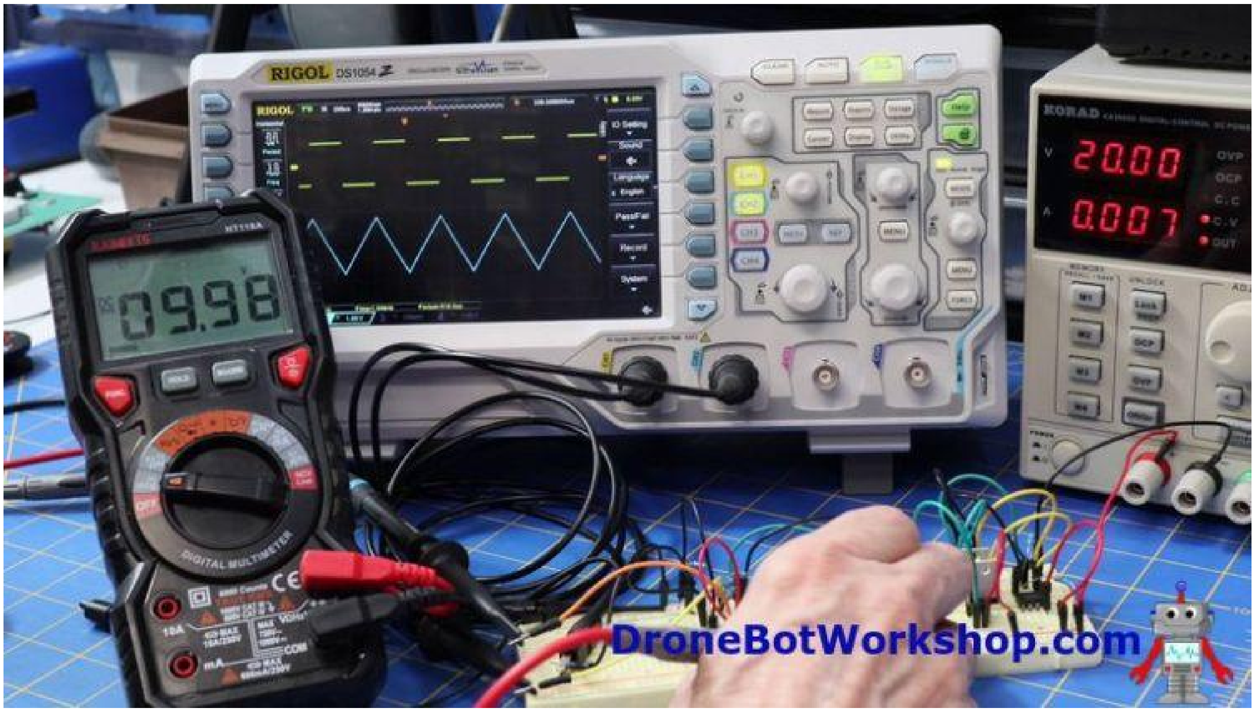
The two output transistors are a complementary pair; in other words, they are NPN and PNP power transistors with the same specifications. The TIP31C and TIP32C have a maximum current rating of 3 amps, if you want to increase this limit, you could substitute a TIP41C and TIP42C, which have a 6-ampere rating. In both cases, you will need to mount heatsinks on the transistors to achieve their maximum current rating.

The only other components are a pair of 10k resistors, which form a voltage divider, and some 100uf filter capacitors. Make sure the filter capacitors are rated to handle the output voltages, I used devices rated at 35 volts.

Testing the Dual Supply

Once the circuit is constructed, you can test it by applying power to the input. **Ensure the input power supply does NOT have its negative side connected top ground! The input voltage MUST be floating**; otherwise, you will risk a short circuit when connecting a device that is also grounded to the output.

I tested the supply using the square and triangle wave generator we constructed earlier. With a 20-volt input, I received two very closely matched output voltages, and the circuit worked properly.



This is an easy method of building a dual power supply. You can also add additional voltage regulation to the output if you wish, but it really shouldn't be necessary.

Conclusion

Operational Amplifiers are truly versatile devices. Their low cost, relative ease of use, and easy availability make them a good choice for many of your designs.

And while it isn't very likely that you'll be building an analog computer soon, you can also use op-amps to enhance your digital designs.

Hopefully, this guide and its associated video will help you to get started with these useful analog components