Electronics 101.10: Op-amps

The arithmetic engines of analogue electronics

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Up until now, we've been learning about discrete components: resistors, capacitors, inductors, diodes, transistors. We've looked at some things we can do with them: filters, amplifiers, and such. In the last issue, we had a fairly deep look at integrated circuits. In this issue, we'll mash that all together by looking at a category of integrated circuit devices that let us do what we were doing before, but more easily and more effectively: operational amplifiers, or op-amps for short.

An op-amp is essentially a sophisticated differential amplifier – they have two inputs, and amplify the difference between the inputs. A key feature of an op-amp is that it has little impact on whatever is connected to its inputs, due to having a very high input impedance. Conversely, it has a very low output impedance, and is able to supply significant current to its load. It also has an incredibly high gain (typically 10^5–10^6: a fraction of a millivolt difference between its inputs can cause the output to go from one extreme to the other.

OP-AMPS ARE HIGH GAIN DIFFERENTIAL AMPLIFIERS

Figure 1 shows the functional block diagram of one of the four op-amps in the LM324N, which we'll be using. Since the input stage is a differential amplifier, an op-amp has - and + inputs. These are better thought of as inverting and non-inverting inputs, respectively, and not negative and positive. **Figure 2** shows the pinout of the LM324N, and **Figure 3** shows the standard symbol for an op-amp.

While many op-amps often require dual voltage power supplies (e.g. +12 V and -12 V), there are some that work with only a positive supply voltage. For the hands-on circuits, we'll be using the LM324N, which you can power with from +3 V to +32 V. Unless specifically noted, the described circuits assume dual (i.e. + and -) supply op-amps.

GOLDEN RULES

As stated in *The Art of Electronics*, there are two rules that an op-amp adheres to:

1. As given above, an op-amp has a high gain: the output jumps to one extreme or the other based on the relative values of the two inputs. It does this as it attempts to make the voltage difference. Due to this, the key to op-amp circuits is to feed this output back to one of the inputs to either enforce or reduce that input difference.

2. The inputs are high impedance, which means they draw no current, and so have a negligible impact on the connected circuit.

We'll see how these two features can be made use of later.

BASIC CIRCUITS

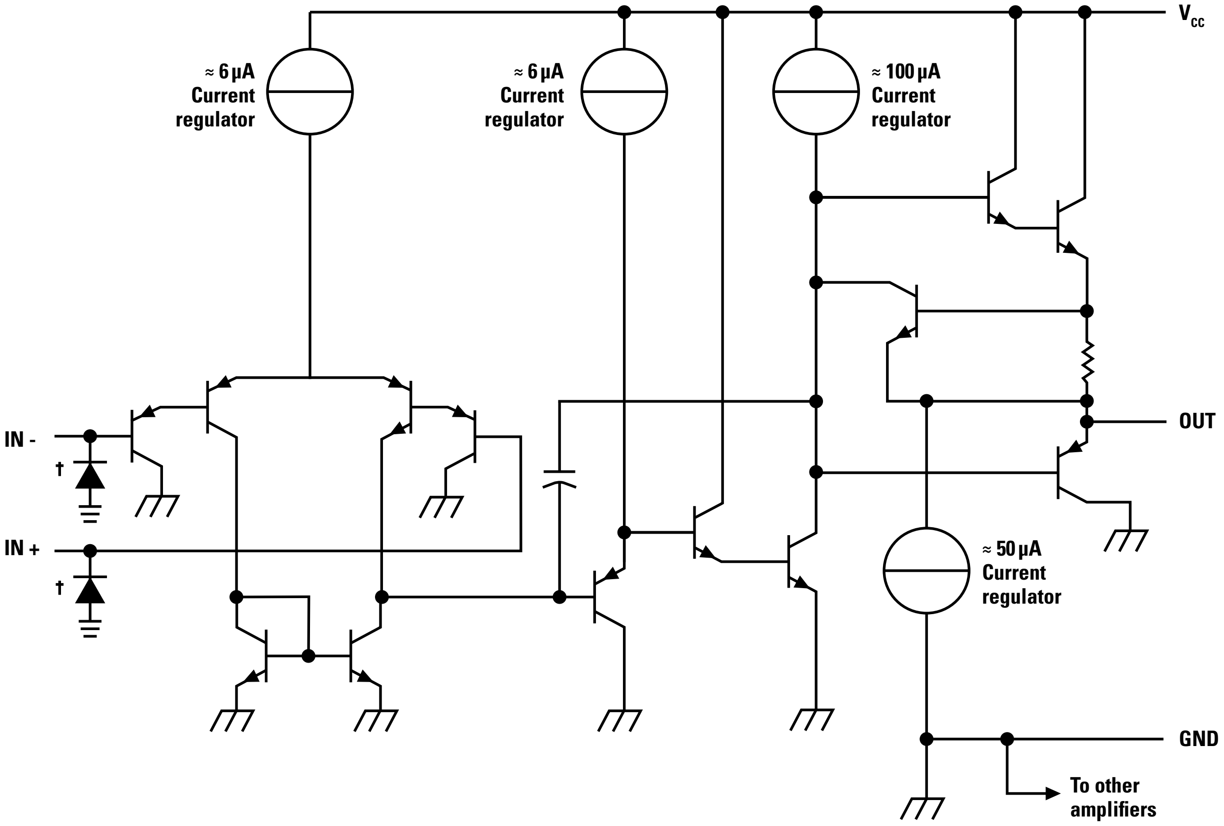
We'll start with some basic circuits that show the essence of op-amp use.

Figure 4 (overleaf) shows a basic inverting amplifier circuit. As you can see, the input signal is applied (through R1) to the inverting input, and the output is fed back to the same input through R2. The non-inverting input is connected to ground. With negative feedback, an op-amp will attempt to make the voltage difference between the two inputs zero. As we've tied the non-inverting input to ground, that's 0 V. R2 has Vout across it and R1 has Vin across it. Now, since the input isn't drawing any current, the current is only flowing through R1 and R2, so Vout/R2 = -Vin/R1. Given that, the gain (Vout/Vin) will be -R2/R1.

Figure 5 (overleaf) shows a simple non-inverting amplifier configuration. Notice that here, the input signal goes into the + (non-inverting) input and the feedback uses the - input. By rule one above, Va = Vin, but Va is at the midpoint of a →

YOU'LL NEED

- Solderless breadboard
- Adjustable 10 kΩ resistor/ potentiometer
- Several 10 kΩ and 100 kΩ resistors
- Capacitors in the 0.1 µF–100 µF range
- CdS photocell
- LED
- LM324N quad op-amp



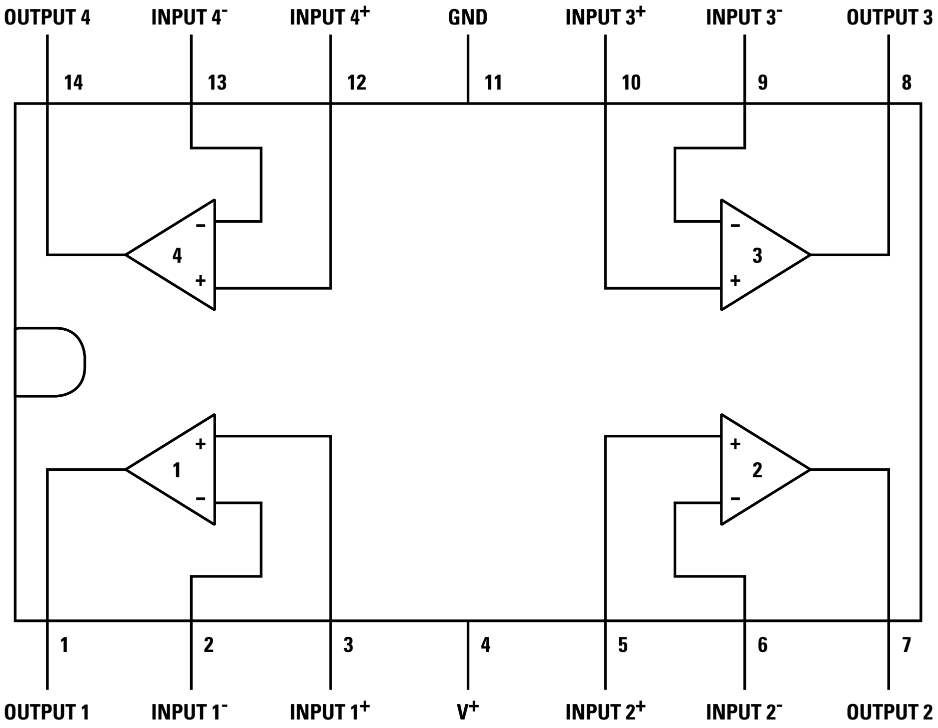
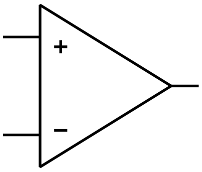


Figure 1 Functional diagram of one of the LM324N's op-amps

Figure 2 Pinout of the LM324N

Figure 3 The standard schematic symbol for an op-amp



voltage divider using R1 and R2 between Vout and ground. This means that Va = Vout R1 / (R1 + R2). Since Va and Vin are by definition equal, the gain Vout/Vin becomes:

```
gain=Vout/(Vout R1 / (R1 + R2))
gain=Vout(R1 + R2) / (Vout R1)
gain=(Vout R1)/(Vout R1) + (Vout R2)/(Vout R1)
gain=1 + (R2/R1)
```

As expected, the gain is a positive number since the amplifier is non-inverting. Note that the gain will always be >= 1.

AC AMPLIFIERS

So far, these have been DC amplifiers. By AC-coupling the input using a capacitor, we can make this into an AC amplifier. See **Figure 6** for the circuit. This will need to use a dual supply op-amp as the DC bias in the input is removed by the capacitive coupling. Since the op-amp's input is of such high impedance that it doesn't allow the capacitor to discharge on its own, R3 provides a path to ground for that.

NON-AMPLIFYING AMPLIFIERS

A follower (aka buffer) is an amplifier that has a gain of 1. So it's a stretch to call it an amplifier. What's the point then? Well, it takes advantage of the op-amp's high input impedance and low output impedance to isolate (buffer) a signal so that it is unaffected by the circuit it is driving. **Figure 7** shows the circuit. Comparing this to the non-inverting amplifier in **Figure 5**, you can see that R1 has infinite resistance, and R2 has 0. The resistor-related term in the gain equation is removed by the 0 numerator, and we are left with a gain of 1. So it doesn't change the signal, it isolates whatever is producing the input from whatever is connected to the output.

INTEGRATOR

An integrator does, well… integration. Specifically integration of the input signal. **Figure 8** shows the circuit. This one is a bit different in that the feedback is through a capacitor rather than a resistor. Since it's a capacitor, the current is the interesting quantity here. Remember that capacitors deal in the storage and movement of electrons. Also, recall from issue 9 that current I = V/R. Since the op-amp input draws no current, all the current to charge/discharge the capacitor is flowing through R, and will be Vin/R, and we get Vin/R = -C(dVout/dT). Moving things around and integrating to get rid of the derivative, we get an equation for Vout at time *t*:

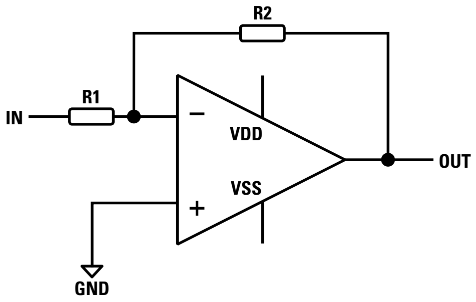


Figure 4
An inverting amplifier circuit

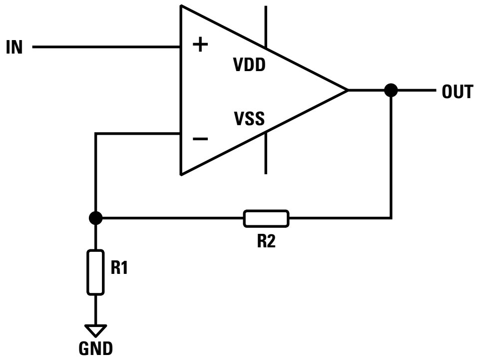


Figure 5
A non-inverting amplifier circuit

QUICK TIP

The op-amp's high input impedance and low output impedance make it an exceptionally good buffer.

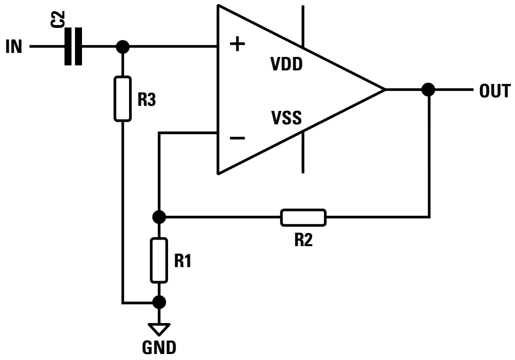


Figure 6
An AC signal amplifier circuit

> **Since it's a capacitor, the current is the interesting quantity here**

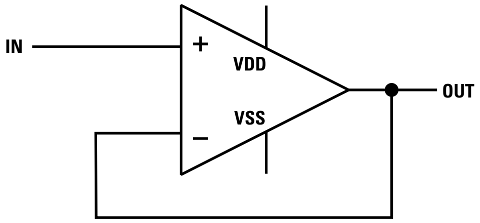


Figure 7
A buffer circuit

$$V_{\text{out}}(t) = -\frac{1}{RC}\int V_{\text{in}}(t)\,dt + \text{const}$$

What this means is that the Vout will change at a rate proportional to the Vin, in the opposite direction (because the input is connected to the op-amp's inverting input). So if Vin is positive, Vout will decrease. Conversely, if Vin is negative, Vout will increase. How fast Vout changes is determined by how negative or positive Vin is. Finally, if Vin is 0 V, Vout doesn't change.

This all assumed a perfect op-amp, which is unlikely. However, by carefully selecting the op-amp to fit the requirements, you can get pretty close.

DIFFERENTIAL AMPLIFIER

Figure 9 shows a classic differential amplifier. The gain is set by R2/R1 – it is critical to correct the operation so that the two R1s and the two R2s are as identical as possible in order to remove any signal that is common to the two inputs. After all, the whole purpose of this circuit is to isolate and amplify the difference in the two input signals. Resistors with a tolerance (i.e. how much they vary from the stated resistance) of 0.01 % are desirable. It's worth noting that the gain (i.e. R2/R1) is applied to the difference in the inputs, so Vout = (V2 - V1)(R2/R1)

MIXER

Since we use a series resistor on the input to an inverting amplifier configuration, why not do that with multiple inputs? This would give us what is called a summing amplifier. See **Figure 10** for an example circuit.

Since the non-inverting input is tied to ground, the inverting input is pushed to stay at 0 V. We know that the op-amp's input doesn't impact current flow, so all the current due to the input signals has to flow through the feedback resistor, RF. Since I = V/R, Vout/Rf = V1/R1 + V2/R2 + V3/R3. If we take the simplest case where all resistors have the same value (R), we get: Vout = R(V1/R + V2/R + V3/R) = V1 + V2 + V3. If we change the values of R1-R3 (the circuit can be extended to more inputs) we get a weighted sum: the portion of each input is determined by the corresponding resistor. If the resistors are adjustable, we have a mixer.

COMPARATORS

The op-amp circuits we've looked at so far have been linear: the output varies in proportion to the input. In contrast, a comparator is a non-linear circuit.

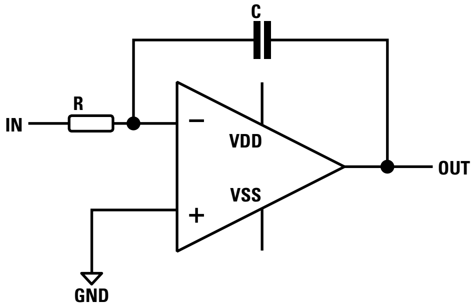


Figure 8
A signal integrator circuit

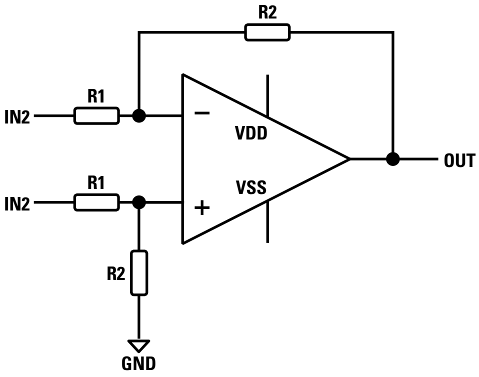


Figure 9
A differential amplifier circuit

Recall that the basic operation of an op-amp is that the output slams hard in the direction that, through feedback, will force the inputs to be equal. Without that feedback, the output snaps all the way in one direction or the other and stays there until the relative value of the inputs changes.

Figure 11 (overleaf) shows the basic comparator circuit. Since the input is connected to the op-amp's inverting input, whenever the input is greater than the voltage set by the R1-R2 voltage divider, i.e. V(R2/(R1+R2)) which we'll call the threshold, the output will be at ground. When the input is less than the threshold, the output will be at V. →

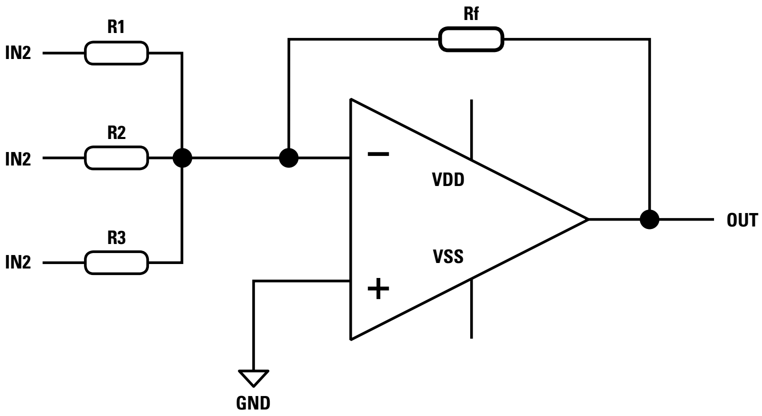


Figure 10
A signal mixer circuit

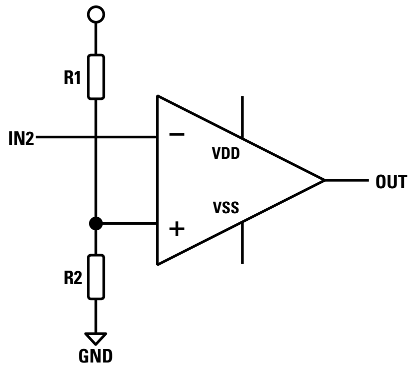


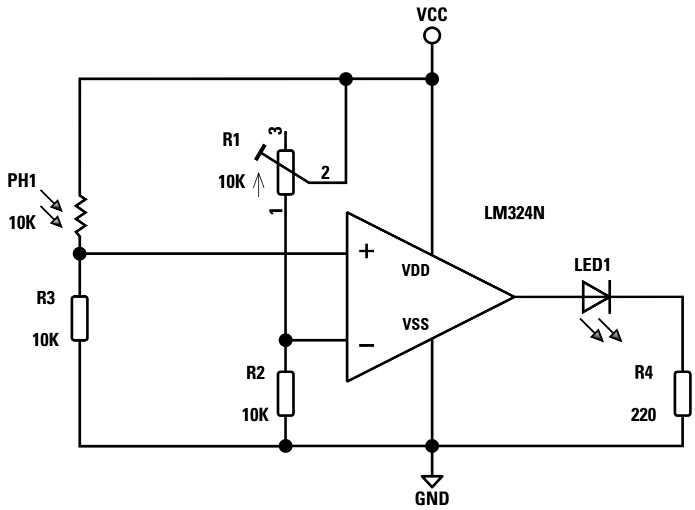
Figure 11
A basic comparator circuit

QUICK TIP

At its heart, an op-amp is a differential amplifier.

Grab your breadboard and some parts. **Figure 12** shows a simple comparator circuit that controls an LED based on the amount of light shining on the photocell. Bright light shining on it will lower its resistance, causing the voltage at the inverting input to be higher. When it gets higher than the non-inverting input, the output switches to 0V and the LED turns off. If it's dark, the resistance of PH1 is higher, so the voltage at the inverting input will be lower. When it's below the voltage at the non-inverting input, the output switches to 5V and the LED lights up. R1 is an adjustable resistor (a potentiometer) and is used to set the voltage at the non-inverting input, and thus the point at which the output and the LED changes state. This translates directly to the amount of light shining on PH1 at that point of change. This is the basics of a night light.

Figure 12
A night light circuit



A problem with this simple comparator design shows itself when the input signal is jittering back and forth across the threshold: the output will switch back and forth between its extremes to match. For the photo comparator, this isn't an issue, but if we want to avoid that jitteriness, we need to add something.

To clean up the jittering, we'll call on the op-amp's best friend: feedback. **Figure 13** shows how to add a feedback resistor to turn the op-amp comparator into what is called a Schmitt trigger.

In this case, we use positive feedback (feedback to the non-inverting input) to affect the threshold depending on the output voltage. The output in the circuit will be at 0V or 5V, so effectively R3 (the feedback resistor) will be in parallel with either R2 or R1. This will change the voltage divider, and hence the threshold. When the output is 0V, the threshold will be slightly lower than what it would otherwise be, and when the output is 5V, the threshold will be slightly higher. The result is that the output state doesn't change when the input would cross the threshold (i.e. what it would be without the feedback resistor in place); to switch the output to 5V, the input has to drop below the new slightly lower threshold, and to switch the output to 0V, the input has to go above the slightly higher threshold. This results in a dead zone between the two new thresholds: if the input is in that zone, the output won't be affected. This is commonly referred to as hysteresis.

This is a lot like debouncing a switch, in that you want to ignore the noise from bouncing mechanical contacts that cause a series of quick presses and releases before settling into one or the other states. The big difference is that with switch debouncing, the hysteresis is in terms of time rather than voltage.

OSCILLATORS

Figure 14 shows a square wave oscillator built around a single op-amp from the LM324N chip. This is configured as a comparator with the non-inverting input setting the threshold. Like the Schmitt comparator, this uses feedback to (assuming we use a 5V supply) set the threshold to 1.68V when the output is at 0V, and 2.77V when the output is at 5V. Here, R5 and R6 form the voltage divider providing 2.5V, and R7 provides the feedback to create the hysteresis. The difference with this circuit is how the inverting input is used. R8 connects it to the output and C1 can use all the current flowing through that to charge and discharge (since the input draws no current). Grab your breadboard and wire this up. Play

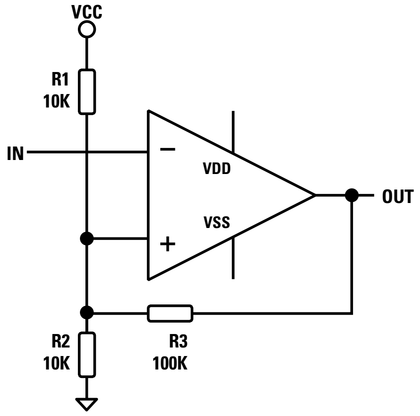


Figure 13
A Schmitt trigger comparator circuit

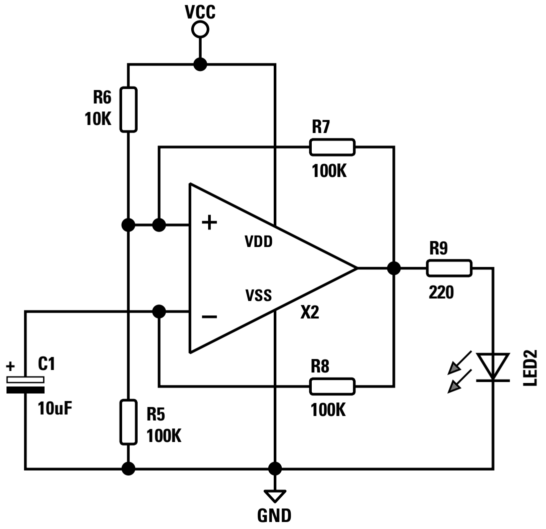


Figure 14
A square wave oscillator circuit

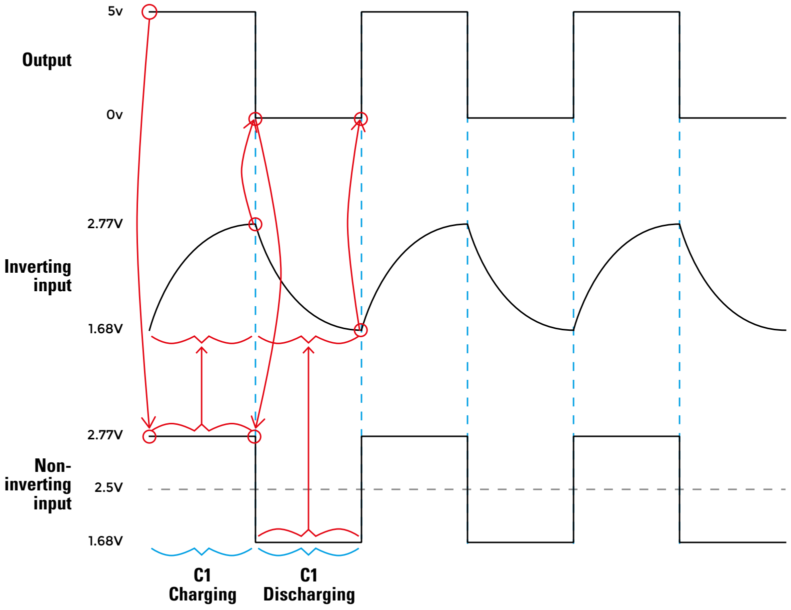


Figure 15
Input and output signals in the oscillator circuit

around with different capacitor values to generate different frequencies.

Assume C1 is empty as a starting point (as it would be when the circuit is powered on). That means that the inverting input is at 0 V. Ignoring the feedback, the voltage divider holds the non-inverting input at 2.5 V. With the non-inverting input at a higher voltage, the output will be 5 V (which means that the non-inverting input is actually at 2.77 V). This causes current to flow through R8, charging C1. When the voltage on C1 exceeds 2.77 V, the inverting input will be at the higher voltage and the output will switch to 0 V. That does two things: changes the voltage at the non-inverting input to 1.68 V, and lets C1 discharge through R8.

As that happens, the voltage at the inverting input drops until it's below 1.68 V, which is the voltage at the non-inverting input. That causes the output to switch to 5 V, and the cycle repeats. So the voltage at the non-inverting input switches between 1.68 V and 2.77 V as the output switches between 0 V and 5 V. At the same time, the output causes C1 to charge and discharge. The frequency of the oscillation is dependent on the RC time constant of R8 and C1. **Figure 15** shows the voltages at the inputs and output over time.

Op-amps are an extremely popular analogue circuit building block, and one of the most widely used types of component. At its heart, it is a very high gain differential amplifier: the output is an amplified version of the difference in voltage between its two inputs. You would be hard-pressed to find any significantly complex analogue device that doesn't contain a few op-amps. Hopefully, this has piqued your interest. If so, there are many places online and in print for learning more.

Get in touch and show us your op amp (or other electronic) creations on twitter at **@HackSpacemag** or email **hackspace@raspberrypi.org**. □

QUICK TIP

If one input is fixed, the differential amplifier becomes a comparator.