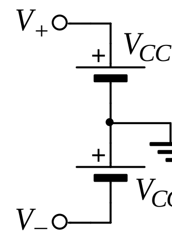
Ideal Operational Amplifier

The modern operational amplifier (Op Amp) is a high-gain, integrated circuit, direct-coupled amplifier, capable of performing linear and non-linear amplification and signal processing functions.

Power Supply

Most Op Amps are powered from dual power supplies of opposite polarities as in the figure. The most common values are +/-15 V.
The common ground point usually is not connected to the Op Amp itself; it becomes the reference ground point.
In order to simplify circuit diagrams, the power supply connections are usually omitted (but theirs presence is understood).



Saturation Voltages

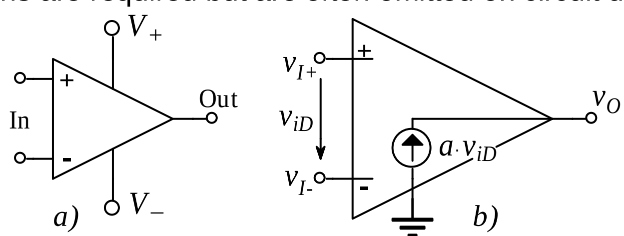
The voltage at the Op Amp output for a resistive load is:

$$-V_{sat-} \le v_o \le +V_{sat+}$$

In general the magnitudes of the saturation voltages are about 2 V below the power supply: $V_{sat-} \cong V_{sat+} \cong V_{CC} - 2$.

Op Amp Symbol Circuit Model of Ideal Op Amp

Power supply connections are required but are often omitted on circuit diagram.



There are two signal input terminals:

- inverting terminal – indicated by a (-) symbol,
- non-inverting terminal, indicated by a (+) symbol, respectively;

and one output signal terminal.

The input voltages are: v_{I+} is the voltage at the non-inverting input and v_{I-} is the voltage at the inverting input.
The signal voltage at either input terminal may be positive or negative with respect to the ground. The symbol sign refer to the polarity of voltage gain (have nothing to do with the polarity of voltage).
Actual Op Amp comes very close to the ideal model when operated over the proper range of conditions.
First condition is that all the circuits are operated as stable, linear circuits. The active circuits improperly designed or constructed posses the potential for instability.
The differential input voltage is: $v_{iD} = v_{I+} - v_{I-}$ (),
and the output voltage is: $v_O = a \cdot v_{iD} = a \cdot (v_{I+} - v_{I-})$, where a is the open-loop differential gain.

Ideal assumptions

1. The ideal impedance of the Op Amp as viewed from the two input terminals is infinite; there is an open circuit across the two input terminals for the Op Amp ideal model.
2. The output impedance of the Op Amp as viewed from the output terminal with respect to the ground is zero; for the ideal model there is no Thevenin resistance in series with the output voltage controlled voltage source (VCVS).
3. The open-loop gain "a" is infinite in the ideal case, $a \to \infty$.

Implications (of the ideal assumptions)

1. The assumption of infinite input impedance implies that no current will flow into or out of either input terminals of the Op Amp.
2. The assumption of zero output impedance implies that the voltage v_O (at the output terminal of the Op Amp) does not depend on the load (does not change as the load is varied, Op Amp produces same output voltage irrespective of the current in the load).
3. For a linear and stable operation, v_O is a finite (not saturated) voltage:

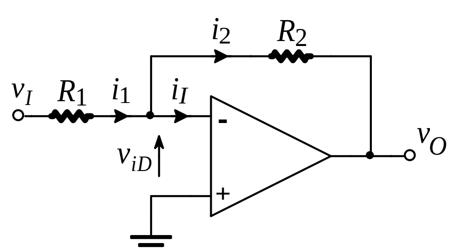
   $-V_{sat-} < v_o < +V_{sat+}$. As $a \to \infty$ and v_O is finite, $v_{iD} = \lim\limits_{a\to\infty} \frac{v_O}{a} = 0$.

The result indicates that the differential voltage is zero; an equivalent implication is:
$v_{I+} - v_{I-} = 0$ or $v_{I+} = v_{I-}$. The voltages at the two input terminals are forced to be equal.
The differential input voltage v_{iD} is not actually zero, but rather it is a very small value. The input terminals must not be connected together in a circuit.
The ideal assumptions and theirs implications are summarized in the next table:

Ideal Op Amp assumption	Implication
1. $R_{in} \to \infty$	Input current is zero
2. $R_{out} \to 0$	Output voltage does not depend on the load
3. $a \to \infty$	Differential input voltage is zero

Analyzing Op Amp Circuits

Inverting Amplifier



The amplifier presented in figure has a gain: $A = \frac{v_O}{v_I}$.

An ideal op amp will be considered. As long as the output voltage is finite (output not saturated: $-V_{sat-} < v_O < +V_{sat+}$), the voltage between the op amp input terminals is zero (practically, negligibly small): $v_{ID} = \frac{v_O}{a} = \frac{v_O}{\infty} = 0$.

Since $v_{iD} = v_{I+} - v_{I-} = 0$, it follows that $v_{I+} = v_{I-}$; we speak of this as: the two input terminals are "tracking each other in potential". We also speak of a "virtual short circuit" that exists between the two input terminals (virtual short, not physically shorted).

Because $v_{I+} = 0$ (the non-inverting terminal is grounded), it follows that $v_{I-} = 0$; we speak of the inverting terminal as being a "virtual-ground" – that is having zero voltage, but not physically connected to ground.

The input current is: $i_1 = \frac{v_I - v_{I-}}{R_1} = \frac{v_I}{R_1}$.

This current cannot flow into the opamp, since the ideal opamp has infinite input resistance and hence draw zero current ($i_I = 0$):

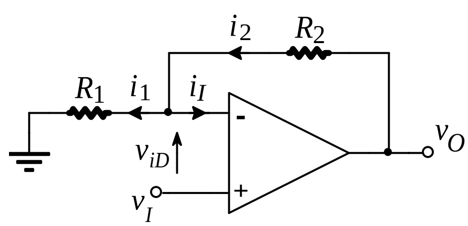
$i_1 = i_I + i_2 = i_2$,

$v_O = v_{I-} - i_2 R_2 = 0 - i_1 R_2 = -\frac{v_I}{R_1} R_2$, and the voltage gain is: $A_v = \frac{v_o}{v_I} = -\frac{R_2}{R_1}$.

Because of the minus sign this configuration is called the inverting configuration.
The resulted voltage gain is much smaller than a, but is stable and predictable. That is, we trade gain for accuracy.

The input resistance of the amplifier is: $R_i = \frac{v_I}{i_I} = \frac{v_I}{i_1} = \frac{v_I}{v_I / R_1} = R_1$.

Non-inverting Amplifier

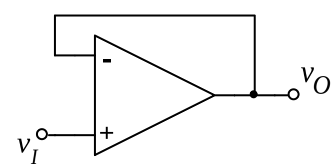


The circuit is presented in figure; the input and the ground terminal from the inverting configuration are interchanged.
The virtual short-circuit between the op amp input terminals gives: $v_{I-} = v_{I+} = v_I$.
The input current is zero because of the infinite input resistance and: $i_2 = i_I + i_1 = i_1$,

$i_1 = \frac{v_{I-}}{R_1} = \frac{v_I}{R_1}$, $v_O = R_2 i_2 + v_{I-} = R_2 i_1 + v_I = R_2 \frac{v_I}{R_1} + v_I$, which yields a voltage gain:

$$A_v = \frac{v_o}{v_I} = 1 + \frac{R_2}{R_1}.$$

The gain is positive – hence the name of the non-inverting amplifier.
The input resistance of this amplifier is ideally infinite since no current will flow into the non-inverting terminal of the op amp.



The circuit can be used as a buffer amplifier to connect a source with high impedance to a low-impedance load. In many applications the buffer is not required to provide any voltage gain; rather it is used mainly as an impedance transformer.
For $R_2 = 0$ and $R_1 = \infty$ (without R_2) we obtain the simplest unity gain amplifier or voltage follower (the output voltage follows the input voltage: $A_v = 1$ and $v_O = v_I$).