Aalborg University Copenhagen
Medialogy MED4 2007

Sensors Technology

Basic electronic elements – operational amplifier

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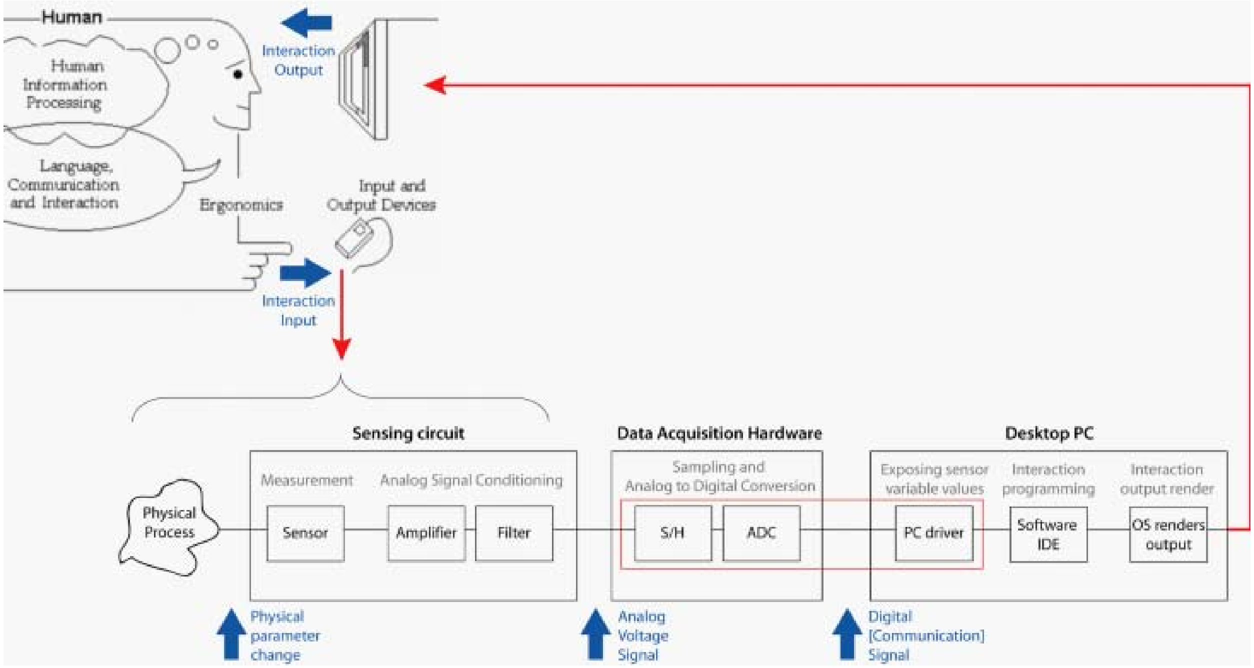
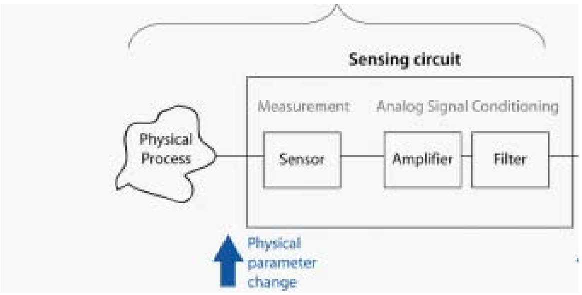
Contents

1 Introduction

We have previously introduced the model that conceptualizes the focus we have in ST:



In these parts of the lectures, we focus on the hardware – electronics part of our sensor-based interaction input system:



The understanding of this part of the process requires in essence two things: understanding of the conversion from a given physical parameter into an electric parameter – which is the sensing process: process of electric measurement that the sensor performs; and understanding concepts in electrical circuits which are used to perform signal conditioning. Both of these require understanding of electrical properties of matter.

So far, we have discussed circuit theory analysis of resistive circuits - and among them, sensor resistive circuits as well. We have also looked at the capacitor as a non-ohmic element, its influence in an electric circuit and the possibilities to use it in a sensor context. We have also looked at both the diode (PN junction) and the transistor, as semiconductor elements.

We now conclude our introduction of basic electronic elements, with the introduction of the operational amplifier. The operational amplifier is actually not a single basic electronic element, like the resistor, or the transistor - it is an implementation of a differential amplifier transistor circuit, packaged as a single integrated circuit, or chip. The layout of the pins of the chip are standardized, and adding different combinations of additional elements, the operational amplifier can be made to perform several useful functions.

2 Differential amplifier

We already discussed the differential amplifier as a very important transistor circuit concept, because it is at the basis of the operational amplifier. "Look under the hood of most op amps, comparators or audio amplifiers, and you'll discover this powerful front-end circuit - the differential amplifier. A simple circuit able to amplify small signals applied between its two inputs, yet reject noise signals common to both inputs. This circuit has a unique topology: two inputs and two outputs. Although you can tap the signal from one output only, taking the difference between both outputs delivers twice the gain! And it improves Common-Mode Rejection (CMR), an essential function when the common-mode signal is a noise source or DC bias from a previous stage. [2]"

The design consists of two common emitter amplifiers, placed in two symmetric branches, powered from the same collector power supply. The branches are further connected at the emitters, and powered with constant current.

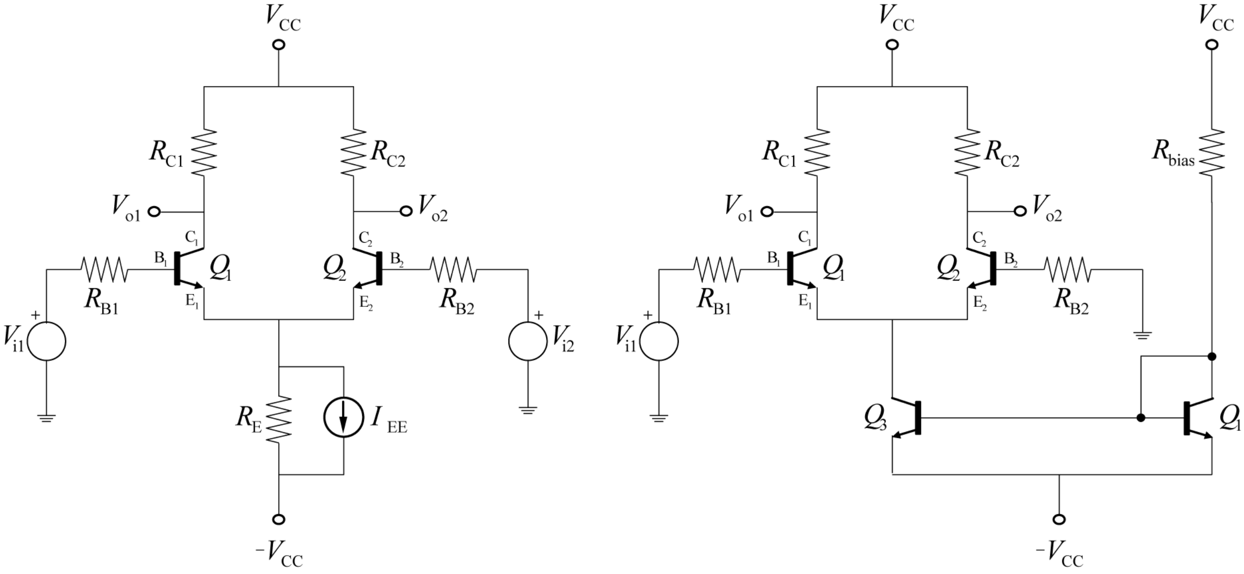


Figure 1. Differential amplifier schematic - left, with constant current source; right, with current mirror used as current source.

The schematic above shows one possibility of implementing a constant current source for the emitter contact. "How does this amplifier amplify differential signals and reject common ones? The bias condition assumes equal voltages at VB1 and VB2, forcing the bias current IE (set by RE) to split equally between the transistors resulting in IC1 = IC2. With RC1 = RC2, equal voltages develop at VC1 and VC2. [2]"

Let us also include the following excerpt: "A differential amplifier is a type of an electronic amplifier that multiplies the difference between two inputs by some constant factor (the differential gain). A differential amplifier is the input stage of operational amplifiers, or op-amps, and emitter coupled logic gates. Note that a differential amplifier is *a more general form of amplifier than one with a single input*; by grounding one input of a differential amplifier, a single-ended amplifier results. [3]"

So, with the two outputs, the circuits behaves symetrically, due to the forced condition that the sums of the emitter currents from both branches must equal the current source. Then, the voltage of each output:
- grows when the input in its own branch grows
- drops when the input in the opposite branch grows.

So, if one of the outputs is 'grounded', the only output left will have voltage that grows when the opposite input grows, and this may be considered a non-inverting input [+], and drops when its own input grows, so this may be considered an inverting input [-].

Another conclusion from this circuit can be reached if we look at the bases of the transistors as the inputs. If both branches sides are balanced (that is, transistors and other elements with same characteristics are used), then for equal input voltages, both base currents are equal, and Vbe of both transistors is equal - as both emitters are connected, the potential of both emitters is kept equal. And this means, as both Vbe's are equal, that the potential of both bases is also equal - which means that *the voltage between the inputs* is *zero*.

In addition, if one or both input voltages change, this results with a change of base and correspondingly collector current in each branch - thus Vbe changes as well; but remember that in essence, there is an exponential relationship between current and voltage when we look at the base emitter junction. That means, even if the change of the currents is considerable, Vbe may still change for only fractions of a volt (say, from 0.620V to 0.638V), so if we still approximate it as 0.6V, we can again conclude that even *when the inputs voltages Vi are changing, the voltage between the two inputs (bases) is kept zero* (as their potentials are nearly equal even then).

However, even when the voltage between the pins is kept nearly zero, it still isn't exactly zero - so if the non-inverting input has a slightly higher potential than the inverting one, the output voltage will tend to be positive; and in the opposite case (non-inverting input has a slightly lower potential than the inverting one), the output voltage will tend to be negative. In all, we could say that Vo = A(Vi1 - Vi2), where A is some amplification, or gain, factor.

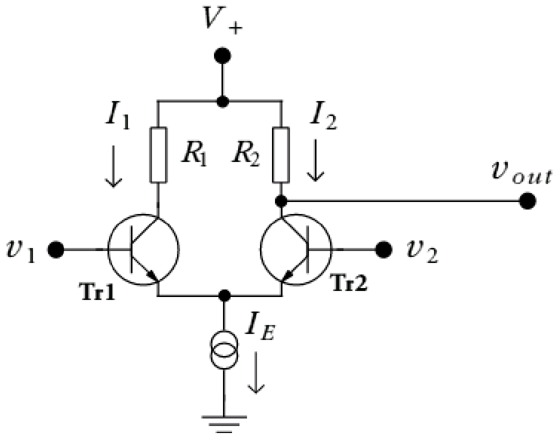
Also, let us remember that when looking into a base of a common emitter amplifier, one sees the resistance in the emitter branched, mulitplied by a factor of 1+ h_{FE}. As this factor can be quite high for some transistors (say around 100 or 200), then even a modest resistance in the emitter branch (say 10 KΩ), will be seen from the base as a resistance some h_{FE} times greater (for h_{FE}=100, the equivalent input resistance will be 1 MΩ). Now, remember that both emitters are actually attached to a current source; and recall that an ideal voltage source has resistance zero (or small), but an ideal current source is modelled with infinite (or large) resistance. As the bases then would see this resistance, multiplied by h_{FE}, we can use the approximation, that *the input resistance of a differential amlifier input is (close to) infinity*.

Finally, notice that if -Vcc is kept on zero potential (ground), then any of the input voltages Vi1 of Vi2 must be greater than the turn-on emitter-base voltage (typically 0.6V) in order to turn the corresponding transistor on. However, if it is indeed a negative potential (say -5V), then even bringing a Vi voltage of 0 volts will still keep the corresponding transistor ON - which will be true for Vi all the way down to some -5 + 0.6 V. So, by using a negative potential as a power supply, we can amplify both positive and negative signals.

All of these conclusions, are in some way implemented in the circuit theory model of an operational amplifier that will be introduced further in this lecture.

At this point, let us introduce an excerpt with a more detailed analysis of the differential amplifier:

" There are many situations where we want to amplify a small difference between two signal levels and ignore any 'common' level both inputs may share. This can be a achieved by some form of Differential Amplifier. Figure 2 shows an example of a differential amplifier stage that uses a pair of bipolar transistors. [13]"



'Long-tailed pair' differential amp

Figure 2. Long-tailed pair differential amp (Ref. [13])

"This particular example uses a *Long-Tailed Pair* connected to a *Current Source*. We can understand how the circuit works simply from an argument based upon symmetry. For simplicity in this diagram we represent the Current Source by the standard symbol of a pair of linked circles. We will look at how a current source actually works later on. For now we can just assume it is an arrangement that insists upon always drawing a fixed current which in this case has the value I_E.

Assume that R1=R2 and that the two transistors are identical. Assume that we start with the two input voltages also being identical. The circuit is arranged so that IE=I1+I2. By symmetry, when v1=v2 it follows that I1=I2, hence I1 = I2 = IE/2.

Now assume we increase, say, v1 by a small amount. This will mean that the transistor, **Tr1**, will try to increase its current level and hence lift the voltage present at its emitter. However as it does this the base-emitter voltage of **Tr2** will fall. Since the current in a bipolar transistor depends upon its base-emitter voltage the result is that the current, I1, rises, and I2 falls. The sum of these currents, IE, does not alter very much, but the balance between the two transistor currents/voltages changes.

The result is that the rise in v1, keeping v2 fixed, causes more current to flow through R1 and less through R2. The reduction in I2 means the voltage drop across R2 will reduce. hence the voltage at its lower end moves up towards V+.

To evaluate this more precisely, we can assume that for each transistor in the pair the collector-emitter current is related to the base-emitter voltage via an expression

$$HI_{CE} = V_{BE} \qquad \textit{Eq 2-1}$$

i.e. we can say that

$$HI_1 = V_{B1} - V_E \quad ; \quad HI_2 = V_{B2} - V_E \qquad \textit{Eq 2-2}$$

where VE is the emitter voltage which the two transistors have in common and VB1 and VB2 are the base voltages. The value H represents the voltage-current gain of each transistor. The sum of these two currents always has a fixed value imposed by the current source, but any difference between them will be such that

$$H(I_1 - I_2) = v_1 - v_2 \qquad \textit{Eq 2-3}$$

where VE vanishes as it is common to both of the initial expressions.

Since I1+I2=IE we can say that the above is equivalent to saying that

$$H(I_E - 2I_2) = v_1 - v_2 \qquad \textit{Eq 2-4}$$

When only concerned about a.c. signals we can ignore the constant IE and say that this becomes

$$i_2 = -\frac{1}{2h_{ib}}(v_1 - v_2) \qquad \textit{Eq 2-5}$$

where hib is one of the small-signal h-parameter values for a bipolar transistor, i2 represents the change in the current in R2 produced when we change the input voltage so that their imbalance from being equal is (v1-v2). Since this change in current appears across R2, and the potential at the top of this is held fixed at V+ it follows that the lower end of R2 which we are using as the output will change in voltage by

$$v_{out} = -\frac{R_2}{2h_{ib}}\left(v_1 - v_2\right) \qquad \textit{Eq 2-6}$$

i.e. the stage has an effective voltage gain of R2/2hib.

Differential amplifiers are particularly useful in three applications:

- When we have an input which has come from some distance and may have had some added interference. Using a pair of wires to send the signal we can then take the difference in potential between them as the signal and reject any 'common mode' voltages on both wires as being induced by interference.
- In feedback arrangements we can use the second input to control the behaviour of the amplifier.
- When we wish to combine two signals we can feed one into one transistor, and the second signal into the other.

Most Operational Amplifier integrated circuits have differential amplifier input stages and hence amplify the difference between two given input levels. Many use bipolar pairs of the kind shown in Figure 2, but similar arrangements using Field Effect Transistors are also often used. [13]"

3 Integrated circuits [IC] - operational amplifier construction (741)

The operational amplifier is based on the differential amplifier - so obviously, it is a whole circuit, and we cannot really treat it as a 'basic' electronic element (of the likes of a resistor or a capacitor). However, it is quite commonly produced as an 8-pin integrated circuit (IC), with a standardized layout for the pins; and in such a form, the operational amplifier finds many uses - so it is an 'element', in the sense of being a basic building block found in many circuits. "The Op Amp is basically three amplifiers or stages. The input differential stage; the gain stage, and the output stage. [12]"

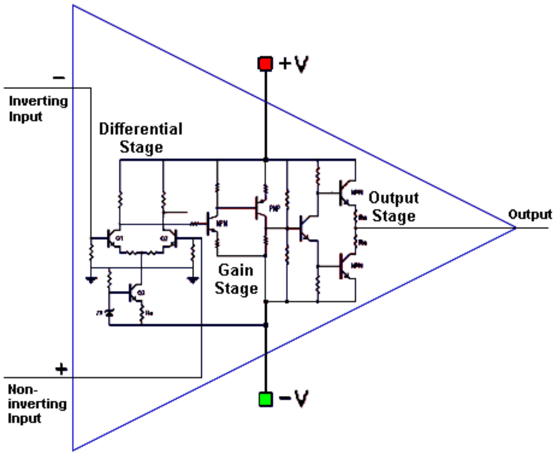


Figure 3. Diagram representing the schematic symbol of an operational amplifier, along with the corresponding circuit schematics (Ref. [12])

A definition of an operational amplifier can be taken from the following exceprt: "An **operational amplifier**, usually referred to as an **op-amp** for brevity, is a DC-coupled high-gain electronic voltage amplifier with differential inputs and, usually, a single output. In its ordinary usage, the output of the op-amp is controlled by negative feedback which, because of the amplifier's high gain, almost completely determines the output voltage for any given input. Simply put, an operational amplifier increases the power of an electric signal.

The operational amplifier was originally designed to perform mathematical operations by using voltage as an analogue of another quantity. This is the basis of the analog computer, where op-amps were used to model the basic mathematical operations (addition, subtraction, integration, differentiation, and so on). However, an ideal operational amplifier is an extremely versatile circuit element, with a great many applications beyond mathematical operations. Practical op-amps, based on transistors, tubes, or other amplifying components and implemented as discrete or integrated circuits, are good approximations to the ideal. [14]"

"Op-amps were originally developed in the vacuum tube era, where they were used in analog computers. Op-amps are now normally implemented as integrated circuits (ICs), though versions with discrete components are used when performance beyond that attainable with ICs is required.

The first integrated op-amp to become widely available, in the late 1960s, was the bipolar Fairchild μA709, created by Bob Widlar in 1965; it was rapidly superseded by the **741**, which has better performance and is more stable and easier to use. The μA741 is still in production, and has become ubiquitous in electronics — many manufacturers produce a version of this classic chip, recognisable by part numbers containing '741.' Better designs have since been introduced, some based on the FET (late 1970s) and MOSFET (early 1980s). Many of these more modern devices can be substituted into an older 741-based circuit and work with no other changes, to give better performance.

Op-amps usually have parameters within tightly specified limits, with standardized packaging and power supply needs. Op-amps have many uses in electronics. With only a handful of external components, they can be made to perform a wide variety of analog signal processing tasks. [14]"

At this point, let's just mention that "A monolithic **integrated circuit** (also known as **IC**, microcircuit, microchip, silicon chip, or chip) is a miniaturized electronic circuit (consisting mainly of semiconductor devices, as well as passive components) that has been manufactured in the surface of a thin substrate of semiconductor material. [15]"

Op-amp ICs (some single, some dual) in 8-pin dual in-line packages ("DIPs")

Figure 4. Op-amp IC's in 8-pin dual in-line package (DIP / DIL)

The schematic of the internal circuitry of a 741 is provided below:

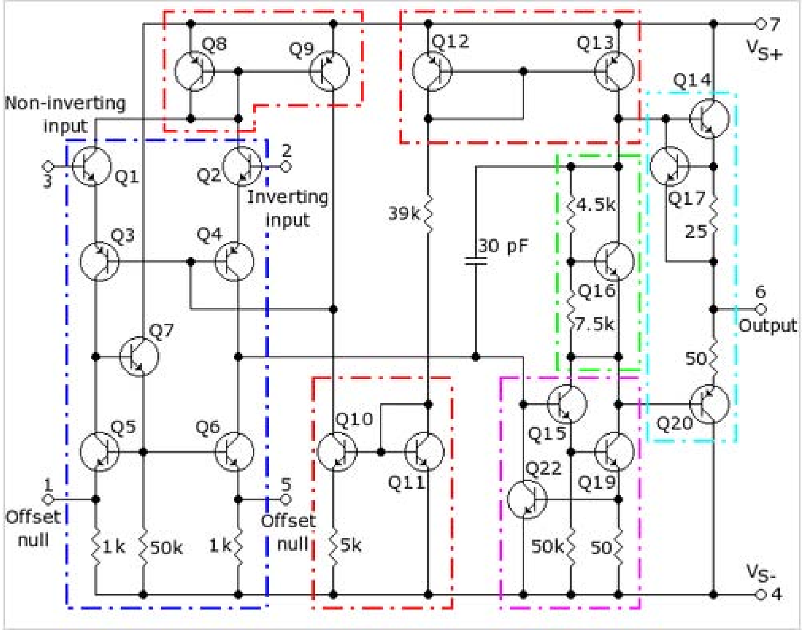


Figure 5.A component level diagram of the common 741 op-amp (Ref. [14])

where: "

- The sections outlined in red are **current mirrors**.
- The blue outlined section is a **differential amplifier**.
- The section outlined in magenta is the **class A gain stag**e.
- The green outlined section (based around Q16) is a voltage level shifter or Vbe multiplier; a type of **voltage source**. (In some discrete component amplifiers this function is achieved with (usually 2) silicon diodes.)
- The **output stage** (outlined in cyan) is a Class AB push-pull emitter follower (Q14, Q20) **amplifier** [14]"

Here is a microscopic photograph of the 741 implemented as a semiconductor monolithic integrated circuit.

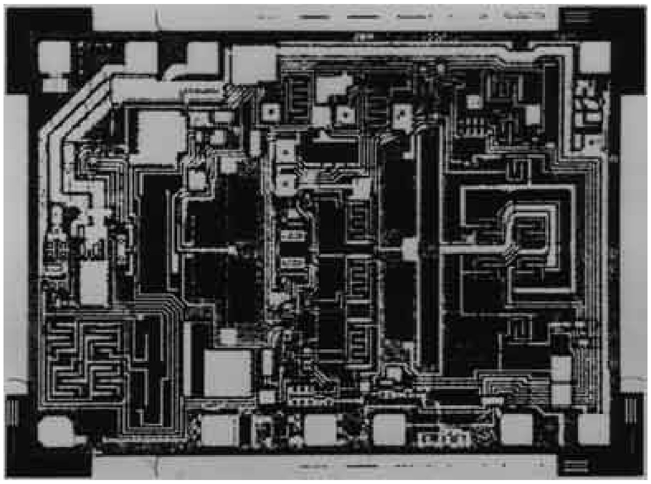


Figure 6. Close-up of a real 741 operational amplifier (Ref. [16])

The understanding of the principle of operation of an opamp is however rooted in the principle of operation of the differential amplifier, as shown in the following excerpt: "The Operational Amplifier (Op-Amp) was developed many years ago for analogue computing. This was in the days when the output information from a calculation was readable with a simple voltmeter. Fortunately for us, the Op-Amp can be misused for a huge variety of functions.

Basically, the Op-Amp is nothing more than a differential amplifier that amplifies the difference between two inputs. One input has a positive effect on the output signal, the other input has a negative effect on the output.

For clarity, the power supply terminals to the amplifier chip are not usually shown, except on detailled circuit diagrams. The Op-Amp requires *two power supplies; a positive voltage supply and a negative voltage supply, both with respect to our circuit ground/Earth/chassis connection.*

The theoretically perfect Op-Amp has an infinite voltage gain, an infinite bandwidth and infinite input impedances. In this way *it just senses an input voltage level without actually interfering with that voltage in any way*. The perfect Op-Amp also has a zero-Ohm output impedance. It may therefore be used to drive heavy (in electronic terms) circuits.

A typical operational amplifier has input impedances of 100M-ohms, 1-ohm output impedance and will drive up to 20mA of output current. Supply voltages may be as high as +20V and -20V (total 40 volts from +ve supply to -ve supply). The typical voltage gain/bandwidth of a normal Op-Amp is about 1 000 000. This is to say that at DC it will have a voltage gain of one Million, but at 1MHz it will only have a voltage gain of 1.

To understand a little more of what is inside the chip, here is a much simplified circuit diagram.

The circuit will function quite well with the component values shown, should you feel the need to built the device. In the real Op-Amp, the silicon diode biasing and current limiting resistors are constant current supplies that enable the device to operate at low supply voltages. [11]"

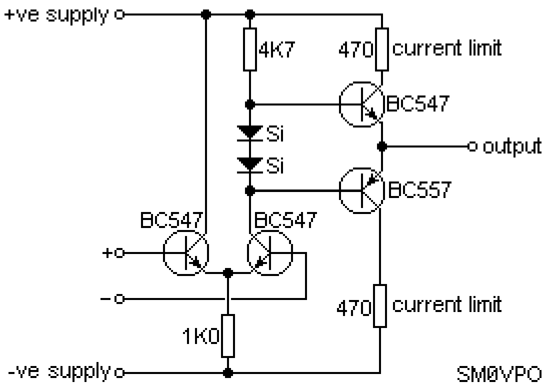


Figure 7. Differential amplifier circuit (Ref. [11])

Now you have a little information about what the device is, let us take a look at what it can do.

The basic function of the Op-Amp is to multiply a voltage level by the gain of the amplifier. If you were to couple a DC level of +1v into the + input of our Op-Amp then the output would be 1v X 1000000 or one Million volts. The output, however, cannot exceed the supply voltage, so the output will be +20v DC.

If you were to couple a DC level of +1v into the - input of our Op-Amp then the output would be -1v X 1000000 or MINUS one Million volts. The output, however, still cannot exceed the supply voltage, so the output will be -20v DC.

If you were to couple a DC level of +1v into both the - and + inputs of our Op-Amp then the output would be (-1v X 1000000) plus (1v X 1000000) = 0v.

In other words, both inputs act on the output simultaneously and the output is the sum of both input functions. If both inputs are identical then the output should always be zero. This is a good test for an Op-Amp. If you connected both inputs to the same input, then the output SHOULD be zero volts. In reality, there are small differences in the circuit's characteristics and components, this will result in a small 'offset' voltage.

The offset voltage can be corrected on several Op-Amps by an internal circuits known as 'offset null' which means that the offset voltage can be trimmed out. In most Op-Amp applications this function is not necessary, but in very accurate systems, such as instrumentation, the function can be very useful. [11]"

4 Operational amplifier as an electronic element

Although operational amplifiers could be found in packages other than 8 pin dips, by now we know that from every operational amplifier, we should at least expect non-inverting and inverting input pins, an output pin, and of course power supply pins. So, the schematic symbol for the op-amp takes this into account - below is "a complete diagram of an operational amplifier (a). A more common version of the diagram is shown in (b), where missing parts are assumed to exist. The inverting input means that the output signal will be 180° out of phase with the input applied to this terminal. On the diagram V++ = +Vcc = +15V (DC) and V-- = -Vcc = -15V (DC). Vcc is typically, but not necessarily, 15V. The positive and negative voltages *are necessary to allow the amplification of both positive and negative signals without special biasing.* [10]"

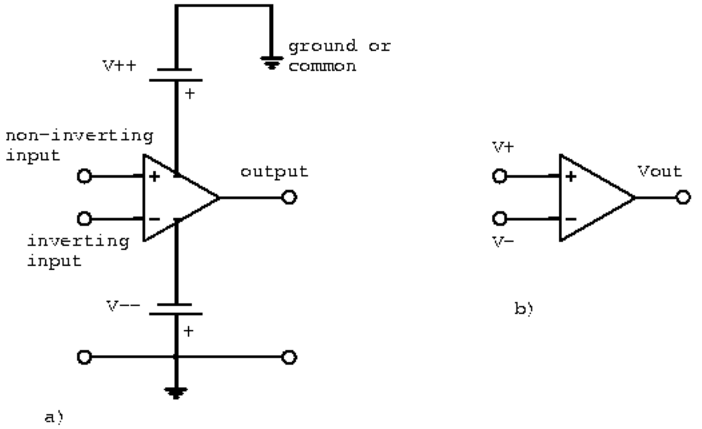


Figure 8. Schematic symbol of an op-amp a) complete b) common (Ref. [10])

For circuit analysis, usually we work wih a so-called **ideal approximation** of an **op-amp**, briefly described here: "Before proceeding we define a few terms:

linear amplifier
- the output is directly proportional to the amplitude of input signal.

open-loop gain, A
- the voltage gain without feedback (~10^6).

closed-loop gain, G
- the voltage gain with negative feedback

negative feedback
- the output is connected to the inverting input forming a feedback loop (usually through a feedback resistor).

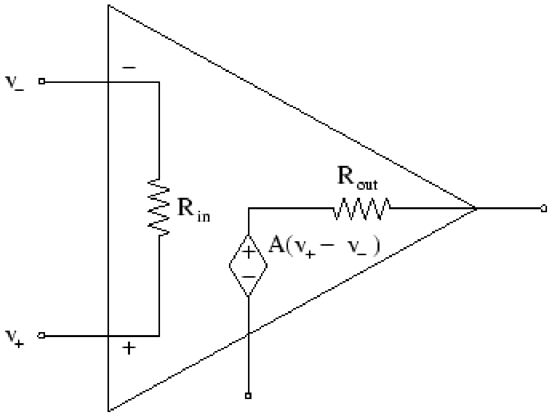


Figure 9. A circuit model of an operational amplifier (op amp) with gain A and input and output resistances Rin and Rout (Ref. [21]).

The following are properties of an **ideal amplifier**, which to a good approximation are obeyed by an operational amplifier:

1. large forward transfer function,
2. virtually nonexistent reverse transfer function,
3. large input impedance, (any signal can be supplied to the op-amp without loading problems) $R_{in} \to \infty$,
4. small output impedance, (the power supplied by the op-amp is not limited) $R_{out} \to 0$,
5. wide bandwidth, and
6. infinite (open-loop) gain $A \to \infty$.

If these approximations are followed two rules can be used to analyze op-amp circuits:

Rule 1:
The input currents I_+ and I_- are zero, ($I_+ = I_- = 0 \ (R_{in} \to \infty)$).
Rule 2:
The voltages V_+ and V_- are equal, ($Z_+ = Z_- \ (A \to \infty)$).

To apply these rules requires negative feedback.

Feedback is used to control and stabilize the amplifier gain. The open-loop gain is too large to be useful since noise will causes the circuit to clip. Stabilization is obtained by feeding the output back into the input (closed negative feedback loop). In this way the closed-loop gain does not depend on the amplifier characteristics. [17]"

So, this brief set of rules (the 'opamp golden rules' - see [19])
- the input currents are zero (input impedance is infinite), and
- the input potentials are equal (open loop gain is infinite, which results with differential voltage difference of potentials of input terminals - being zero)

is all that we need to start analysing circuits with operational amplifiers. In reality, of course our results will deviate from such calculations - but they will provide results useful enough.

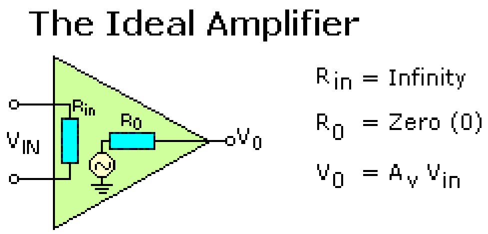


Figure 10. The ideal amplifier opamp model (Ref. [18]

A different excerpt discussing this model is found here: "The amplifier's differential inputs consist of an inverting input and a non-inverting input and ideally the op-amp amplifies only the difference in voltage between the two. This is called the '**differential input voltage.**' In its most common use, the op-amp's output voltage is controlled by feeding a fraction of the output signal back to the inverting input. This is known as **negative feedback**. If that fraction is zero, i.e., there is no negative feedback, the amplifier is said to be running '**open loop**' and its output is the differential input voltage multiplied by the total gain of the amplifier, as shown by the following equation:

$$V_{OUT} = (V_{+} - V_{-}) \cdot G_{openloop} = (V_{+} - V_{-}) \cdot A \qquad \text{Eq 4-1}$$

Because the open-loop gain is typically very large, op-amps are not usually used without negative feedback. Unless the differential input voltage is extremely small, open-loop operation results in op-amp saturation. Another typical configuration of op-amps is the *positive feedback*, which takes a fraction of the output signal back to the non-inverting input. An important application of it is the comparator with hysteresis.
For any input voltages the ideal op-amp has infinite open-loop gain, infinite bandwidth, infinite input impedances resulting in zero input currents, infinite slew rate, zero output impedance and zero noise.

Real op-amps can only approximate to this ideal, and the actual parameters are subject to drift over time and with changes in temperature, input conditions, etc. Modern integrated FET or MOSFET op-amps approximate more closely these ideals than bipolar ICs where large signals must be handled at room temperature over a limited bandwidth; input impedance, in particular, is much higher, although the bipolar op-amps usually exhibit superior (i.e., lower) input offset drift and noise characteristics.

Where the limitations of real devices can be ignored, an op-amp can be viewed as a black box with gain; circuit function and parameters are determined by feedback, usually negative. IC op-amps as implemented in practice are moderately complex integrated circuits. [14]"

4.1 Measuring (testing) opamps

The reason for measuring transistors and diodes was to find the proper pins - and to also make sure it is working properly. When we talk about operational amplifiers, we should mention that most are produced in packaging for integrated circuits, known as dual in-line package (DIP or DIL).

As mentioned previously, operational amplifiers are commonly produced in 8 pin DIP packages; for quite a few common operational amplifiers, like 741, TL071, TL081 the pinout of the 8 pin IC is the same, but it is always wise to check the datasheet of the component first.

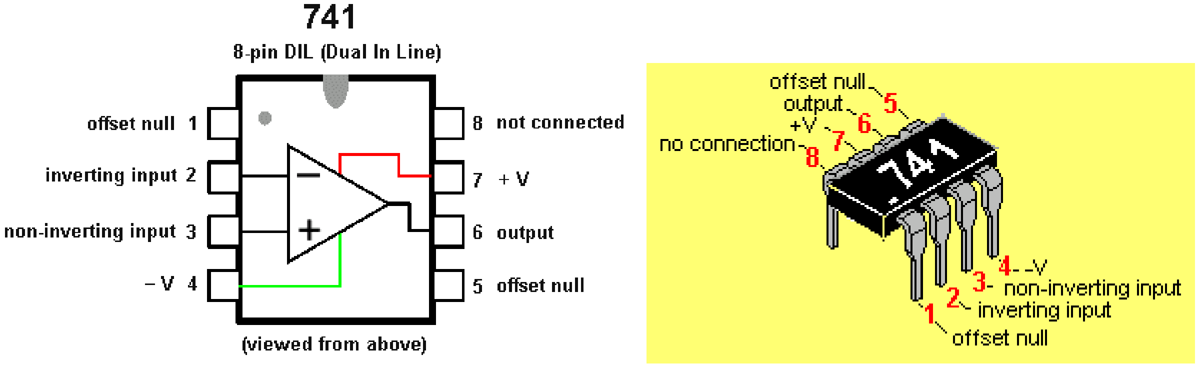


Figure 11. Pinout for 741 (and other) op-amps, for single opamp in 8 pin DIP (ref. [22])

Commonly a dot will be printed, either in the middle of a side, or in a corner - that is to indicate which part of the chip looks 'up' when viewed from the top - in that orientation, pin number 1 is the one to the left of the dot. Note that there exists packaging with two opamps in a single 8-pin DIP package as well. One can also find four operationa amplifiers (quad) packed in a single 16-pin DIP.

In relation to measurement, note the following excerpt: "Working on a project with an OP-AMP requires a lot of skill and understanding.The input impedance of an OP-AMP is very high and probing either input with a multimeter or CRO [cathode ray oscilloscope] will change the voltage on the input and alter the state of the output. The reason is this: The voltage on either input is extremely critical. It only has to change by 1/10th of a millivolt and the output will change a considerable amount. The actual change will depend on the gain of the OP-AMP and this is determined by the value of the components surrounding it.If the gain is not controlled, it can be as high as 10,000 to 100,000 but most OP-AMP have surrounding components that limit the gain to between 2 and 200.

It is also impossible to measure the difference in potential between the inverting input and non-inverting input. Thus the normal method of probing and testing an OP-AMP with a multimeter or CRO DOES NOT WORK! You have to use a new method of testing. It's simple and quite brilliant. It's a 47k on jumper leads with a short length of tinned wire in the second alligator clip to act as a probe. The lead can be connected between the pin under investigation and either the positive, 0v rail or negative rail, while monitoring (measuring) the output of the OP-AMP.

Don't be tricked by a CRO. It puts a load on the OP-AMP and if the line under investigation is HIGH IMPEDANCE, the CRO will affect the amplitude of the signal.The amplitude on the display will be reduced (attenuated) as the frequency increases. For instance, for a 10MHz CRO, the amplitude will be 50% of the real value when the signal is 10MHz. The load from the leads of the probe on the CRO will attenuate (reduce) the signal and if the circuit is operating at say 100MHz, the load of the CRO can quite often 'kill' the operation of the circuit [4]". However, consider also that for most of lour applications, the opamp would not be in such a sensitive range - so it can well survive a measerument with an oscilloscope probe - one just has to be aware that it too influences the opamp.

The following advice may be useful as well: "If you suspect an op-amp is faulty, check it by substitution but first:

1. Is each pin of the op-amp connected?
   Check visually that none of its pins have become wrapped under its body instead of being inserted into the board.

2. Is the output finite?
   If the output is within a volt or so of either power rail then either it has failed, or there is an excessive voltage at its inputs.

3. Is the input consistent with the output?
   Measure the voltage between the inverting and non-inverting inputs, it should be within millivolts of zero. [5]"

"There is actually very little that can go wrong in an opamp based circuit. Opamps usually work or they don't - intermittent states can occur, but are very uncommon. It might be assumed that opamps can be faulty from new, and while this is certainly possible it is extremely rare. Over the years, I have built hundreds of opamp circuits, and in all that time I've only seen a couple of new devices faulty from the beginning.

Almost all faults with a newly built opamp based circuit will be the result of wiring mistakes. It is easy to make mistakes using prototype board, but a great deal harder with a PCB. However, incorrect placement of resistors or capacitors can have very unexpected results. [7]"

5 Symmetric (split) power supply

It was previously mentioned that one most use both negative and positive power supply, in order to properly amplify voltages around zero: "The op-amp is usually powered by a dual polarity power supply in the range of +/- 5 volts to +/- 15 volts. A simple dual polarity power supply is shown in the figure below which can be assembled with two 9 volt batteries. [20]"

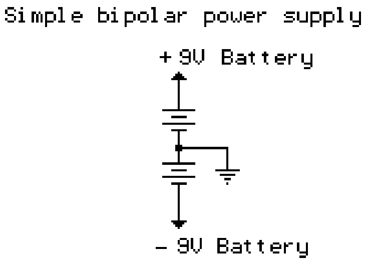


Figure 12. A simple bipolar power supply (Ref. [20])

This type of a power supply - having a ground, positive and negative terminal is known as a **symmetric**, **split**, **bipolar** or **dual** voltage (power) supply. On the other hand, using a single battery would be considered using a **single** or **unipolar supply** (of power / voltage). This is initially necesarry, to account for amplifying negative voltages, as well as for compensating for the transistor turn-on voltage (in the differential amplifier made of BJT transistors) - later on, we will see an example of this necesitty.

In this section, we will include several discussions on implementation of a symmetric supply. As we have seen, a symmetric supply can be implemented with two batteries (or two adapters, or two lab voltage sources), simply by connecting the positive terminal of the one and the negative terminal of the other, and declaring that as common ground. Note that the psitive and negative terminals of a symmetric source are also known as *supply rails*. However, it is not always convenient to use two power supplies, hence in opamp design, this issue is adressed in two ways - either a design of a symmetric power section; or designing the opamp circuit to work with a single supply (which necesarilly means change of it operating point to somewhere between the supply rail potentials).

"An OP-AMP connected to a single voltage rail will produce an output from 0v to approx rail voltage.
An OP-AMP connected to dual rails will produce an output from –V to +V [22]"

Initially, one can think about this problem in termis of a voltage divider circuit: "you will need a power supply which can provide +10 volts, -10 volts and a common ground. However, the power supply at your station [may not be] equipped to provide both positive and negative 10 volts relative to earth ground. So we are going to 'trick' the op-amp circuit by a clever use of a single power supply. []

From the standpoint of the bench (20 V) power supply, is ground, common is 10 volts and is 20 volts. However, from the standpoint of the op-amp, common will be used as ground (not the same as earth ground) so that is now only 10 volts and is -10 volts. We have switched reference frames so that is now only 10 volts and is -10 volts. Measure and record the values of and using common as the reference (ground) node. [6]"

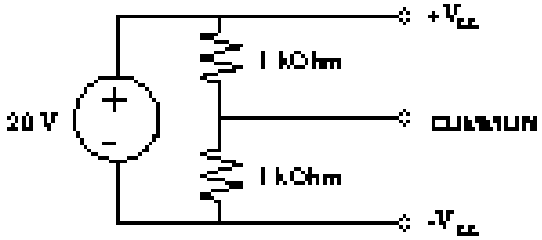


Figure 13.Voltage divider approach to obtaining symmetric from single votlage supply (Ref. [6])

However, this is an approach that will not work always - the resistances should be kept quite smaller than those used with the opamp, which guarantees greater currents and greater power consumption; otherwise they will also interfere with the operation of the rest of the circuit. A further discussion is included below:

"In many standard applications, operational amplifiers are used to amplify periodical signals around a certain center value. As positive and negative phases of most analogous signals are typically at a same level (more or less symmetric to a center line), a reference voltage must be provided to the OP to allow the amplification of both, positive as well as negative phases.

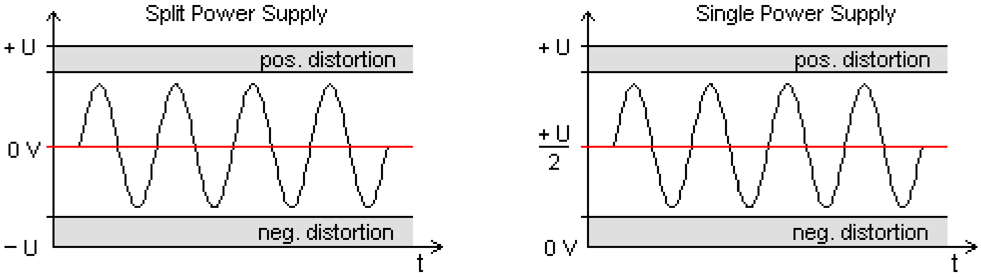


Figure 14. Left - AC input signal symmetric around the zero level, which can be amplified with a symmetric supply; right - AC input signal symmetric around half of the supply voltage, which can be amplified with a single supply (Ref. [9])

This reference voltage is usually half of the entire supply voltage and is supplied to the non-inverting input. If this input is already used as a signal-input (non-inverting amplifiers), the reference voltage should be provided via high impedance resistors.

Split Power Supply: The easiest way to provide an operational amplifier with the necessary voltage arrangement is to use a split supply. Although the design of a symmetric voltage supply circuit is a bit more complicated than a single one, the amplifier circuits themselves will be reduced to a few components.

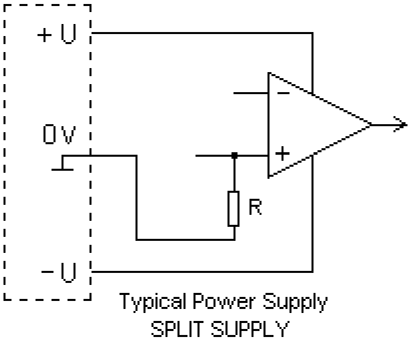
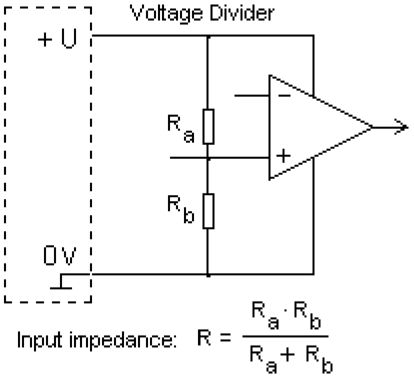


Figure 15.Typical split power supply for op-amp (Ref. [9])



Single Power Supply: In single supplies you will have to create this third voltage source. There are several possibilities to obtain a middle reference voltage from one single supply. Most often, a simple resistance divider is used.

Figure 16. Typical single power supply for op-amp, with voltage divider biasing (Ref. [9])

The disadvantage of this circuit is that both resistances (Ra,Rb) reduce the global input impedance (for a non-inverting amplifier). A better solution is provided with a third resistance between the positive input and the divider. Another advantage is (but only if the condenser is used), that some other OP's may use the same reference point.

There is also a possibility to split up the supply voltage with an OP. As the output impedance of the operational amplifier is very low, in some applications this virtual center is used as a new (virtual) Ground. [9]"

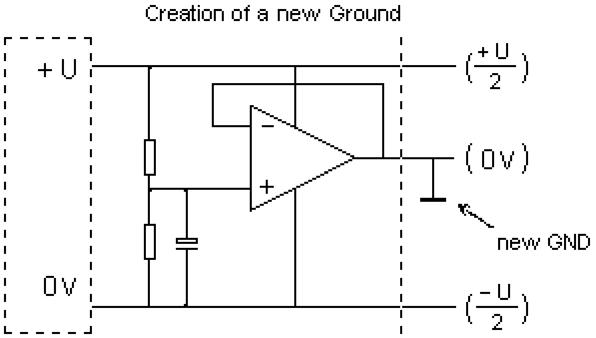
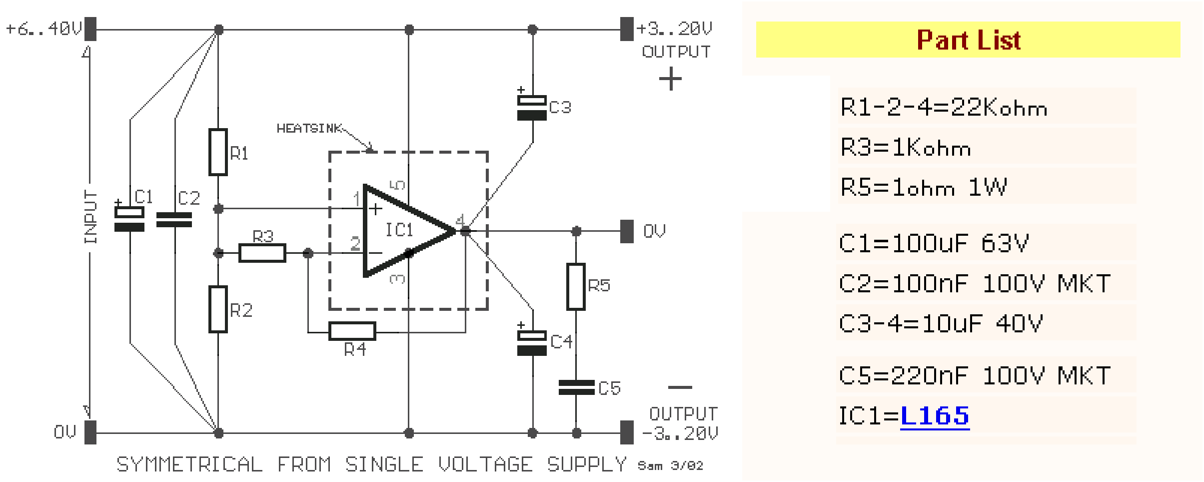


Figure 17. Using one op-amp to convert single to a symmetric power supply, and create a virtual ground (Ref. [9])

A practical implementation of the solution for a single-to-symmetric power supply converter, given on Figure 17, is given in the resource below - for low power applications, common opamps lke TL081 can be used with this circuit without a problem.



Part List

R1-2-4=22Kohm
R3=1Kohm
R5=1ohm 1W
C1=100uF 63V
C2=100nF 100V MKT
C3-4=10uF 40V
C5=220nF 100V MKT
IC1=L165

Figure 18. Schematic and parts list for single to symmetric voltage supply (Ref. [8])

Also, single supply design is quite common as well - for more, see [23], [24], [25].

6 Basic circuits

In this section, we analyze several basic circuits that are based on an operational amplifier. By wiring external components to an operational amplifier, it can be made to perform many functions.

All of the circuits below are discussed for a opamp which is powered by a symmetric power supply.

Here we wil look at the comparator; voltage follower; inverting and non-inverting amplifier; summer; and differential and instrumentation amplifier. Note that there are many more ways to use an operational amplifier - they can be used as differentiators or integrators (which at the same time represent high-pass and low-pass filters, respectively); as active elements in oscillators; exponentiators, logarithmers, multipliers; triggers in digital logic, etc. For an overview, see [28].

6.1 Comparator

The simplest use of an operational amplifier is as a comparator: "Without external components the op-amp functions as a **comparator**. This is because of the high open loop gain, due to which very small input signal differences are sufficient to drive the output stage into saturation (positive or negative). The maximum output voltage range is determined by the supply voltages, which can be unipolar (+Uc relative to Ground) or bipolar (+Uc and −Uc relative to Ground). A real op-amp has a switching threshold of a few millivolts, compared with the theoretical value of zero differential input voltage. This value is called the **offset voltage.** [33]"

"In electronics, a comparator is a device which compares two voltages or currents and switches its output to indicate which is larger. More generally, the term is also used to refer to a device that compares two items of data.

A standard op-amp without negative feedback can be used as a comparator, as indicated in the following diagram.

When the non-inverting input (V+) is at a higher voltage than the inverting input (V-), the high gain of the op-amp causes it to output the most positive voltage it can. When the non-inverting input (V+) drops below the inverting input (V-), the op-amp outputs the most negative voltage it can.

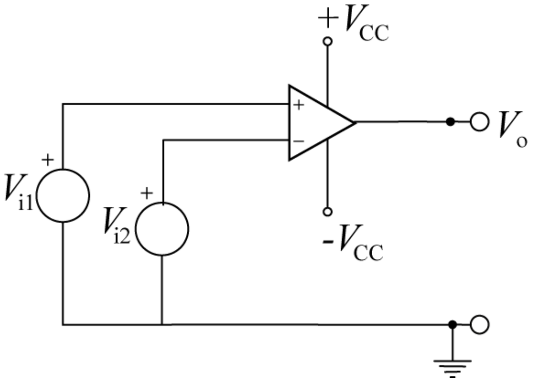


Figure 19. Schematic of opamp as a comparator

So, the comparator could be described with these equations:

$$\begin{cases} V_o = +V_{CC}\ ; V_{i1} > V_{i2} \\ V_o = -V_{CC}\ ; V_{i1} < V_{i2} \end{cases}$$

Since the output voltage is limited by the supply voltage, for an op-amp that uses a balanced, split supply, (powered by ± VS) this action can be written:

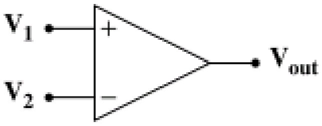
Vout = VS sgn(V+ − V−)

where sgn(x) is the signum function. Generally, the positive and negative supplies VS will not match absolute value:

Vout <= VS+ when (V+ > V-) else VS- when (V+ < V-).

Equality of input values is very difficult to achieve in practice. The speed at which the change in output results from a change in input (often called the slew rate in operational amplifiers) is typically in the order of 10ns to 100ns, but can be as slow as a few tens of µs.

A dedicated voltage comparator chip, such as the LM339, is designed to interface directly to digital logic (for example TTL or CMOS). [27]"



Note that the comparator schematic is usually given in much less detail than above.

Figure 20. Opamp as comparator schematic (Ref. [28])

Note also there are issues with using normal opamps as comparators. One particularly difficult combination is using a single source as power supply, which makes the most negative in the circuit ground, and trying to compare to zero potential (by fixing one of the inputs to ground). Usually, either a constantly high or low signal is obtained, and the circuit will not switch. This may be avoided by use of a symmetric supply.

Note that there are are special implementations of an op-amp known as voltage comparators - which are predominantly meant for interfacing with digital electronics: "If the inverting input of an op-amp is higher in voltage than the noninverting input, the output saturates negatively, while if the reverse is the case, it saturates postively. Therefore, the op-amp can detect whether one node is higher in voltage than another, often a useful function. However, an op-amp is not really intended for this kind of duty, and there are some inconveniences, such as the output saturation. In spite of this, op-amps can sometimes be used for the purpose, especially the single-supply op-amps that will go to V-. There are, however, *circuits specially built for use as* **comparators**, such as the LM311 and its FET-input sister, the LF311. We'll use the LM311 as the example here. It might be well to say that *it is not an op-amp, and* ***cannot*** *be used as an op-amp*. Among other things, it would not be stable. [26]"

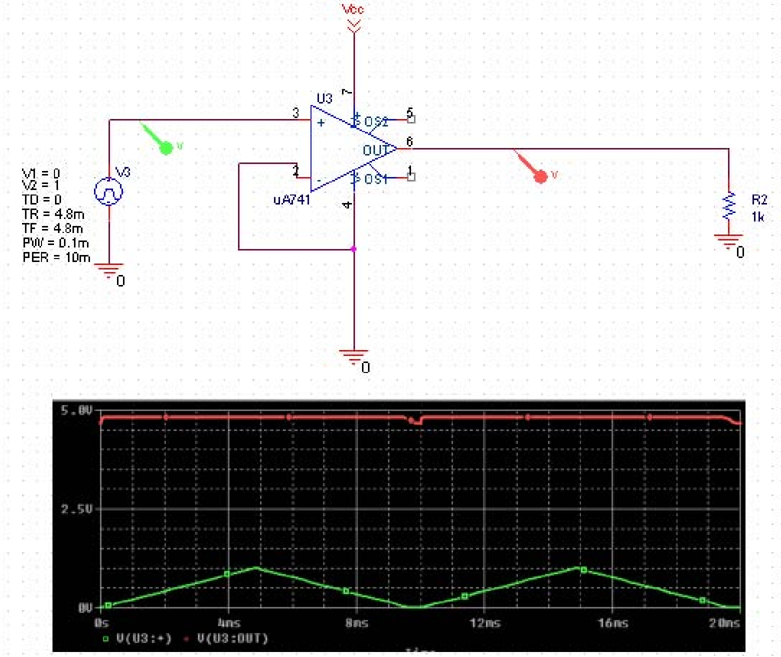


Figure 21. Simulation of a single-supply 741 as a comparator

Note that if trying to use a real comparator with a single supply, you will not be able to compare with ground - it the above simulation, the voltage should drop to zero at the points where the input drops to zero; however it stays almost constant during the entire run. Obviously, with a symmetric supply we'd expect the above circuit will behave properly - but: "Build any opamp circuit, apply 0V to its input, and what do you expect at the output? Although you'd be tempted to say 0 V, there's actually an error voltage present at its output. What causes this error? You can trace the error back to a number of unbalances in the op amp's internal transistors and resistors. To account for this in a circuit design, the net error is modeled as an offset voltage, Voff, in series with op amp's input terminals. How will it affect your circuit? That depends on the op amp itself and your circuit design. [34]"

It is also advisable to use Falstads circuit simulator applet, to visualise the flow of current in this circuit.

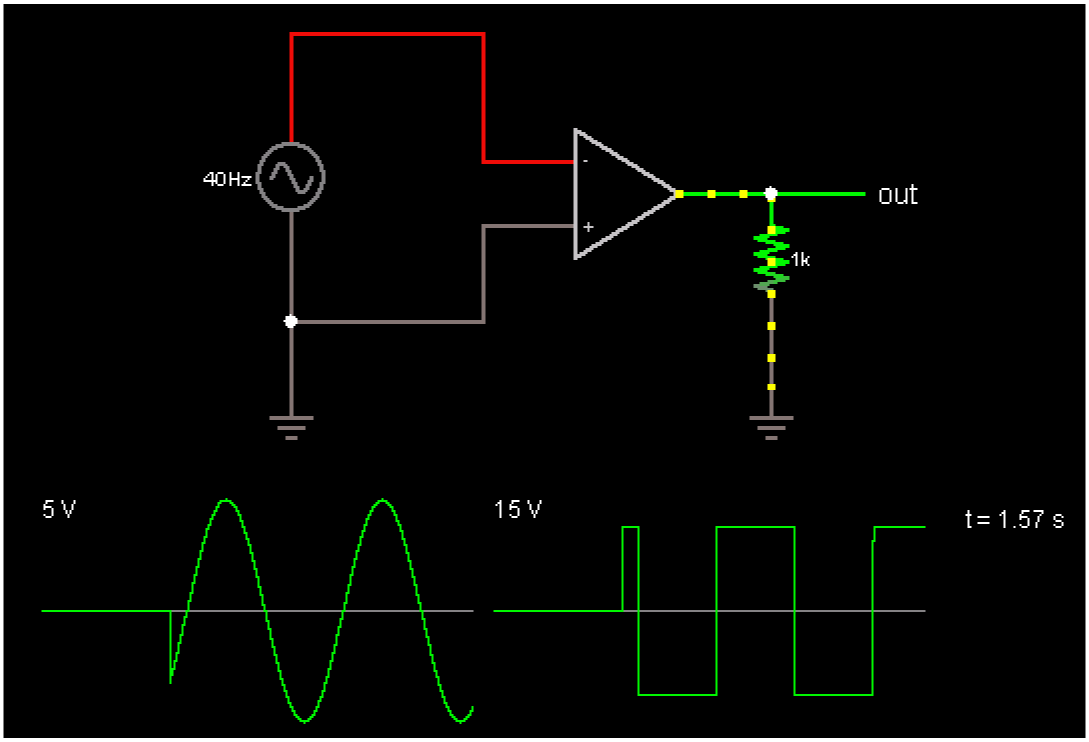


Figure 22.Visualising the flow of current in an op-amp comparator using Falstads applet (Ref. [1])

The Falstad applet doesn't allow many parameters to be changed - however, you can change the positive end negative power supply of the opamp (by editing its properties), and follow the effects.

6.2 Voltage follower (buffer)

The voltage follower is the next most simple opamp circuit. Whereas the comparator has no feedback (and displays the full, near infinite open-loop amplification), the voltage follower implements a negative feedback by connecting the output to the inverting input. As this is a 'total' feedback, the amplification is 1 (also known as *unity gain*) - that is, the input is duplicated (followed) at the output. Although there is no amplification as such, the benefit is that the original source of the input voltage now 'sees' the near infinite input resistance of the opamp, instead of whatever finite resistance of the intended load - which might have disrupted the operation of the source is connected directly to it.

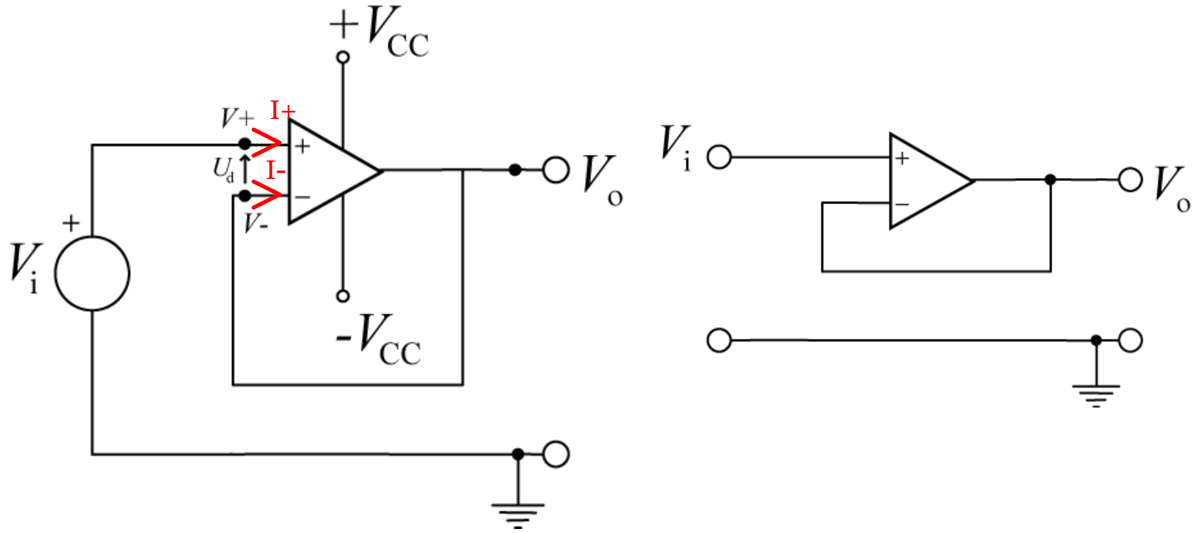


Figure 23. Schematic of an opamp voltage follower (left); simplified schematic (right)

The opamp equations are

$$I_+ = I_- = 0$$
$$V_+ = V_- \rightarrow U_d = 0$$

where $U_d = V_+ - V_-$ is the differential voltage.

From the connections, it is obvious that

$V_i = V_+ \qquad V_o = V_-$

So, as the differential voltage is zero, it follows that $V_o = V_i$.

The only difference is that the resistance that the source Vi sees is almost infinite - meaning there is almost no current flowing through Vi; the source Vi is thereby isolated (buffered) from the input resistance of the next stage which now should be attached at Vo instead.

Note finally that the circuit works because
$V_o = A \cdot U_d = A \cdot (V_+ - V_-) = A \cdot (V_i - V_0)$

Growth of Vi as amplified as AV+, which tends to infinity, but as whole of the output is brought to the inverting input as well, which then figures with a minus sign, so the infinite gain is compensated (as Vd tends to zero). However, if the inverting and non-inverting input *switch places*, there is no more voltage following - growth of input Vi goes to inverting input, and shows up as -AVi in the output expression. That negative voltage then comes back on the non-inverting input, so again we have -AVi in the output expression. So in this case, it turns out that Vo = -2AVi, which basically means that the opamp will immediately clip into the negative supply voltage as the output, in case of this wrong wiring. Because of this, you ***cannot*** make an *inverting* follower, by simply switching the inverting and non-inverting inputs in the regular voltage follower. This is in general true for all the opamp circuits discussed here - the non-inverting and inverting input are ***not*** *reversable*.

"You draw very little power from the signal source, avoiding 'loading' effects. This circuit is a useful first stage. The voltage follower is often used for the construction of buffers for logic circuits. [29]"

"If we connect the output of an op-amp to its inverting (-) input, the output voltage will seek whatever level is necessary to balance the inverting input's voltage with that applied to the noninverting (+) input. If this feedback connection is direct, as in a straight piece of wire, the output voltage will precisely 'follow' the noninverting input's voltage. [30]"

"Most sensor interfaces take a range of voltages as input, and convert them into a digital represention. If you make your own sensors, or use sensors not perfectly matched to your system, you can usually improve the quality of your data by scaling the voltages into the precise range needed by your interface. The voltage follower is an extremely simple circuit that simply outputs a low impedance voltage that is identical to the input. This would be fairly useless, except that it changes high impedance inputs to low impedance, and makes the signal stronger. Used in conjunction with an inverting op amp, it can be a simple way to condition your signals. [31]"

"Voltage follower - Used as a buffer amplifier, to eliminate loading effects or to interface impedances (connecting a device with a high source impedance to a device with a low input impedance). Realistically, the differential input impedance of the op-amp itself, [is from] 1 MΩ to 1 TΩ. [28]"

"A **buffer amplifier** (sometimes simply called a buffer) is one that provides *electrical impedance transformation* from one circuit to another.

Typically a buffer amplifier is used to transfer a voltage from a first circuit, having a high output impedance level, to a second circuit with a low input impedance level. The interposed buffer amplifier prevents the second circuit from loading the first circuit unacceptably and interfering with its desired operation.

If the voltage is transferred unchanged (the voltage gain is 1), the amplifier is a **unity gain buffer**; also known as a **voltage follower**.

Although the voltage gain of a buffer amplifier may be (approximately) unity, it usually provides considerable current gain and thus power gain. However, it is commonplace to say that it has a gain of 1 (or the equivalent 0 dB), referring to the voltage gain.

A unity gain buffer amplifier may be constructed very simply by connecting the output of an operational amplifier to its inverting input (negative feedback), and connecting a signal source to the non-inverting input. For this circuit, Vout is simply equal to Vin.

The importance of this circuit does not come from any change in voltage, but from the input and output impedances of the op-amp. The input impedance of the op-amp is very high (MΩ to 10 TΩ), meaning that the input of the op-amp does not load down the source or draw any current from it. Because the output impedance of the op-amp is very low, *it drives the load as if it were a perfect voltage source*. [32]"

Ff using the voltage follower with a single supply, one might culd some problems with BJT based opamps like the 741 - in the simulation below, as 741 is used as a follower with a single supply; the input voltage is traingular, changing from 0 to 1 volt (green).

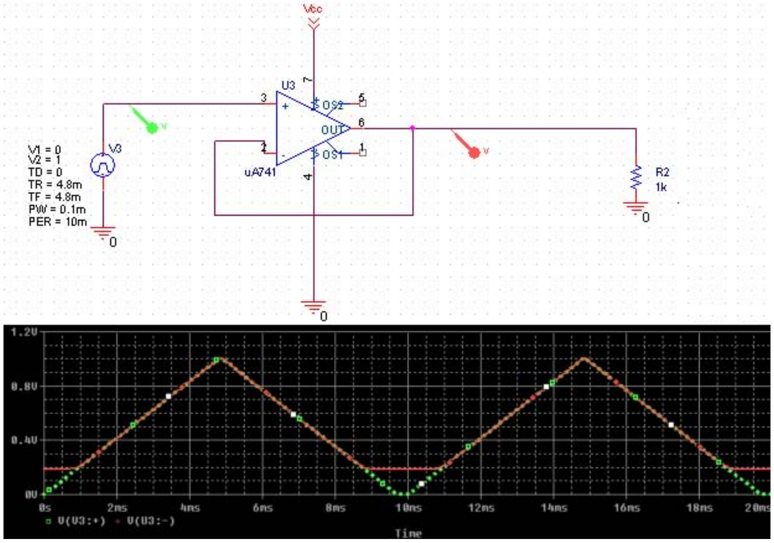


Figure 24. Schematic of a single supply follower

Notice that the output (red) stays at around 0.2V, when the input is below 0.2V - this is already a noticeable distortion; the reasons for this could be seen as the base-emitter turn-on voltages of the differential section. Note that opamps based on other technlogies (FET) might exhibit different behavior. Obviously, if a symmetric supply is used, the negative voltage at the emitter opens the transistors even when the input is 0 (and below zero) so this effect is then not present.

It is also advisable to use Falstads circuit simulator applet, to visualise the flow of current in this circuit.

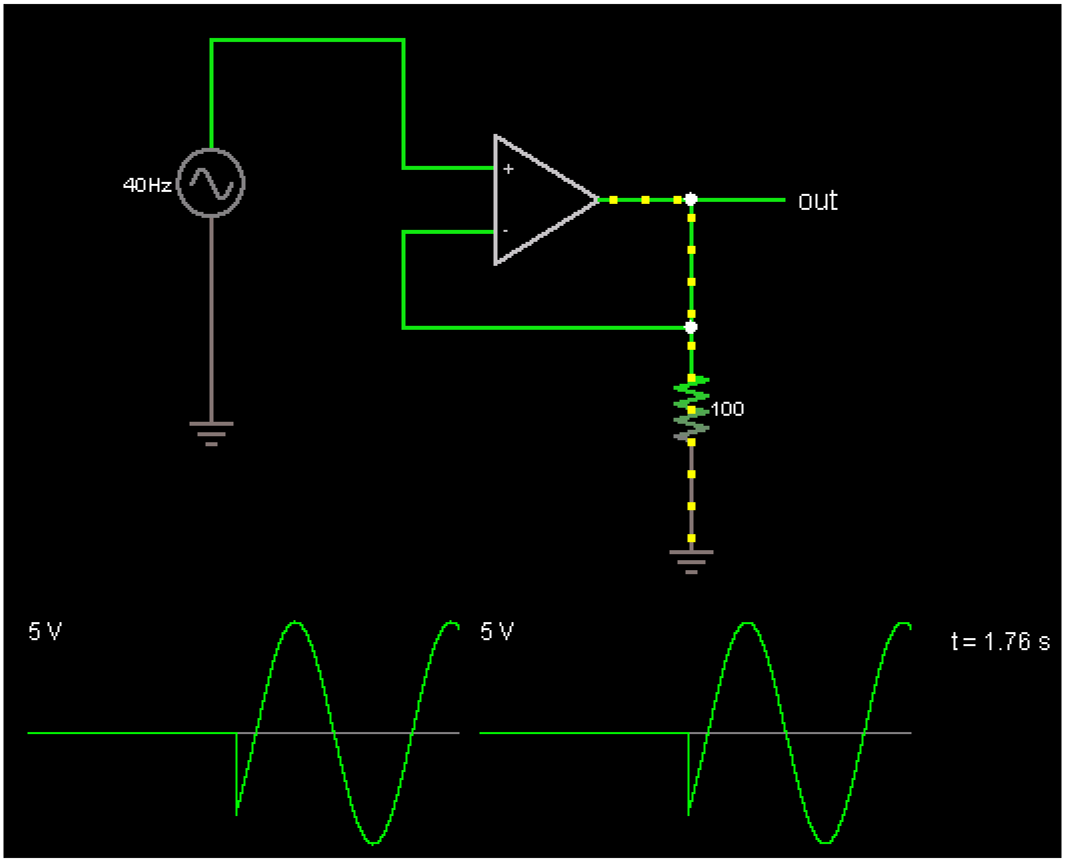


Figure 25.Visualising the flow of current in an op-amp voltage follower using Falstads applet (Ref. [1])

6.3 Opamp amplifiers

Opamp amplifiers come in two varieties - inverting and non-inverting, and in the minimal configuration can be implemented with a pair of resistors (or a single potentiometer) and an opamp. Again, one cannot cross from one to the other by simply swithing the inverting and non-inverting pin in the schematic - therefore we will look at these circuits separately.

6.3.1 Inverting amplifier

The schematic of the inverting amplifier is shown to the right. The op-amp equations are

$$I_+ = I_- = 0$$
$$V_+ = V_- \rightarrow U_d = 0$$

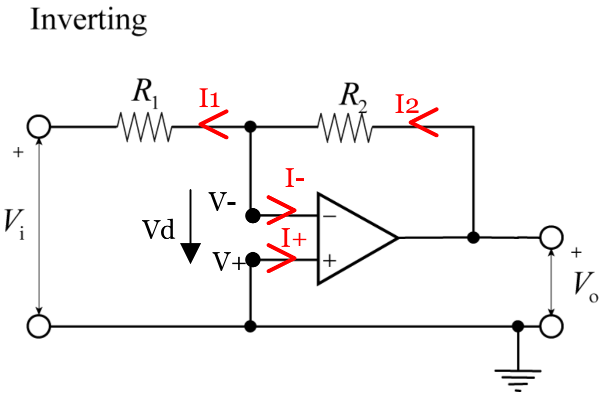


Figure 26. Schematic of an inverting op-amp amplifier

where $U_d = V_+ - V_-$ is the differential voltage.

Since I+ = 0, then I1 = I2 (KCL: $+I_2 - I_- - I_1 = 0$)

Since V+ is connected to ground, and the differential voltage Vd is zero, then V- must also keep the ground potential (zero). Then we can write expressions for currents I1 and I2 according to Ohms law:

$$I_1 = \frac{V_- - V_i}{R_1} = \frac{0 - V_i}{R_1} = -\frac{V_i}{R_1}$$
$$I_2 = \frac{V_o - V_-}{R_2} = \frac{V_o - 0}{R_2} = \frac{V_o}{R_2}$$

and since I2 = I1:

$$-\frac{V_i}{R_1} = \frac{V_0}{R_2} \rightarrow V_0 = -V_i \frac{R_2}{R_1}$$

Which means that the output voltage will be amplified by the ratio of R2 and R1, and will be out of phase (the output will be inverted) in relation to the input voltage.

Since the gain is determined only by the ratio of the resistances, knowing that potentiometer can effectively be modelled by a series connection of resistors, we can replace the fixed R1 and R2 with a potentiometer, and obtain the exact same circuit:

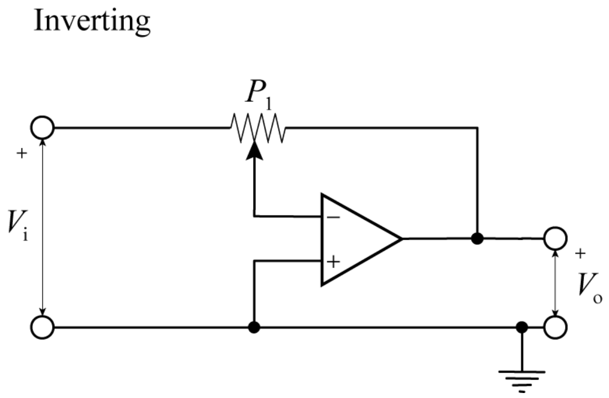


Figure 27. Inverting amplifier implemented with a potentiometer/trimmer

We only have to remember that when the potentiometer is set in the middle, then the equivalent R1 and R2 are equal, so we should obtain a voltage follower - in the direction where the R2 side grows over R1, we will have amplification, and in the opposite direction - attenuation of the signal.

For more, see [28]

It is also advisable to use Falstads circuit simulator applet, to visualise the flow of current in this circuit.

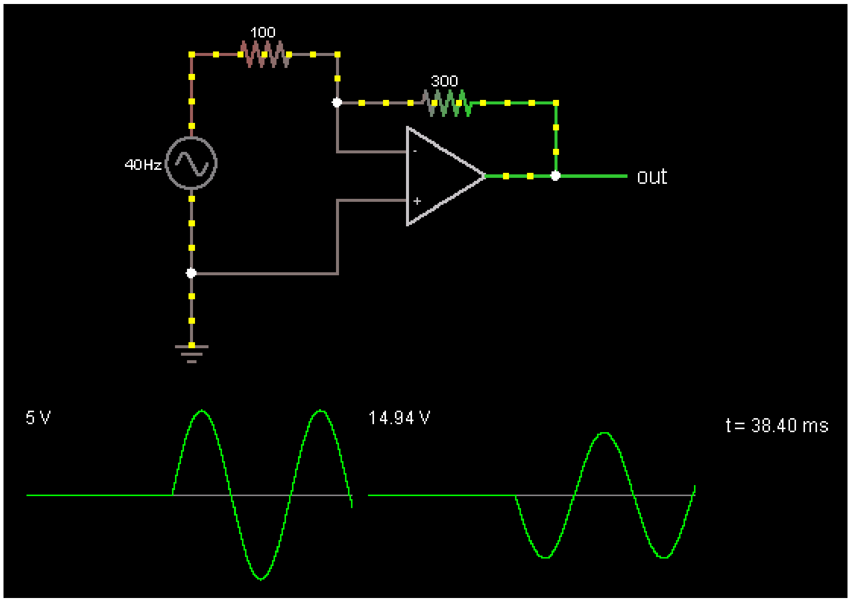


Figure 28.Visualising the flow of current in an op-amp inverting amplifier using Falstads applet (Ref. [1])

6.3.2 Non-inverting amplifier

The schematic of the inverting amplifier is shown to the right. The op-amp equations are

$$I_+ = I_- = 0$$
$$V_+ = V_- \to U_d = 0$$

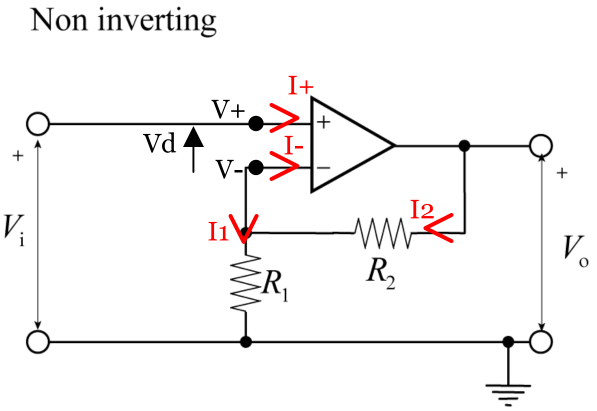


Figure 29. Schematic of an non-inverting op-amp amplifier

where $U_d = V_+ - V_-$ is the differential voltage.

Since I- = 0, then I1 = I2 (KCL: $+I_2 - I_- - I_1 = 0$)

Since Vi is connected to V+, and the differential voltage Vd is zero, then V- must also keep the potential Vi.

Then we can write expressions for currents I1 and I2 according to Ohms law:

$$I_1 = \frac{V_- - 0}{R_1} = \frac{V_i}{R_1}$$
$$I_2 = \frac{V_o - V_-}{R_2} = \frac{V_o - V_i}{R_2}$$

and since I2 = I1:

$$\frac{V_-}{R_1} = \frac{V_0 - V_-}{R_2} \to \frac{V_0}{R_2} = V_i \frac{R_2 + R_1}{R_2 R_1} \to V_0 = V_i \left(1 + \frac{R_2}{R_1}\right)$$

Which means that again, the output voltage will be amplified by the ratio of R2 and R1, but this time will be in phase with the input voltage. (Notice that the same expression could be obtained by looking at V-=Vi as a voltage divider output voltage, with input Vo).

Again, since the gain is determined only by the ratio of the resistances, knowing that potentiometer can effectively be modelled by a series connection of resistors, we can replace the fixed R1 and R2 with a potentiometer, and obtain the exact same circuit:

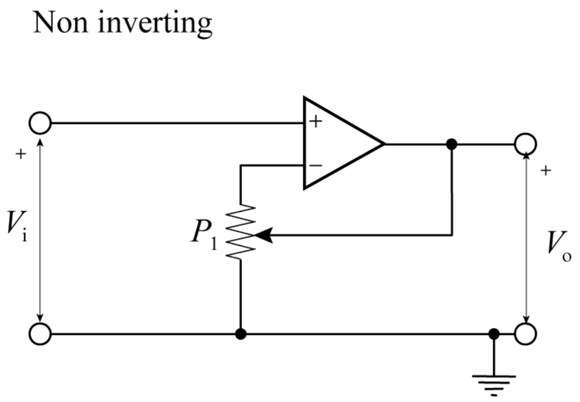


Figure 30. Non-inverting amplifier implemented with a potentiometer/trimmer

We only have to remember that when the potentiometer is set in the middle, then the equivalent R1 and R2 are equal, so we should obtain twice the input signal - in the direction where the R2 side grows over R1, we will have strong amplification (more than 2), and in the opposite direction - amplification between 1 and 2 (when R2 is zero, we have a voltage follower).

For more, see [28]

It is also advisable to use Falstads circuit simulator applet, to visualise the flow of current in this circuit.

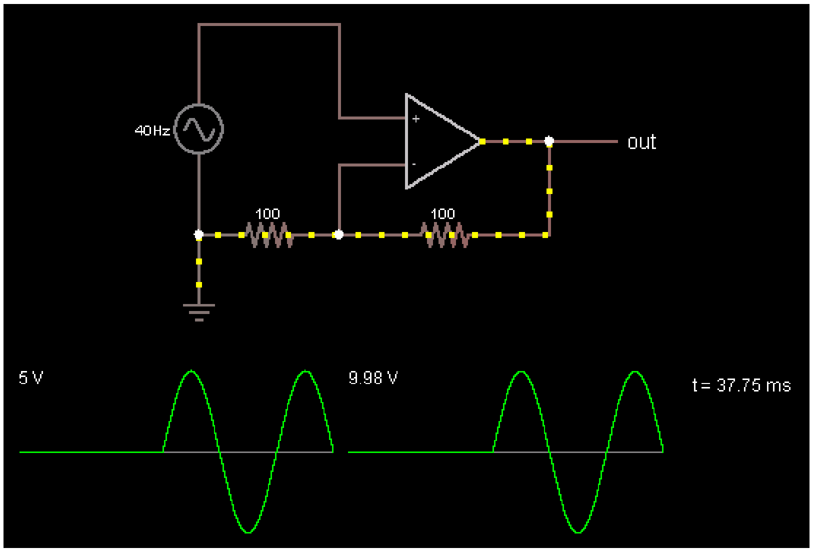


Figure 31. Visualising the flow of current in an op-amp inverting amplifier using Falstads applet (Ref. [1])

6.3.3 Analogy for divided feedback in opamps

Although there is no hydraulic analogy for opamps as such, there is still another physical analogy which can be applied to opamp amplifiers - as they both make use of feedback through voltage dividers, it may be useful to have an analogy for this process: "A helpful analogy for understanding divided feedback amplifier circuits is that of a mechanical lever, with relative motion of the lever's ends representing change in input and output voltages, and the fulcrum (pivot point) representing the location of the ground point, real or virtual.

If we draw a lever diagram next to the amplifier schematic, with the distance between fulcrum and lever ends representative of resistor values, the motion of the lever will signify changes in voltage at the input and output terminals of the amplifier.

With the inverting configuration, the ground point of the feedback voltage divider is the op-amp's inverting input with the input to the left and the output to the right. This is mechanically equivalent to a *first-class* lever, where the input force (effort) is on the opposite side of the fulcrum from the output (load).

With equal-value resistors (equal-lengths of lever on each side of the fulcrum), the output voltage (displacement) will be equal in magnitude to the input voltage (displacement), but of the opposite polarity (direction). A positive input results in a negative output.

Changing the resistor ratio R2/R1 changes the gain of the amplifier circuit, just as changing the fulcrum position on the lever changes its mechanical displacement 'gain.' Consider the following example, where R2 is made twice as large as R1."

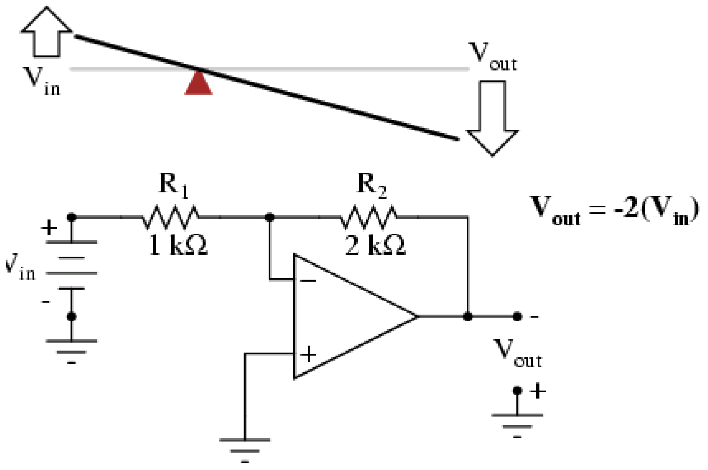
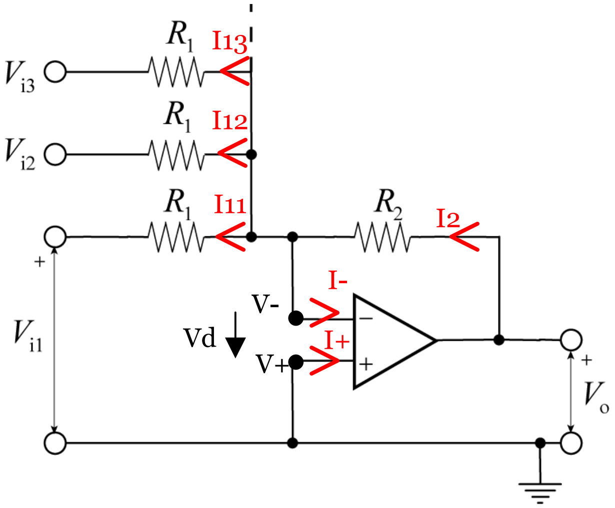


Figure 32. Mechanical lever analogy of divided feedback in an inverting amplifier (Ref. [35])

6.4 Summing amplifier (summer, mixer)

The schematic of the inverting amplifier is shown to the right. The circuit is also interesting because it represents the simplest implementantion of an analog audio mixer.



The op-amp equations are

$$I_+ = I_- = 0$$
$$V_+ = V_- \rightarrow U_d = 0$$

Figure 33. Schematic of an op-amp summer

where $U_d = V_+ - V_-$ is the differential voltage.

Since I- = 0, then I2 = I11+I12+I13+... (KCL: $+I_2$ $-I_-$ $-I_{11}$ $-I_{12}$ $-I_{13}$ - ... = 0)

Since V+ is connected to ground, and the differential voltage Vd is zero, then V- must also keep the ground potential (zero). Then we can write expressions for currents I11... and I2 according to Ohms law - essentially it is the same construction as the inferting amplifier:

$$I_2 = \frac{V_o - V_-}{R_2} = \frac{V_o - 0}{R_2} = \frac{V_o}{R_2}$$
$$I_{11} = \frac{V_- - V_{i1}}{R_1} = \frac{0 - V_{i1}}{R_1} = -\frac{V_{i1}}{R_1}$$
$$I_{12} = \frac{V_- - V_{i2}}{R_1} = \frac{0 - V_{i2}}{R_1} = -\frac{V_{i2}}{R_1}$$

and since I2 = I11+I12+... :

$$\frac{V_0}{R_2} = -\left(\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_1} + \ldots\right)$$

In general, the output voltage is the inverted sum of the input voltages (each multiplied by the ratio of R2 and their own resistor). When R2=R1, then Vo=-(Vi1+Vi2+...).

As this is an inverting circuit - obviously we would need an inverter (an inverting amplifier with amplification 1, or unity gain) placed after this circuit, if we wanted to truly obtain the sum of the signals in phase with its originating inputs. (Obviously, the kind of feedback in a non-inverting amlifier does not facilitate making a non-inverting mixer out of it).

For more, see [28]

It is also advisable to use Falstads circuit simulator applet, to visualise the flow of current in this circuit.

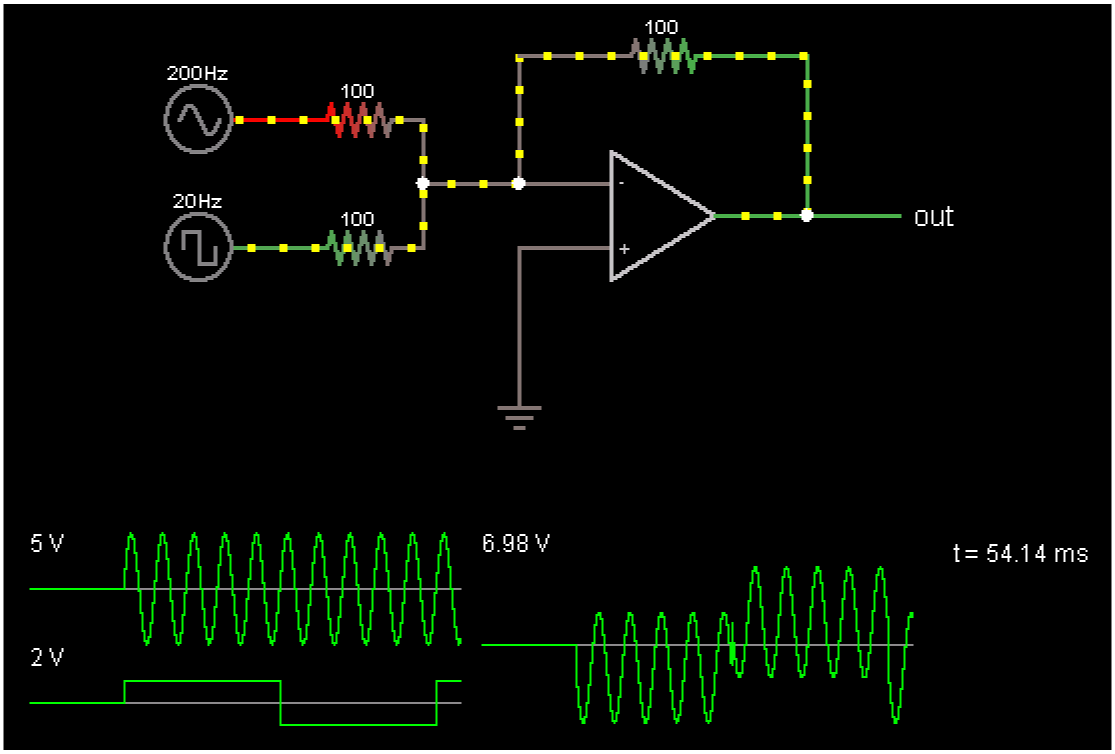


Figure 34. Visualising the flow of current in an op-amp summer using Falstads applet (Ref. [1])

6.5 Differential opamp amplifier

One of the more important circuits for interfacing some more difficult sensors is the differential opamp amplifier. Typically here we think of sensor circuits whose outputs are very small voltages, not referenced to ground.

The schematic of the inverting amplifier is shown to the right. The op-amp equations are

$$I_+ = I_- = 0$$
$$V_+ = V_- \rightarrow U_d = 0$$

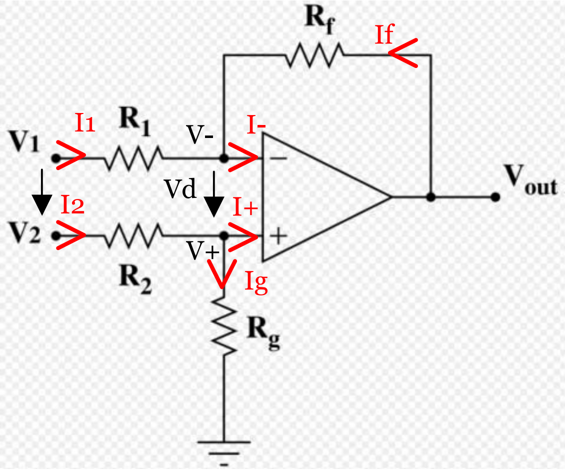


Figure 35. Schematic of a differential op-amp amplifier (Ref. [28])

where $U_d = V_+ - V_-$ is the differential voltage.

We can write Kirchoff current laws for the inverting and non-inverting node:

$$I_f + I_1 - I_- = 0 \rightarrow I_f = -I_1 \quad \text{(KCL node V-)}$$
$$I_2 - I_g - I_+ = 0 \rightarrow I_2 = I_g \quad \text{(KCL node V+)}$$

Then we can write Ohm' law for all four resistors:

$$I_f = \frac{V_o - V_-}{R_f} \qquad I_g = \frac{V_+ - 0}{R_g} \qquad I_1 = \frac{V_1 - V_-}{R_1} \qquad I_2 = \frac{V_2 - V_+}{R_2}$$

However, we can first recognize that V+ is set by a voltage divider from V2:

$$V_+ = \frac{R_g}{R_2 + R_g} V_2$$

Then, as If = -I1:

$$\frac{V_o - V_-}{R_f} = -\frac{V_1 - V_-}{R_1} \quad \text{->} \quad V_o = \frac{R_f}{R_1}\left(-V_1 + V_-\right) + V_- \quad \text{->} \quad V_o = \frac{R_f + R_1}{R_1} V_- - \frac{R_f}{R_1} V_1$$

However, since V- = V+

$$V_o = \frac{R_f + R_1}{R_1} \frac{R_g}{R_2 + R_g} V_2 - \frac{R_f}{R_1} V_1$$

When R1=R2 and Rf=Rg, we have *amplified difference*:

$$V_o = \frac{R_f}{R_1}\left(V_2 - V_1\right)$$

and when all resistances are equal, obviously Vo = V2 - V1, which is a difference amplifier.

For more, see [28]

It is also advisable to use Falstads circuit simulator applet, to visualise the flow of current in this circuit.

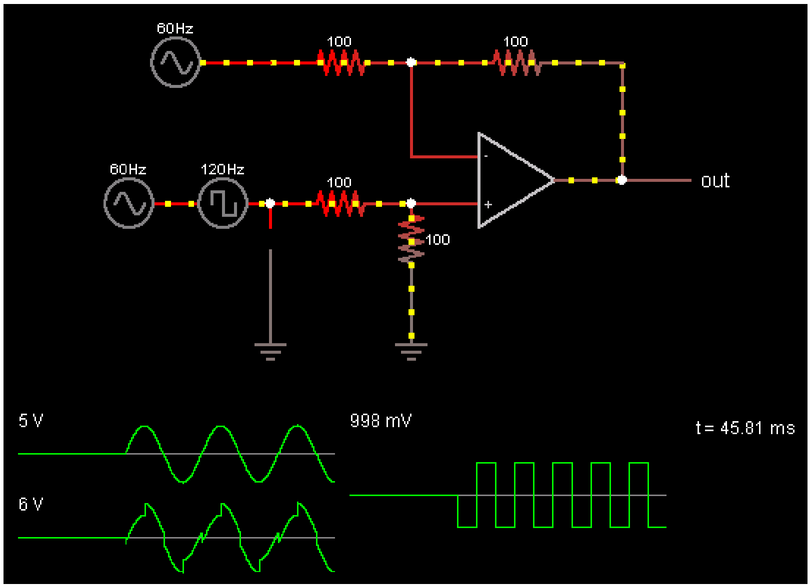


Figure 36.Visualising the flow of current in an op-amp differential amplifier using Falstads applet (Ref. [1])

6.5.1 Instrumentation amplifier

The instrumentation amplifier is essentially an opamp differential amplifier, with two additional opamps to serve as buffers for each of the differential inputs: "Instrumentation amplifier combines very high input impedance, high common-mode rejection, low DC offset, and other properties used in making very accurate, low-noise measurements. Is made by adding a inverting buffer to each input of the differential amplifier to increase the input impedance. [28]"

The schematic of an instrumentation amplifier is shown below.

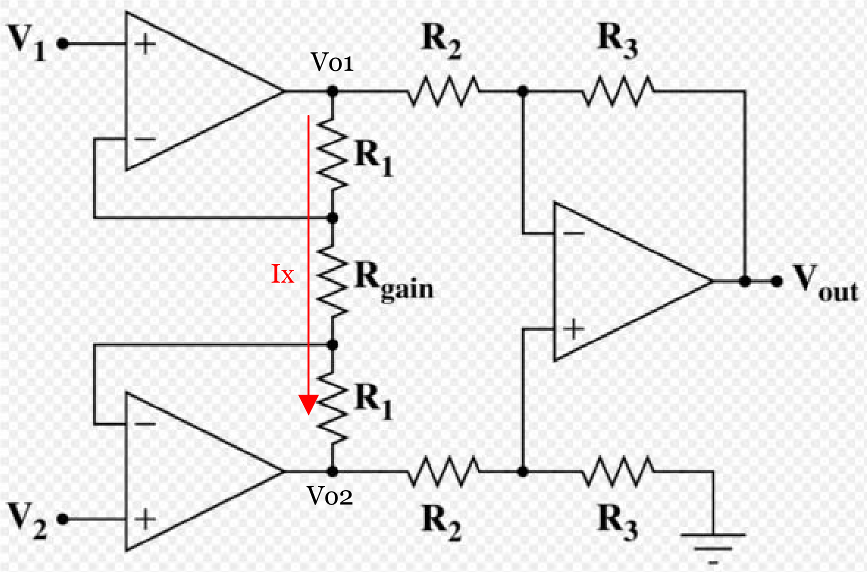


Figure 37. Schematic of an instrumentation amplifier (Ref. [28])

From the image, we can recognize that points Vo1 and Vo2 are inputs of the differential amplifier, so we can write directly the expression for the output voltage of differential amplifier:

$$V_o = \frac{R_3}{R_2}\left(V_{o2} - V_{o1}\right)$$

As I+ and I- must be zero, single current Ix flows through R1, Rgain and second R1. We can write three expressions for this current through potentials:

$$I_x = \frac{V_{o1} - V_1}{R_1} = \frac{V_2 - V_{o2}}{R_1} = \frac{V_{o1} - V_{o2}}{2R_1 + R_{gain}}$$

From the current expressions, we can express Vo through Ix:

$$V_{o2} - V_{o1} = -I_x \left(2R_1 + R_{gain}\right) \quad \text{->} \qquad V_o = -I_x \frac{R_3}{R_2}\left(2R_1 + R_{gain}\right)$$

Again from the current expressions, we can express V2-V1 through Ix:

$$2I_x = \frac{V_{o1} - V_{o2} + V_2 - V_1}{R_1} = \frac{I_x\left(2R_1 + R_{gain}\right) + V_2 - V_1}{R_1} \qquad \text{->} \qquad V_2 - V_1 = -I_x \cdot R_{gain}$$

We finally replace this Ix, expressed trhough V2-V1, into the expression for Vo expressed trhough Ix; and we obtain dependency directly between Vo and V2-V1:

$$V_o = \frac{V_2 - V_1}{R_{gain}} \frac{R_3}{R_2}\left(2R_1 + R_{gain}\right)$$

For more, see [28]

7 Sensing application

Although the operational amplifier does not have a 'sensor' conterpart, it is almost unavoidable for sensor circuits. As mentioned, the primary aplication is where sensor circuits produce small voltages in response to a physical parameter - then the signals produced can be easily affected by circuits connected to it. Here a follower is unavoidable as an impedance buffer. In addition, if these signals are not referenced to a common ground - then the differential amplifier is what needs to be applied to amplify the signal.

This sort of a situation, demanding a differential amplifier, is common with piezoelectric elements - which instead of changing a parameter like resistance, generate small ammounts of emf (voltage) in response to force: "The voltage range that a piezo sensor can produce can be up to a few thousand volts, and it can generate changes as small as a few microvolts. Because of this, piezos can be difficult to read across their entire sensitivity range. One common way to read miniscule changes from a piezo is to use an operational amplifier, or op amp. Op amps take a very small voltage signal and amplify it to a range that's readable. They can be used for many other functions as well, like reading the difference between two voltages, the sum of two voltages, and more. They've got a reputation among physical computing hobbyists for being difficult to use, but they don't have to be.[37]"

"High impedance transducers such as piezoelectric sensors, hydrophones, and some accelerometers require an amplifier that converts a transfer of charge into a voltage change. Due to the high DC output impedance of these devices, appropriate buffer amplifiers are required. The basic circuit for an inverting charge sensitive amplifier is shown below [36]"

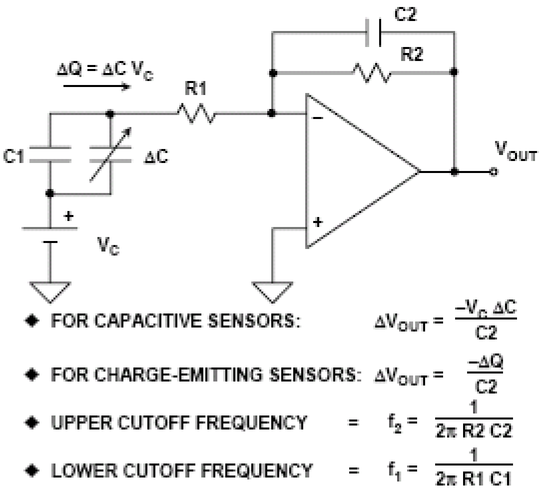


Figure 38. Charge amplifier basic principles (Ref. [36])

In addition, when interfacing strain gauges, commonly a Wheatstone bridge is used - it produces a small voltage output not referenced to ground, which must be amplified with a differential amplifier; more commonly, an instrumentation amplifier is used with a strain gauge Wheatstone bridge. (For more, see [38])

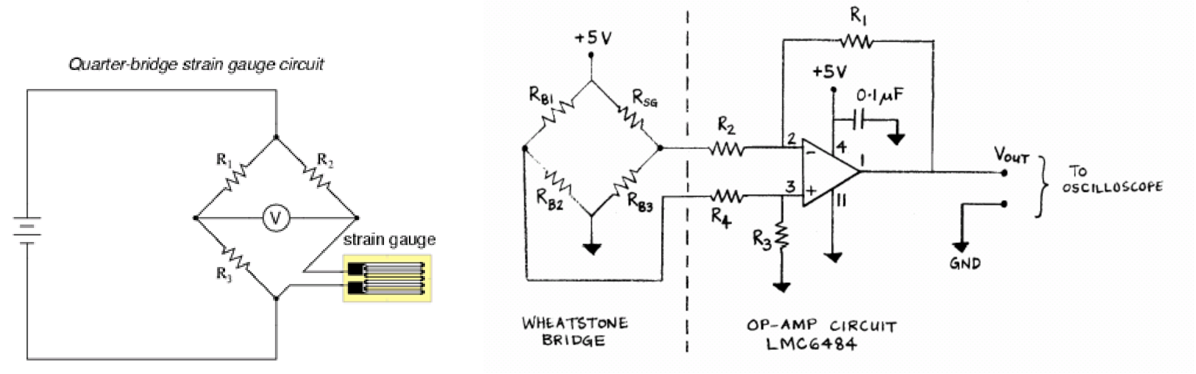


Figure 39. Left - interfacing a strain gauge through a Wheatstone bridge (Ref. [39]), right - amplifying the wheatstone bridge output with a single-supply differential amplifier (Ref. [40])

Finally, operational amplifiers can also be used to interface photodiodes, as previously seen - or can be used as an integral part of a Wien Bridge oscillator in capacitive sensing applications. For a good general overview of use of operational amplifiers for interfacing sensors, see [36].

8 PE Questions

- What is an operational amplifier? What are the set of rules used to model the opamp?
- What are some common circuits implemented using an operational amplifier?

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