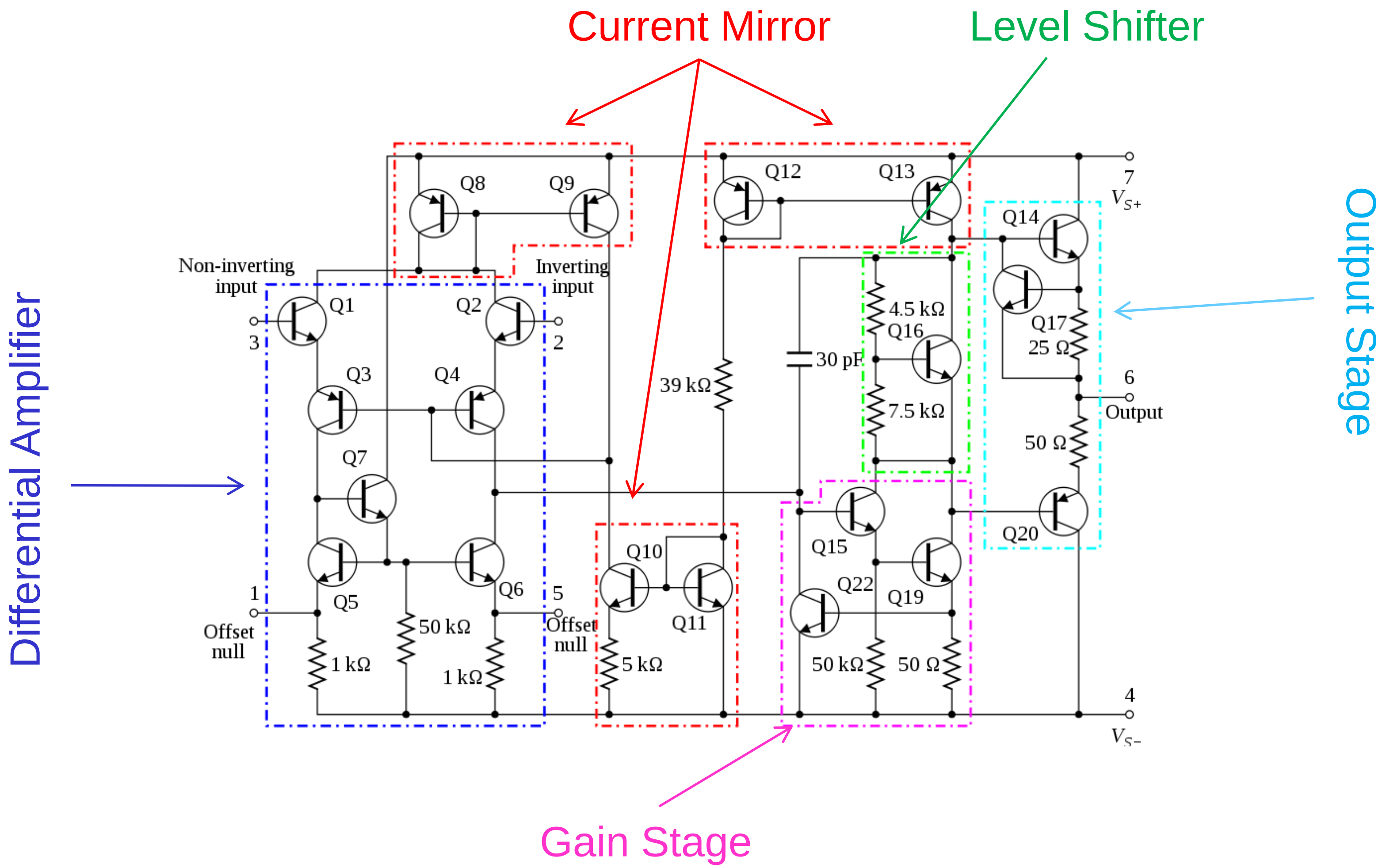
Operational Amplifier
(Op-Amp)

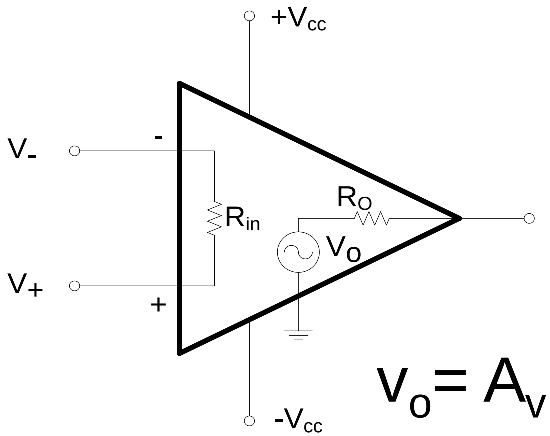
Circuit Diagram of an Op-Amp (IC 741)



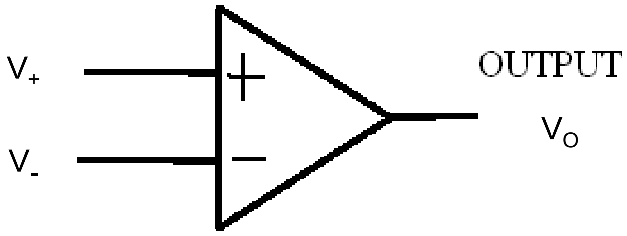
Operational Amplifier (Op-Amp)

- An Op-Amp is a very high gain amplifier having a number of differential amplifier stages
- It has high input impedance (typically a few Mega ohm)
- It has a low output impedance (less than 100Ω)

Op-Amp Model



$v_o = A_v(v_+ - v_-)$



Symbol

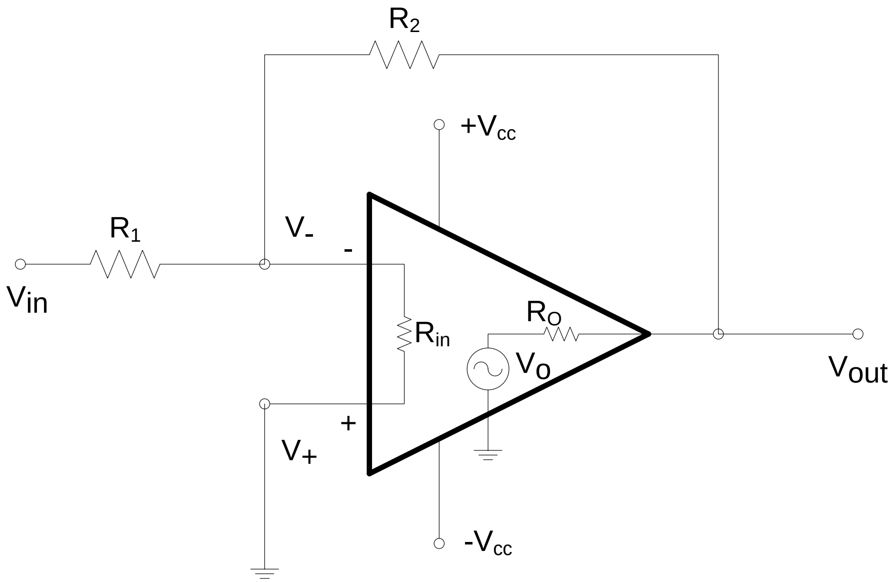
In a good Op-Amp

$A_v \rightarrow \infty \quad R_{in} \rightarrow \infty \quad R_o \rightarrow 0$

If v_+ is even slightly higher than v_-, $v_o = +V_{cc}$
If v_+ is even slightly lower than v_-, $v_o = -V_{cc}$

Cannot be used as an amplifier by itself!

Consider the circuit shown below



$$v_+ = 0 \quad v_o = -A_v v_-$$

$$\frac{v_{in} - v_-}{R_1} + \frac{v_o - v_-}{R_2 + R_O} = \frac{v_-}{R_{in}}$$

$$v_-\left[\frac{1}{R_2 + R_O} + \frac{1}{R_1} + \frac{1}{R_{in}}\right] - \frac{v_o}{R_2 + R_o} = \frac{1}{R_1} v_{in}$$

$$-\frac{v_o}{A_v}\left[\frac{1}{R_2 + R_O} + \frac{1}{R_1} + \frac{1}{R_{in}}\right] - \frac{v_o}{R_2 + R_o} = \frac{1}{R_1} v_{in}$$

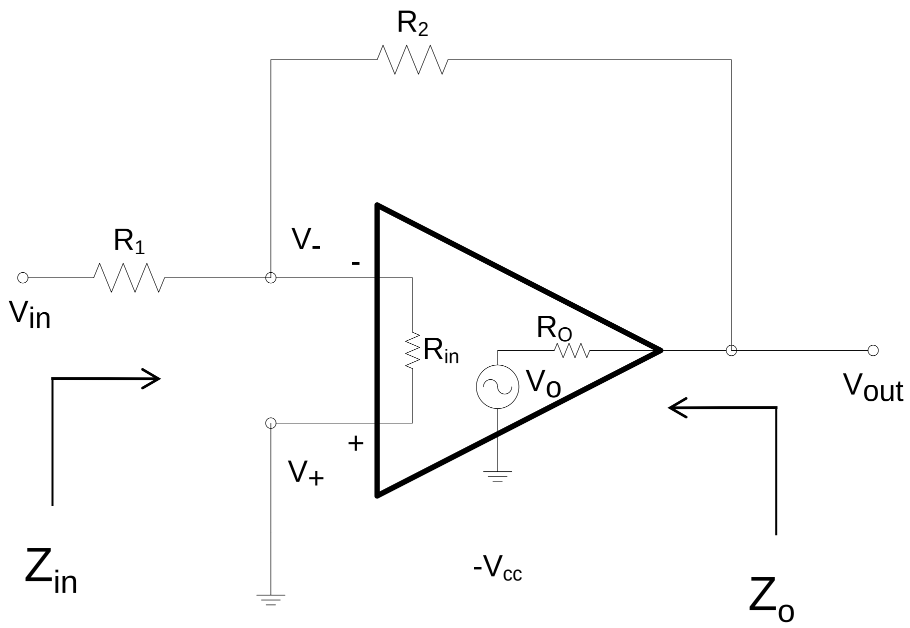
For $A_v \to \infty$, we get $v_o\left[-\frac{1}{R_2 + R_O}\right] = \frac{v_{in}}{R_1}$ and $\underbrace{v_- = -\frac{v_o}{A_v} \to 0}$

$$\left[\frac{v_0}{R_O + R_2}\right] R_2 = v_{out}$$

The (-) terminal is effectively at ground. This is referred to as **"Virtual Ground"**

Gain $\frac{v_{out}}{v_{in}} = -\frac{R_2}{R_1}$

Interesting Points



With $A_v \rightarrow \infty$,

Gain = $-R_2/R_1$
(does not depend on A_v)

(+) is at Ground
(-) is at Virtual Ground

$Z_{in} = R_1$
$Z_{out} = R_O || R_2 \approx R_O$

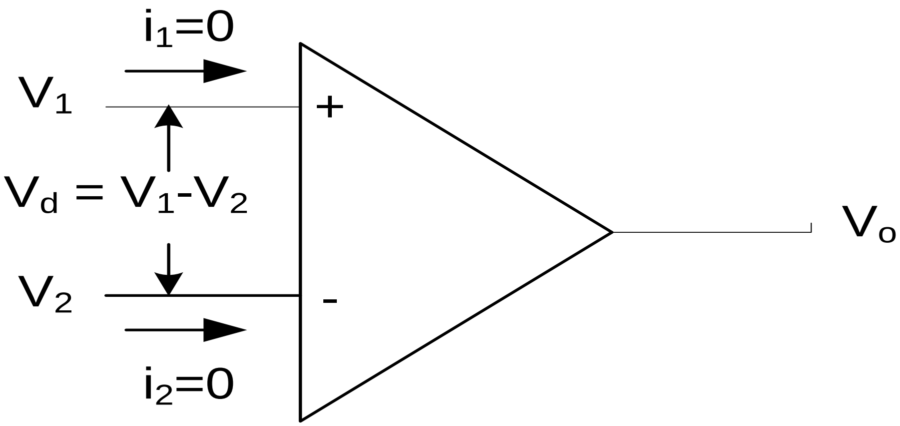
Concept of Virtual Ground

1. $V_- \approx 0$ V (-) terminal is at ground potential
2. No Current Enters the (-) terminal of the Op-Amp
   Valid only when there is feedback connection between the output and the (-) terminal.

Characteristics of an ideal OP-Amp

- Input Resistance $R_i = \infty$
- Output Resistance $R_o = 0$
- Voltage Gain $A_v = \infty$
- Bandwidth = ∞ (i.e. can work over a wide range of frequencies)
- Perfect balance i.e $v_o = 0$ when $v_1 = v_2$
- Characteristics do not drift with temperature

Ideal Op-Amp analysis



i) $R_i = \infty$,

No current enters into op-amp

Voltage Gain $A_v = \infty$ or, $v_o / v_d = \infty$

or, $v_d = v_o/\infty = 0$ [since v_o is finite]

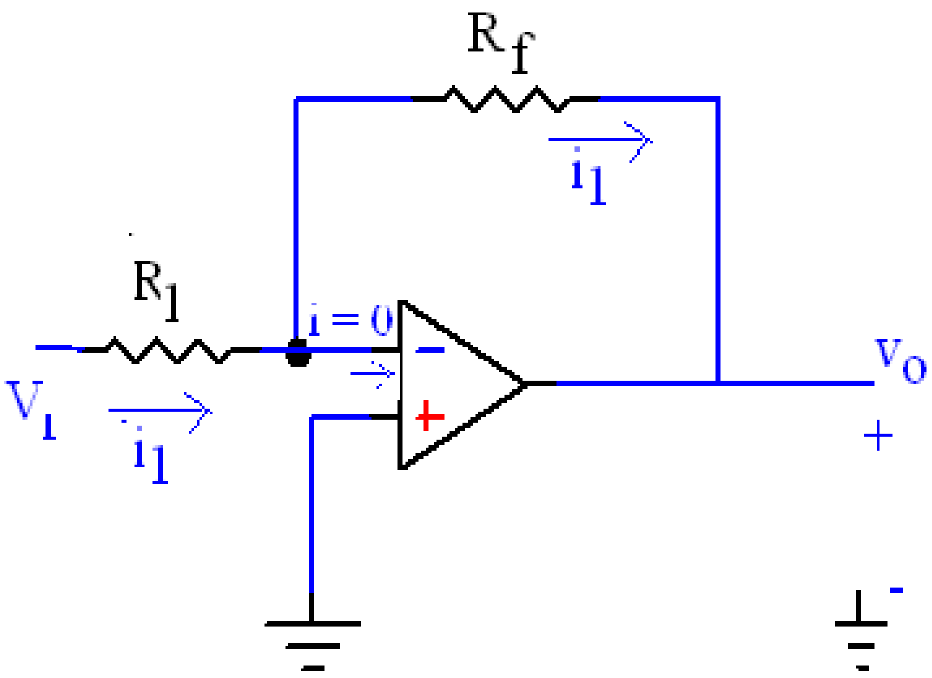
Therefore, $v_1 - v_2 = 0$

or,

ii) $\mathbf{v_1 = v_2}$

Simple OP-AMP Circuits

1. Inverting Amplifier



Using KVL,

$v_1 - i_1R_1 = 0$

$\Rightarrow \quad i_1 = v_1/R_1$

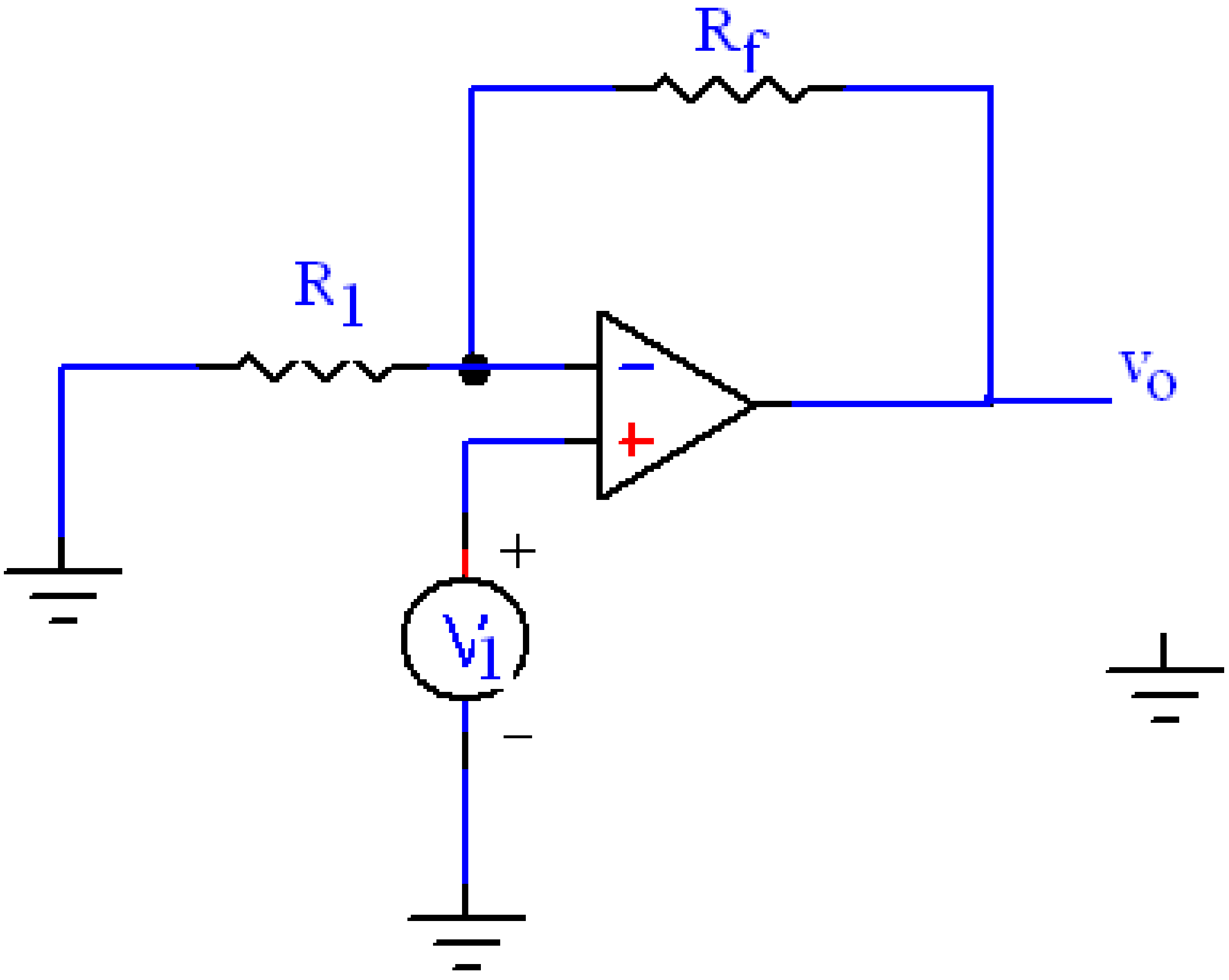
&

$0 - i_1R_f - v_o = 0$

or, $v_o = -i_1R_f = -v_1R_f/R_1$

$v_0/v_1 = -R_f/R_1$

2. **Non Inverting Amplifier**

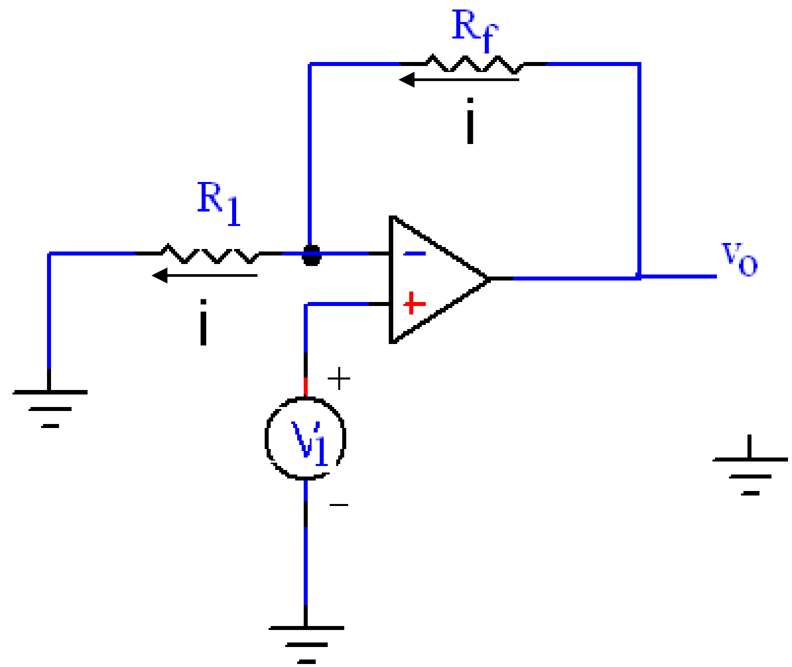


$$v_- = v_+ = v_1$$

$$i = \frac{v_1}{R_1} = \frac{v_o - v_1}{R_f}$$

$$v_o = R_f \left[\frac{1}{R_1} + \frac{1}{R_f} \right] v_1$$

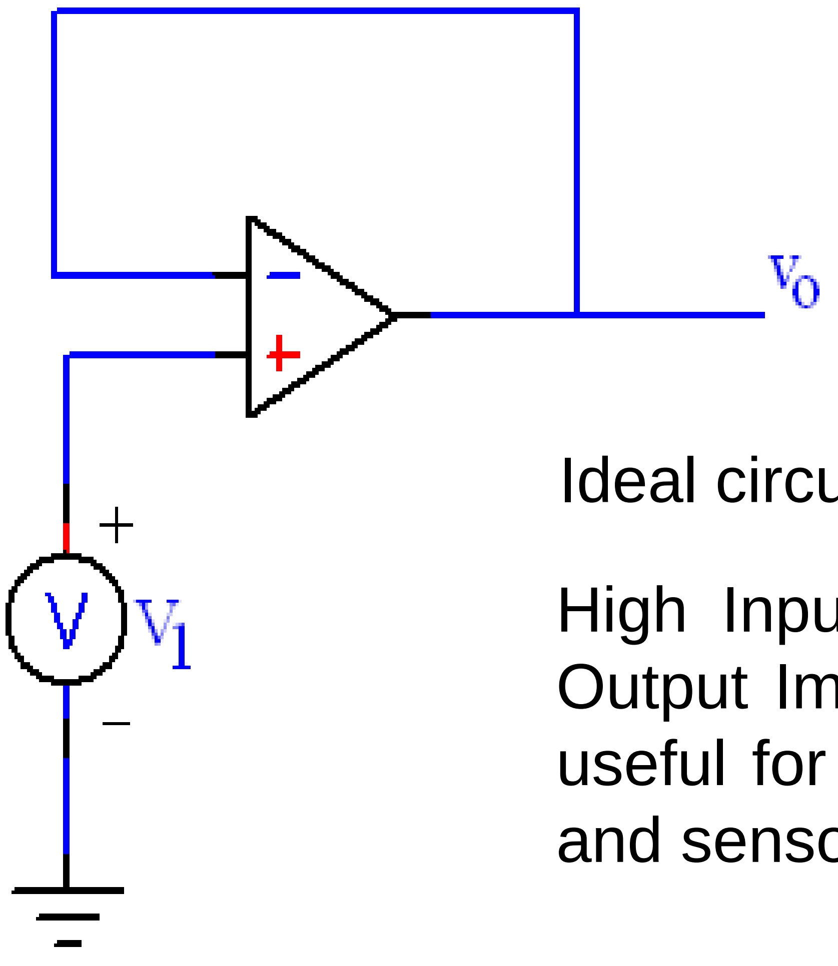
Gain $$\frac{v_o}{v_o} = \left(1 + \frac{R_f}{R_1} \right)$$



Input Impedance = ∞

Output Impedance = R_o

3. Voltage Follower



$$v_o = v_1$$

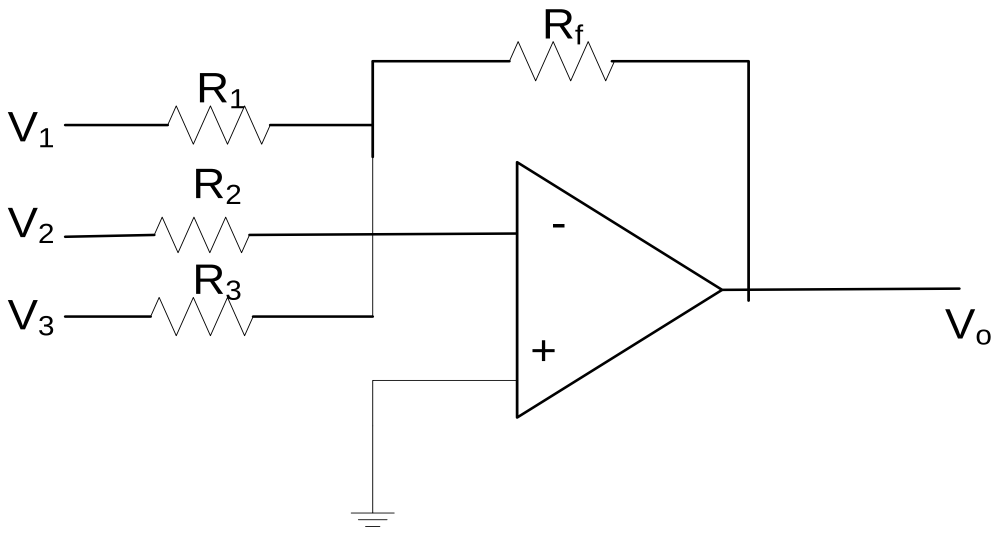
Ideal circuit to test Op-Amp

High Input Impedance and Low Output Impedance also makes it useful for interfacing transducers and sensors to other circuits

4. Summing Amplifier

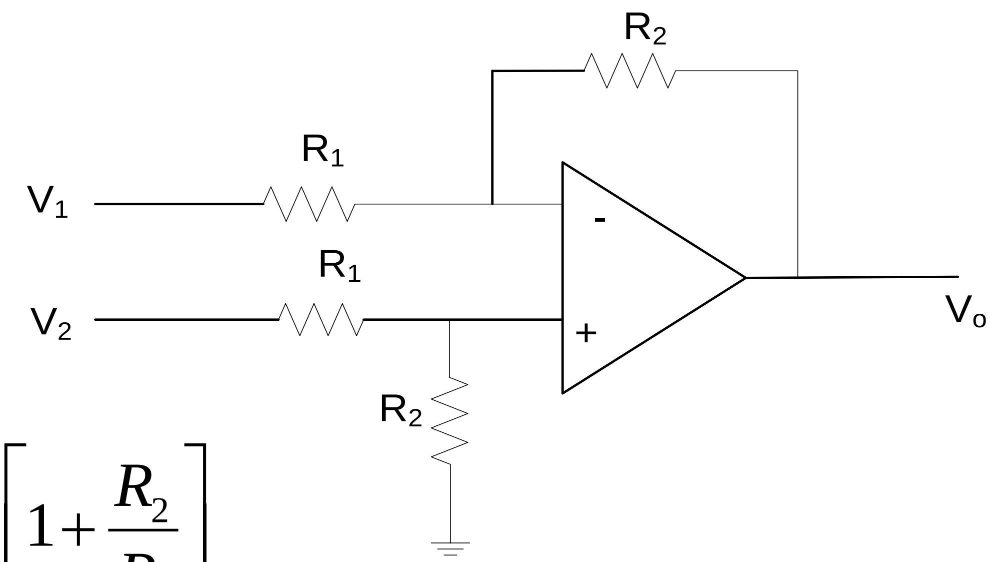
Use superposition (i.e. consider one source at a time and add their respective outputs)

Can also be done directly



$$v_o = -\left[\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3 \right]$$

Difference Amplifier (or Voltage Subtractor)



Use Superposition
(can also be done directly)

If v_2=0, $$v_{o1} = -\frac{R_2}{R_1} v_1$$

If v_1=0, $$v_{o2} = v_2 \left[\frac{R_2}{R_1 + R_2} \right] \left[1 + \frac{R_2}{R_1} \right]$$

$$= v_2 \frac{R_2}{R_1}$$

Therefore, $$v_o = v_{o1} + v_{o2} = \frac{R_2}{R_1}(v_2 - v_1)$$

Difference Gain = R_2/R_1

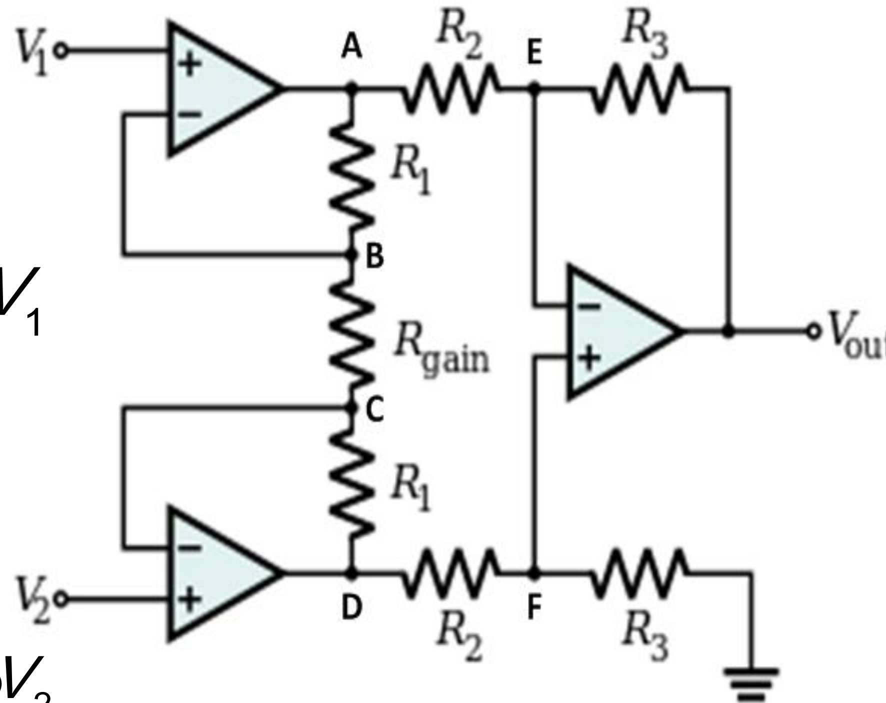
Tutorial Problem

(Instrumentation Amplifier)

$$V_B = V_1 \quad V_C = V_2 \quad V_D = 1.5V_2 - 0.5V_1$$

$$V_A = 1.5V_1 - 0.5V_2$$

$$V_E = V_F = 1.4706V_2 - 0.4902V_1$$



$$V_{out} = 75.006V_2 - 25.002V_1 - 75V_1 + 25V_2$$
$$= 100.006V_2 - 100.002V_1$$
$$= 100.004(V_2 - V_1) + 0.002(V_2 + V_1)$$

R_1=10K R_2=2K
R_3=100K R_{gain}=20K

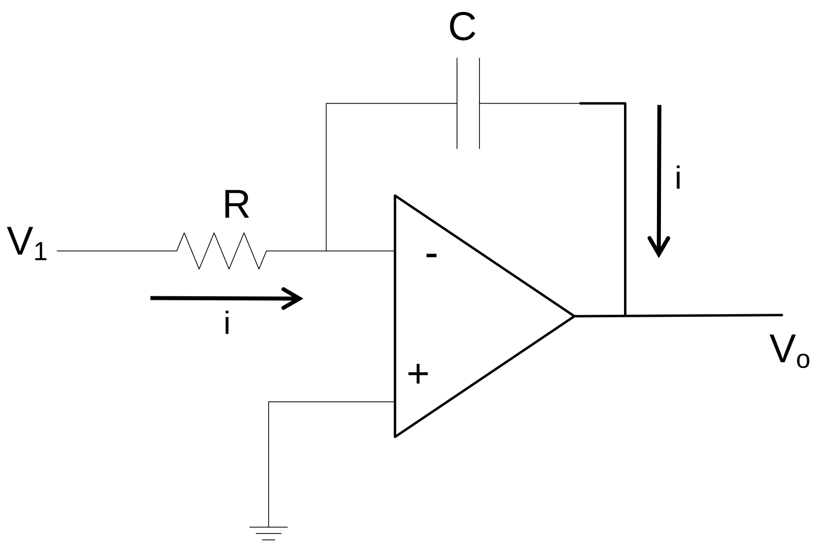
$$\frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2}$$

Gain can be varied by just changing one resistor, R_{gain}

Circuit also has high input impedance and very low CMRR

Integrator

$$i = \frac{v_1}{R} \qquad v_o = -\frac{1}{C}\int_0^t i\,dt \quad \text{with } v_o(0) = 0$$

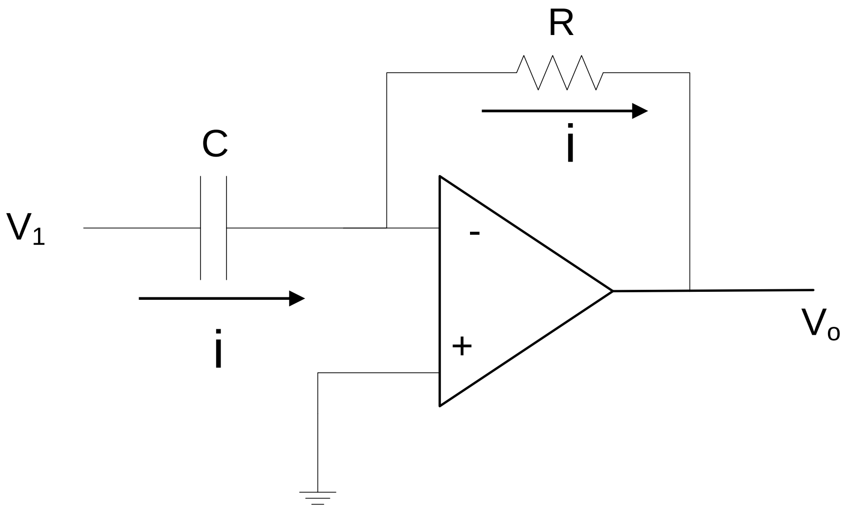


Therefore,

$$v_o = -\frac{1}{RC}\int_0^t v_1\,dt \quad \text{with } v_o(0) = 0$$

v_o

Differentiator



$$v_1 = \frac{1}{C}\int_0^t i\,dt \quad \text{with } v_1(0) = 0$$

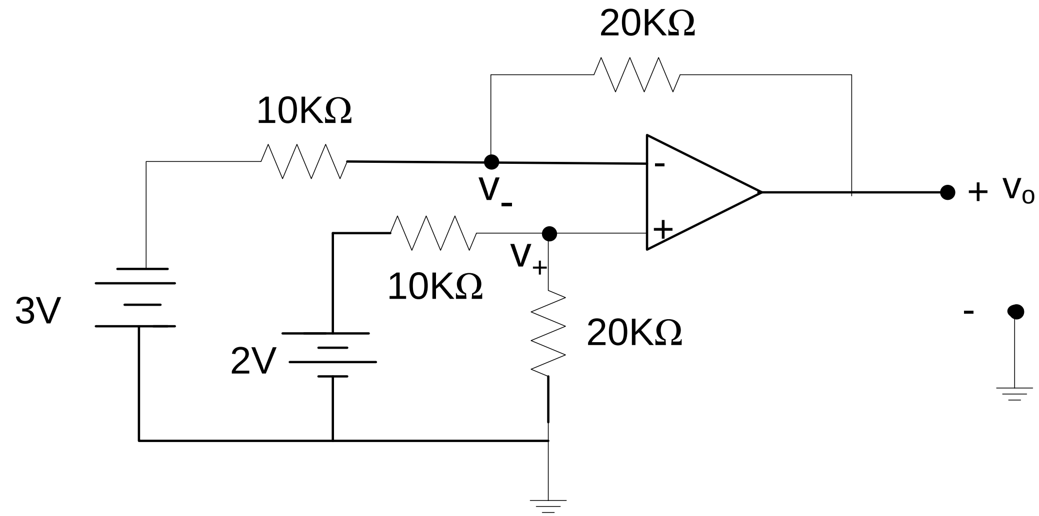
$$v_o = -iR$$

Therefore, $$v_1 = -\frac{1}{RC}\int_0^t v_o\,dt$$

or $$v_o = -RC\,\frac{dv_1}{dt}$$

Example

Find v_o in the given circuit.



$$v_- = v_+ = 2 \times \frac{20}{30} = \frac{4}{3}$$

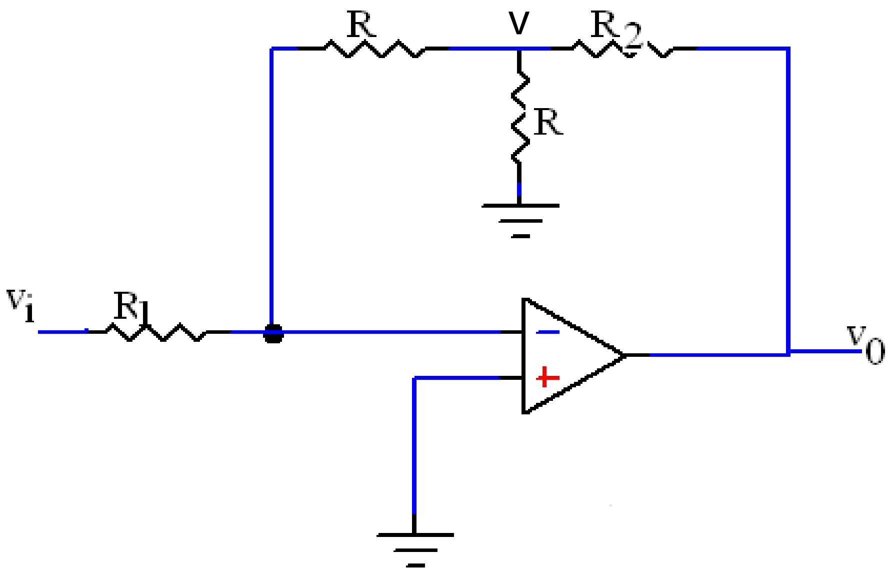
$$\frac{v_o - v_-}{20} = \frac{v_- - (-3)}{10}$$

$$\frac{v_o}{20} = v_- \left(\frac{1}{10} + \frac{1}{20} \right) + \frac{3}{10}$$

$$v_0 = 3v_- + 6 = 10 \text{ V}$$

Example

Find the gain v_o/v_i in the given circuit.



$v_- = v_+ = 0$ Virtual Ground at (-)

$$\frac{v_i}{R_1} = -\frac{v}{R} \qquad \Rightarrow \qquad v = -\frac{R}{R_1}v_i$$

$$\frac{v_o - v}{R_2} = \frac{v}{R} + \frac{v}{R} = \frac{2v}{R}$$

$$v_o = v\left[1 + \frac{2R_2}{R}\right]$$

$$= -\left[\frac{R}{R_1}\right]\left[1 + \frac{2R_2}{R}\right]v_i$$

$$= -\left(\frac{R + 2R_2}{R_1}\right)v_i$$

Gain $\quad A_V = \frac{v_o}{v_i} = -\left(\frac{R + 2R_2}{R_1}\right)$

Voltage Controlled Current Source
(with grounded load)

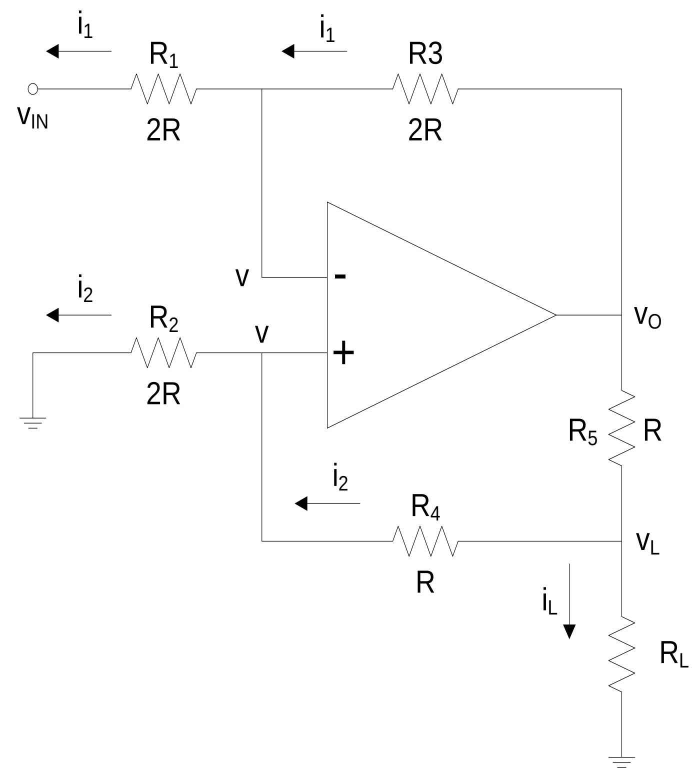
$$i_1 = \frac{v - v_{IN}}{2R} = \frac{v_O - v}{2R} \quad \Rightarrow \quad 2v - v_O = v_{IN}$$

$$i_2 = \frac{v}{2R} = \frac{v_L - v}{R} \quad \Rightarrow \quad v_L = \frac{3}{2}v$$

$$i_L = \frac{v_O - v_L}{R} - \frac{v_L - v}{R} = \frac{v_O - 3v + v}{R} = \frac{v_O - 2v}{R}$$

Therefore, $i_L = -\frac{v_{IN}}{R}$

Note that i_L does not depend on R_L, implying that we have got a current source!

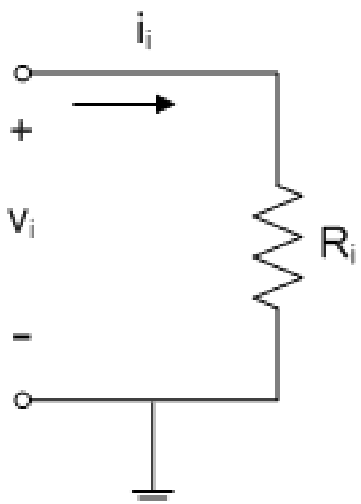


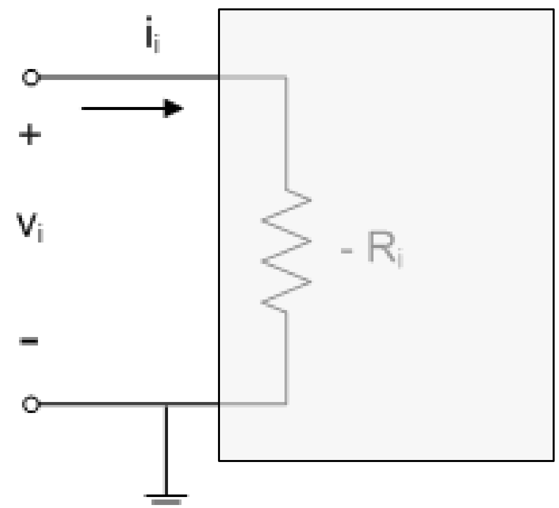
General Condition:

$R_1 = R_2$ & $R_3 = R_4 + R_5$

Creating an effectively “Negative Resistance”

What is “Negative Resistance”?

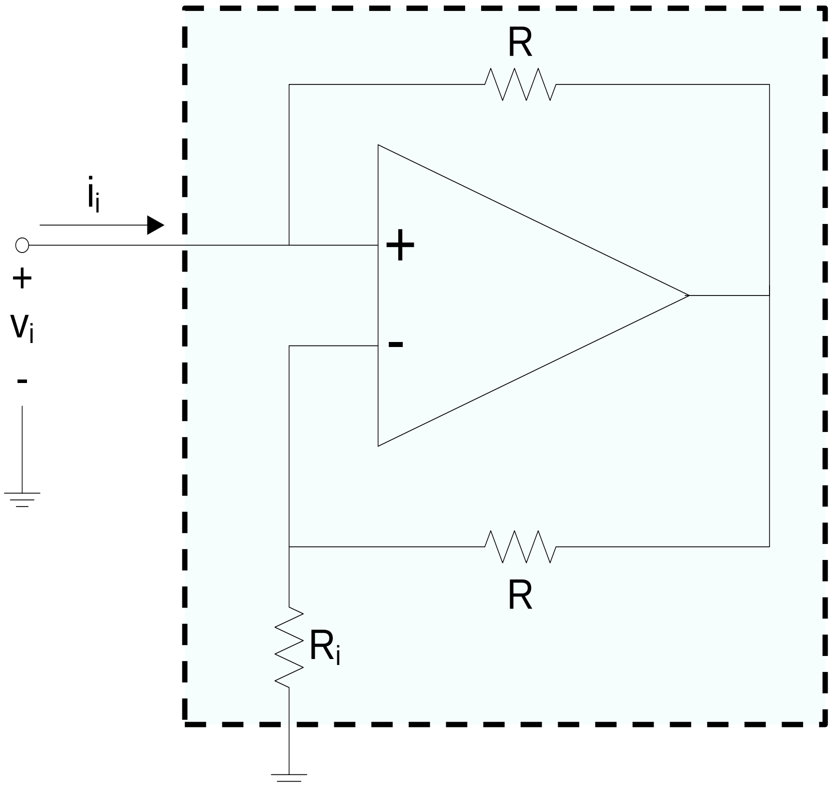




Normal Resistance $\frac{v_i}{i_i} = R_i$

Negative Resistance $\frac{v_i}{i_i} = -R_i$

Creating an effectively "Negative Resistance"



Let v_O = opamp output voltage
and $v_+ = v_- = v_i$

$$\frac{v_i}{R_i} = \frac{v_O - v_i}{R} \quad \Rightarrow \quad v_O = v_i\left(1 + \frac{R}{R_i}\right)$$

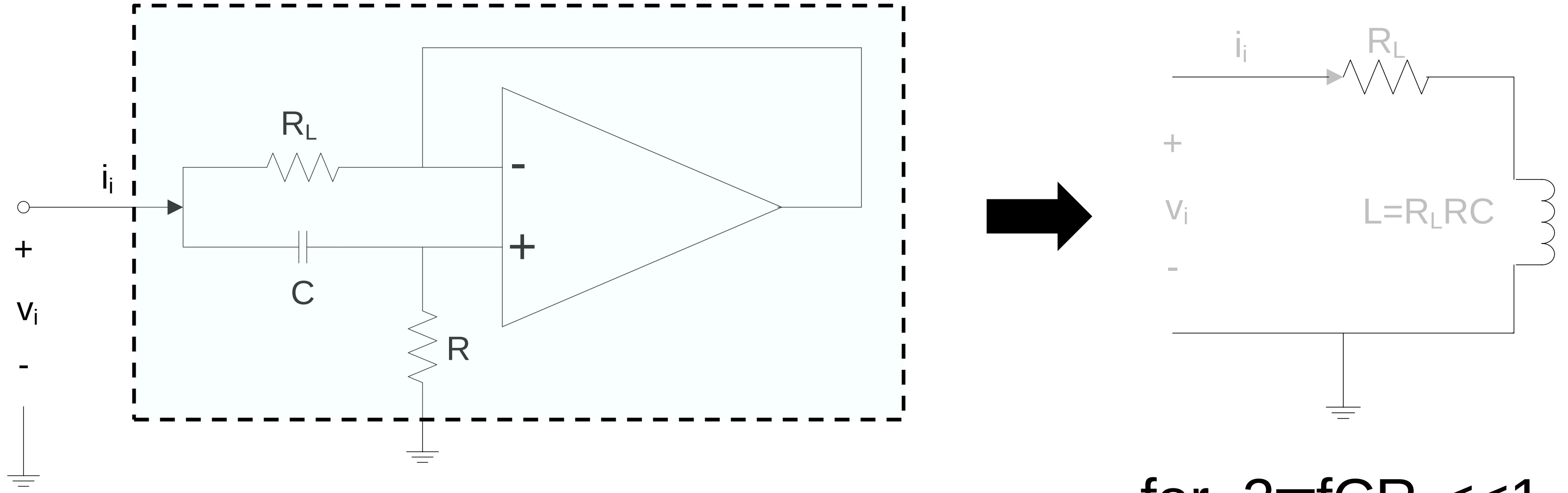
$$i_i = \frac{v_i - v_O}{R} = -\frac{v_i}{R_i}$$

Therefore, $\frac{v_i}{i_i} = -R_i$

$\frac{v_i}{i_i} = -R_i$ Negative Resistance

Using Capacitors to make Inductors

(practical to do only small values of inductances)



for $2\pi f C R_L << 1$

Using phasors, show that

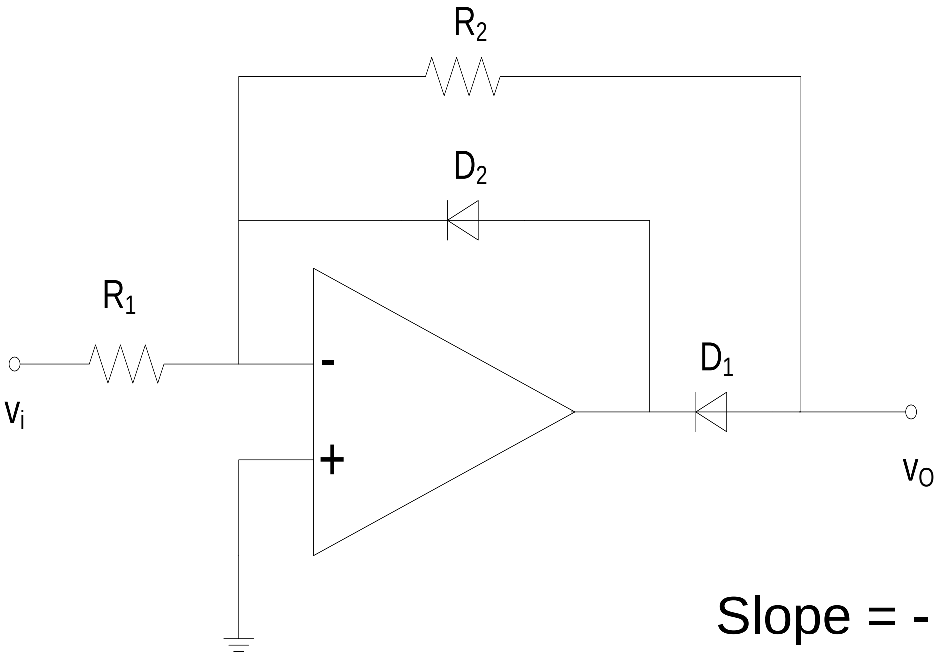
$$\frac{v_i}{i_i} = \frac{R_L + j\varpi RCR_L}{(1 + j\varpi CR_L)} = R_L + j\varpi RCR_L$$

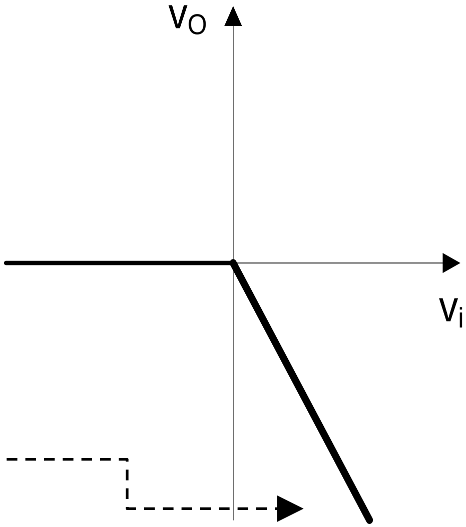
Precision Rectifier

The simple half-wave and full-wave rectifiers we saw earlier have one big drawback – They do not work for small voltages (say a few millivolts). The input voltage must cross the threshold which forward biases the diode for rectification to occur.

Using Op-Amps, we can design rectifiers which do not have this disadvantage.

Half-Wave Precision Rectifier

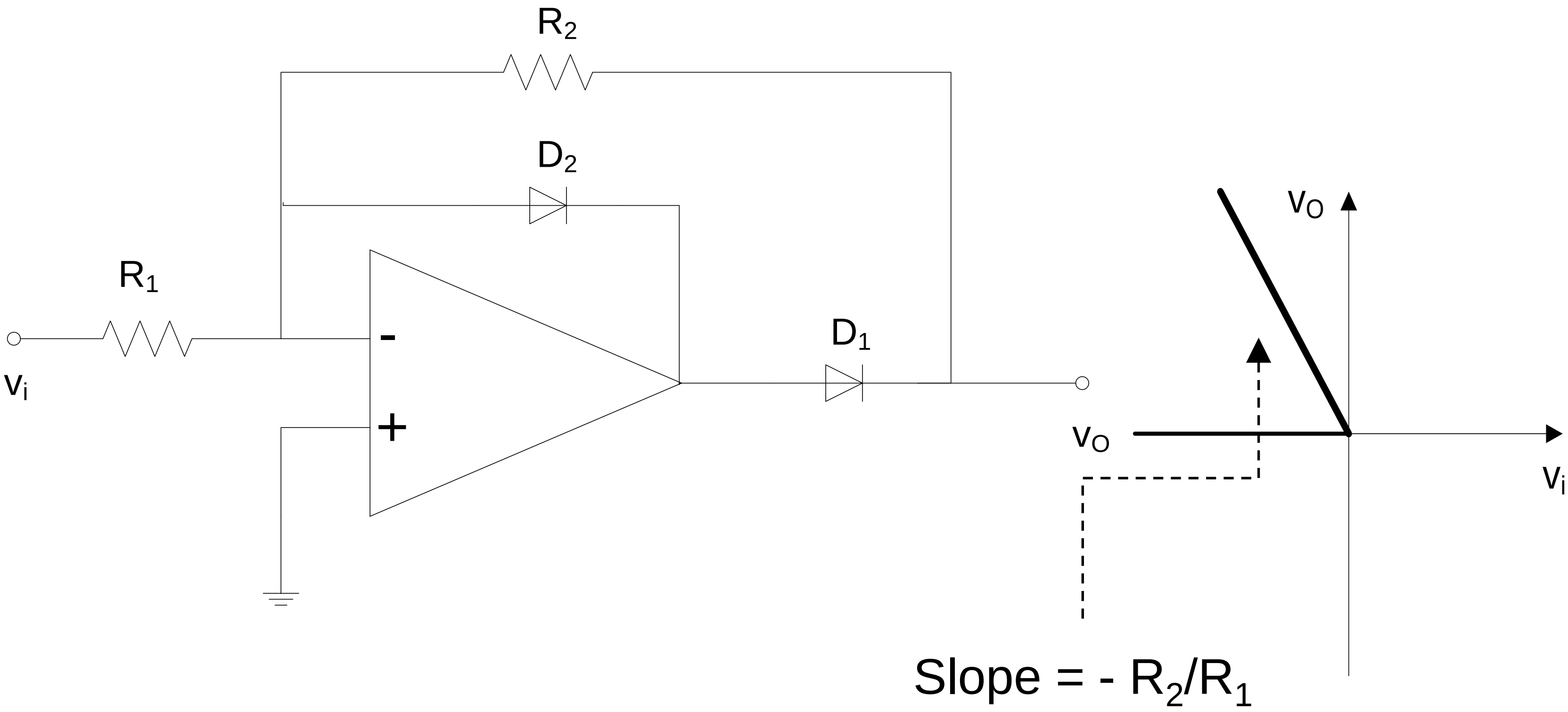




Slope = - R_2/R_1

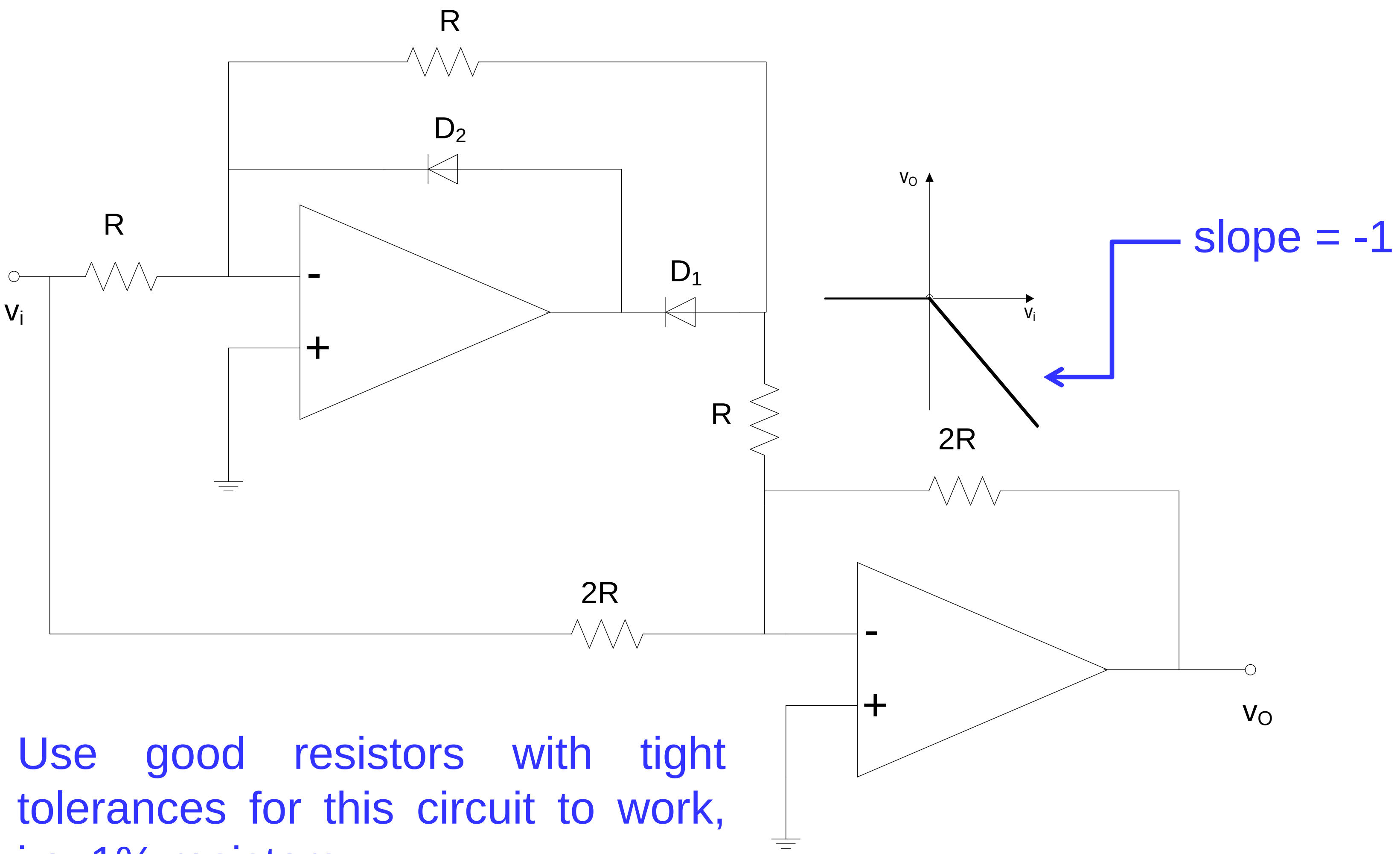
You will be making this circuit in EC102 Lab next semester

What happens when you reverse the diodes?



Build a full wave rectifier using these two half-wave rectifiers and a difference amplifier – *needs three opamps!*

Full-Wave Precision Rectifier



Use good resistors with tight tolerances for this circuit to work, i.e. 1% resistors,