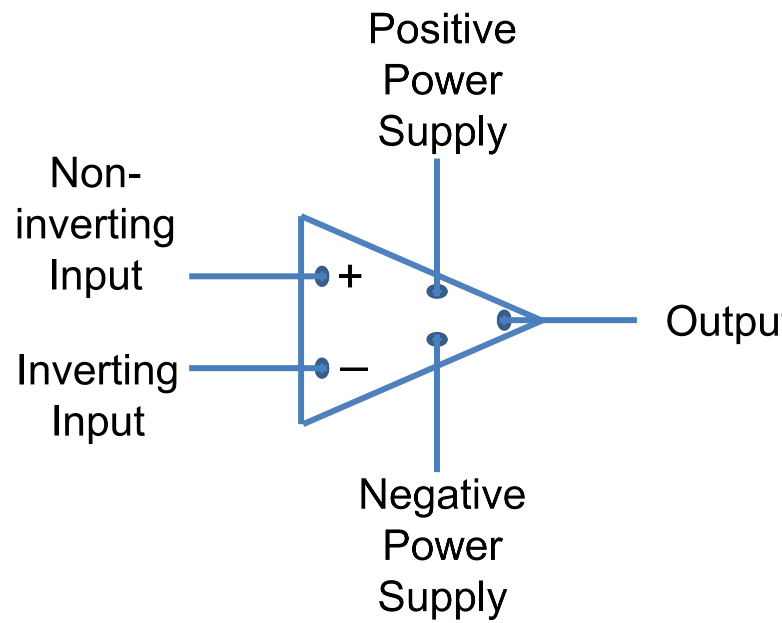
Operational Amplifiers

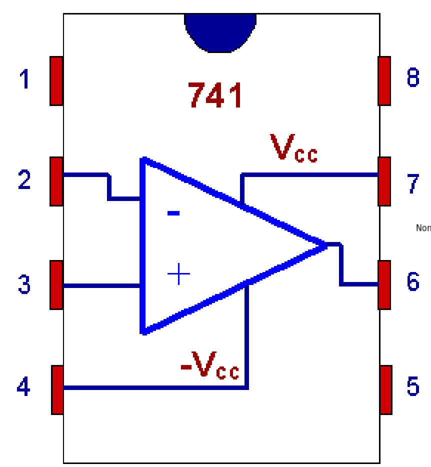
An operational amplifier (Op Amp) is an amplification circuit that is commonly used in a wide variety of applications. Its schematic diagram is as shown and has 5 terminals:

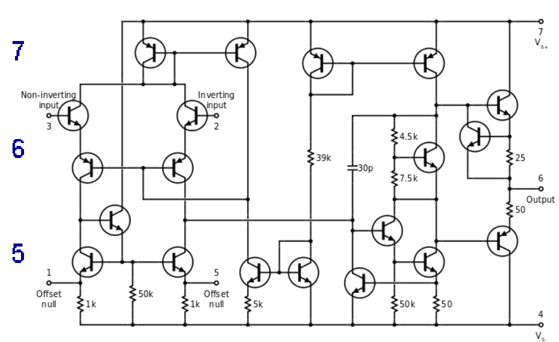
1) Inverting input (-)
2) Non-inverting input (+)
3) Positive power supply
4) Negative power supply
5) Output



Op amps are typically integrated onto a chip like the one shown here.

Internally, they consist of a number of transistors, but we will not concern ourselves with the internal workings in this course.

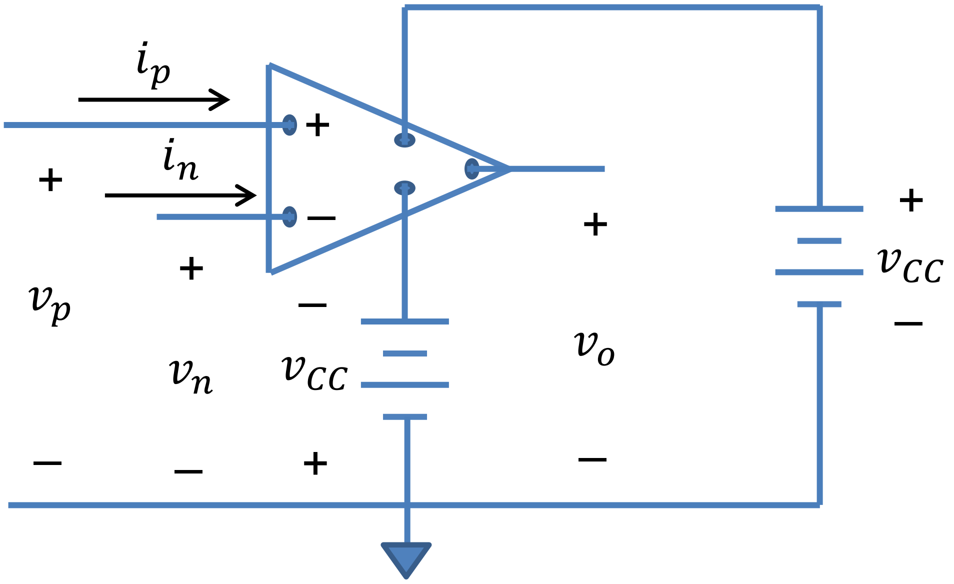




Operational Amplifiers

The voltages and currents associated with an op-amp are defined as shown (assuming supply voltages of $+V_{CC}$ and $-V_{CC}$.)

v_p = voltage on non-inverting input (w.r.t. ground).
v_n = voltage on inverting input (w.r.t. ground).
v_o = voltage on output (w.r.t. ground).
i_p = current flowing into non-inverting input.
i_n = current flowing into inverting input.



Operational Amplifiers

The op-amp is essentially an amplifier that produces an output which is proportional to the voltage difference between the input terminals:

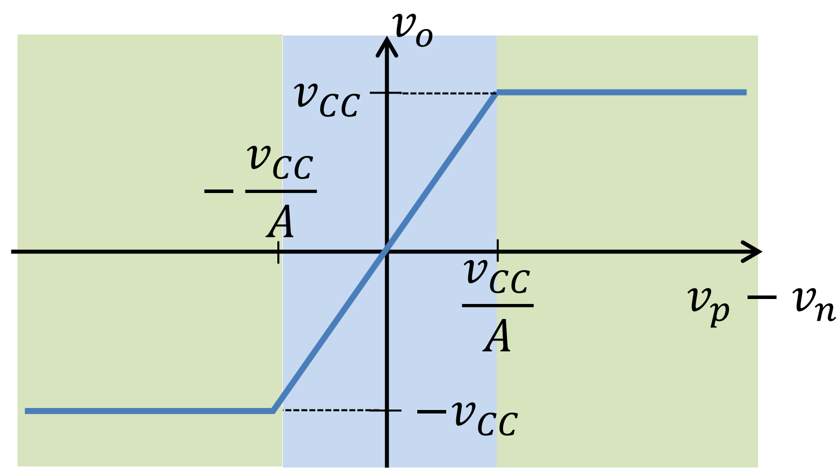
$$v_o = A(v_p - v_n)$$

Where A is a large positive number ($A \sim 10^6$).

If the input gets too large, the op amp cannot produce an output larger than v_{CC} and the op amp output is saturated at $v_o = v_{CC}$. Similarly, if the input is too negative, the output saturates at $v_o = -v_{CC}$.

The behavior of the op amp is characterized by the picture shown…

… or by the piecewise mathematical equation given →



negative saturation region

linear region

positive saturation region

$$v_o = \begin{cases} v_{CC}, & v_p - v_n > \frac{v_{CC}}{A}, \\ A(v_p - v_n), & |v_p - v_n| < \frac{v_{CC}}{A}, \\ -v_{CC}, & v_p - v_n < -\frac{v_{CC}}{A}. \end{cases}$$

Ideal Op Amp Equations

Virtual Short Condition

Using typical numbers, $A \sim 10^6$, $v_{CC} = 20V$ (upper limit), then the linear region occurs when $|v_p - v_n| < 20\mu V$. Hence, for an op-amp operating in its linear mode, $|v_p - v_n| \approx 0$.

$$v_p = v_n.$$

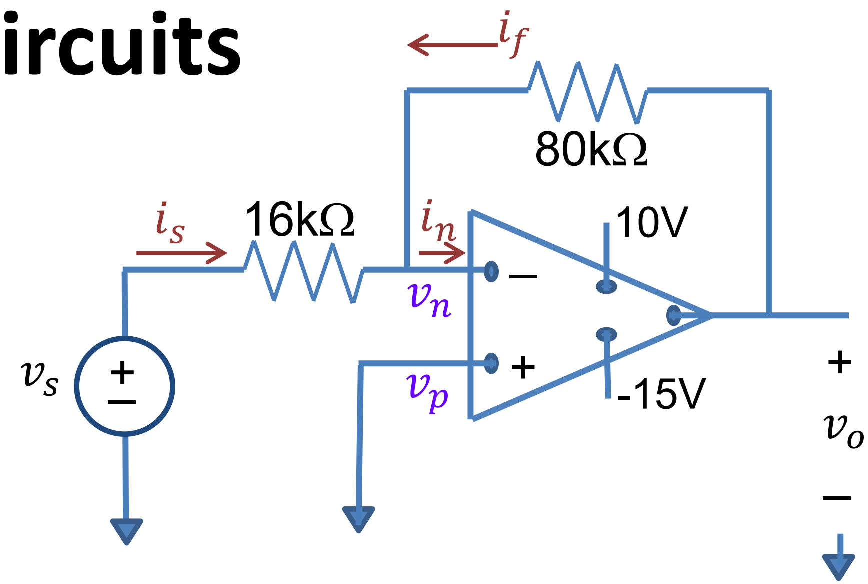
Infinite Input Resistance Condition

For op amps, the equivalent resistance seen looking into the input terminals is very large $\sim 1M\Omega$ (ideally infinite). In which case, the current flowing into (or out of) the input terminals is very small (ideally zero) resulting in the ideal constraint that

$$i_n = i_p = 0.$$

These equations form the starting point from which we analyze any op amp circuit.

Analyzing Op Amp Circuits



Example

Assuming ideal operation of the op amp,
(a) Find v_o as a function of v_s.
(b) Specify the range of v_s to avoid saturation of the op amp.

Step 1: Use the infinite input resistance condition ($i_n = 0$) and KCL at the inverting input.

$$i_n = i_s + i_f = 0.$$

Step 2: Use the virtual short condition ($v_p = v_n$) and the fact that the non-inverting input terminal is connected to ground ($v_p = 0$).

$$v_n = 0 \rightarrow i_s = \frac{v_s}{16k\Omega} \text{ and } i_f = \frac{v_o}{80k\Omega}.$$

(a) Put the results of Steps 1 and 2 together.

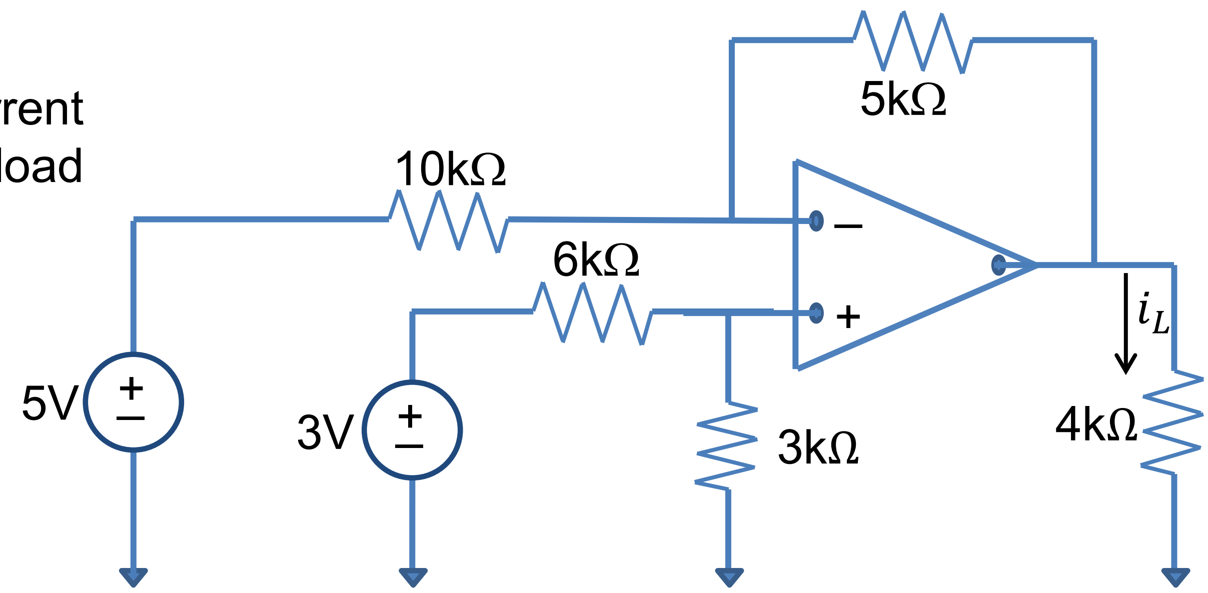
$$\frac{v_s}{16k\Omega} + \frac{v_o}{80k\Omega} = 0 \rightarrow v_o = -5v_s.$$

(b) In order to avoid saturation, the output of the op amp must satisfy

$$-15 < v_o < 10$$
$$-15 < -5v_s < 10$$
$$-2 < v_s < 3.$$

Example

Find i_L, the current flowing through the load resistor.



Example

Find v_1, v_o, i_2, i_o.