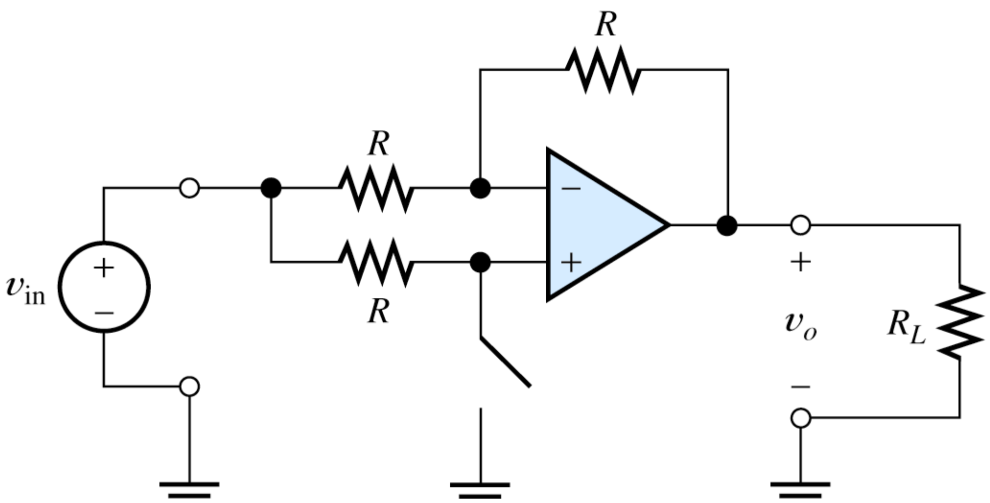
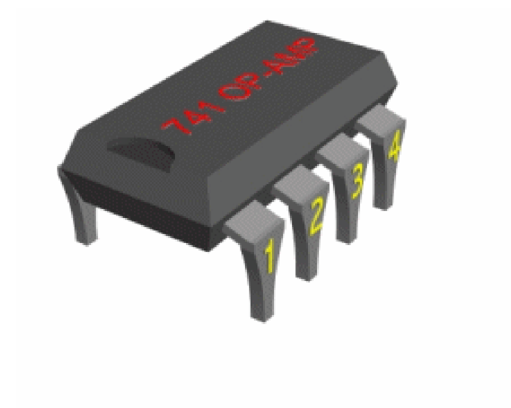
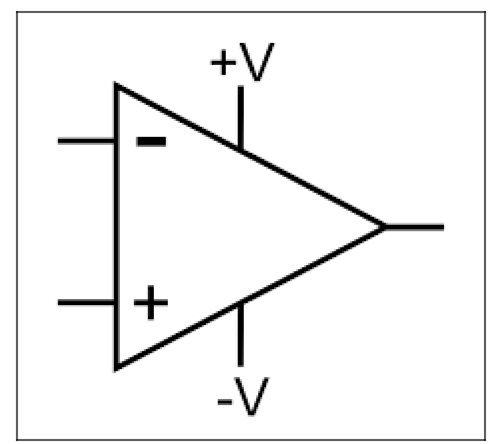
Operational Amplifiers

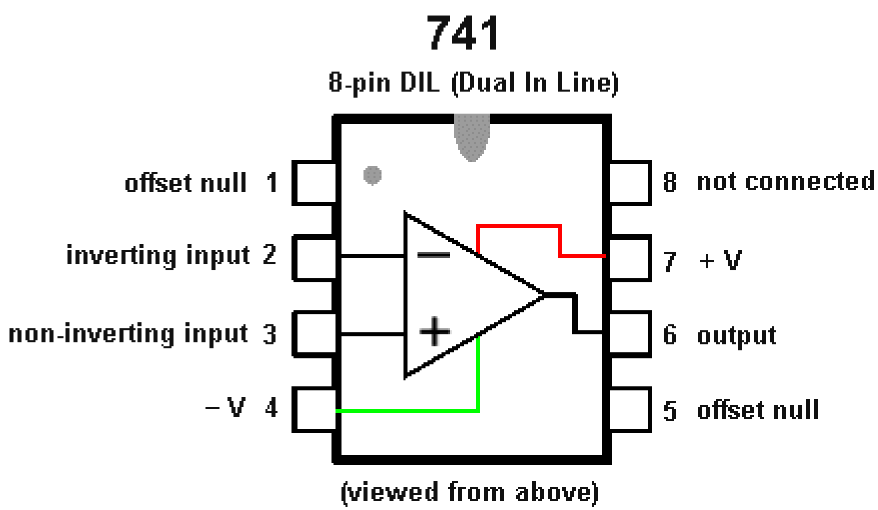


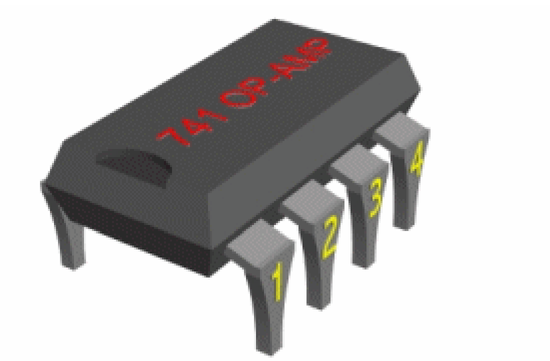




Operational amplifiers (op-amps)

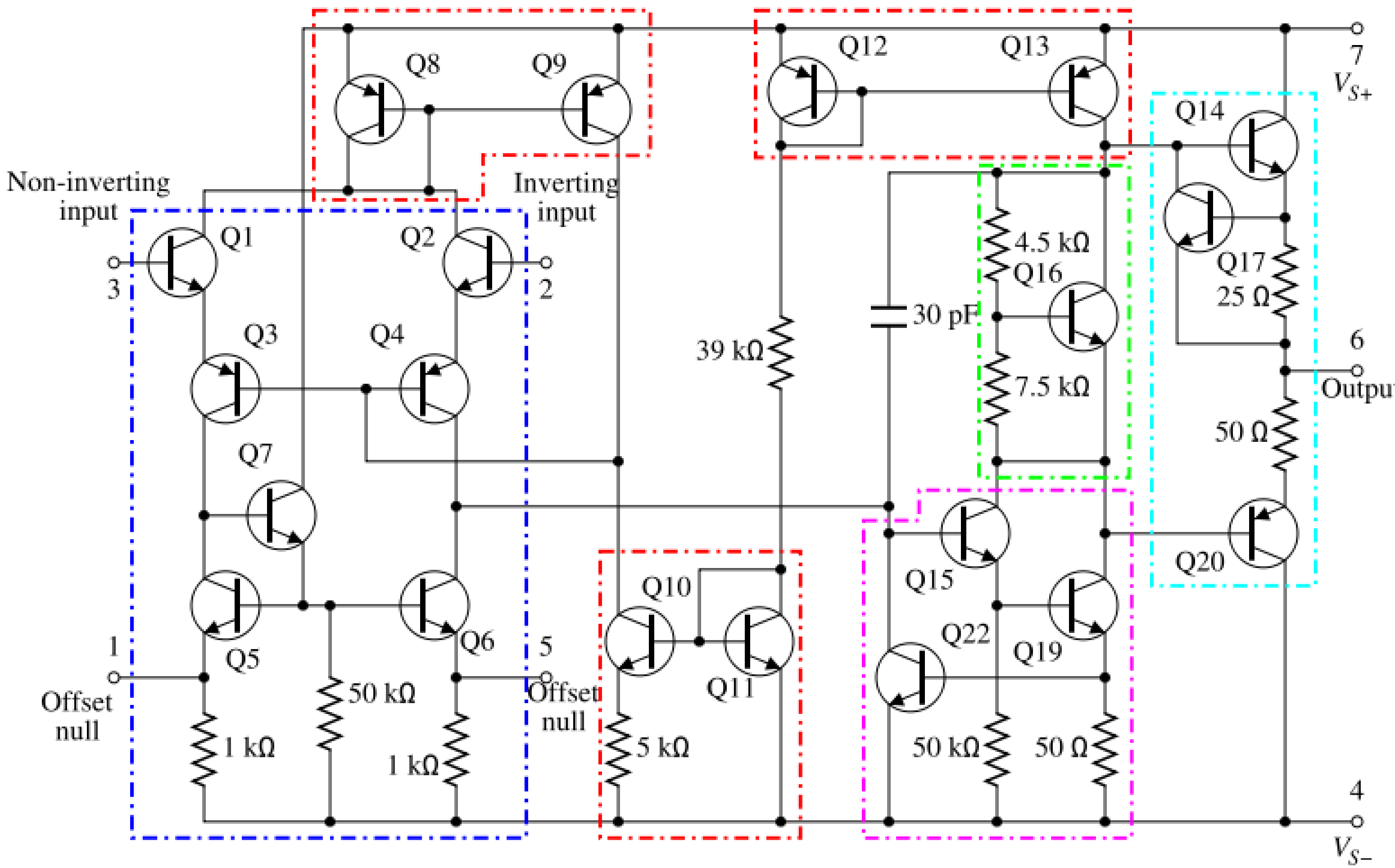
741 Amplifier is the most popular amplifier it has A_{vo}=100000 (voltage gain without load)





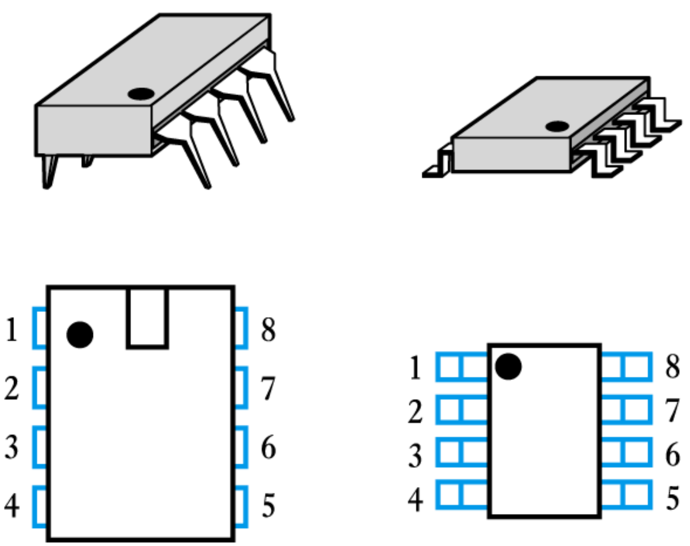
Operational amplifiers (op-amps)

741 Amplifier BJT transistor level schematic



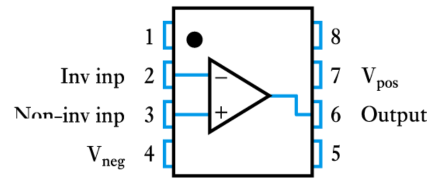
Operational amplifiers (**op-amps**) are among the most widely used integrated circuits (ICs) in electronics.

A single package will often contain several op-amps

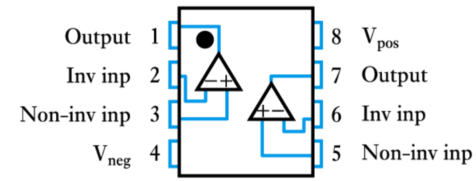


(a) A DIL package

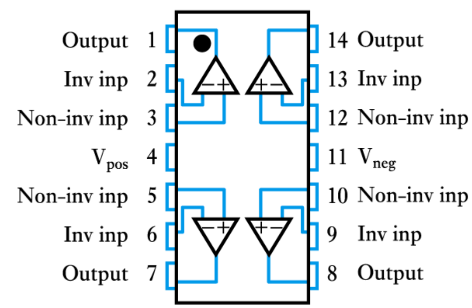
(b) An SMT package



(a) A single op-amp



(b) A dual op-amp

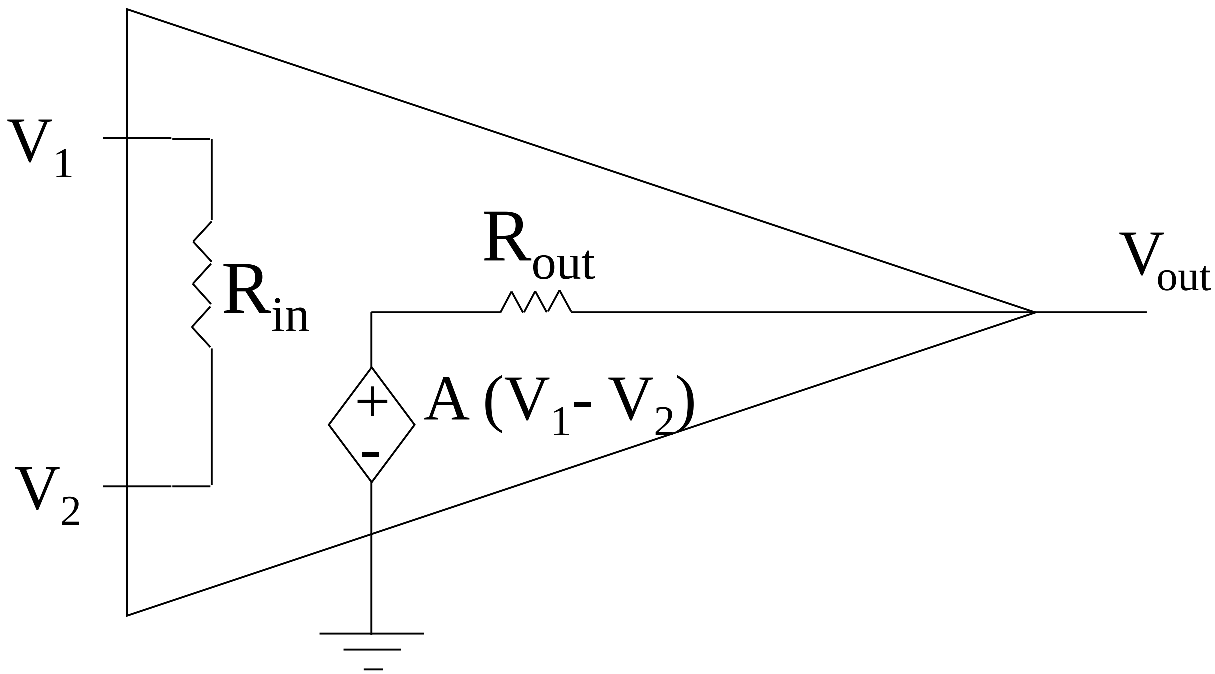


(c) A quad op-amp

Operational Amplifier Model

An operational amplifier circuit is designed so that

1) $V_{out} = A\,(V_1 - V_2)$ (**A** is a very large gain)
2) Input resistance (**R_{in}**) is very large
3) Output resistance (**R_{out}**) is very low

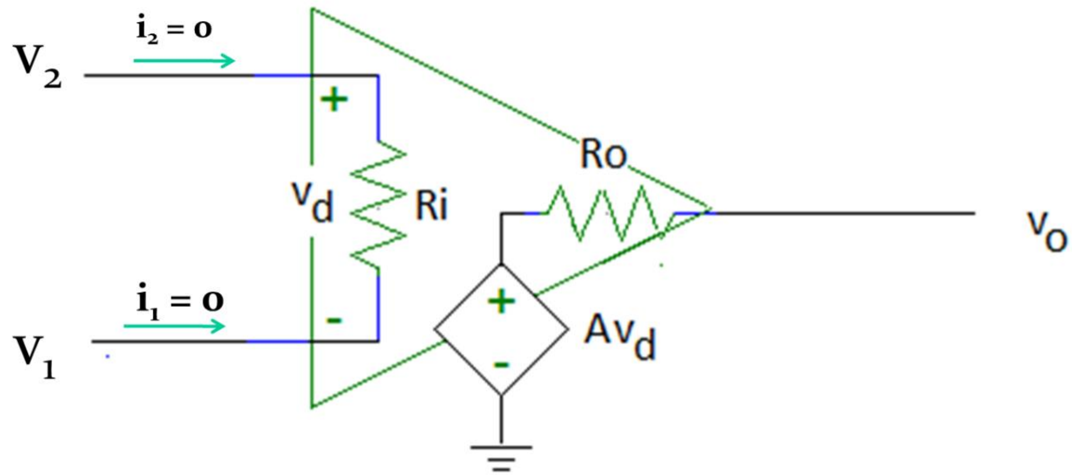


Typical Op Amp Parameters

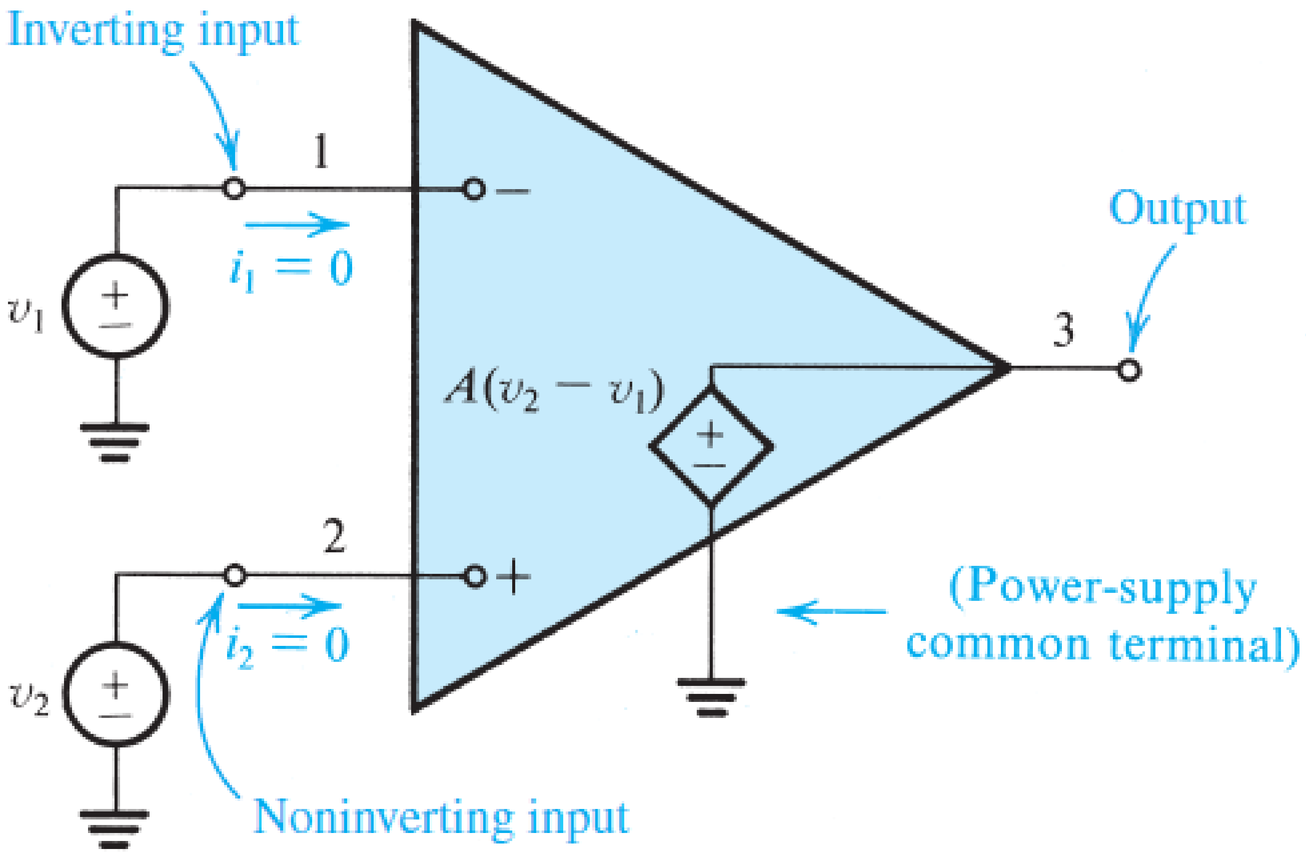
Parameter	Variable	Typical Ranges	Ideal Values
Open-Loop Voltage Gain	A	10^5 to 10^8	∞
Input Resistance	R_i	10^5 to 10^{13} Ω	∞ Ω
Output Resistance	R_o	10 to 100 Ω	0 Ω
Supply Voltage	Vcc/V^+ $-Vcc/V^-$	5 to 30 V -30V to 0V	N/A N/A

An Ideal Operational Amplifier

- $R_i = \infty$
- Therefore, $i_1 = i_2 = 0A$
- $R_o = 0$



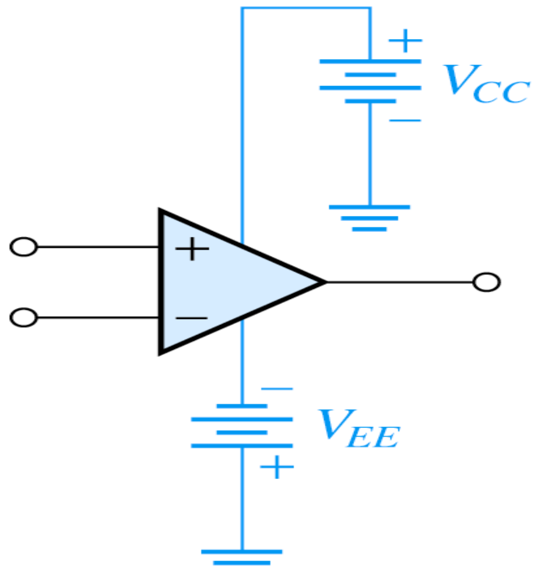
An Ideal Operational Amplifier



Equivalent circuit of the ideal op amp.

An Ideal Operational Amplifier

A real op-amp must have a DC supply voltage which is often not shown on the schematics.



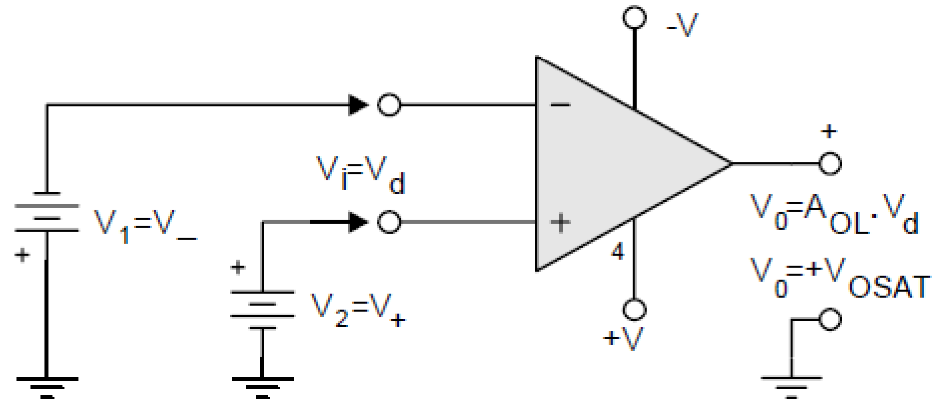
Op-amp symbol showing the dc power supplies, V_{CC} and V_{EE}.

Op-amps

$$V_{out} = A_{OL}\,(V_2 - V_1)$$

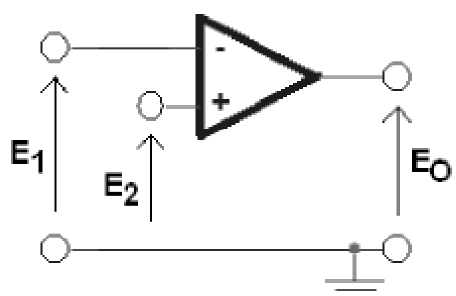
Output voltage of an Op-amp can not be greater than DC supply voltage.

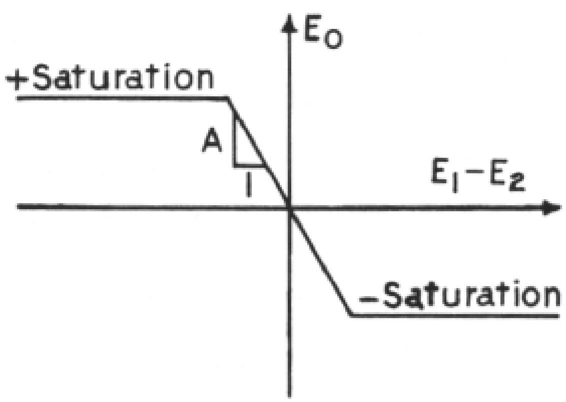
Maximum output voltage is usually slightly lower than the DC supply voltage and called as saturation voltage.



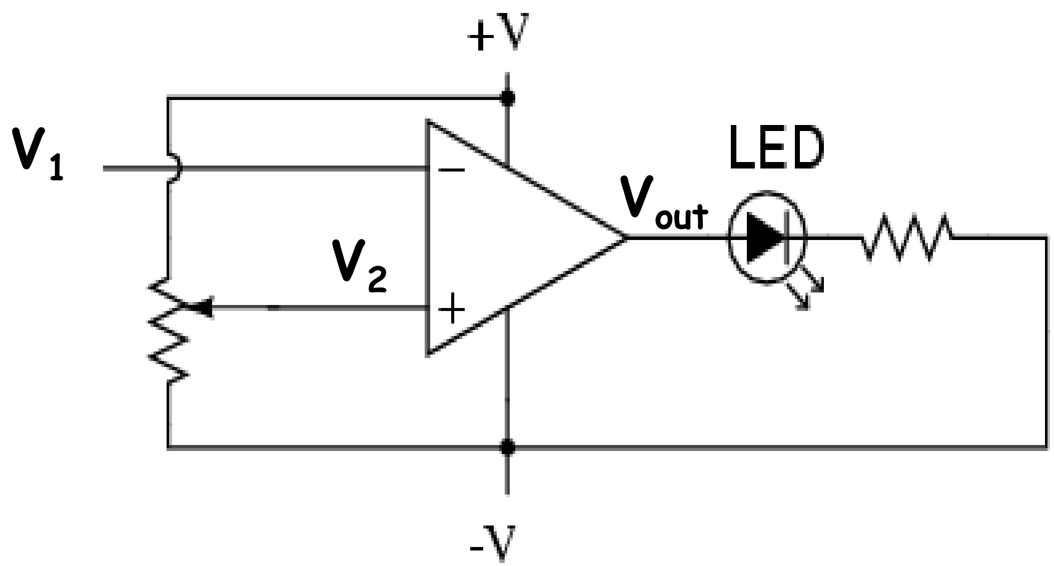
$V_2 > V_1$ ise $V_d = +$ $\quad V_O = +V_{SAT}$'dir

$V_2 < V_1$ ise $V_d = -$ $\quad V_O = -V_{SAT}$'dir



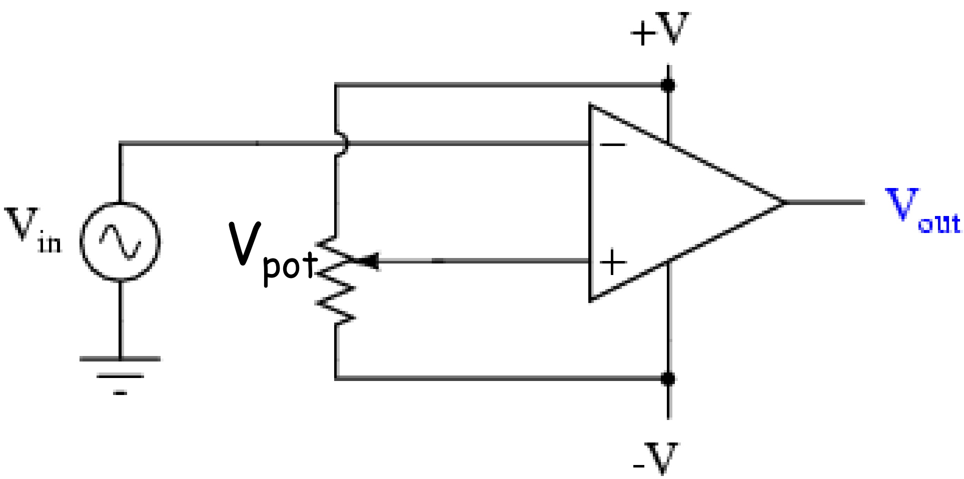


Comparator

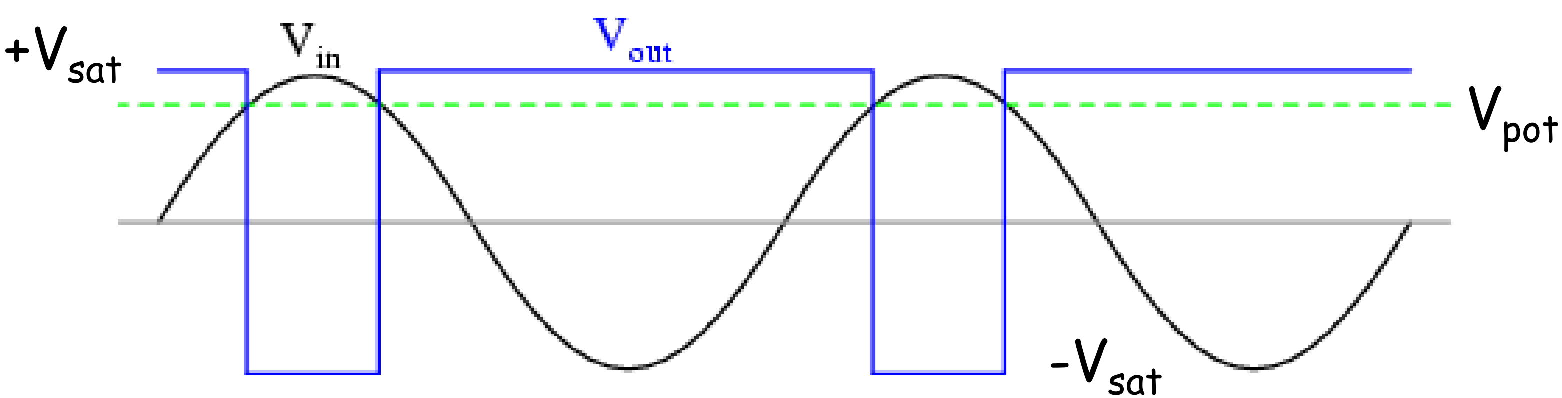


Applications: Low-voltage alarms, night light controller

Pulse Width Modulator



- Output changes when $V_{in} \sim= V_{pot}$



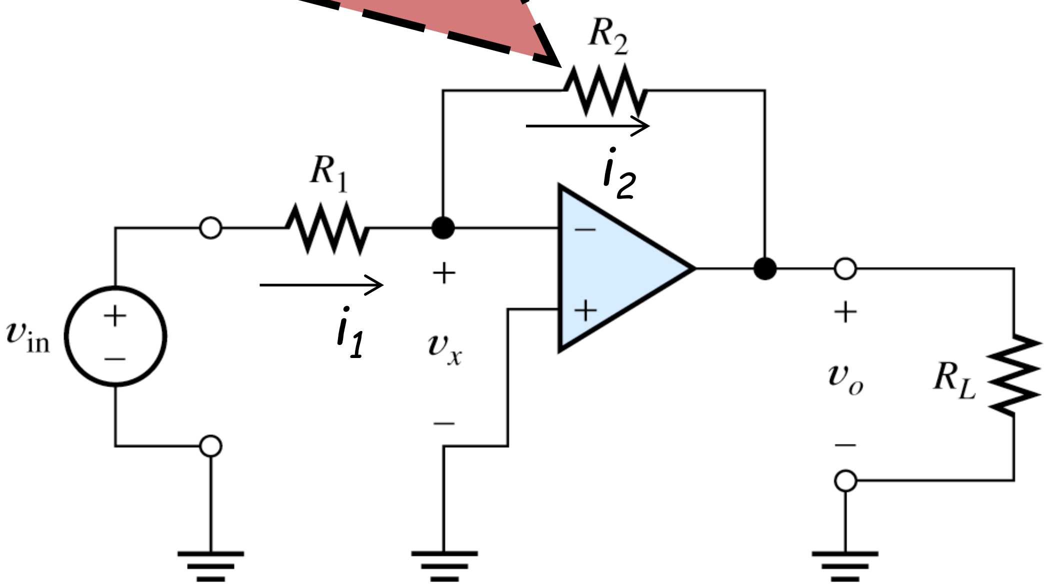
Application: Motor controllers

Negative feedback

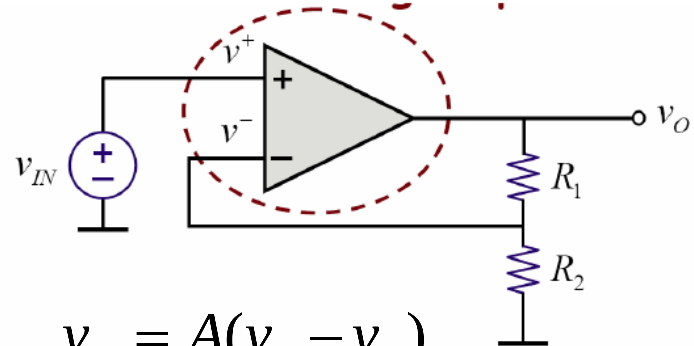
Op-amp are almost always used with a negative feedback:

- Part of the output signal is returned to the input.
- Feedback reduces the gain of op-amp.

Negative feedback forces the voltage at the inverting input terminal to be equal to the voltage at the noninverting input terminal.



When A is very large:



$$v_O = A(v_+ - v_-)$$

$$v_- = \frac{v_O R_2}{R_1 + R_2}$$

$$v_O = \frac{A v_{IN}}{\cancel{1} + \frac{AR_2}{R_1 + R_2}}$$

$$v_O = \frac{\cancel{A} v_{IN}}{\cancel{A} \cdot \frac{R_2}{R_1 + R_2}}$$

$$v_O \approx v_{IN} \frac{R_1 + R_2}{R_2}$$

Take $A=10^6$, $R_1=9R$, $R_2=R$

$$v_O = \frac{10^6 v_{IN}}{\cancel{1} + \frac{10^6 R}{9R + R}}$$

$$v_O = \frac{10^6 v_{IN}}{\cancel{1} + 10^6 \cdot \frac{1}{10}}$$

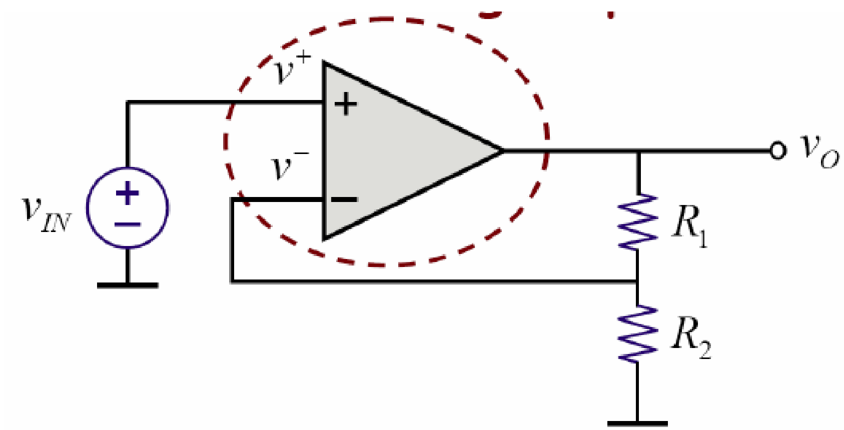
$$v_O \approx v_{IN} \cdot 10$$

- Gain now determined only by resistance ratio
- Doesn't depend on A (or temperature, frequency, variations in fabrication).

Why use Negative feedback?:

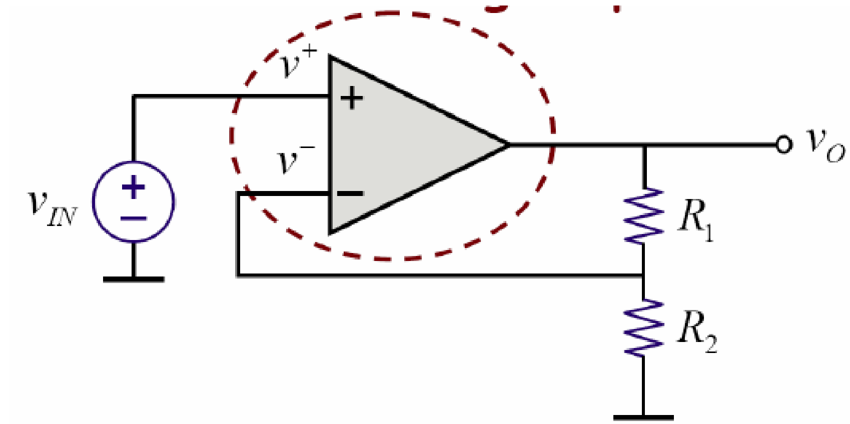
•Makes properties predictable - independent of temperature, manufacturing differences or other properties of the opamp.

• Circuit properties only depend upon the external feedback network and so can be easily controlled.



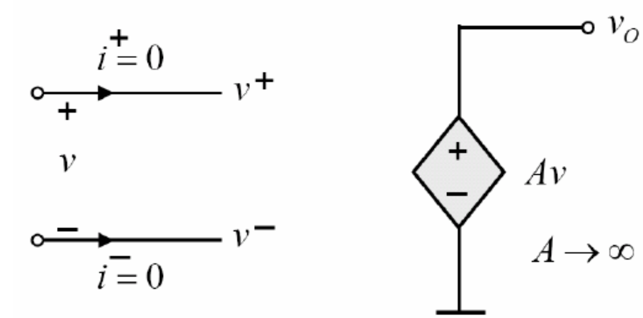
More insight (*Under negative feedback*)

$$v_O \approx v_{IN} \frac{R_1 + R_2}{R_2}$$



$$v^+ - v^- = \frac{v_O}{A} = \frac{\left(\frac{R_1 + R_2}{R_2}\right) v_{IN}}{A} \rightarrow 0$$

$$v^+ \approx v^-$$

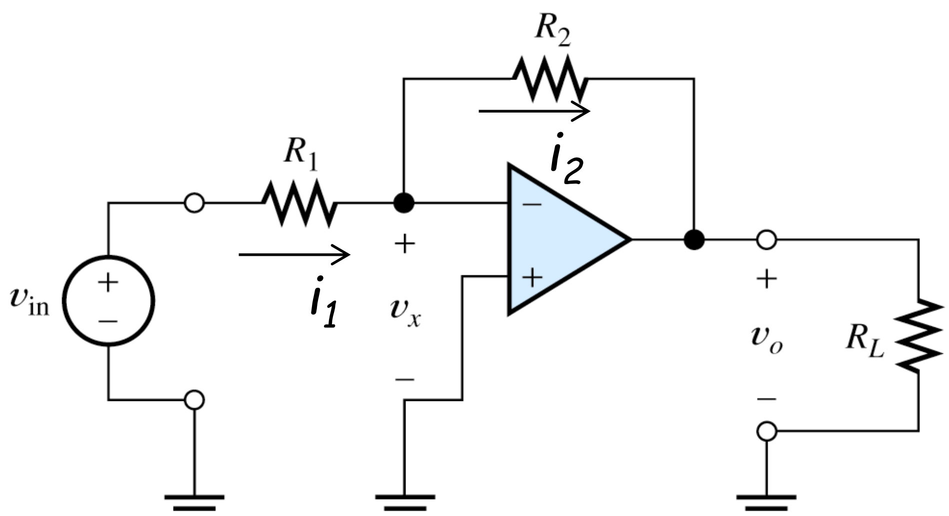


- We also know
  - $i^+ \approx 0$
  - $i^- \approx 0$
- Helpful for analysis (under negative feedback)
- Two "Golden Rules«

1) No current flows into the op-amp
2) $v^+ \approx v^-$

Inverting Amplifier

Since negative feedback forces the voltage at the inverting input terminal (v_-) to be equal to the voltage at the noninverting input terminal (v_+), v_x is equal to zero.



$v_- = v_+ = 0V$

$i_1 = v_{in} / R_1$

$i_2 = i_1$ and

$v_o = -i_2 R_2 = -v_{in} R_2 / R_1$

So

$A_v = v_o / v_{in} = -R_2 / R_1$

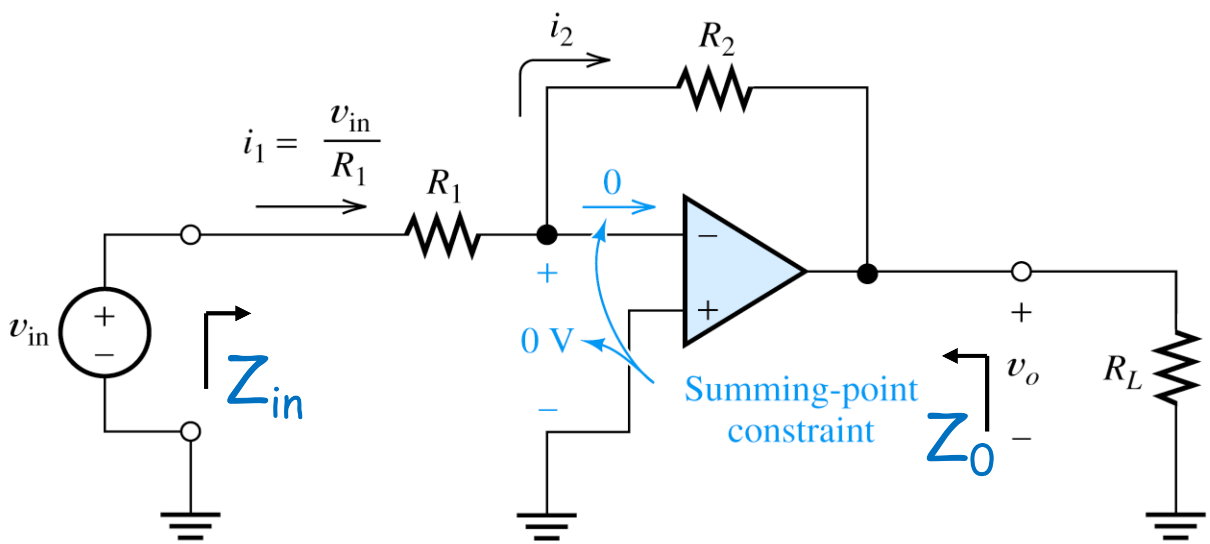
Inverting Amplifier

Since $v_o = -i_2 R_2 = -v_{in} R_2 / R_1$

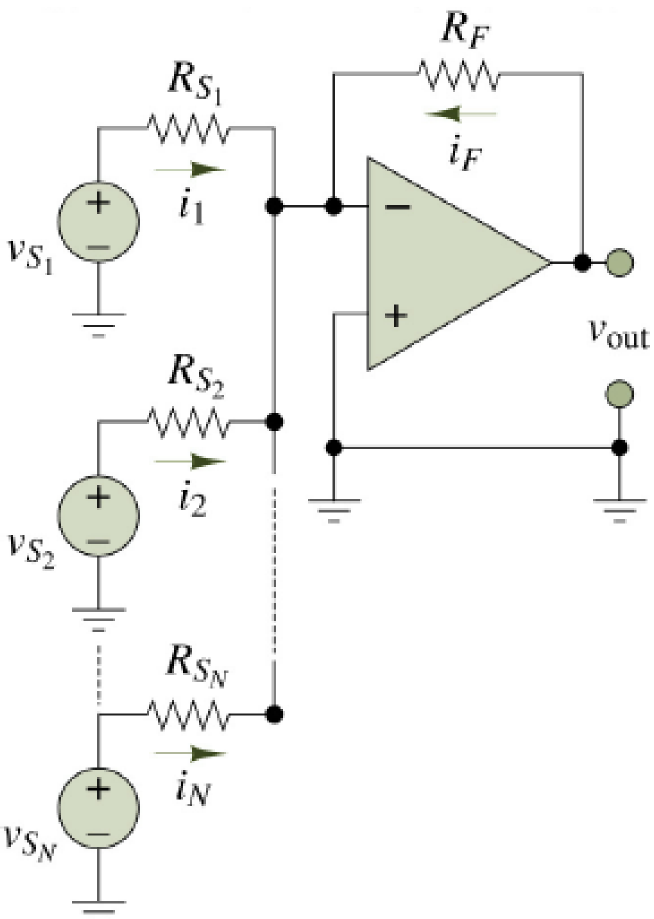
We see that the output voltage does not depend on the <u>load resistance.</u>

The output impedance of the inverting amplifier is zero.

The input impedance is: $Z_{in} = v_{in}/i_1 = R_1$



Summing Amplifier



The output voltage in summing amplifier is $v_{out}=i_f*R_f$ since $v_-=v_+=0$

$$i_1 + i_2 + \ldots\ldots + i_N = -i_F$$

$$\frac{v_{S1}}{R_{S1}} + \frac{v_{S2}}{R_{S2}} + \ldots\ldots + \frac{v_{SN}}{R_{SN}} = -\frac{v_{out}}{R_F}$$

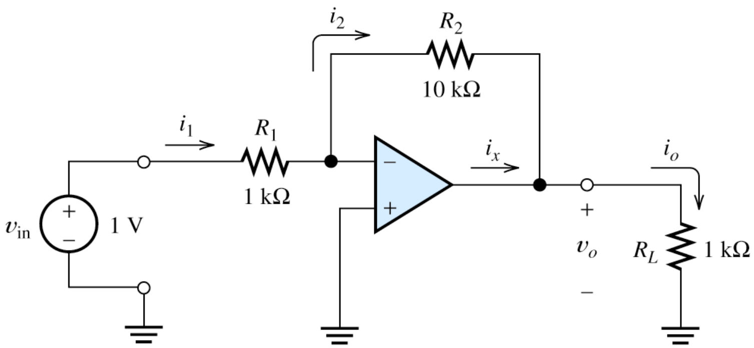
$$v_{out} = -\left(\frac{R_F}{R_{S1}} v_{S1} + \frac{R_F}{R_{S2}} v_{S2} + \ldots\ldots + \frac{R_F}{R_{SN}} v_{SN}\right)$$

If $R_{S1} = R_{S2} = \ldots = R_{SN} = R_S$

$$v_{out} = -\frac{R_F}{R_S}(v_{S1} + v_{S2} + \ldots + v_{SN})$$

Exercise

Find the currents and voltages in these two circuits:

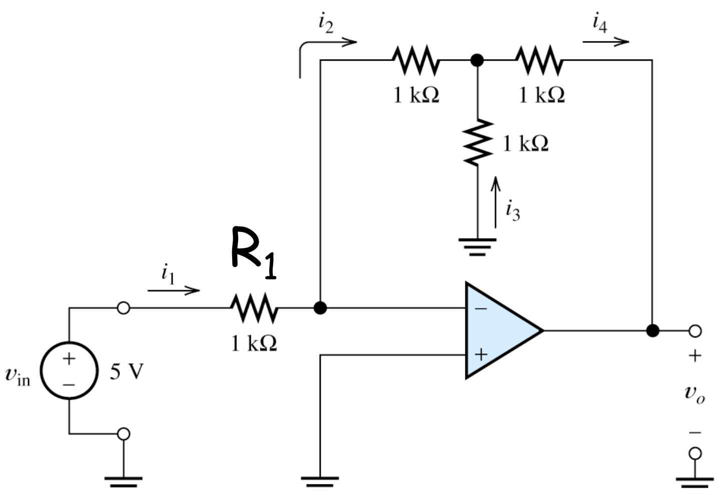


(a)

a) $i_1 = v_{in}/R_1 = 1V/1k\,\Omega = 1mA$

$i_2 = i_1 = 1mA$ from KCL
$v_o = -i_2 * R_2 = -10V$ from KVL
$i_o = v_o/R_L = -10mA$ from Ohms law

$i_x = i_o - i_2 = -10mA - 1mA = -11mA$



(b)

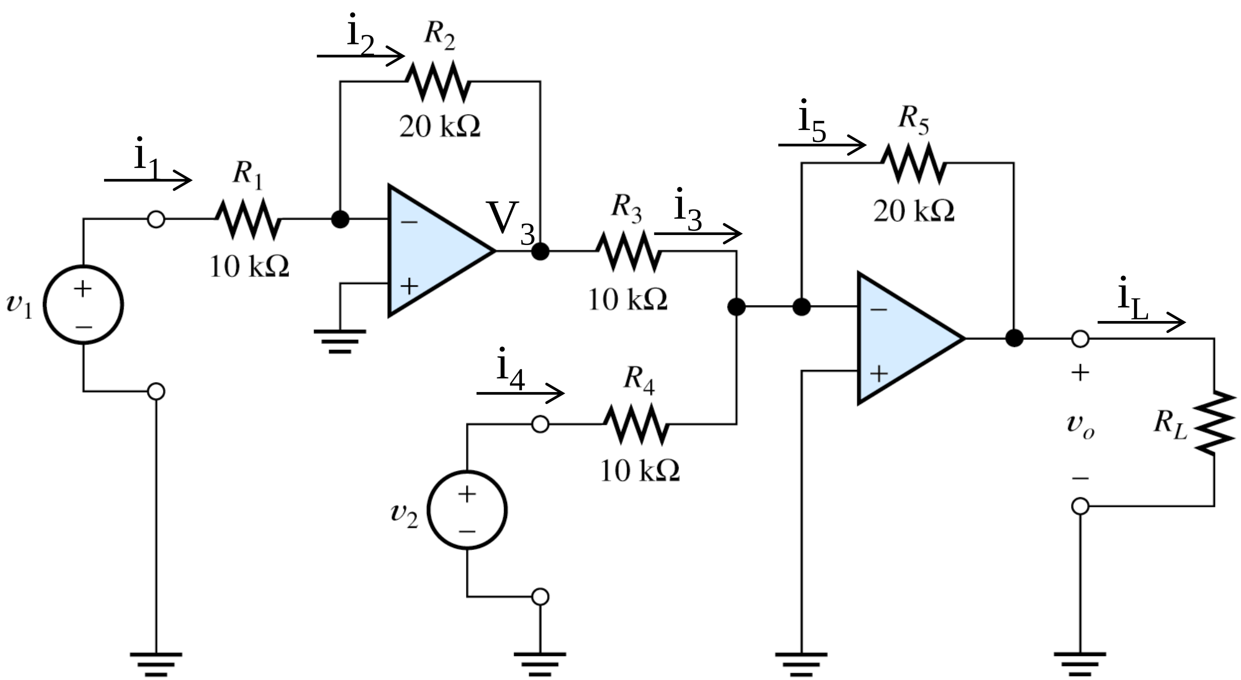
b) $i_1 = v_{in}/R_1 = 5mA$

$i_2 = i_1 = 5mA$
$i_2 * 1k\Omega = i_3 * 1k\Omega \Rightarrow i_3 = 5mA$
$i_4 = i_2 + i_3 = 10mA$

$v_o = -\, i_2 * 1k\,\Omega - i_4 * 1k\,\Omega = -15\ V$

Exercise

Find expression for the output voltage in the amplifier circuit:



$i_1 = v_1/R_1 = v_1/10k\,\Omega$

$i_2 = i_1 = v_1/10mA$

$v_3 = -\, i_2 * R_2 = -\, v_1/10k\,\Omega * 20k\,\Omega = -2v_1$

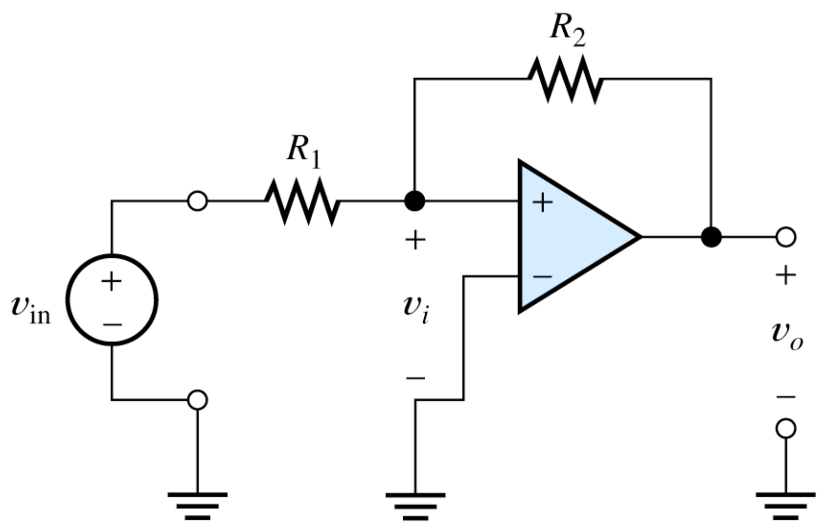
$i_5 = i_3 + i_4 = v_3/10k\,\Omega + v_2/10k\,\Omega$

$v_o = -\, i_5 * R_5 = -(v_3/10k\,\Omega + v_2/10k\,\Omega) * 20k\,\Omega = -2v_3 - 2v_2 = 4v_1 - 2v_2$

Positive Feedback

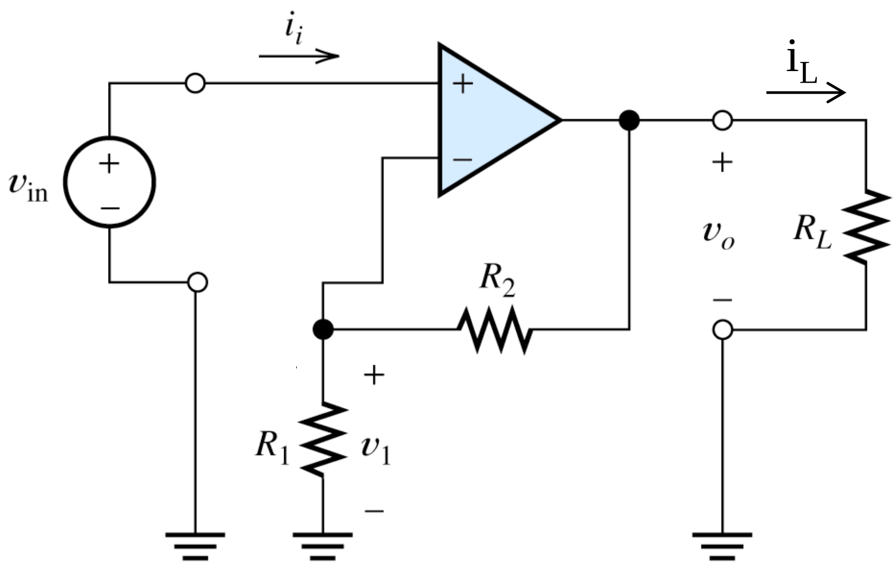
When we flip the polarization of the op-amp as shown on the figure we will get a positive feedback that **saturates** the amplifier output.

This is not a good idea.



Circuit with positive feedback.

Noninverting Amplifier



Noninverting amplifier.

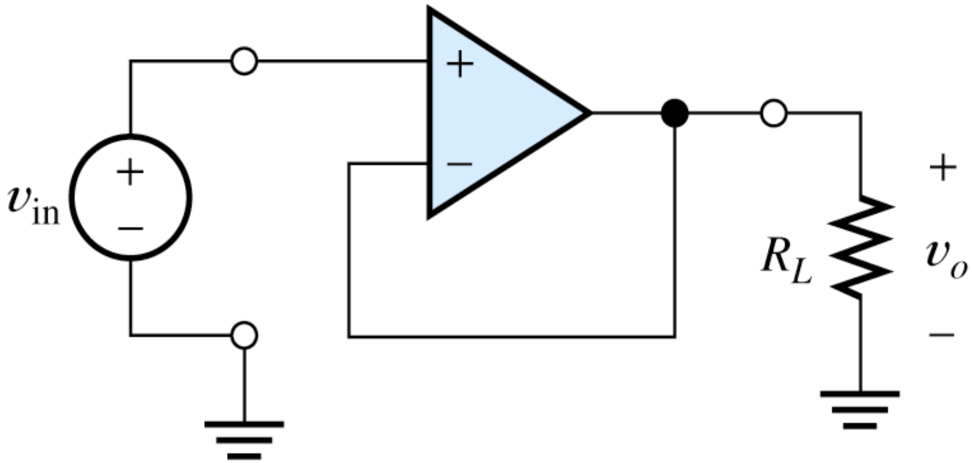
$v_1 = v_{in}$

$v_{in}/R_1 + (v_{in} - v_o)/R_2 = 0$

Thus the voltage gain of noninverting amplifier is:

$$\boxed{A_v = v_o / v_{in} = 1 + R_2 / R_1}$$

Voltage Follower



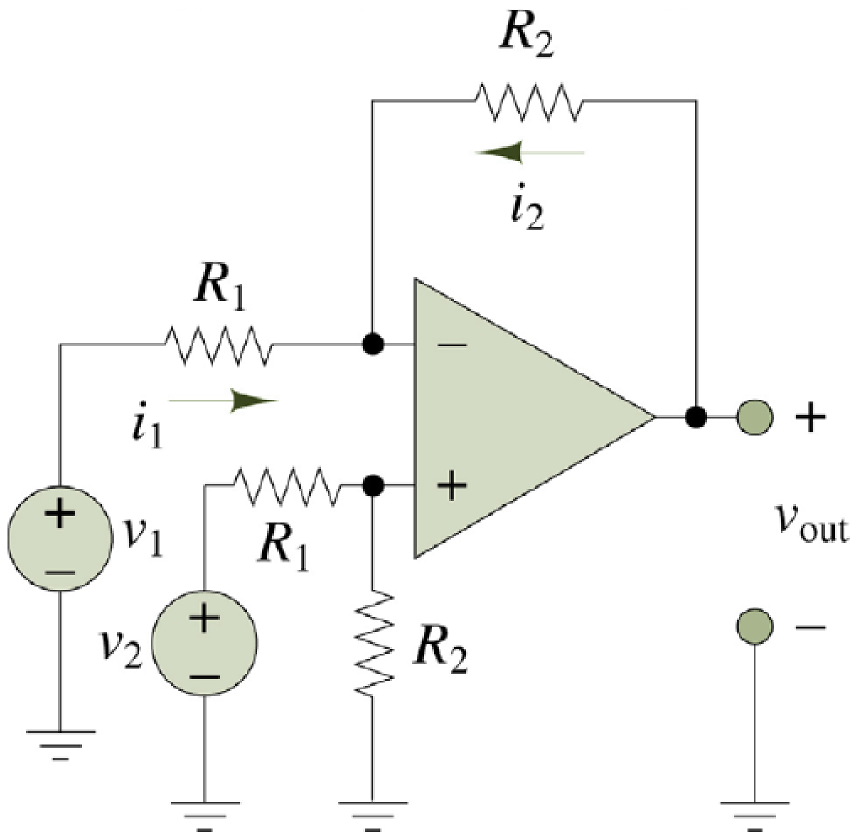
The voltage follower which has $A_v = 1$.

- What's the application of this circuit?
- Buffer

    voltage gain = 1
    input impedance=∞
    output impedance=0

    Useful interface between different circuits:
    Has minimum effect on previous and next circuit in signal chain

Differential Amplifier (subtractor)



$i_1 + i_2 = 0$

$$\frac{v_1 - v^-}{R_1} = -\frac{v_{out} - v^-}{R_2}$$

$$v^- = v^+$$

$$v^+ = \frac{R_2}{R_1 + R_2} v_2 = v^-$$

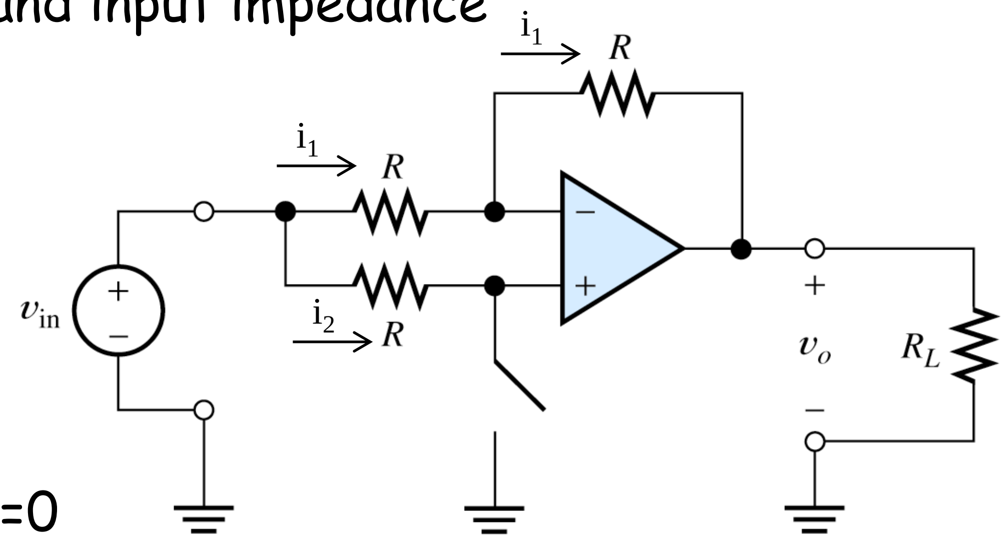
$$v_{out} = \frac{R_2}{R_1}(v_2 - v_1)$$

Exercise

Find voltage gain $A_v = v_o / v_{in}$ and input impedance

a. **With the switch open**

b. With the switch closed



a. **With the switch open**

$i_2=0$ and $i_1{*}R=i_2{*}R$ => $i_1=0$

so $v_{in}=v_o$ and $A_v=v_o/v_{in}=1$

Input impedance:

$Z_{in}=v_{in}/i_{in} = v_{in}/0 = \text{inf}$

Exercise

Find voltage gain $A_v = v_o/v_{in}$ and input impedance

a. With the switch open

b. **With the switch closed**

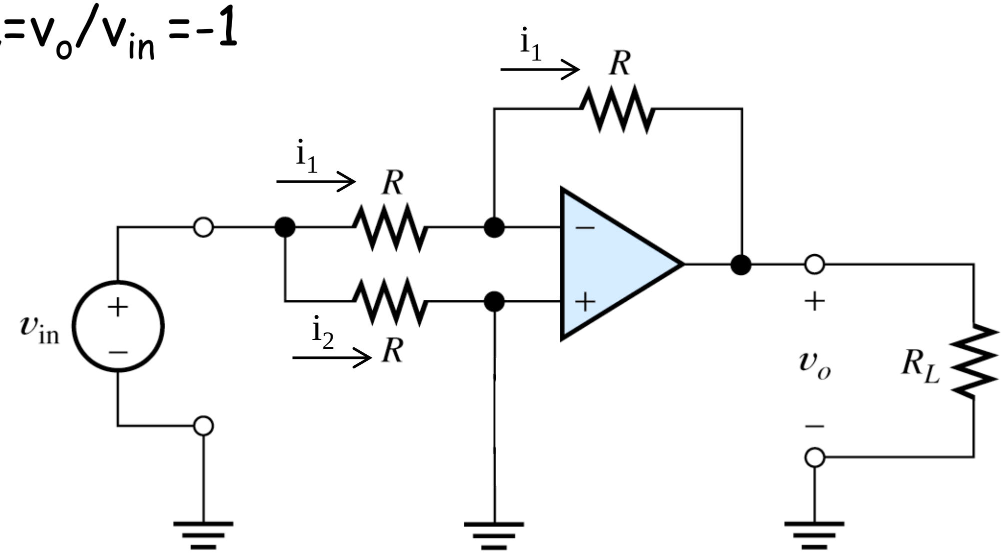
b. **for closed switch:** $i_2 = v_{in}/R$

and $i_1 * R = i_2 * R \Rightarrow i_1 = i_2$

$v_{in} = i_1 * R + i_1 * R + v_o$

so $v_{in} = v_{in}/R * R + v_{in}/R * R + v_o \Rightarrow -v_{in} = v_o$

and $A_v = v_o/v_{in} = -1$



Exercise

Find voltage gain $A_v=v_o/v_{in}$ and input impedance

a. With the switch open

b. With the switch closed

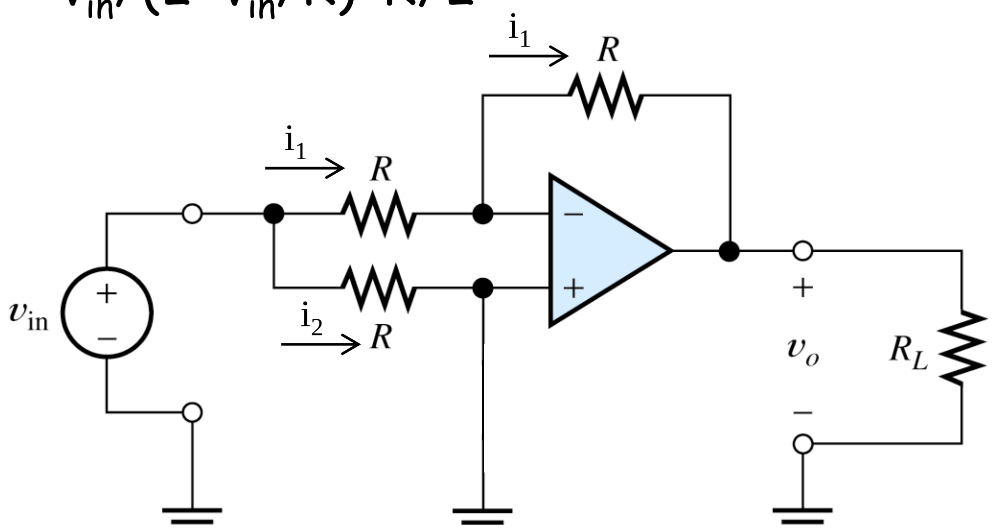
b. $i_2=v_{in}/R$

Input impedance: $Z_{in}=v_{in}/i_{in}$

$=v_{in}/(i_1+i_2)$

and $i_1=i_2$ =>

$Z_{in}=v_{in}/i_{in}$ $=v_{in}/(2*v_{in}/R)=R/2$



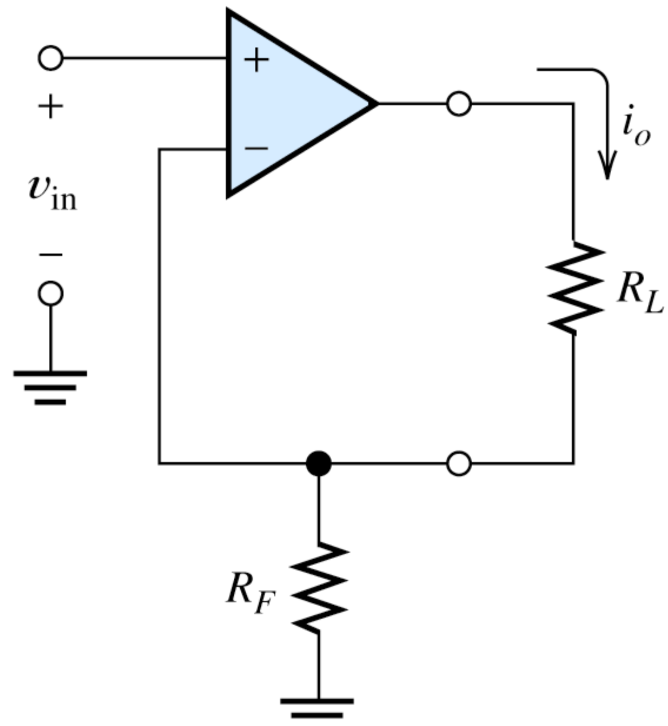
Voltage to Current Converter

Find the output current i_o as a function of v_{in}

$v_{in} = i_o * R_f$

so

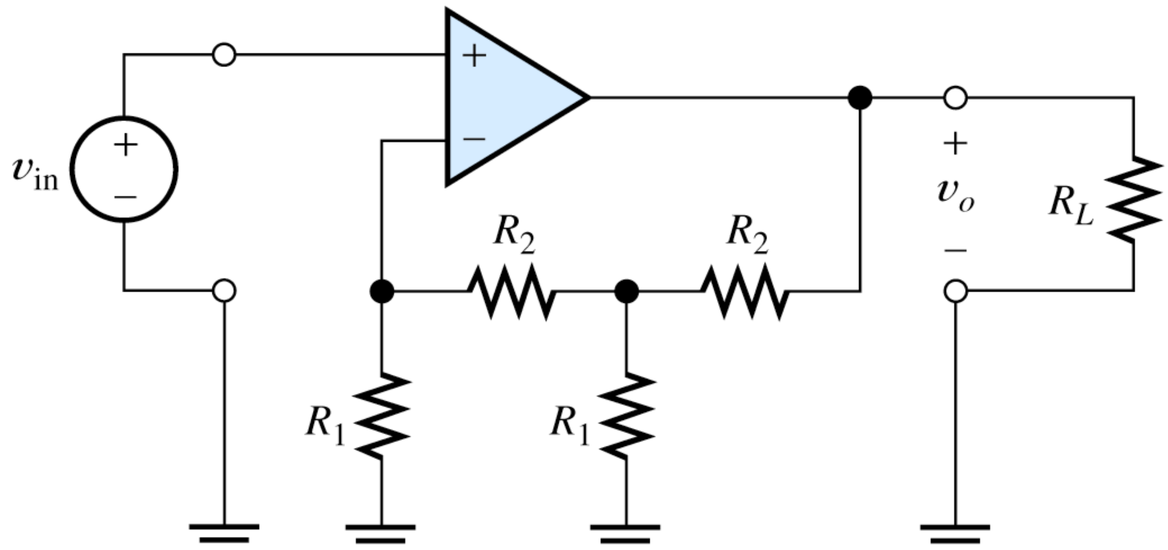
$i_o = v_{in}/R_f$



Exercise

a) Calculate the voltage gain v_o/v_{in} for R_1=10 kΩ, R_2 = 100 kΩ

b) Find the input resistance



Exercise

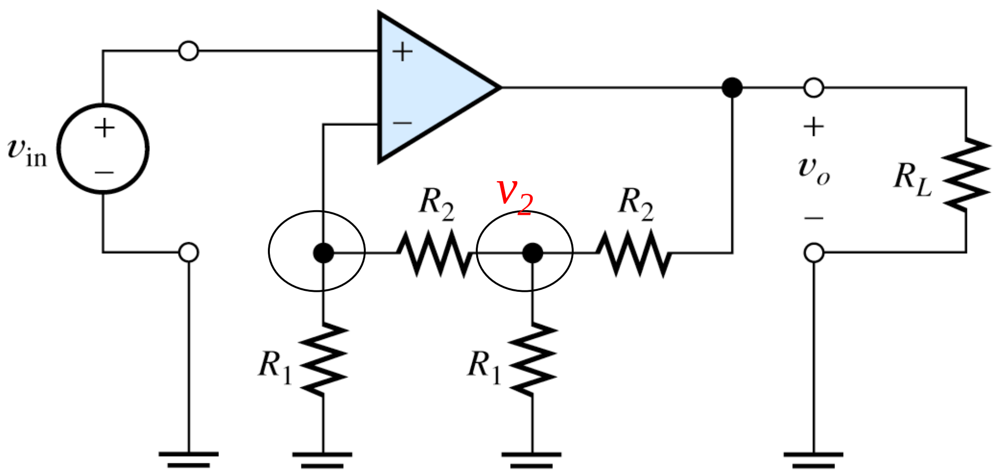
a) Calculate the voltage gain v_o/v_{in} for R_1=10kΩ, R_2 = 100 kΩ

b) Find the input resistance

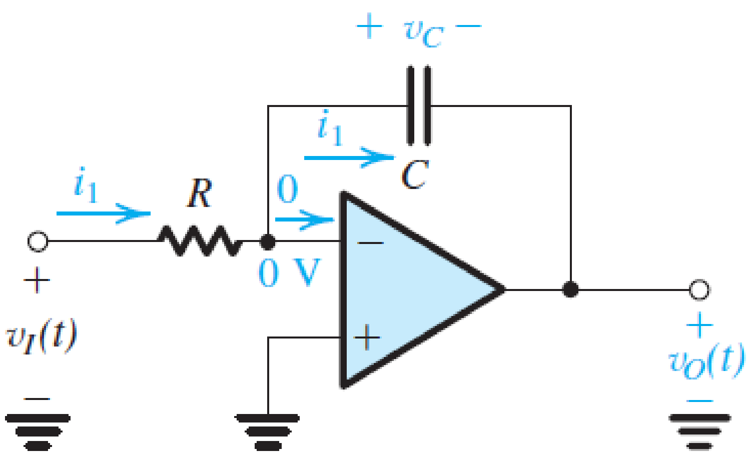
From KCL1: $v_{in}/R_1 + (v_{in}-v_2)/R_2 = 0 \Rightarrow v_2 = v_{in}(1+R_2/R_1) = 11v_{in}$

From KCL2: $(v_2-v_{in})/R_2 + v_2/R_1 + (v_2-v_0)/R_2 = 0 \Rightarrow$

$v_0 = (v_2-v_{in}) + v_2R_2/R_1 + v_2 \Rightarrow$ $\boxed{v_0/v_{in} = 131}$



Op-amp integrator



$$i_1 = \frac{v_i - v_-}{R} = \frac{v_i}{R}$$

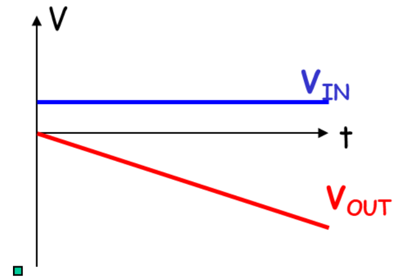
$$i_1 = i_C = \mathrm{C}\frac{dv_c}{dt} = \mathrm{C}\frac{dv_o}{dt}$$

Combining the 2 Eq.s and integrating

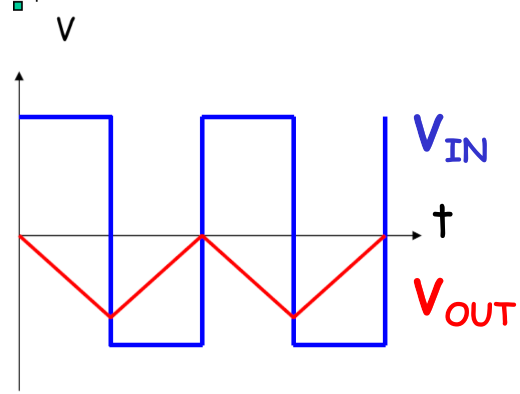
$$\mathrm{C}\frac{dv_o}{dt} = \frac{v_i}{R}$$

$$V_{\text{out}} = \int_0^t -\frac{V_{\text{in}}}{RC}\,dt + V_{\text{initial}}$$

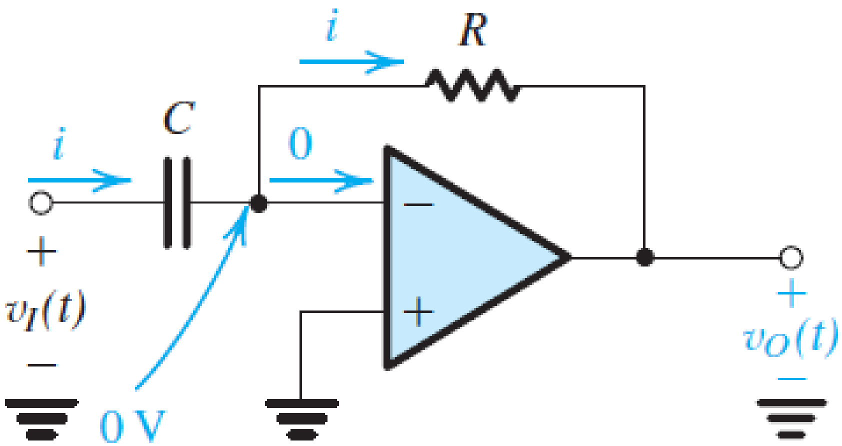
Integrator response to a constant voltage:



What's the integrator response to a square wave?



Differentiating Op-Amp



$$i = i_C = \mathrm{C}\frac{dv_c}{dt} = \mathrm{C}\frac{dv_i}{dt}$$

$$i = \frac{v_- - v_o}{R} = -\frac{v_o}{R}$$

Combining the 2 Eq.s

$$\mathrm{C}\frac{dv_i}{dt} = -\frac{v_o}{R}$$

$$v_o = -\mathrm{RC}\frac{dv_i}{dt}$$

Op-Amp Imperfections in a Linear Mode

We consider the following op-amp imperfections:

Input and output impedances:

Ideal opamp $R_{in} = \infty; \quad R_{out} = 0\Omega$

Real op-amp has $R_{in} = 1M\Omega - 10^{12}\Omega;$

$R_{out} = 1\Omega - 100\Omega$

Nonlinear Limitations

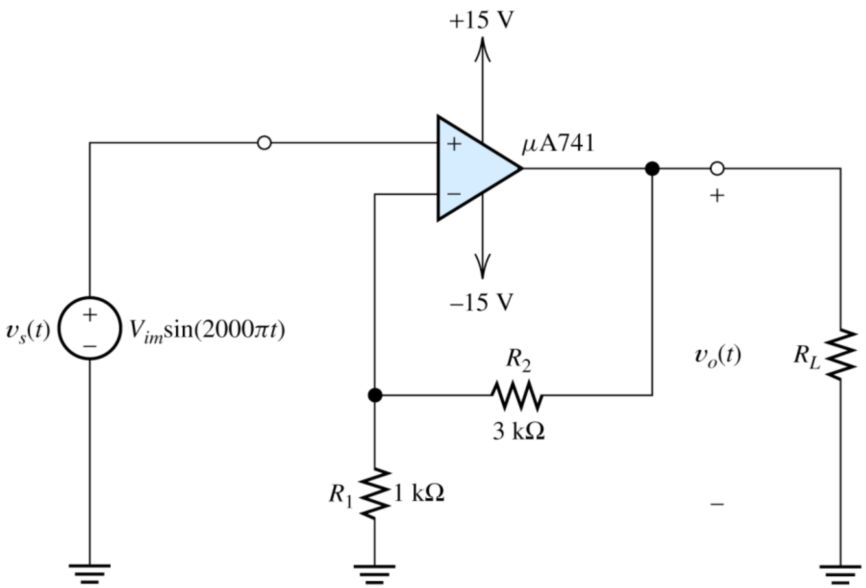
Nonlinear limitations:

Output voltage swing is limited and depend on power supply voltage for

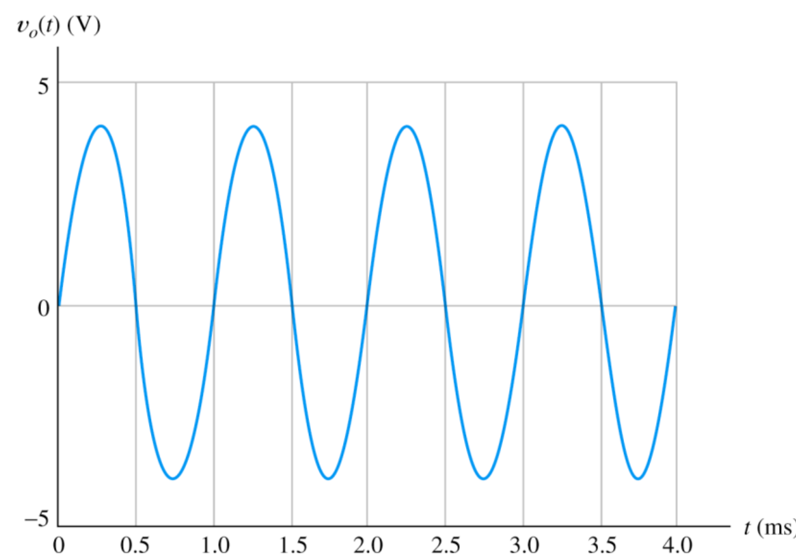
$$V_{DD} \in (-15V, +15V), \quad v_o(t) \in (-12V, +12V)$$

Maximum output current is limited

$$\text{for} \quad \mu A741 \quad \text{amplifier} \quad i_o(t) \in (-40mA, +40mA)$$



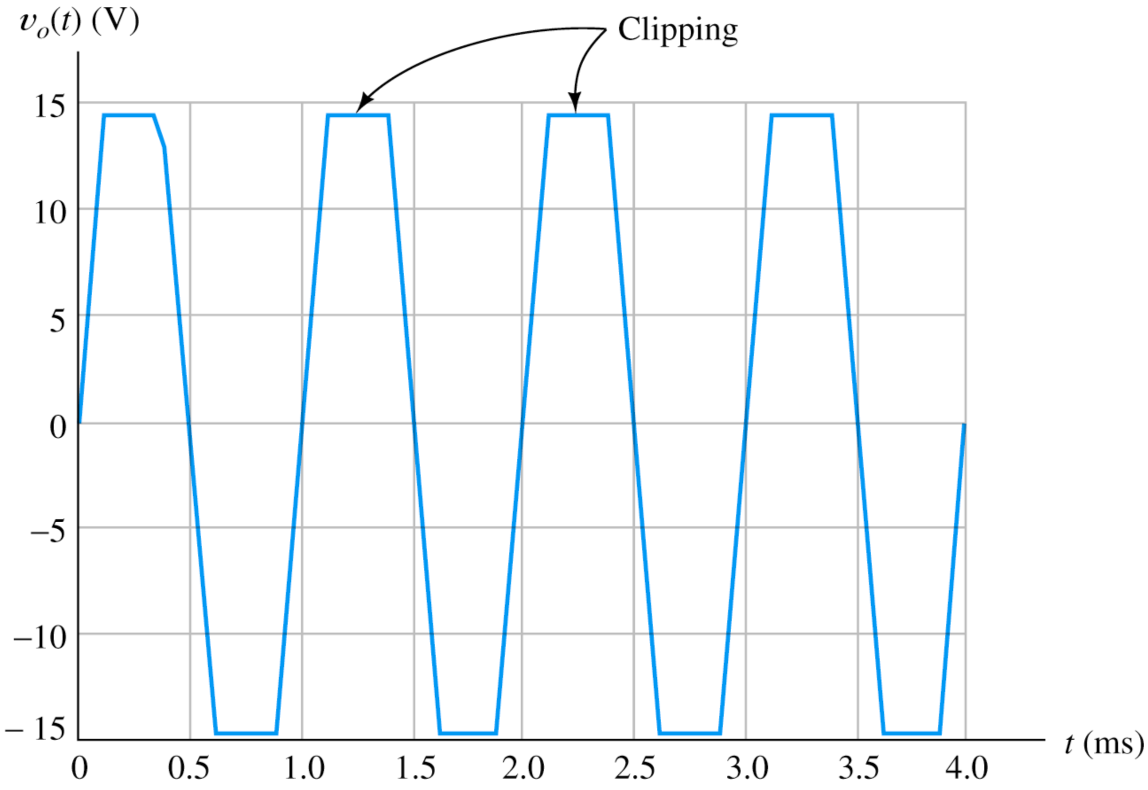
Noninverting amplifier used to demonstrate various nonlinear limitations of op amps.



Output of the circuit of Figure 14.23 for $R_L = 10$ kΩ and $V_{im} = 1$ V. None of the limitations are exceeded, and $v_o(t) = 4v_s(t)$.

Nonlinear Limitations

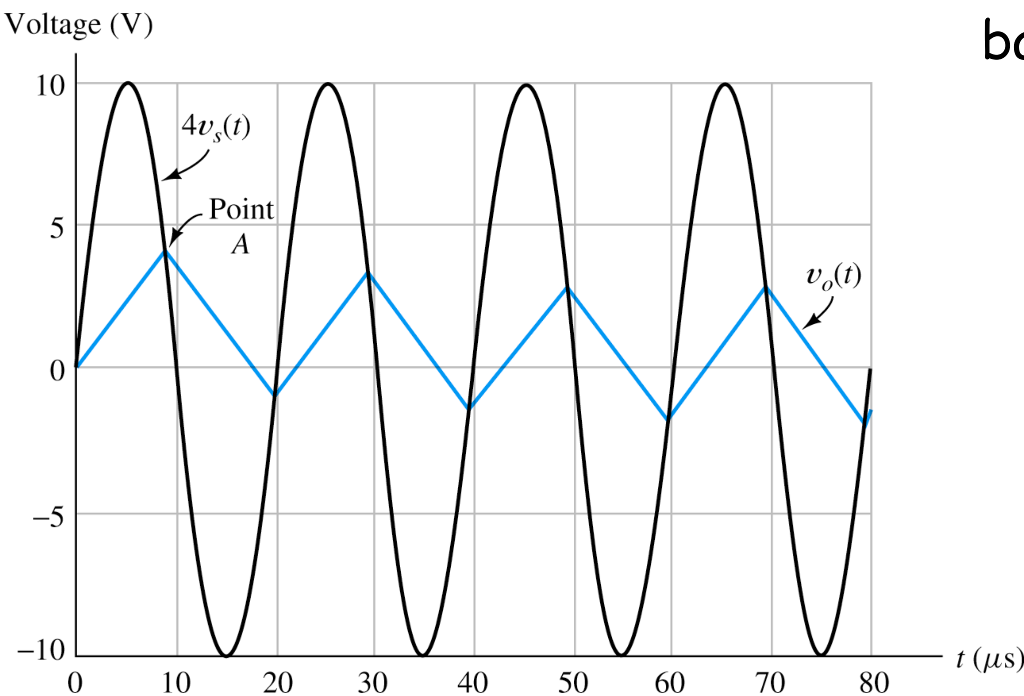
When voltage or current limits are exceeded, clipping of the output signal occurs causing large nonlinear distortions



Nonlinear Limitations

Another nonlinear limitation is limited rate of change of the **output signal** known as the slew-rate limit SR

$$\left|\frac{dv_o}{dt}\right| \le SR$$



Using slew rate (SR), we can find maximum frequency known as full-power bandwidth.

Assuming:

$$v_o(t) = V_{om}\sin(\omega t)$$

$$\frac{dv_o}{dt} = \omega V_{om}\cos(\omega t) \le$$

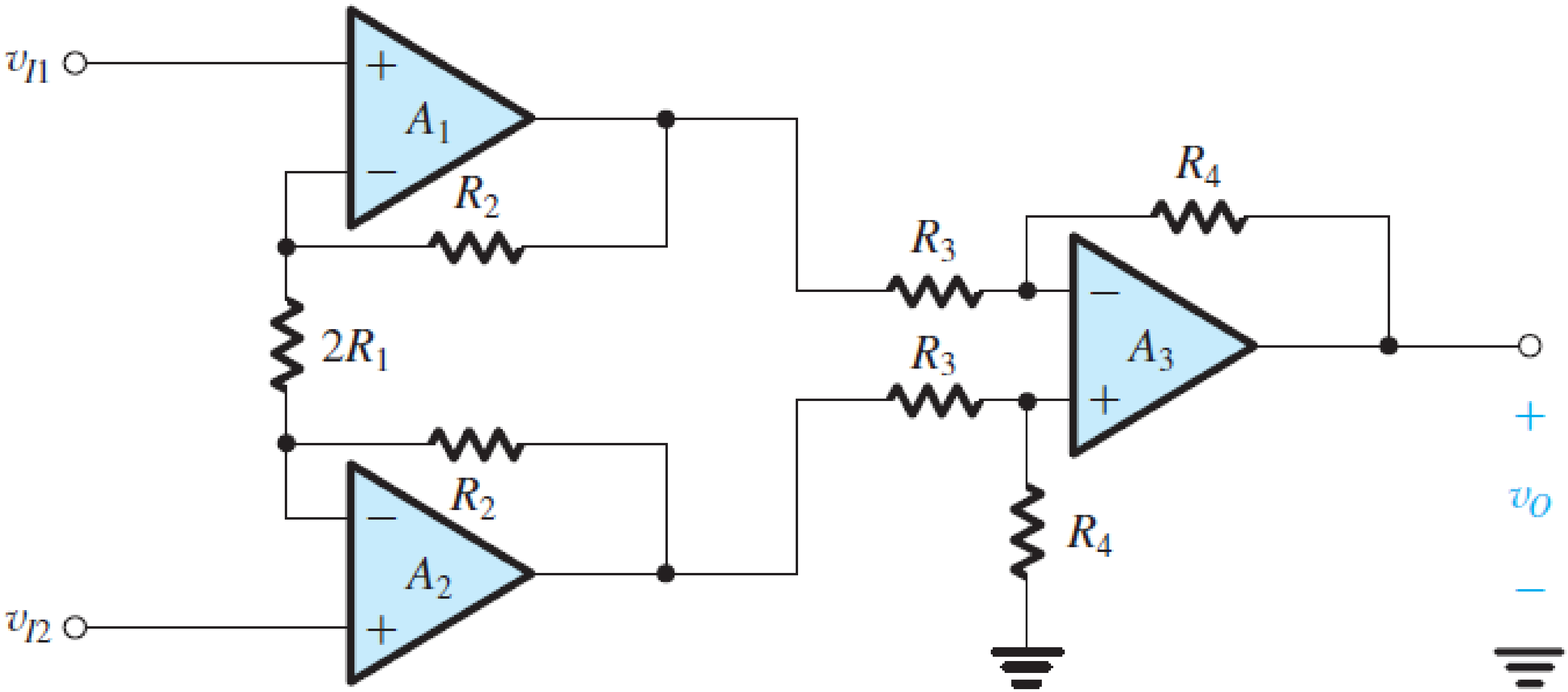
$$\le 2\pi\ f\ V_{om} \le SR$$

So the full-power bandwidth

$$f_{FP} \le \frac{SR}{2\pi V_{om}}$$

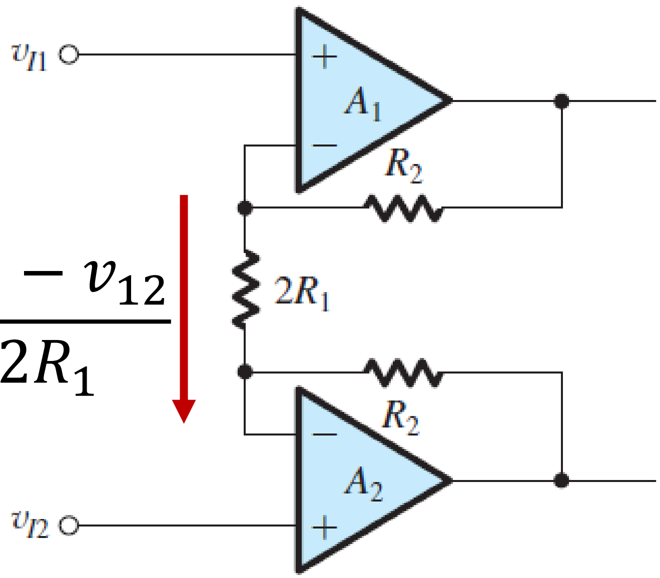
maximum frequency

Instrumentation Amplifier



Instrumentation Amplifier -First Stage

$$v_{01} - v_{o2} = 2i(R_1 + R_2) = 2\,\frac{v_{i1} - v_{12}}{2R_1}\,(R_1 + R_2)$$

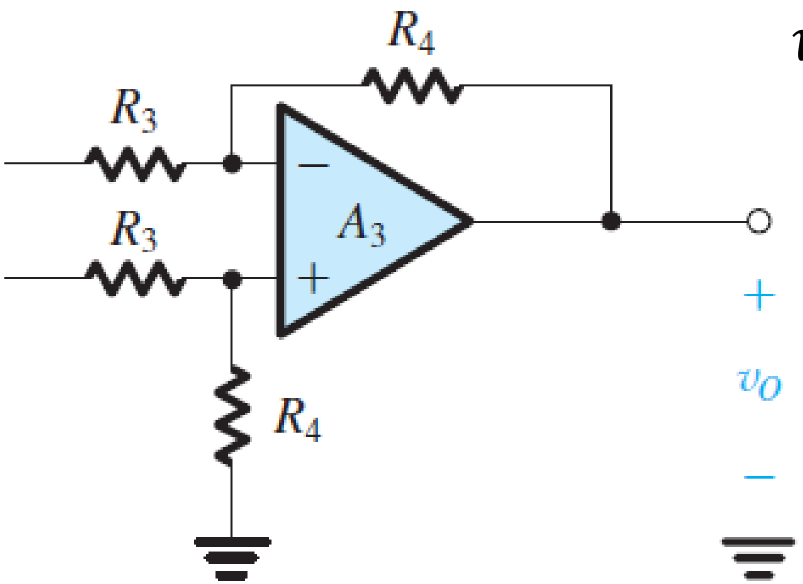


$$i = \frac{v_{i1} - v_{12}}{2R_1}$$

$$v_{01} - v_{o2} = \frac{R_1 + R_2}{R_1}\,(v_{i1} - v_{i2})$$

$$A_d = \frac{v_{01} - v_{o2}}{v_{i1} - v_{i2}} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

Instrumentation Amplifier –Second Stage

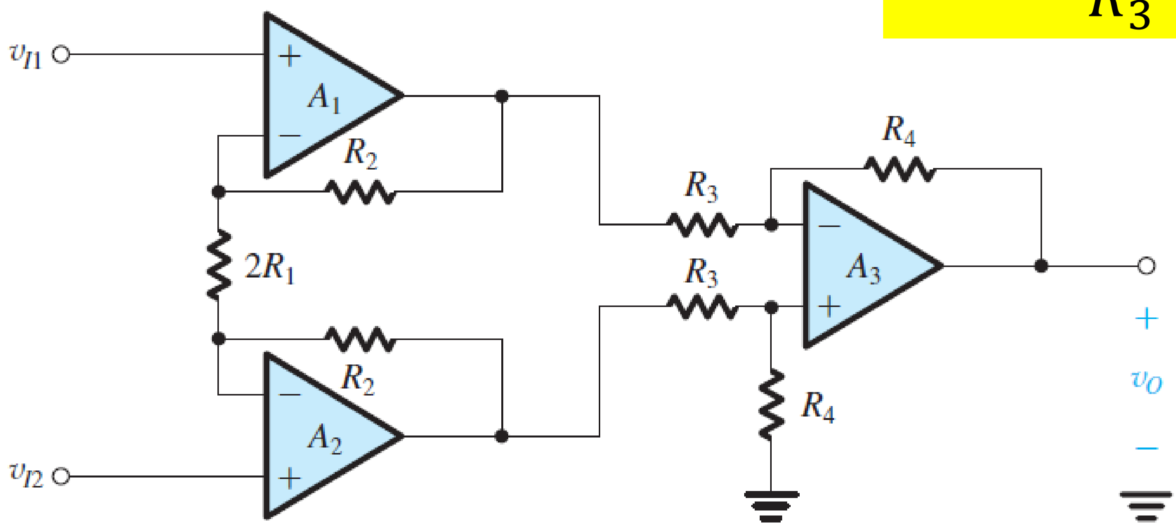


$$v_o = -\frac{R_4}{R_3}\, v_{o1} + \frac{R_4}{R_3 + R_4}\left[\frac{R_4}{R_3} + 1\right] v_{o2}$$

$$v_o = -\frac{R_4}{R_3}\,[v_{o1} - v_{o2}]$$

Instrumentation Amplifier -Both Stages

$$v_o = -\frac{R_4}{R_3}\left(1+\frac{R_2}{R_1}\right)\,[v_{i1}-v_{i2}]$$



$$v_{01}-v_{o2}=\frac{R_1+R_2}{R_1}\ (v_{i1}-v_{i2})$$

$$v_o=-\frac{R_4}{R_3}\,[v_{o1}-v_{o2}]$$