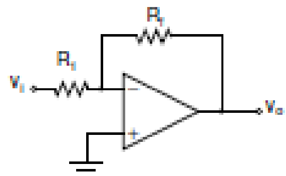
## Inverting amplifier

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.



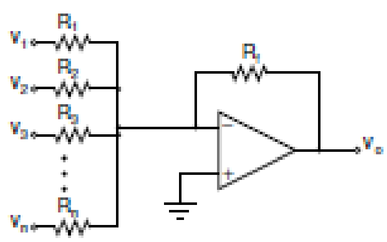

## Summing amplifier

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,

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

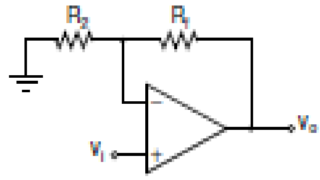
and

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

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

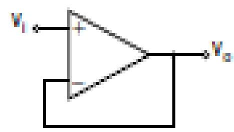
$$v_o = \left(1 + \frac{R_2}{R_1}\right) v_i$$

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

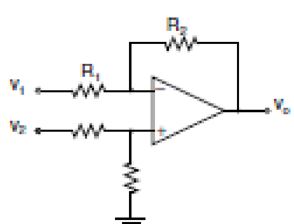
$$v_o = \frac{R_1 + R_2}{R_1} v_- - \frac{R_2}{R_1} v_1$$

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

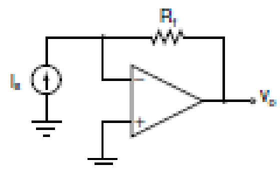
Since the source current $i_s$ can not flow into the amplifier's inverting input, it must flow thorugh $R_f$. Since the inverting input is virtual ground,

$$v_o = -i_s R_f$$

Also, the virtual ground assumption implies that

$$R_i = 0$$

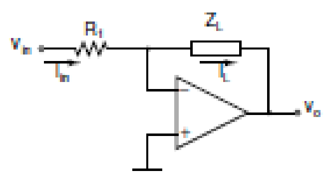
for this circuit.



## Voltage-to-current converter

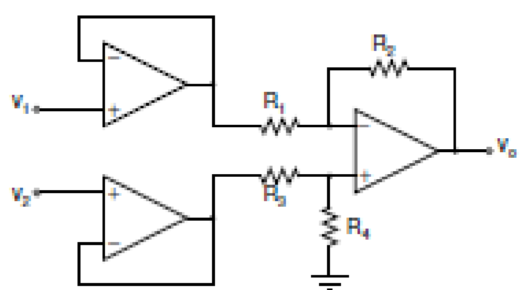
In this cricuit, the load is not grounded but takes the place of the feedback resistor. Since the inverting input is virtual ground,

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



# 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.



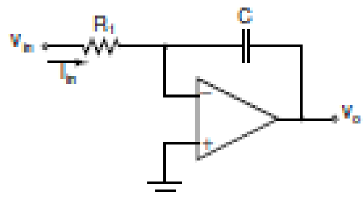
## Integrator

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

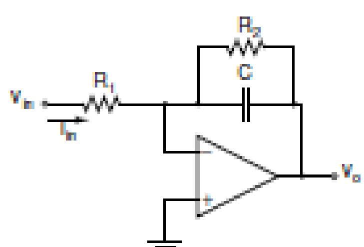
Here we assume that the input is sinusoidal. Thus we can use the concepts of impedance and reactance and work in the frequency domain. Thus, the circuit is an inverting amplifier, but the feedback resistor as been replaced with $Z_f$, the parallel combination of $R_2$ and $C$. Therefore,

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

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.



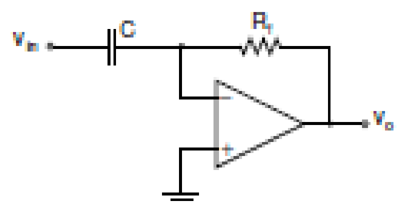
## Differentiator

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

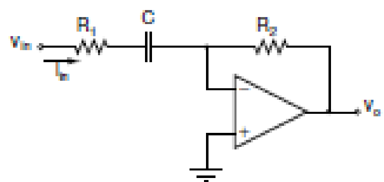
Like in the low-pass filter, we consider $v_{in}$ to be sinusoidal and apply impedance concepts. The configuration is again like the inverting amplifier, but the resistor $R_1$ as been replaced with $Z_1$, which is $R_1$ in series with $C$. Thus

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

and

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

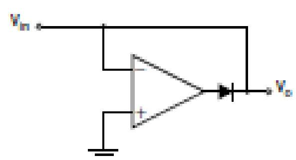
which is small for $s$ small.




### 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

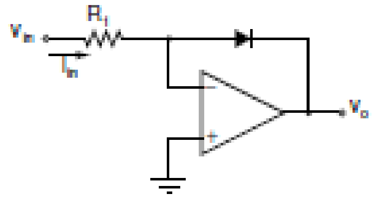
Here output and diode's voltage are equal in magnitude and of opposite signs. Since

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

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

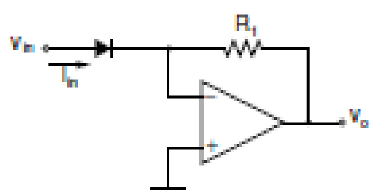
$$i_D \approx I_S exp\left(\frac{v_D}{V_T}\right)$$

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.