Basic Op Amp Circuits

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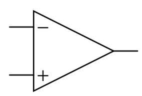
1 Introduction

The operational amplifier (*op amp or OA* for short) is perhaps the most important building block for the design of analog circuits. Combined with simple negative feedback networks, op amps allow engineers to build many circuits in a simple fashion, at low cost and using relatively few discrete components. Good knowledge of the op amp characteristics and aplications is essencial for a sucessful analog engineer.



Op amps are *differential amplifiers*, and their output voltage is proportional to the difference of the two input voltages. The op amp's schematic symbol is shown in the above figure. The two input terminals, called the inverting and non-inverting, are labeled with - and +, respectively. Most op amps are designed to work with two supplies usually connected to positive and negative voltages of equal magnitute (like the uA741 which works with $\pm 15V$). Some, however, work with a single-voltage supply. An example is the LM358. The supply connections may or may not be shown in a schematic diagram.

2 Basic Op Amp Circuits

Ideal Op Amp Analysis

An ideal analysis assumes that

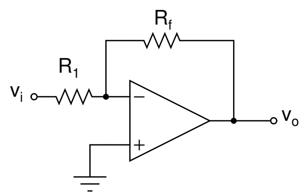
- the op amp has infinite gain so the the loop gain $A\beta = \infty$ and $A_f = 1/\beta$;
- the input impedance is ∞, so the input terminals drain no current;
- negative feedback forces the voltage difference at the op amp inputs to vanish, and the the inputs are *virtually* connected; when one of the two inputs is connected to ground, the other one is said to be at *virtual ground* ;
- the op amp output resistance is zero.

A few examples of the most common op amp circuits and their analysis assuming the ideal op amp model follow.

Inverting amplifier

Since the op amp takes no input current, the same current flows through R_1 and R_2. Because the non-inverting input is grounded, a *virtual ground* exist in the inverting input by virtue of the infinite gain and the negative feedback being used. Thus $v_i = i \times R_1$ and $v_o = -i \times R_2$. It follows that the gain of the inverting amplifier is $\frac{v_o}{v_i} = -\frac{R_2}{R_1}$.

The input impedance $R_i = R_1$. To find the output impedance, apply a test current source to the output and ground to v_i. Because of virtual ground, no current flows through R_1. Since no current flows into the inverting input, the current through R_2 must be 0 as well. Thus, independently of the test current, v_o remains grounded in the ideal op amp. Consecuently the output resistance is ideally 0.



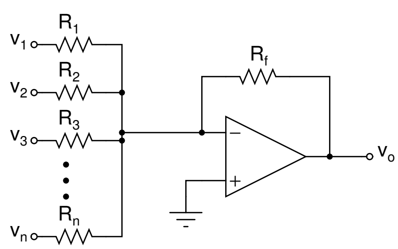
Summing amplifier

A KCL at the inverting input yields

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + ... + \frac{v_n}{R_n} = -\frac{v_o}{R_f}$$

Thus

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + ... + \frac{R_f}{R_n}v_n\right)$$



Non-inverting amplifier

Since the two terminals must be at the same voltage,

$$i_1 = \frac{-v_i}{R_1}$$

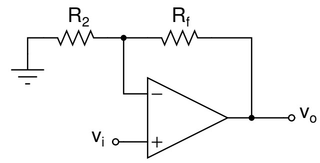
and

$$i_2 = \frac{-v_i - v_o}{R_2}$$

But no current flows into the inverting terminal, so $i_1 = i_2$. Substituting into this equation and solving for v_o yields

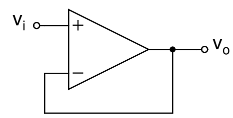
$$v_o = \left(1 + \frac{R_2}{R_1}\right) v_i$$

Input impedance R_i is infinite. Output impedance is very low.



Voltage follower or *buffer* amplifier

Since $R_f = 0$ and this configuration is the same than the non-inverting amplifier, the gain is unity. The input impedance is, however, infinity. So this configuration elliminates loading, allowing a source with a relatively large Thevenin's resistance to be connected to a load with a relatively small resistance.



Difference amplifier

This circuit provides an output voltage that is proportional to the difference of the two inputs. Applying KCL at the inverting terminal yields

$$i_1 = \frac{v_1 - v_-}{R_1} = i_2 = \frac{v_- - v_o}{R_2}$$

Solving for v_o and reordering terms gives

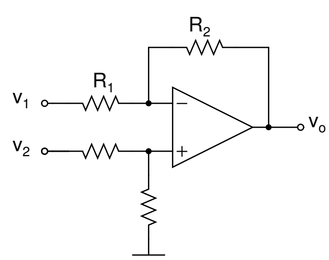
$$v_o = \frac{R_1 + R_2}{R_1} v_- - \frac{R_2}{R_1} v_1$$

Since $v_- = v_+ = \frac{R_4}{R_3 + R_4} v_2$,

$$v_o = \frac{R_1 + R_2}{R_1} \frac{R_4}{R_3 + R_4} v_2 - \frac{R_2}{R_1} v_1$$

By choosing $R_1 = R_3$ and $R_2 = R_4$ one gets that

$$v_o = \frac{R_2}{R_1} (v_2 - v_1)$$



Current-to-voltage converter

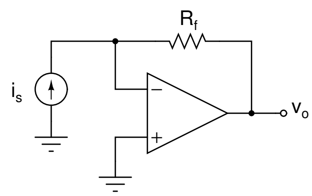
Since the source current i_s can not flow into the amplifier's inverting input, it must flow thorugh R_f. Since the inverting input is virtual ground,

$$v_o = -i_s R_f$$

Also, the virtual ground assumption implies that

$$R_i = 0$$

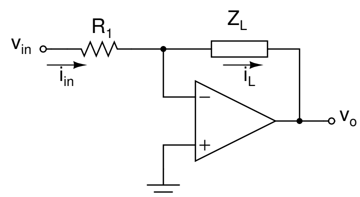
for this circuit.



Voltage-to-current converter

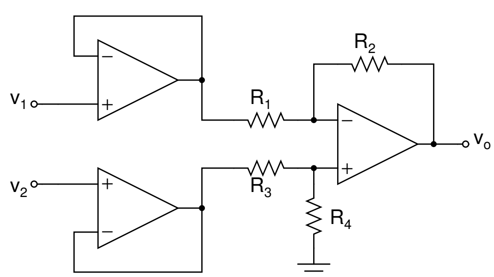
In this cricuit, the load is not grounded but takes the place of the feedback resistor. Since the inverting input is virtual ground,

$$i_L = i_{in} = \frac{v_{in}}{R_1}$$



Instrumentation amplifier

This amplifier is just two buffers followed by a differential amplifier. So it is a differential amplifier but the two sources see an infinite resistance load.



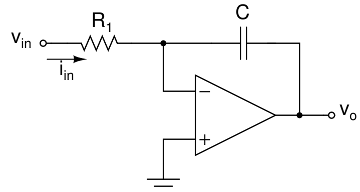
Integrator

Let v_{in} be an arbitrary function of time. The current through the capacitor is $i_{in} = \frac{v_{in}}{R_1}$. From the capacitor law,

$$i_C = C\frac{dv_C}{dt}$$

or

$$v_o = -v_C = -\frac{1}{C}\int i_C dt = -\frac{1}{R_1 C}\int v_{in} dt$$



Active low-pass filter

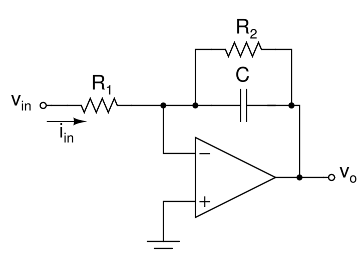
Here we assume that the input is sinusoidal. Thus we can use the concepts of impedance and reactance and work in the frequency domain. Thus, the circuit is an inverting amplifier, but the feedback resistor as been replaced with Z_f, the parallel combination of R_2 and C. Therefore,

$$Z_f = \frac{\frac{1}{sC}R_2}{\frac{1}{sC} + R_2} = \frac{R_2}{1 + sCR_2}$$

From the expression for the inverting amplifier's gain,

$$v_o(s) = -\frac{Z_f}{R_1} = -\frac{R_2}{R_1}\frac{1}{1 + sCR_2}v_i(s)$$

which is small for s large.



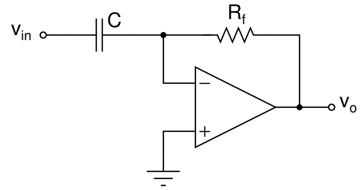
Differentiator

Here the input current is determined by the capacitor law,

$$i_{in} = C\frac{dv_{in}}{dt}$$

Thus

$$v_o = -R_f i_{in} = -R_f C\frac{dv_{in}}{dt}$$



Active high-pass filter

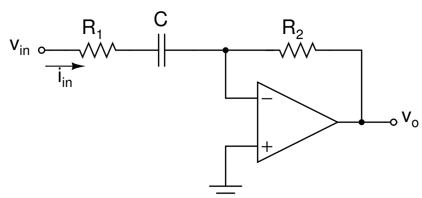
Like in the low-pass filter, we consider v_{in} to be sinusoidal and apply impedance concepts. The configuration is again like the inverting amplifier, but the resistor R_1 as been replaced with Z_1, which is R_1 in series with C. Thus

$$Z_1 = R_1 + \frac{1}{sC} = \frac{sR_1C + 1}{sC}$$

and

$$v_o = -\frac{R_f}{Z_1} = -\frac{sCR_f}{sR_1C + 1}$$

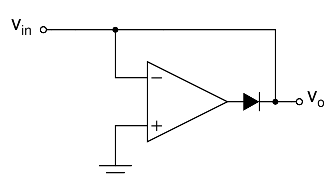
which is small for s small.



Precision half-wave rectifier

In this circuit, the diode conducts when the op amp output is positive and larger than $0.7V$, i.e. when the non-inverting inputs exceeds the inverting by $\frac{0.7}{A_{open-loop}}$ volts, where $A_{open-loop}$ represents the op amp open-loop gain, taken to be infinity for an ideal device. Thus as soon as the input becomes negative, the diode conducts and the output becomes virtual ground. If the input is positive, the diode is an open circuit and the output is directly connected to the input.

The circuit is used to rectify signals whose amplitude is smaller than the $0.7V$ required to forward-bias the diode.



Logarithmic Amplifier

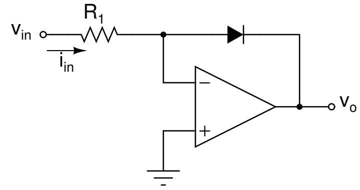
Here output and diode's voltage are equal in magnitude and of opposite signs. Since

$$i_D \approx I_S exp\left(\frac{v_D}{V_T}\right)$$

where V_T is the thermal voltage, equal to $25mV$ at room temperature. It follows that

$$v_o = -v_D = -V_T\left(log(v_{in}/R_1) - logI_s\right)$$

and is thus proportional to the logarithm off the input.



Anti-logarithmic Amplifier

The current i_{IN} is given by

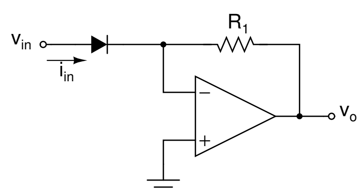
$$i_D \approx I_S exp\left(\frac{v_D}{V_T}\right)$$

or

$$i_{IN} \approx I_S exp\left(\frac{v_{IN}}{V_T}\right)$$

Thus the output voltage is

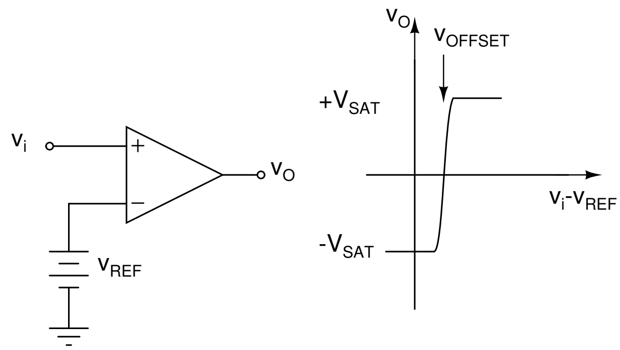
$$v_O = -i_{IN}R_f \approx I_S R_f exp\left(\frac{v_{IN}}{V_T}\right)$$



Comparator

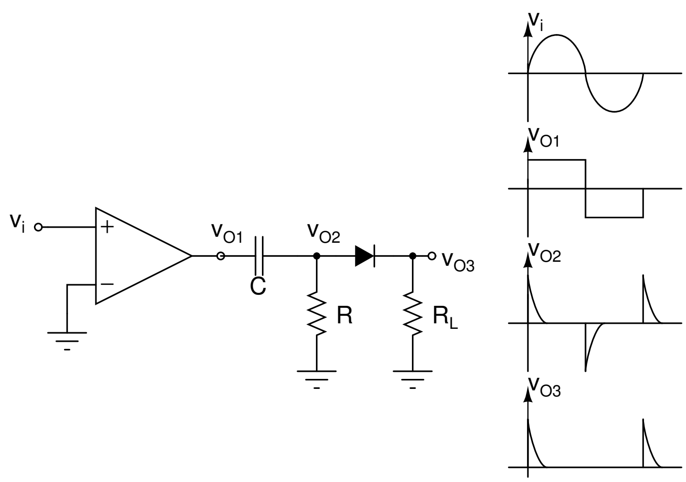
An op amp can be used as a comparator in a circuit like the one shown below. This is a non-linear circuit in which the output saturates to about 90 % of the positive and negative supply voltages. The polarity of the output voltage depends on the sign of the differential input, $v_i - v_{REF}$.

The sketch shows non-ideal characteristics tipically found in op amps. The offset voltage, v_{OFFSET}, is on the order of few millivolts and causes the transition from low to high to be slightly displaced from the origin. v_{OFFSET} can be negative or positive, and is zero in an ideal op amp. The posibility of having voltages between plus and minus v_{SAT}, a consecuense of the finite gain of practical op amps, is also shown. This part of the curve would be vertical if the op amp is ideal. Special integrated circuits (like the MC1530) are specially build to be used as comparators and minimize these non-ideal effects.



Zero-crossing Detector

If the inverting input of a comparator is connected to ground, the device's output switches from positive to negative saturation when the input goes from positive to negative, and viceversa. Output v_{O1} on the following sketch displays this vehavior.

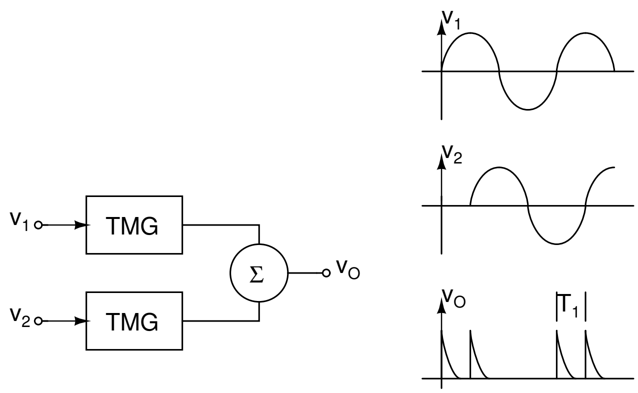


Timing-marker Generator

If an RC network is connected to the output of a zero-crossing detector, capacitor charging and discharging produce the waveform v_{O2} shown in the above sketch. This signal is rectified to produce the waveform labeled v_{O3}. The circuit is called a *timing-markers generator*, or TMG, for obvious reasons.

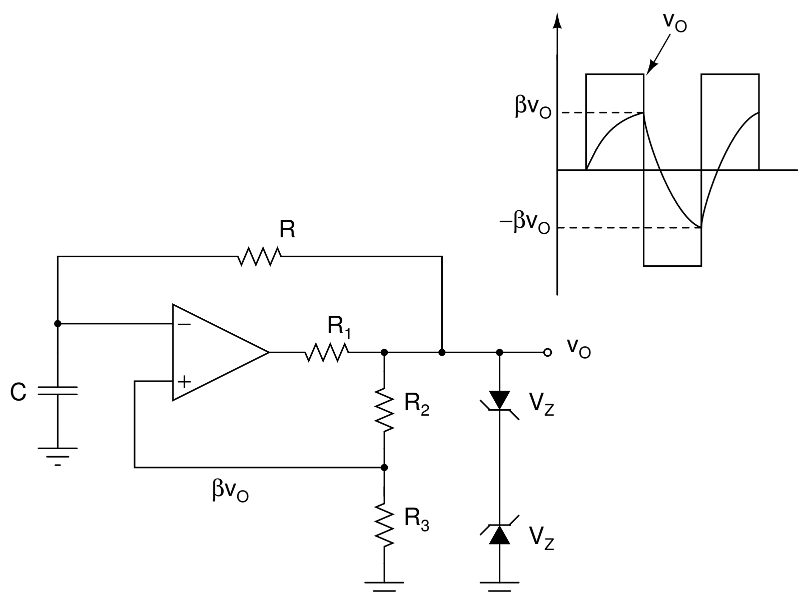
Phase Meter

Combining two TMG and an adder, as shown in the following figure, one can build the so called *phase meter*. The time difference T_1 is proportional to the phase difference between the two sinusoidal inputs.



Square Wave Generator

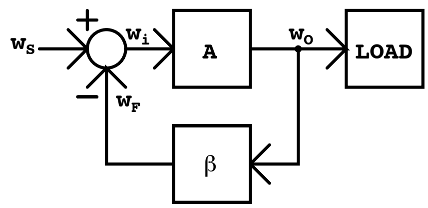
This circuit is an oscillator that generates a square wave. It is also known as an *astable multivibrator*. The op amp works as a comparator. Let's assume that the op amp output goes high on power-on, thus making $v_O = +V_Z$. The capacitor charges with a time constant $\tau = RC$. When the capacitor voltage reaches $\beta v_O = \frac{R_3}{R_2+R_3}$, the op amp output switches low, and $v_O = -V_Z$ as shown in the graph.



3 Real Op Amps

Error Function

Linear op-amp circuits use negative feedback and thus can be described by the theory of feedback systems. A general negative-feedback system can be represented by the following block diagram:



Since

$$\omega_O = A\left(\omega_S - \beta \times \omega_O\right)$$

we can solve for $A_f = \frac{\omega_O}{\omega_S}$ to get

$$\begin{aligned} A_f &= \frac{A}{1+\beta A} \\ &= \frac{A}{T}\frac{1}{1+\frac{1}{T}} \\ &= A_{ideal}\frac{1}{1+\frac{1}{T}} \end{aligned}$$

where

$$A_{ideal} = \lim_{\beta A \to \infty} A_f = \frac{A}{T}$$

Since the loop gain T is equal to βA,

$$A_{ideal} = \frac{1}{\beta}$$

and

$$A_f = \frac{1}{\beta}\frac{1}{1+\frac{1}{T}}$$

The quantity

$$\frac{1}{1+\frac{1}{T}}$$

is known as the *error function* and gives a direct indication of how much the system departs from the ideal.

Equivalently, the loop gain T can also be used to quantify the difference between real and ideal op amp behavior. A full feedback analysis for the non-inverting and inverting amplifier configurations give the results that are summarized in the following table;

	non-inverting	inverting
T	$\frac{R_{22}}{r_o+R_{22}} a \frac{r_d}{r_d+R_{11}} \frac{R_1}{R_1+R_2}$	$a\frac{R_1\|\|R_2\|\|r_d}{r_o+R_2}$