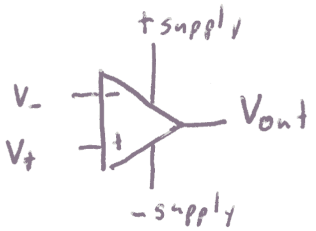
Op-amps

What is an Op-amp?



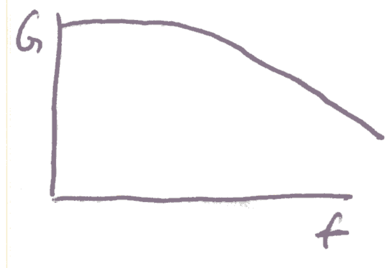
An integrated circuit amplifier built from transistors, resistors, capacitors and diodes

V_+ = non-inverting input
V_- = inverting input

[LF 411 has 24 transistors
11 resistors
1 capacitor
4 diodes]

Properties

1) Very high input impedance
2) Very high voltage gain [$G > 50{,}000$]
3) The op-amp attempts to make $V_{out} = G(V_+ - V_-)$
   with the limitation : $V_{-supply} < V_{out} < V_{+supply}$
4) Gain depends on frequency:

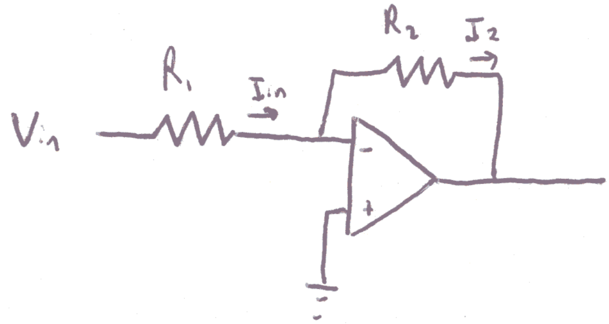


The high gain is much too high for most applications. Op-amps are almost always used in circuits with feedback.

In such a circuit: Two "Golden Rules"

I) The op-amp "tries" to make $V_+ = V_-$

II) The inputs draw (almost) no current.



Questions:

- what is the gain of this circuit?
- what is the input impedance?
- what is the output impedance?

$$\text{Gain} = \frac{V_{out}}{V_{in}}$$

rule I says: $V_- = V_+$ so $V_- = 0$

rule II says: no current is drawn into the op-amp

so $I_{in} = I_2$

$$\frac{V_{in}}{R_1} = \frac{-V_{out}}{R_2}$$

or

$$\boxed{\frac{V_{out}}{V_{in}} = \frac{-R_2}{R_1}}$$

We don't need to know the exact value of the open-loop gain!

To see how this works, imagine starting with $V_{in} = 0$, $V_{out} = 0$

Now increase Vin just a little. Current starts to flow through R_1 and R_2 (since no current flows into the amp). This raises V_- above 0 so the op-amp swings its output down. V_{out} goes down until

$$G(V_+ - V_-) = V_{out}$$

If you don't want to believe in rule I:

① $$\frac{V_{in} - V_-}{R_1} = \frac{V_- - V_{out}}{R_2}$$

② $$-G V_- = V_{out}$$

① + ② → $$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}\left[\frac{1}{1 + \frac{1 + R_2/R_1}{G}}\right]$$

as long as $G \gg R_2/R_1$, then $\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$

so $V_- = -\frac{V_{out}}{G}$ → always very close to 0.

V_- is called a virtual ground. Its not connected to ground, but the op-amp maintains its potential at very near ground.

Input impedance

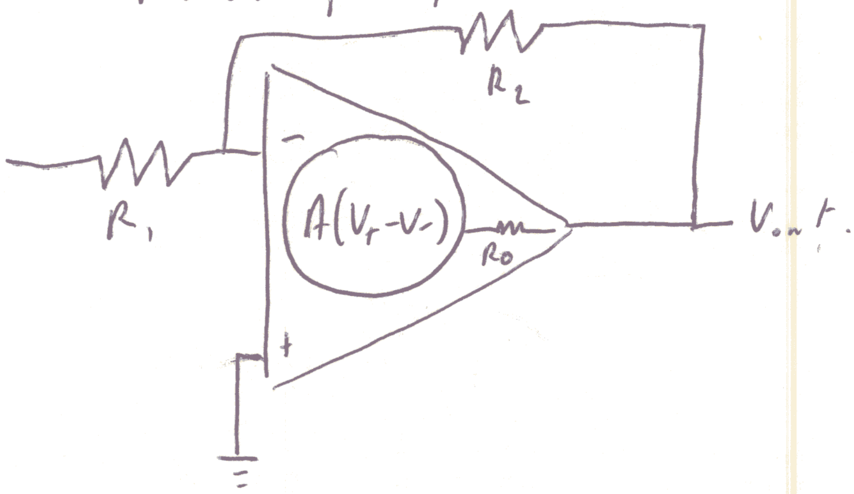
$$Z_{in} \equiv \frac{V_{in}}{I_{in}}$$

since $V_- \approx 0$, $Z_{in} = \frac{V_{in}}{I_{in}} = R_1$

Many signal sources demand a high input impedance amplifier!

Output impedance?

Model op-amp as:



To calculate Z_{out}, short input to ground, then apply voltage V at the output terminal

then: $$Z_{out} = \frac{V}{I_{out}}$$

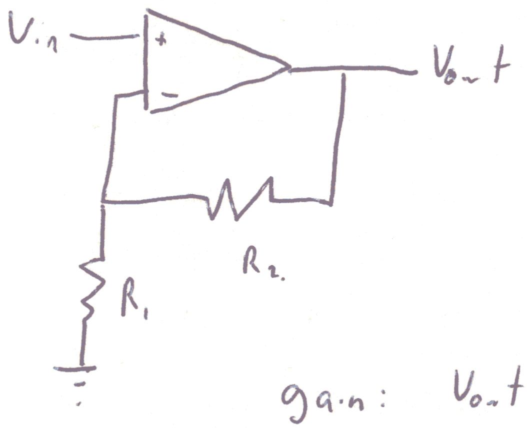
what is I_{out}? $$I_{out} = \frac{V_{out} - A(V_+ - V_-)}{R_0}$$

if $V_{out} = V$, then $V_- = \frac{R_1}{R_1 + R_2} V$

so $$I_{out} = \frac{V + A \frac{R_1}{R_1+R_2} V}{R_0} = \frac{V}{R_0}\left(1 + \frac{AR_1}{R_1+R_2}\right)$$

$$Z_{out} = \frac{R_0}{1 + A\frac{R_1}{R_1+R_2}}$$ Z_{out} is small!

Non inverting amplifier



gain: $$V_{out} \times \frac{R_1}{R_1 + R_2} = V_{in}$$

so $$\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

Input impedance: depends on op amp, typically $10^8 - 10^{12}\,\Omega$

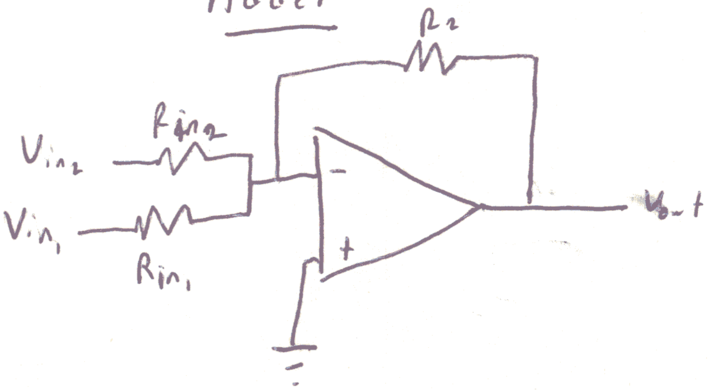
Output impedance: still less than $1\,\Omega$

Op amp Non-idealities.

1) Input offset current: rule II isn't quite true.
2) Open loop gain is frequency dependent.
3) Slew rate: max rate of change of V_{out}
4) Output current maximum
5) Offset voltage: with shorted inputs there is still an output voltage.

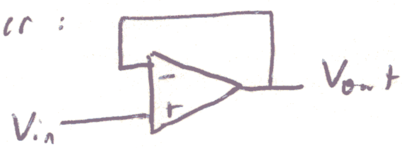
Other Op-amp applications

Adder



$$V_{out} = \left(\frac{V_{in_1}}{R_{in_1}} + \frac{V_{in_2}}{R_{in_2}}\right) R_2$$

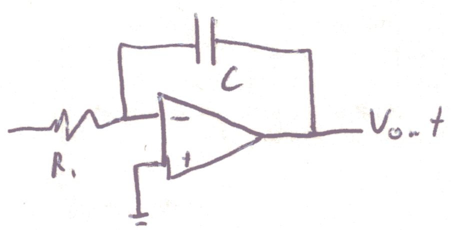
Follower:



No voltage gain, but can have large current gain.

Multiply, divide (using diode to take ln or exp)

Integrate:

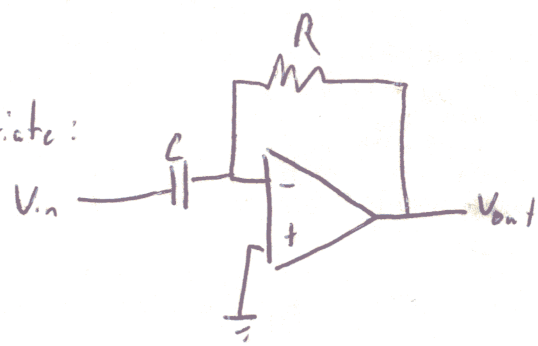


$$V_{out} = -\frac{1}{R_1 C}\int V_{in}\, dt.$$

From: $V_- = 0$, $I_{in} = \frac{V_{in}}{R_1}$, $q = \int I_{in} dt.$

and $V_{out} = -\frac{q}{C}$

Differentiate:



$$V_{out} = -RC\frac{dV_{in}}{dt}.$$

From: $V_{out} = -IR = -R\frac{dq}{dt}$ and $V_{in} = \frac{q}{C}.$