Lecture 11: Op-Amps – Part I

ELEC1111 Electrical and Telecommunications Engineering

UNSW AUSTRALIA

Never Stand Still | Faculty of Engineering | School of Electrical Engineering and Telecommunications

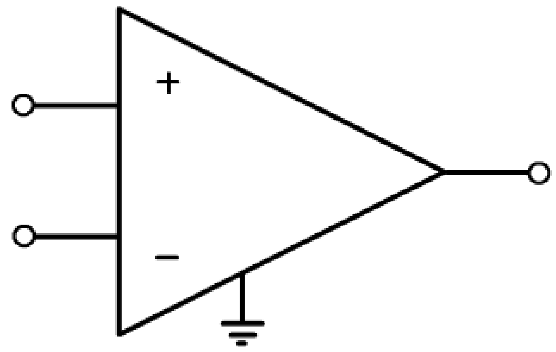
What is an Op-Amp?

It is an electronic unit that behaves like a voltage-controlled voltage source

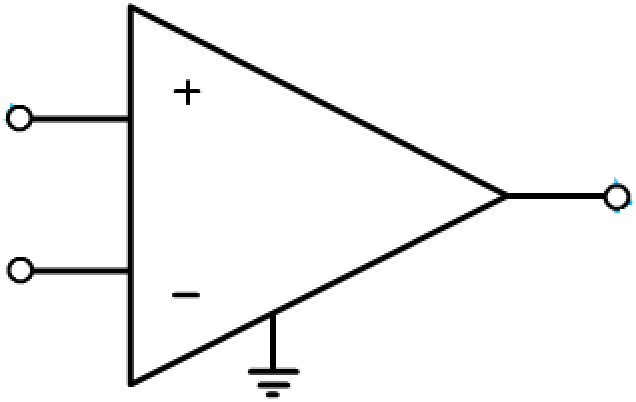
It is an active circuit element designed to perform mathematical operations of addition, subtraction, multiplication, division, differentiation and integration (with appropriate surrounding circuit elements)

Operational Amplifiers (Op-Amps)

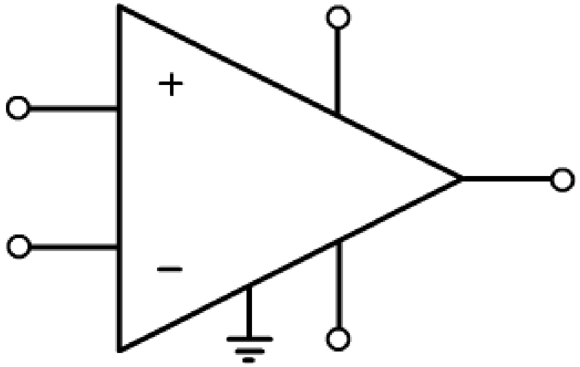
Operational Amplifiers (Op-Amps) are devices that have very high input impedance and very high gain.



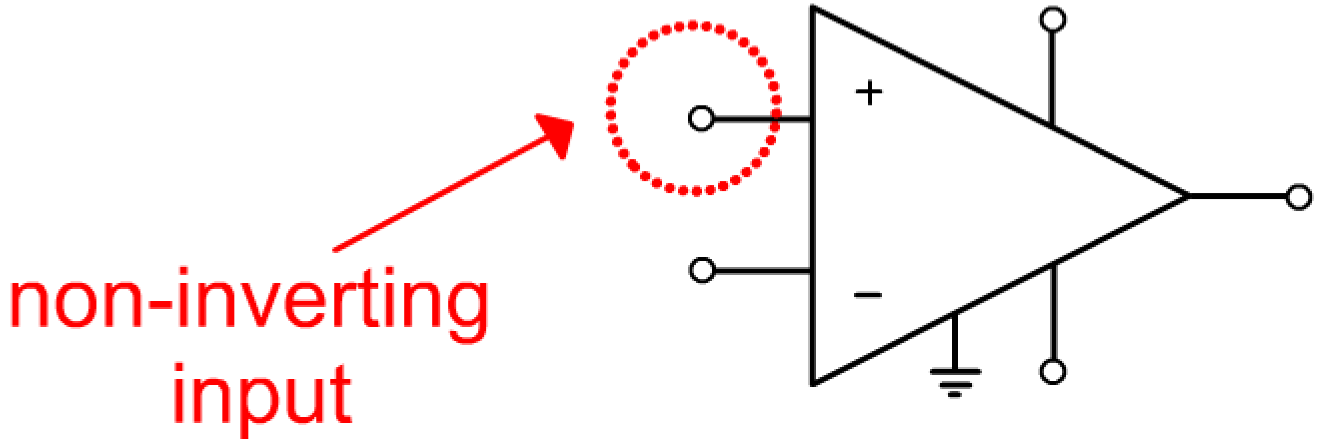
Op-Amps are often used to amplify small signals.



The operational amplifier has two input terminals, two supply terminals, one output terminal, and a ground connection.



The input terminal denoted with a "+" is known as the *non-inverting terminal.*



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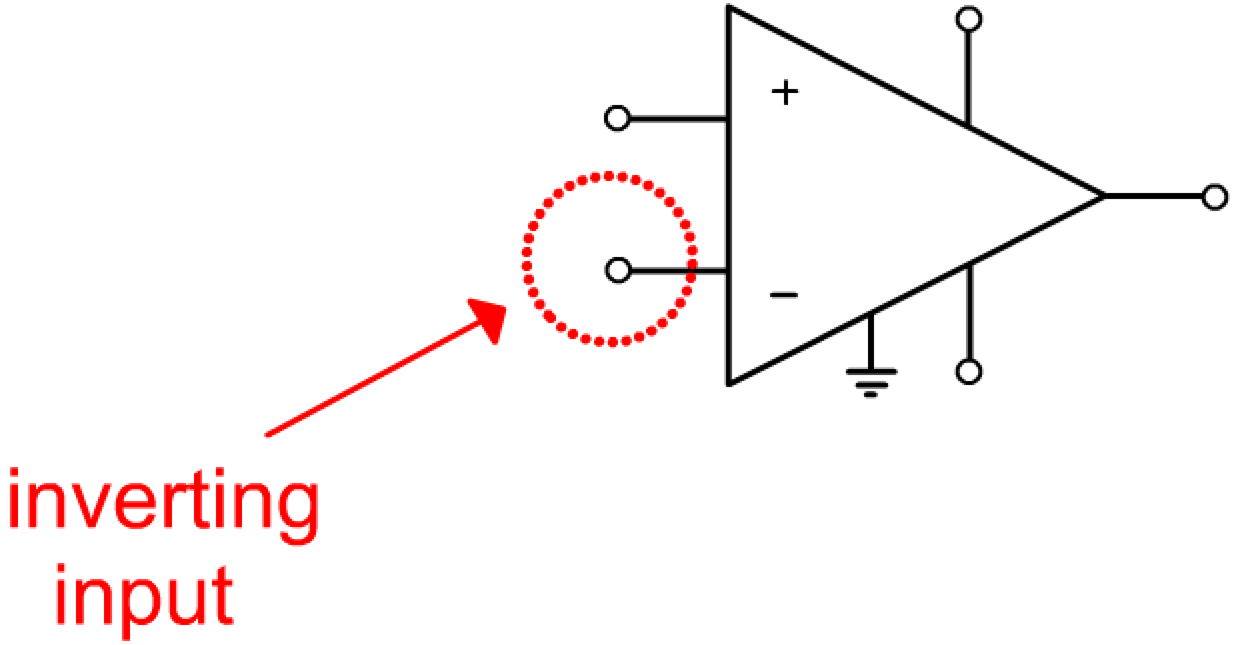
The input terminal denoted with a "-" is known as the *inverting terminal.*



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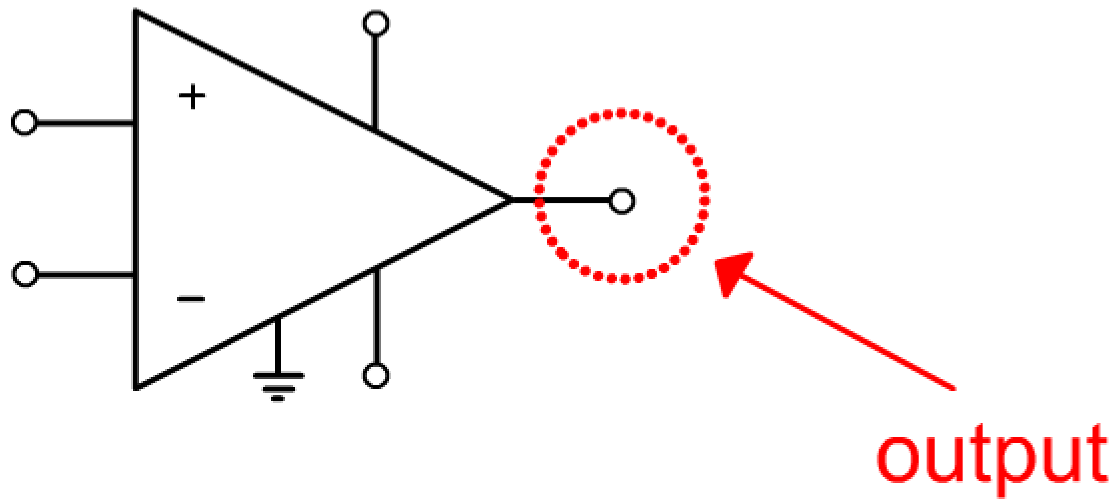
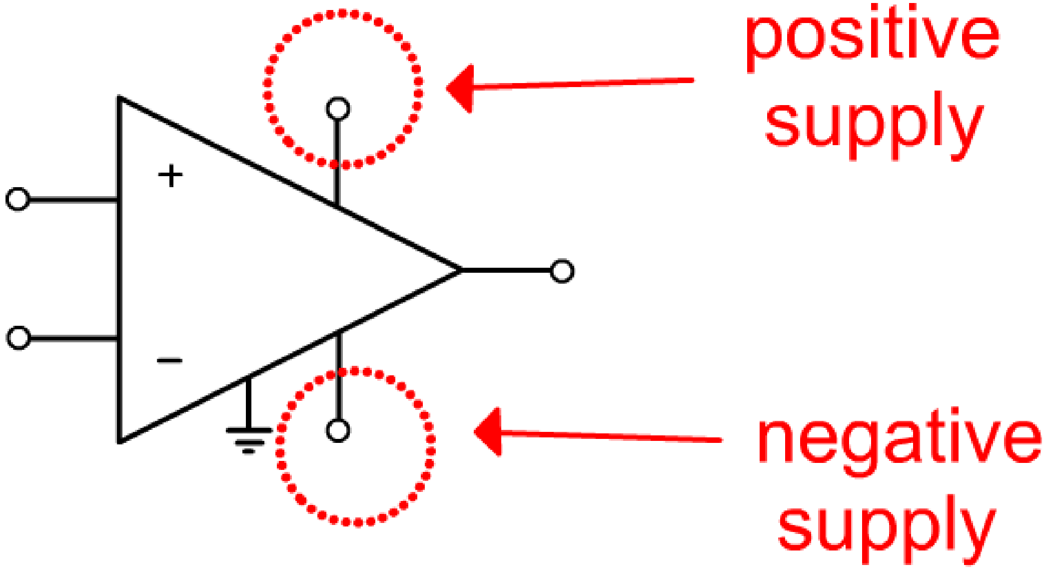
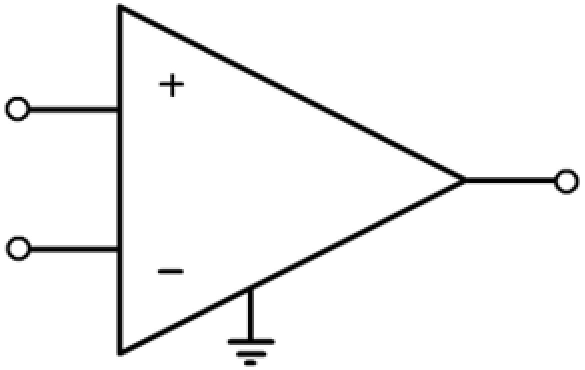
The single terminal opposite to the input terminals is the *output terminal.*



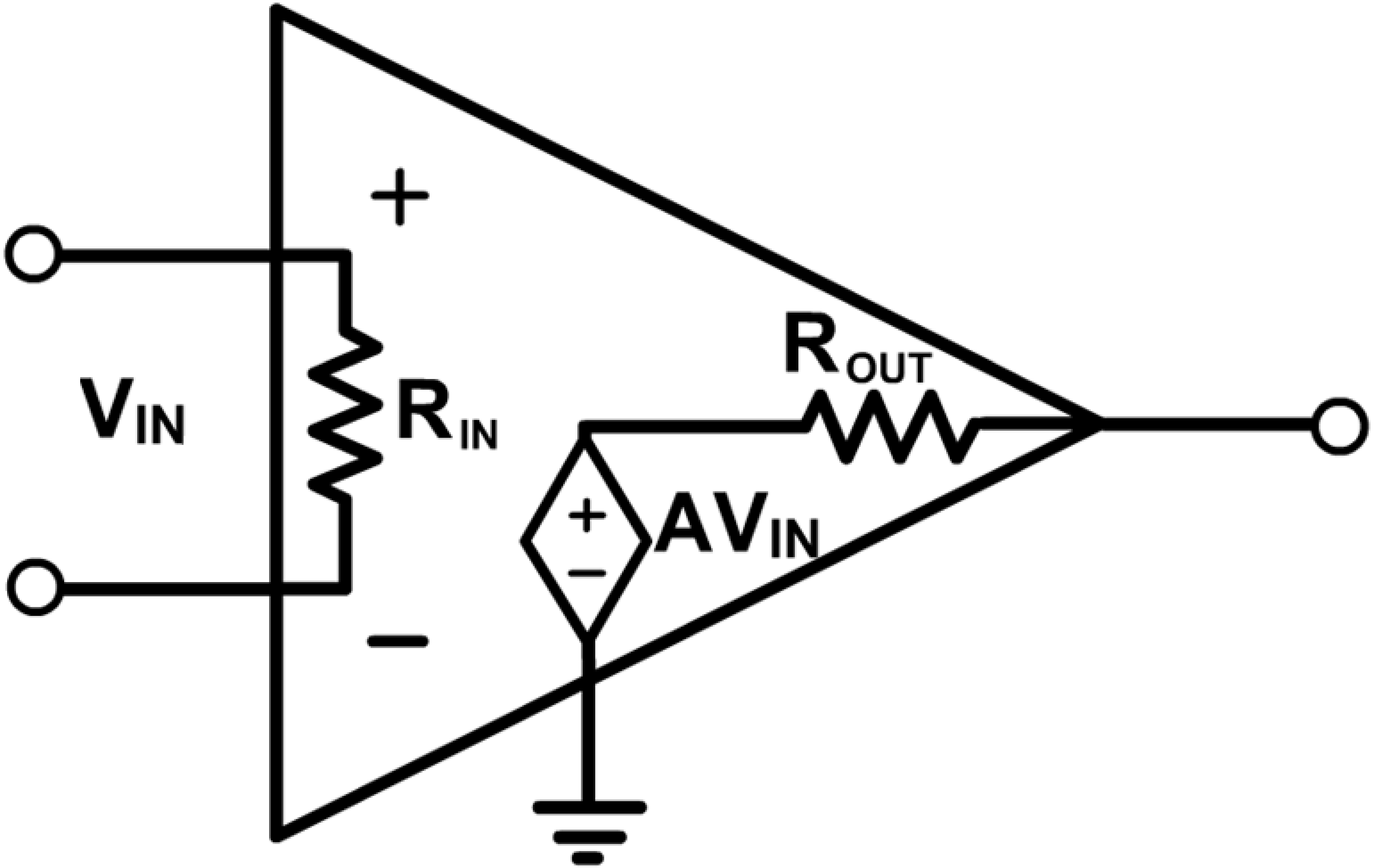
The op-amp may also be depicted as having two additional supply terminals. These terminals are connected to a positive and negative voltage source, and supply the necessary power for amplification.



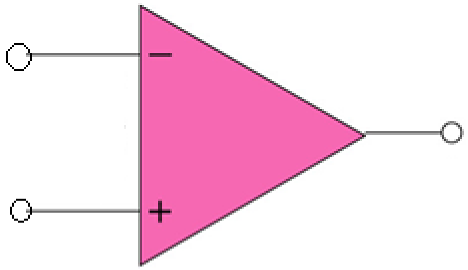
For simplicity, the operational amplifiers in this will be depicted as having only four terminals. This last terminal denotes the grounding of internal components.

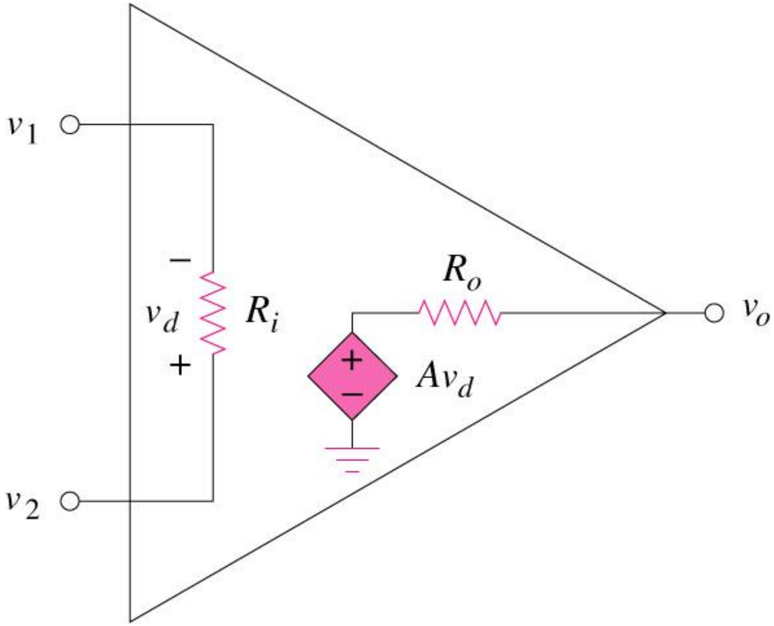


Internally, an operational amplifier can be modeled using resistors and a dependent voltage source.



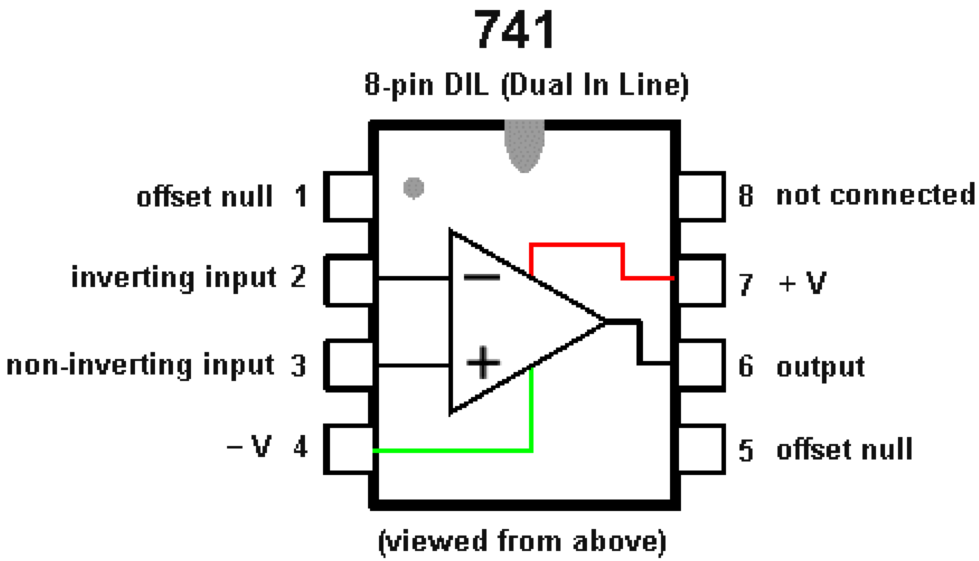
Equivalent circuit of an op amp

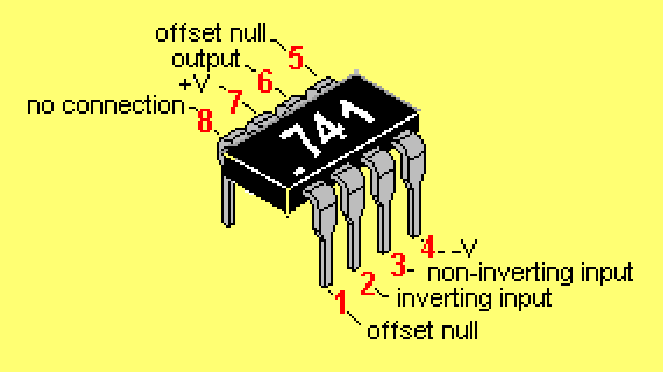




$$v_d = v_2 - v_1 \qquad v_o = Av_d = A(v_2 - v_1)$$

Op Amp integrated circuit





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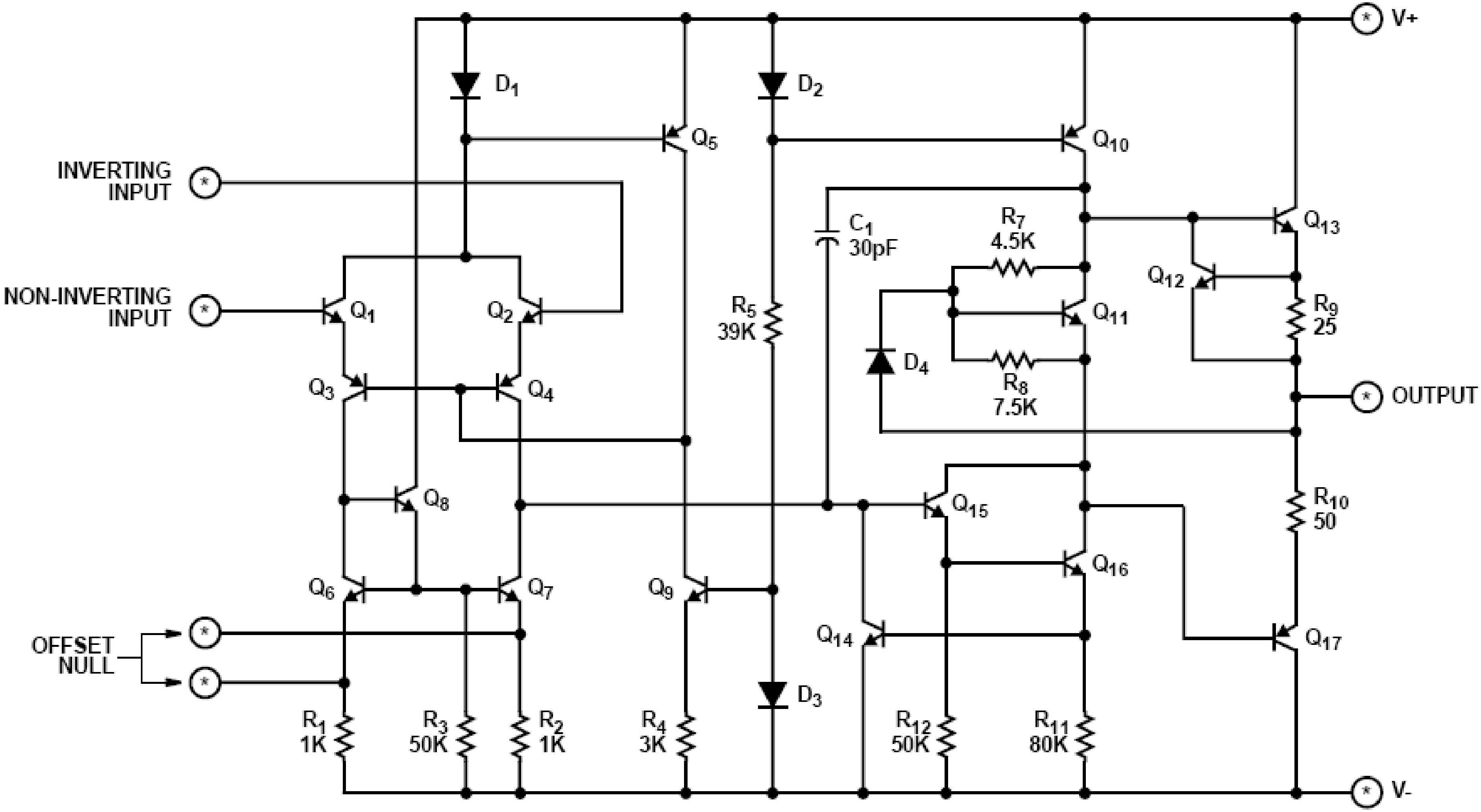
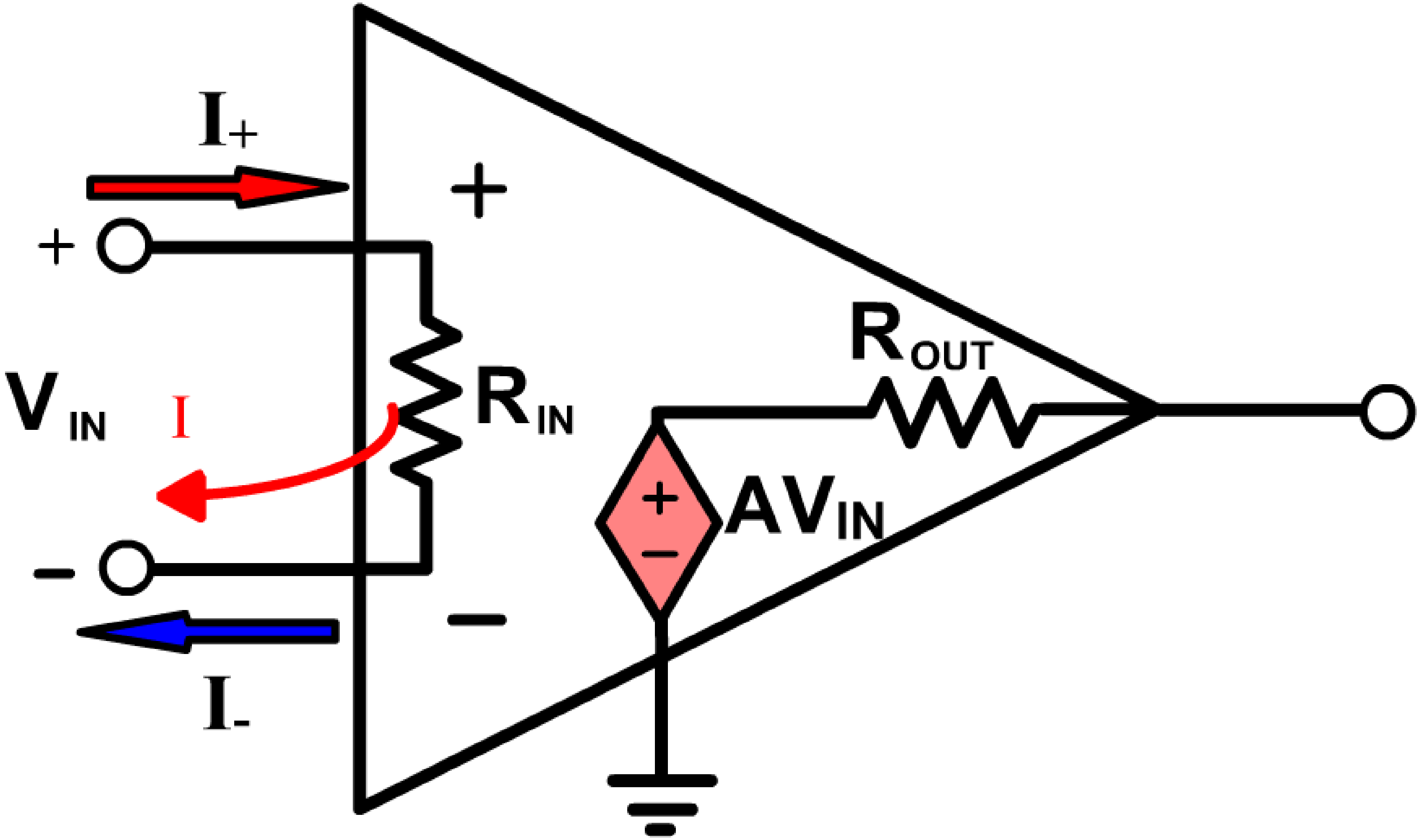
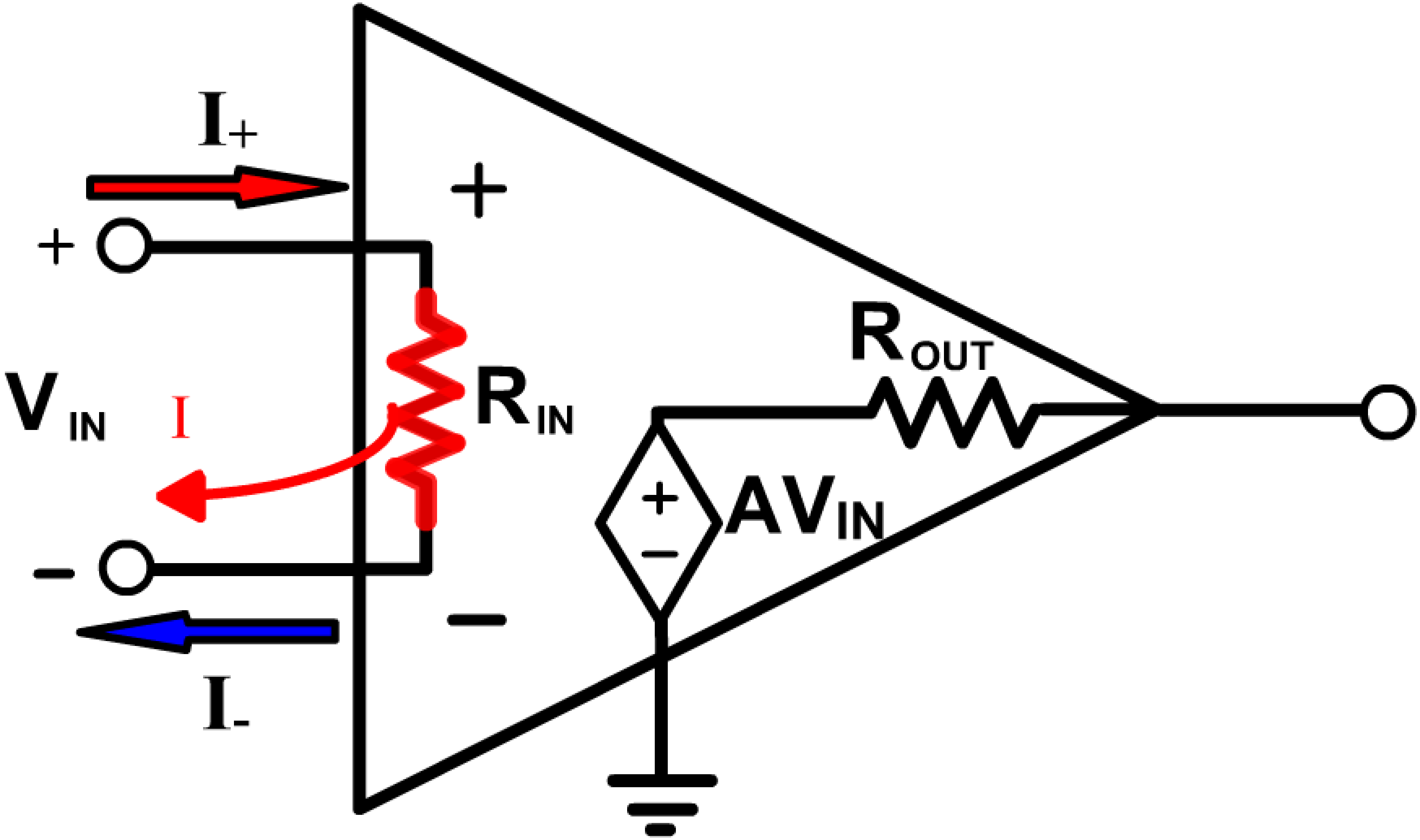
Op Amp chip – what's inside ?



The dependent voltage source produces a scaled output, proportional to the voltage across R_{IN}



The input impedance R_{IN} is very large (MΩ).

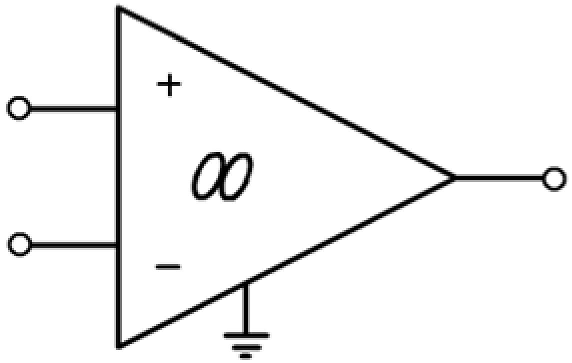


Typical ranges for op amp parameters

Parameter	Typical range	Ideal values
Open-loop 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, V_{CC}	5 to 24 V	

Since R_{IN} is very large, little I flows. As R_{IN} increases, the current approaches zero. This leads to the ideal op-amp relations.

The ideal op-amp is described by two equations dictating the voltage and current at the input terminals. The ∞ symbol here denotes the ideal op-amp.

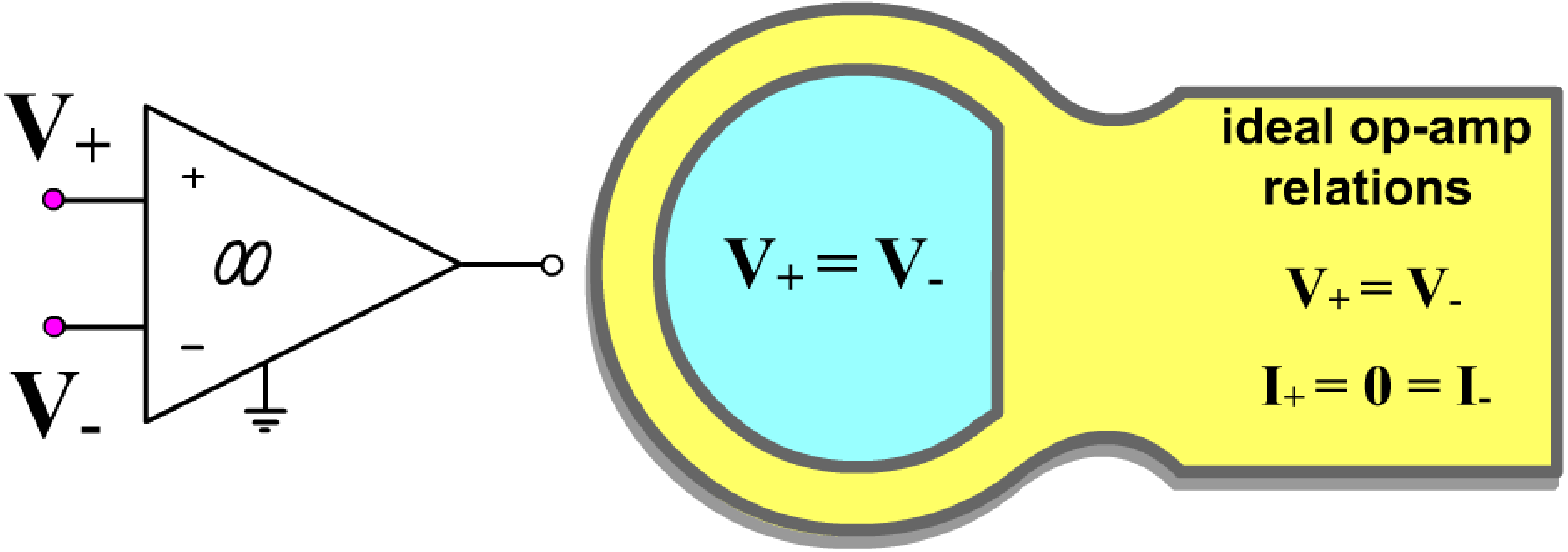


ideal op-amp relations

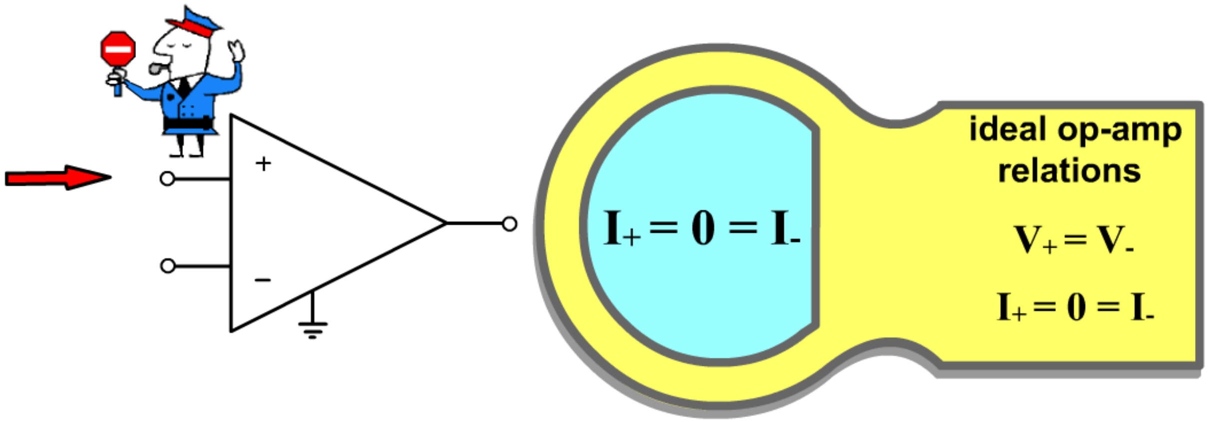
$$V_+ = V_-$$

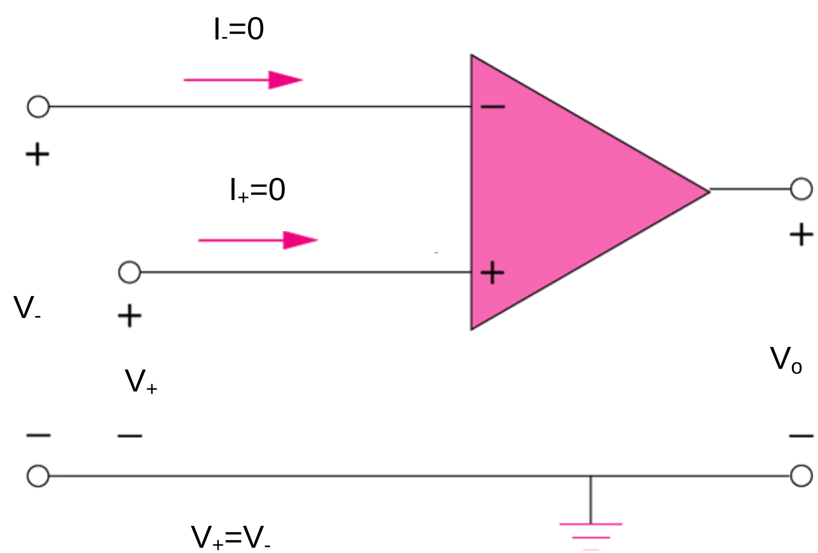
$$I_+ = 0 = I_-$$

The first equation states that the voltages at the inverting terminal and the non-inverting terminal are same.



The second ideal op-amp relation requires that both input currents be equal to zero.



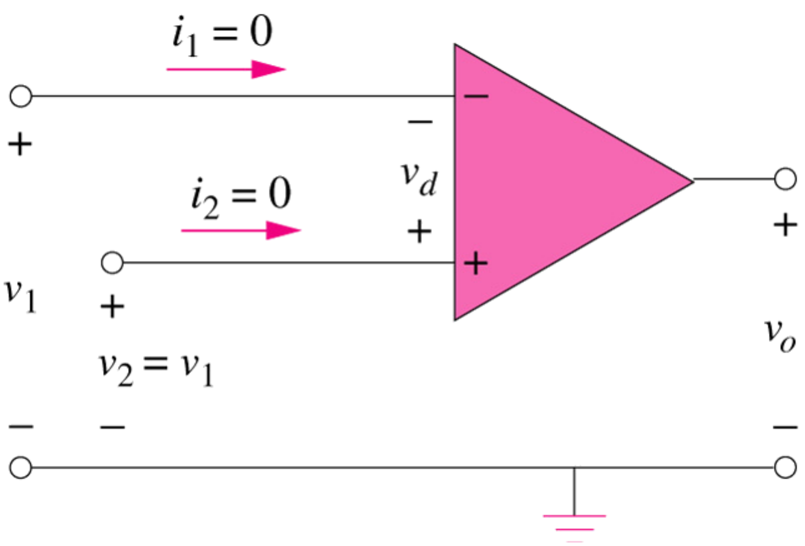


Ideal Op Amp characteristics

An ideal op amp has the following characteristics:

means no feedback path output → input

1. Infinite open-loop gain, $A \approx \infty$
2. Infinite input resistance, $R_i \approx \infty$
3. Zero output resistance, $R_o \approx 0$



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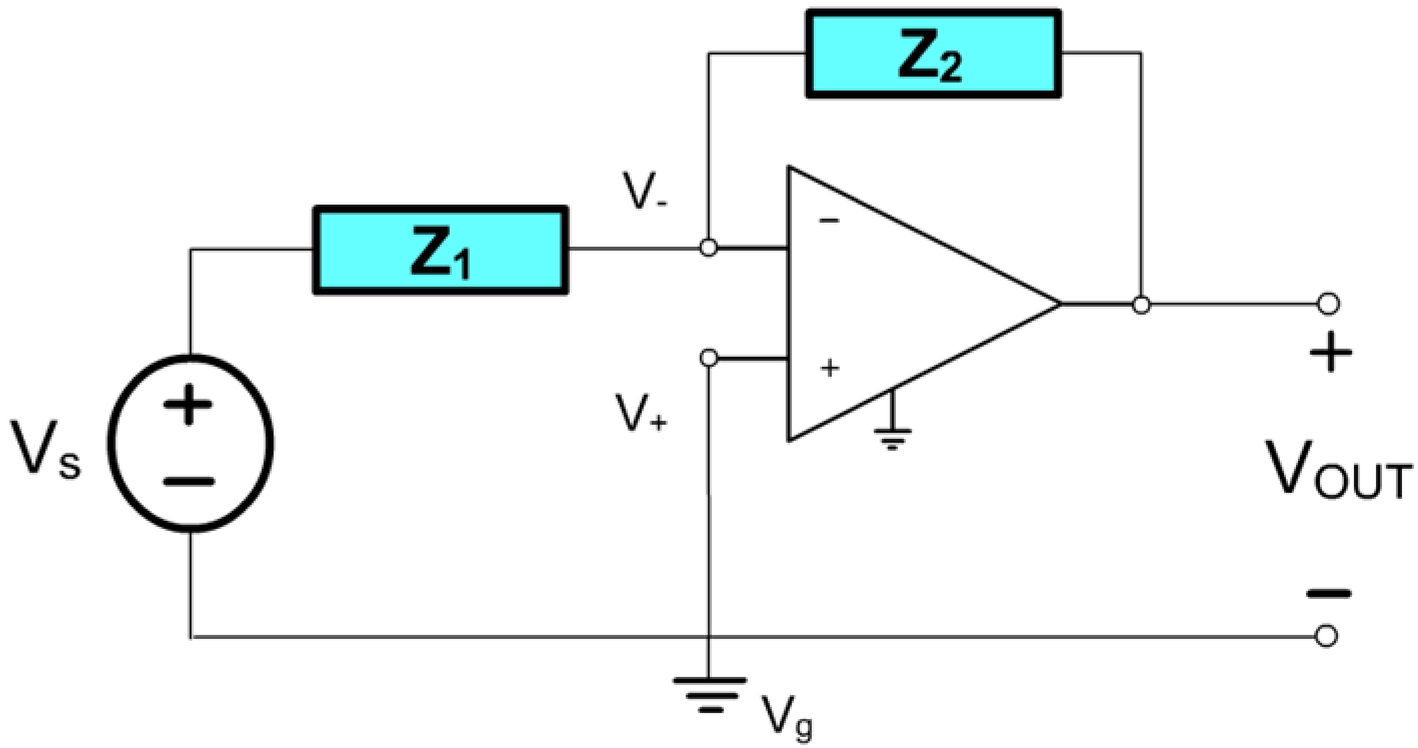
Op-Amp Inverting Configuration

A common configuration is the *Inverting Configuration* shown below. In this configuration, negative gain is achieved.



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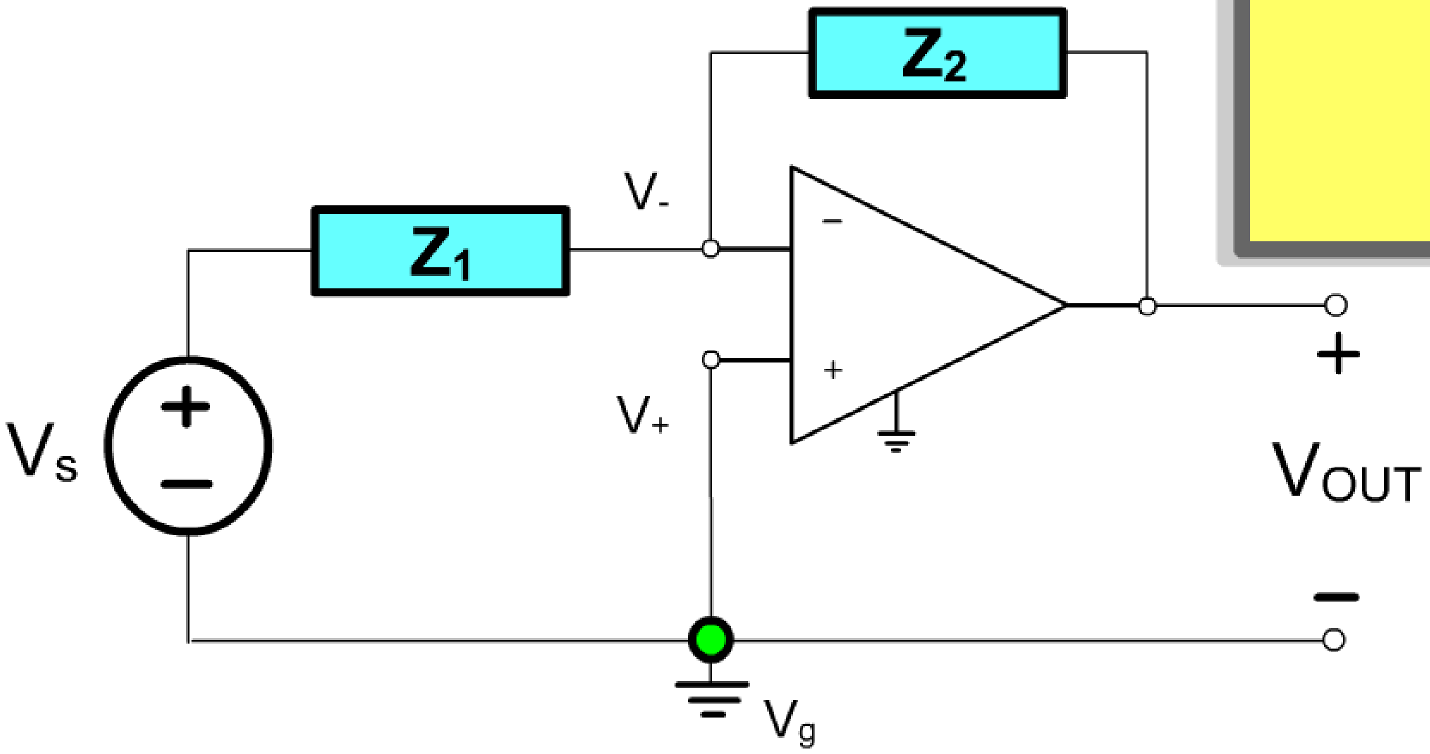
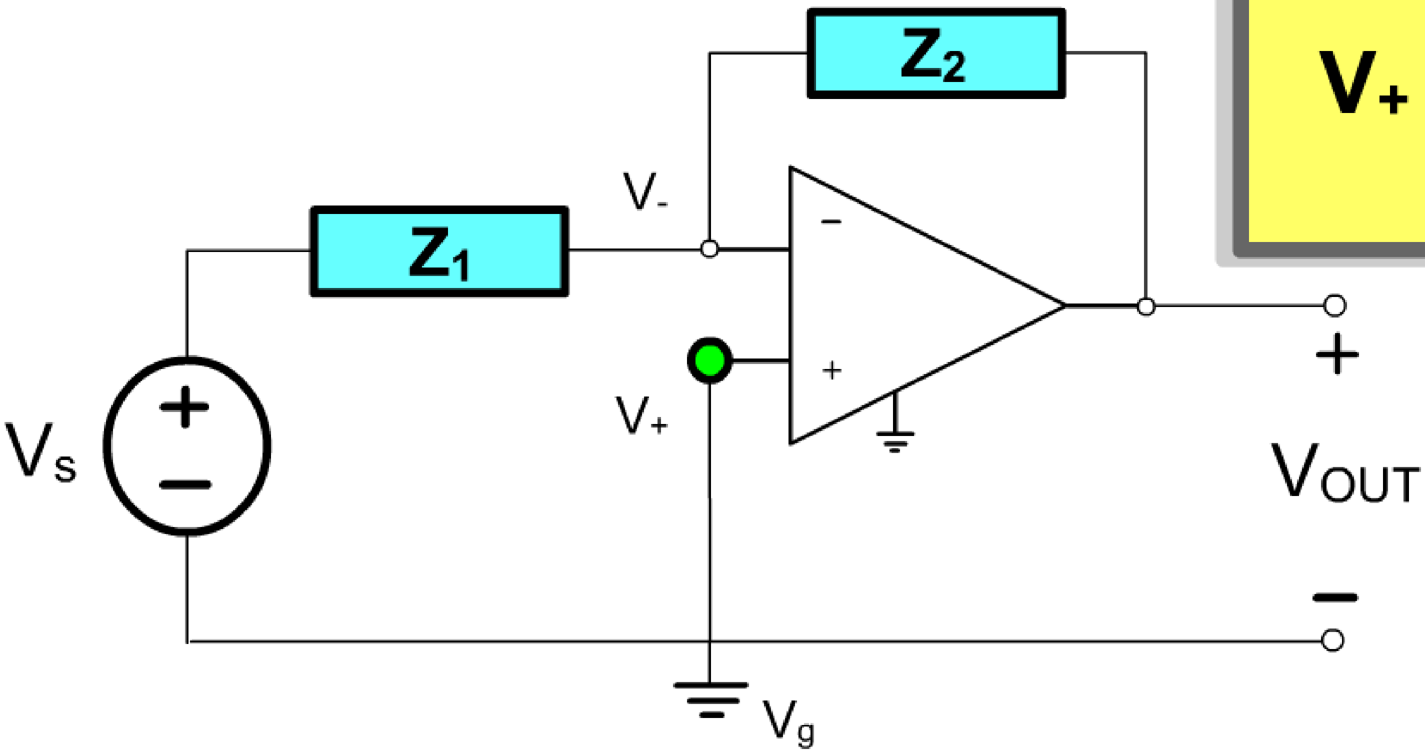
Begin this analysis from the ground node, whose voltage is always chosen as zero.



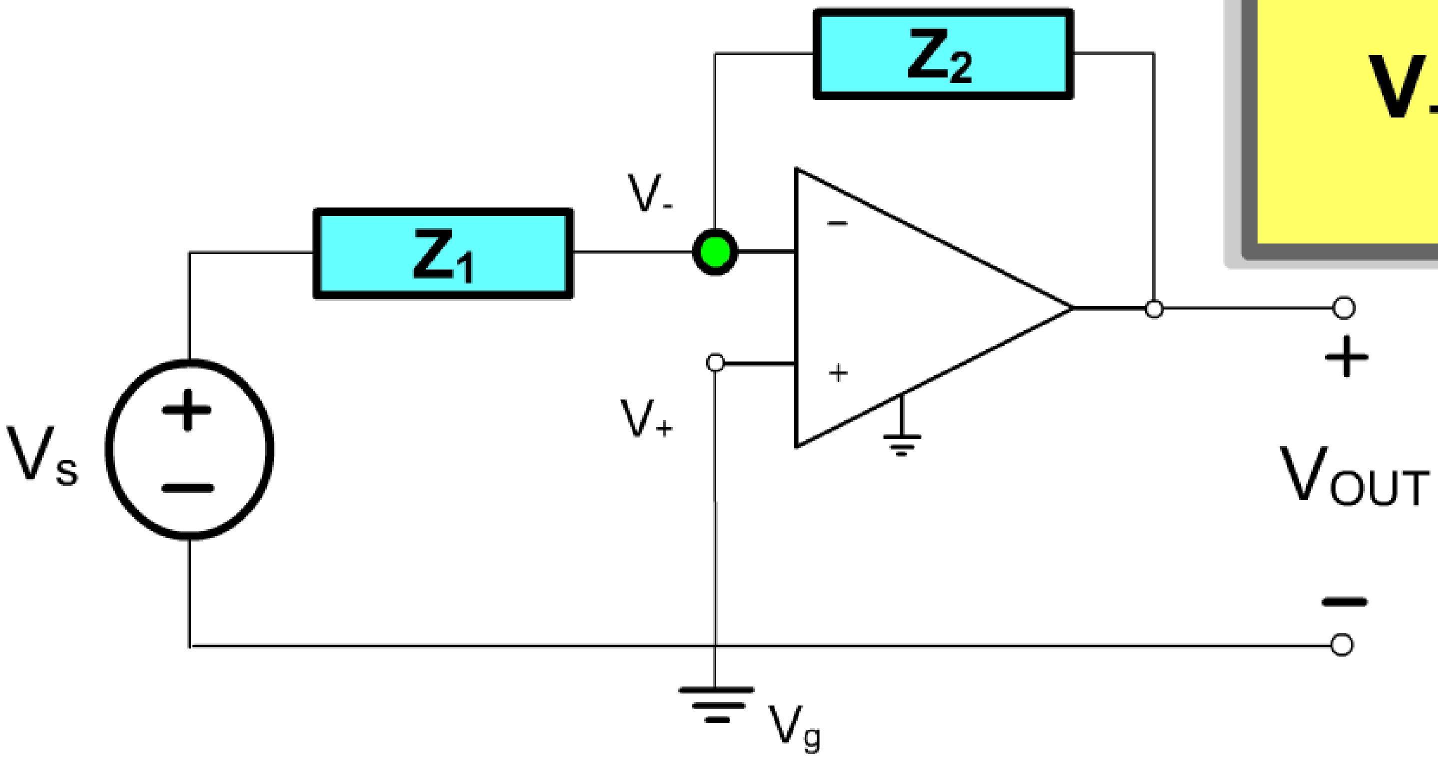
$V_g = 0$

The non-inverting terminal is connected to ground, and therefore has a voltage of zero.



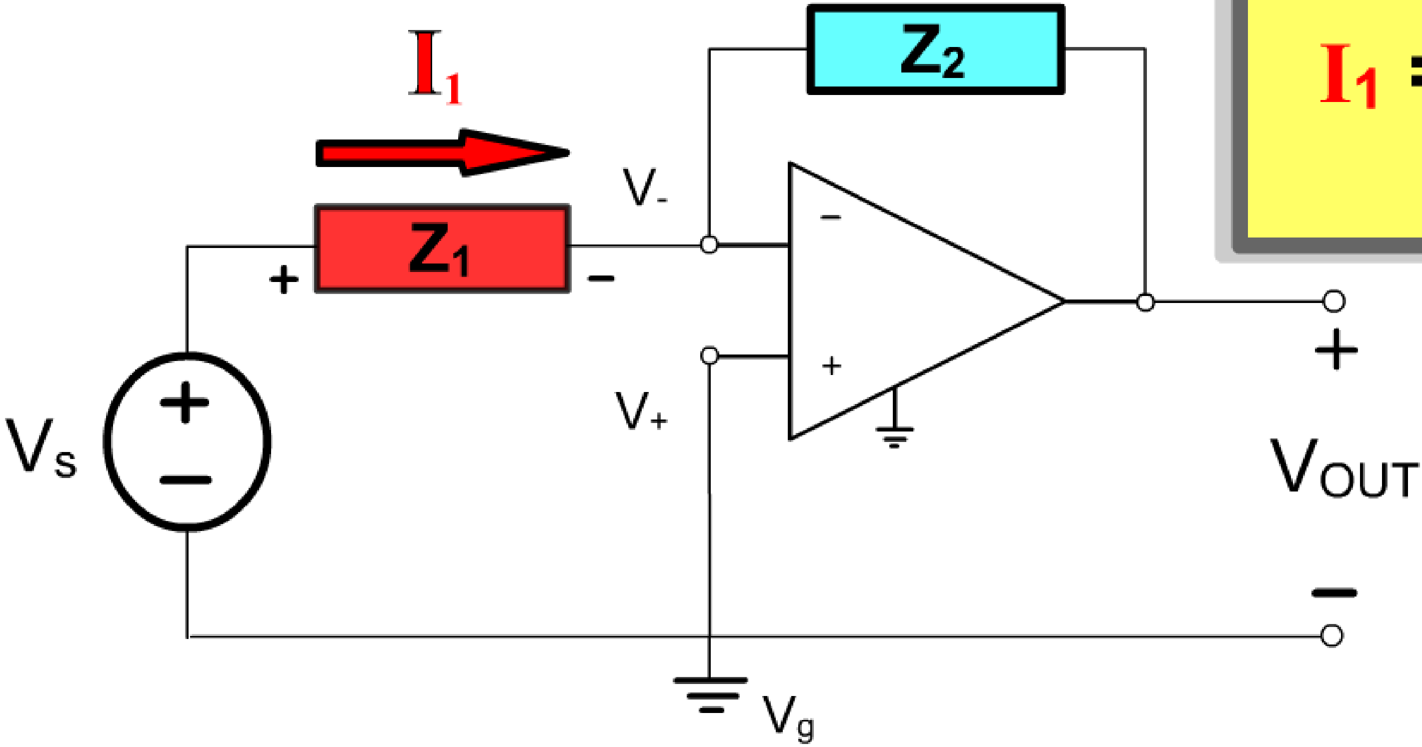
$$V_+ = V_g = 0$$

The ideal op-amp relations state that both the inverting terminal and the non-inverting terminal have the same potential.



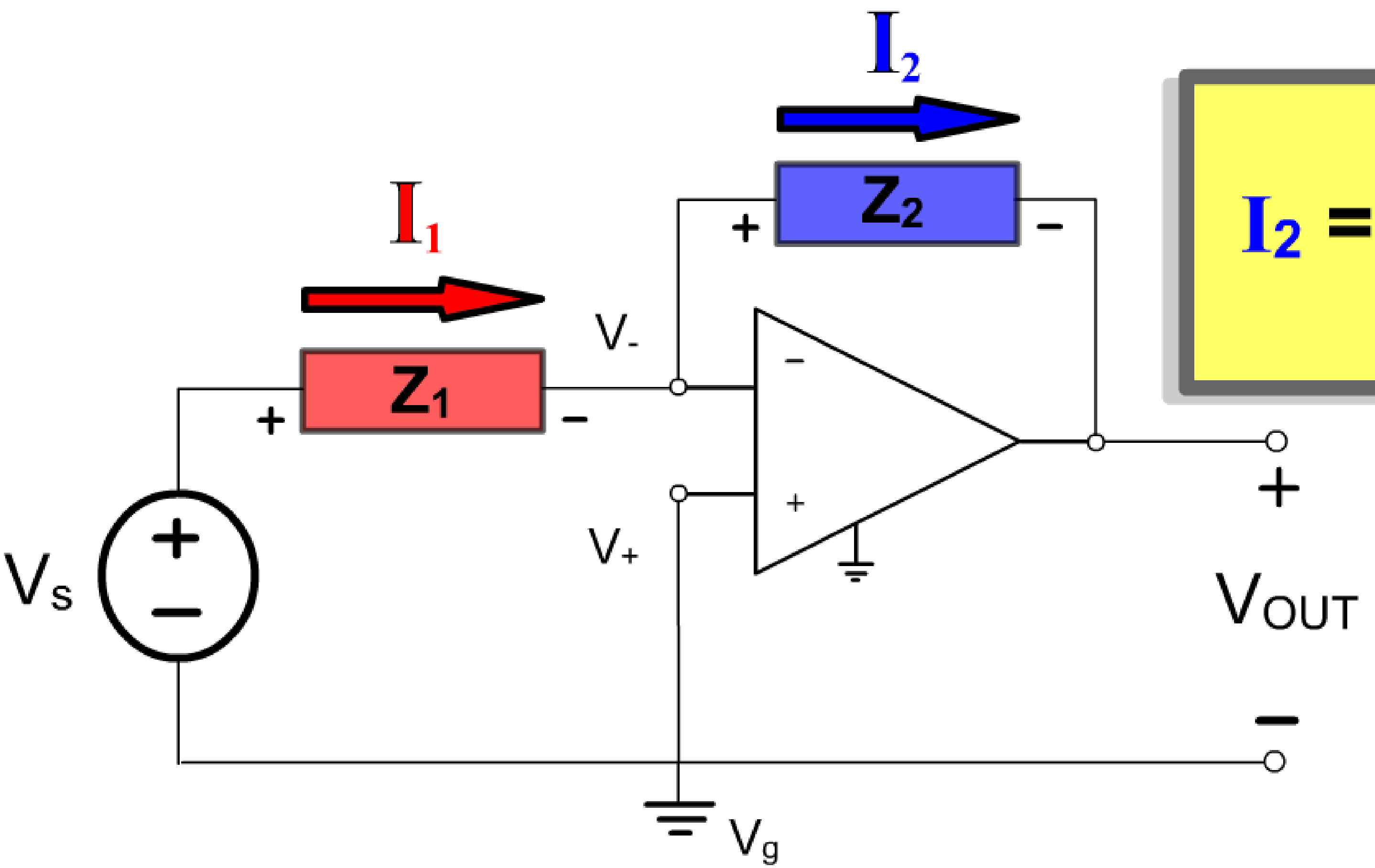
$$V_- = V_+ = 0$$

Now examine the current across R_1. This can determined by Ohm's law.



$$I_1 = \frac{V_S - \cancelto{0}{V_-}}{Z_1}$$

The current across R_2 can also be found via Ohm's law.



$$I_2 = \frac{\overset{0}{\cancel{V_-}} - V_{OUT}}{Z_2}$$

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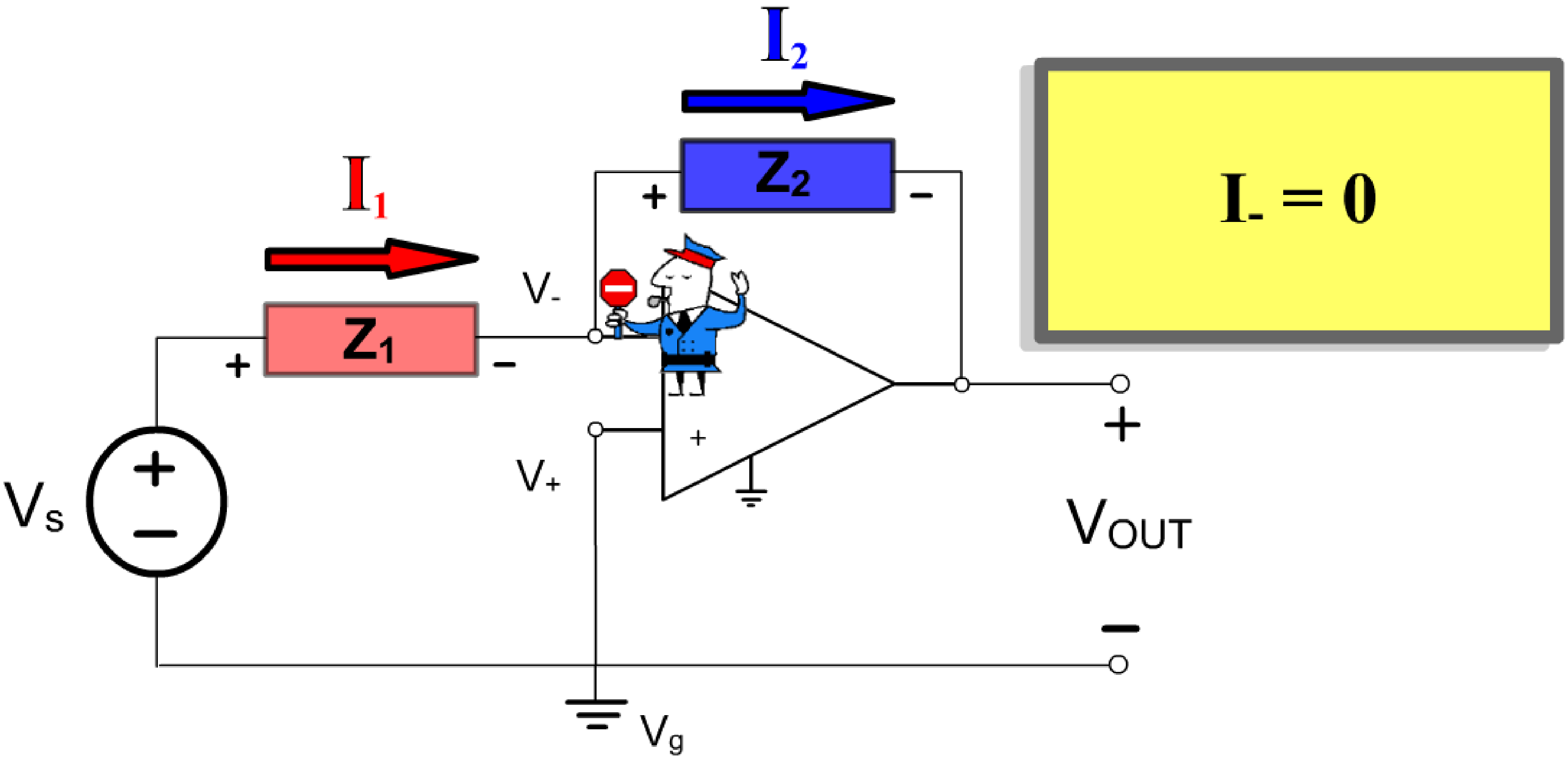
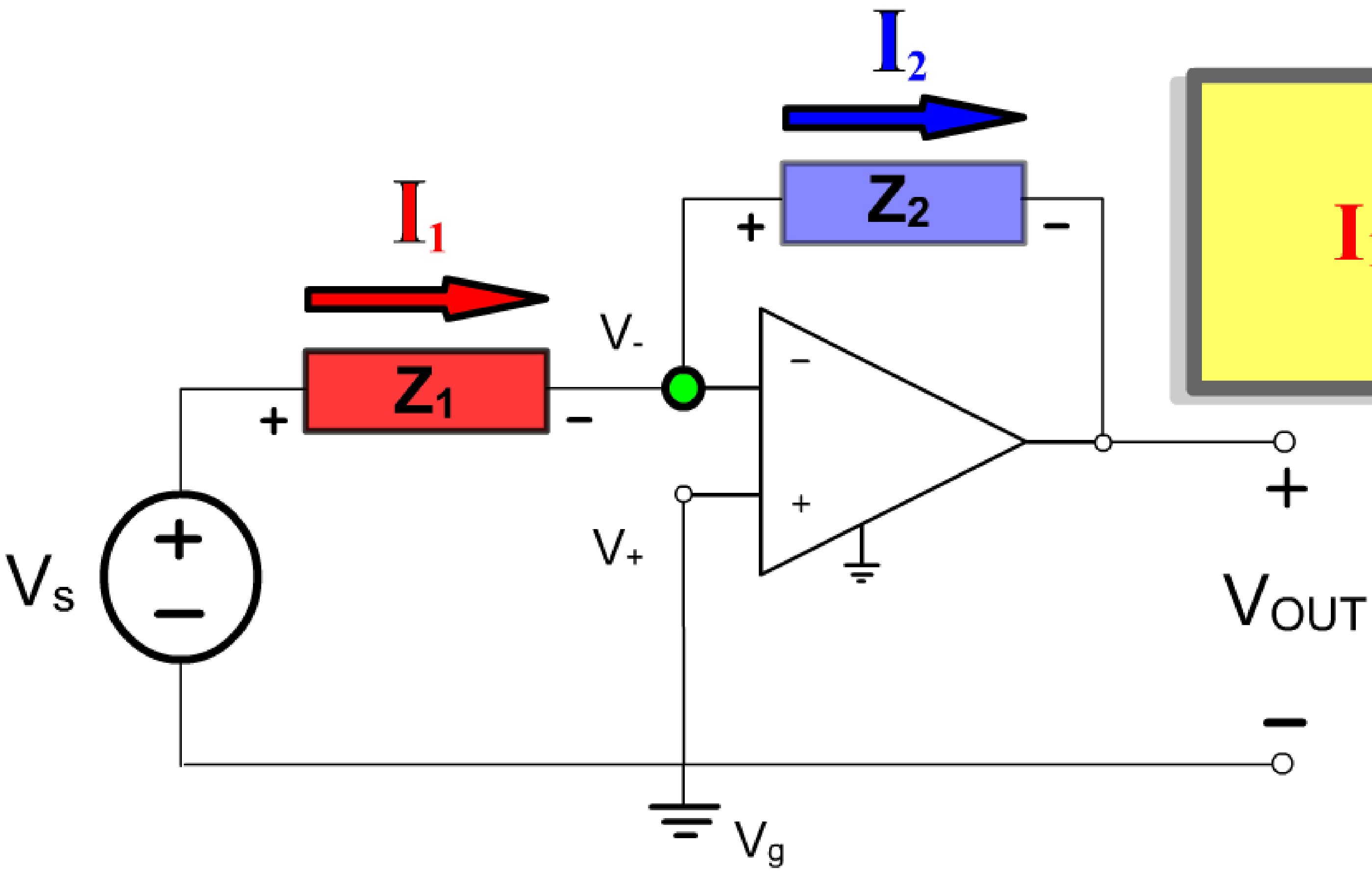
According to the ideal op-amp equations, no current enters the input terminals.



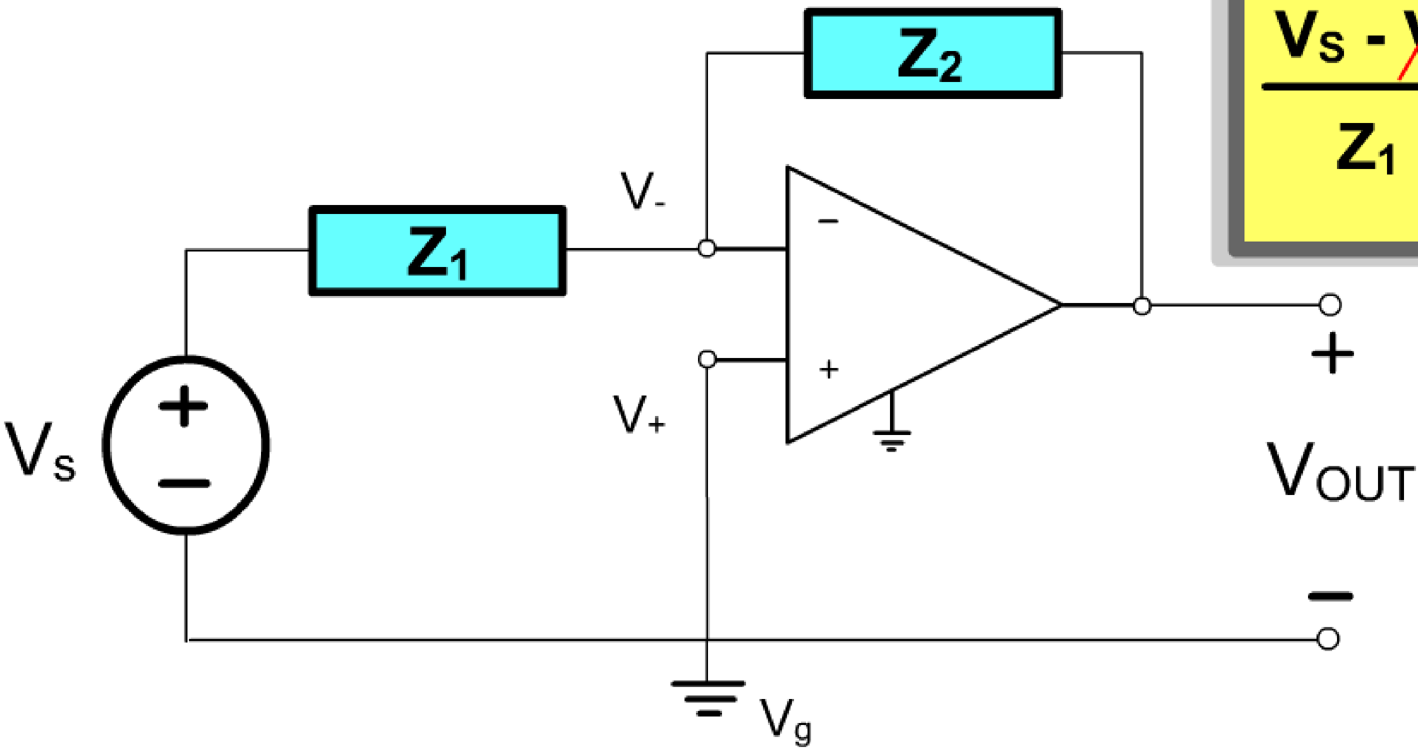
Applying KCL at the inverting terminal is simple. The only entering current, I_1, equals the only current leaving, I_2.



$$I_1 = I_2 + \cancel{I_-}^{\,0}$$

All of the information needed to solve for the ouput is now known. Substitute for I_1 and I_2 in the KCL equation.

$$\frac{V_S - \cancelto{0}{V_-}}{Z_1} = \frac{\cancelto{0}{V_-} - V_{OUT}}{Z_2}$$



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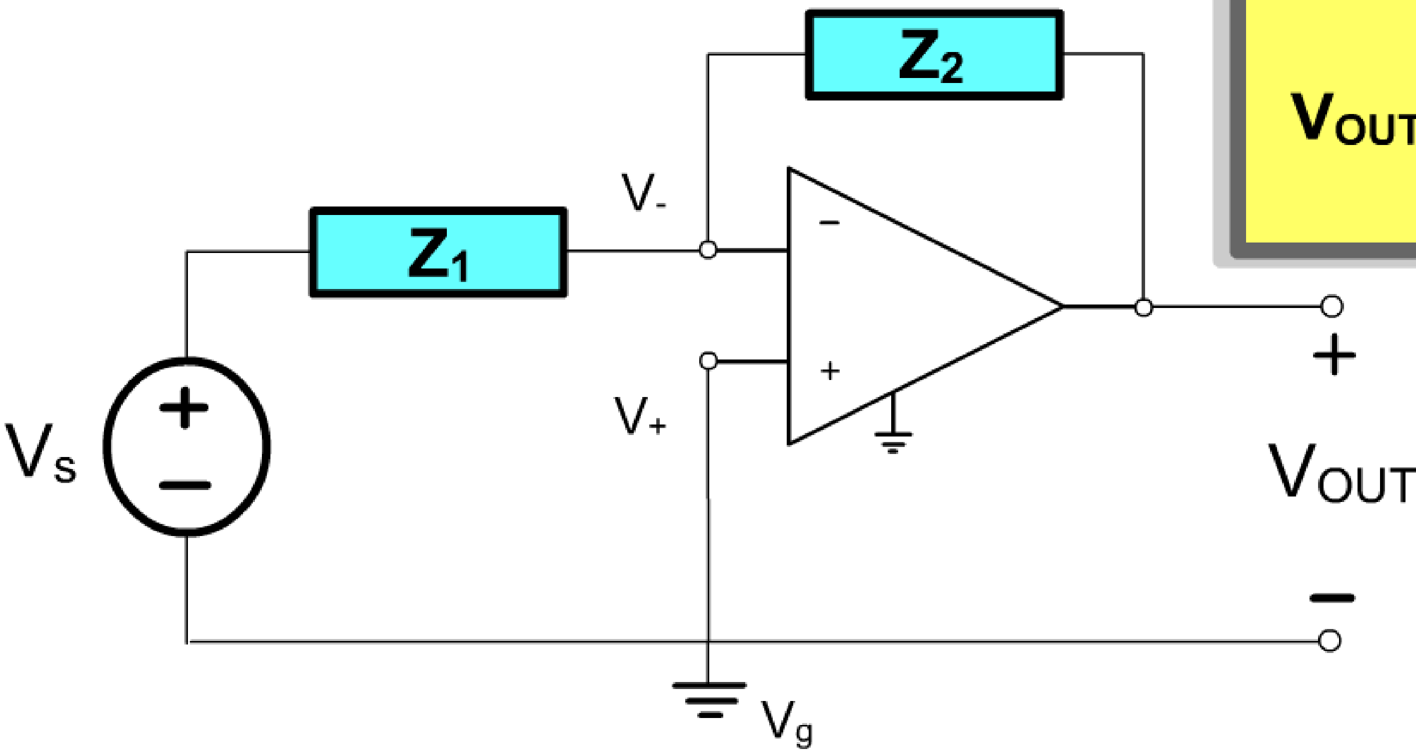
Now solve the equation for V_{OUT} to find the solution.



the solution is

$$V_{OUT} = -\frac{Z_2}{Z_1} V_S$$

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Gain & Transfer function

The *transfer function* (TF) of the Op-Amp **circuit** is

$$TF = \frac{v_o}{v_i}$$

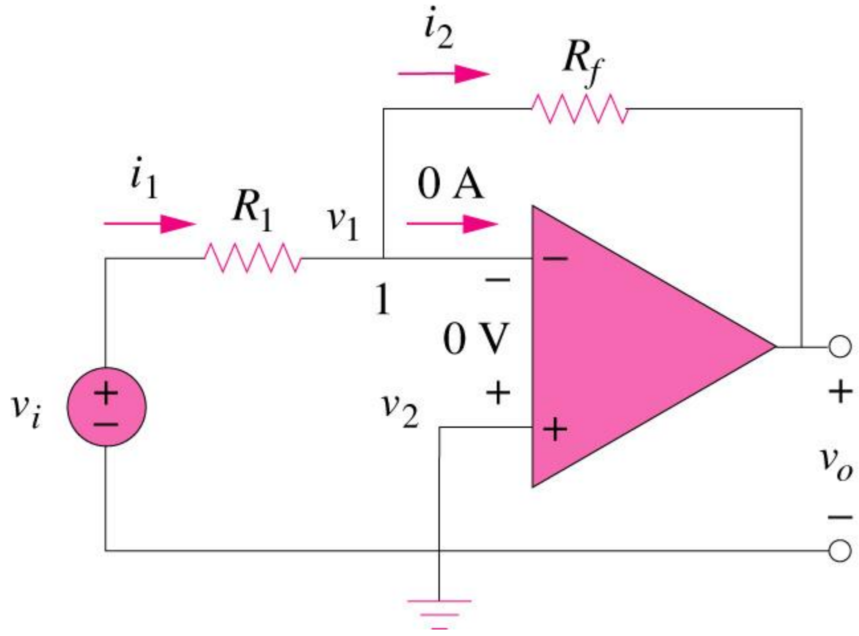
The voltage *gain* of the Op-Amp **circuit** is

$$A = |TF| = \left|\frac{v_o}{v_i}\right|$$

This is a **closed-loop** voltage gain; there is a path from the output back to the input (via Z_2)

Inverting Op Amp

- An inverting amplifier reverses the polarity of the input signal while amplifying it



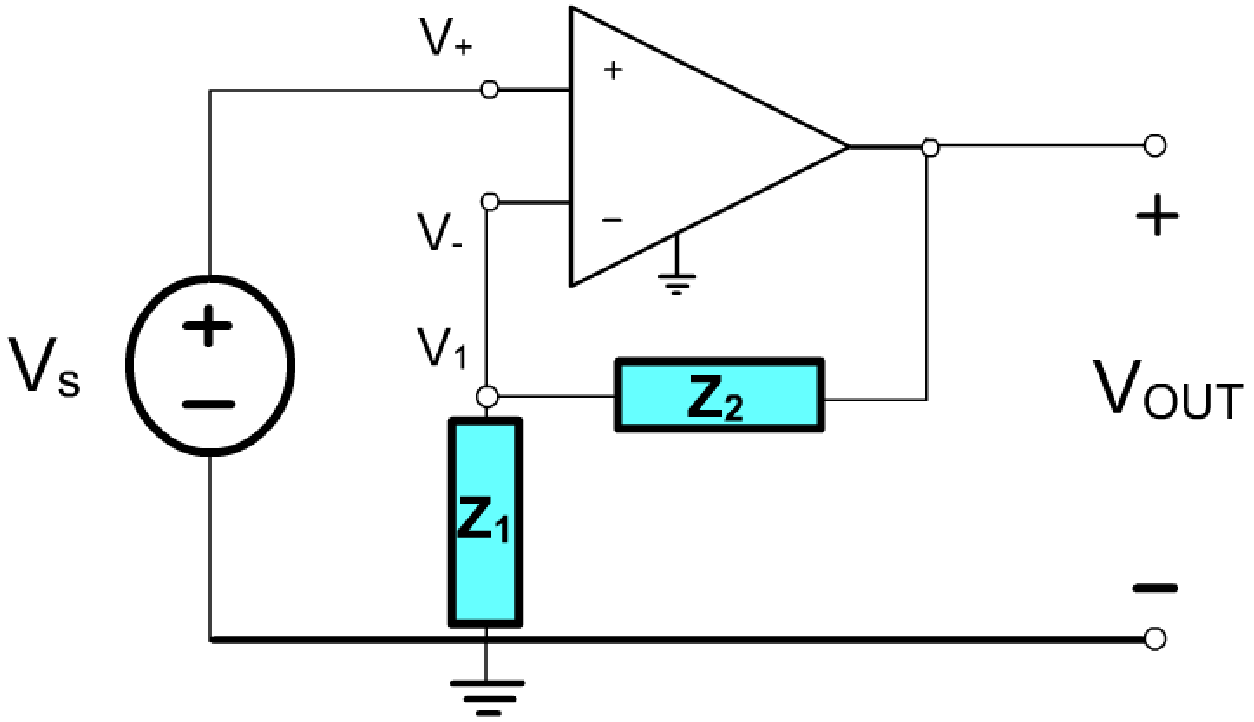
$$v_o = -\frac{R_f}{R_1} v_i$$

$$\frac{v_o}{v_i} = -\frac{R_f}{R_1}$$

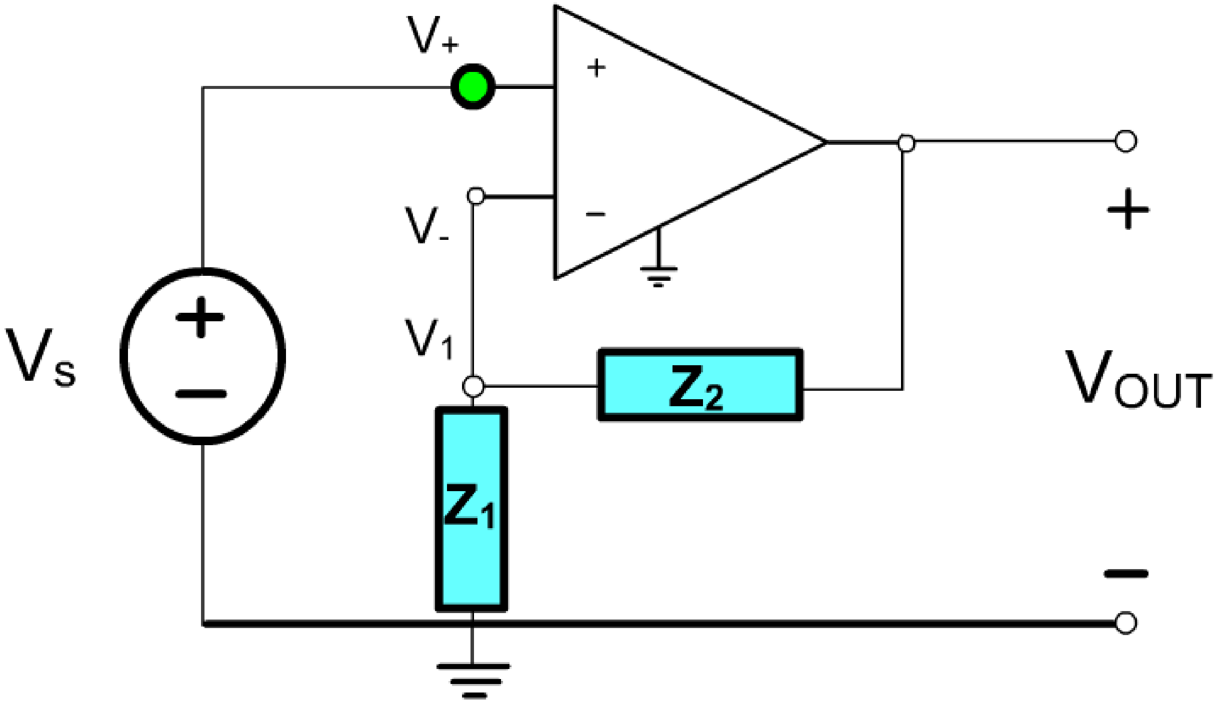
$$A = -\frac{R_f}{R_1}$$

Op-Amp Non-Inverting Configuration

In the non-inverting op-amp configuration the gain is positive.

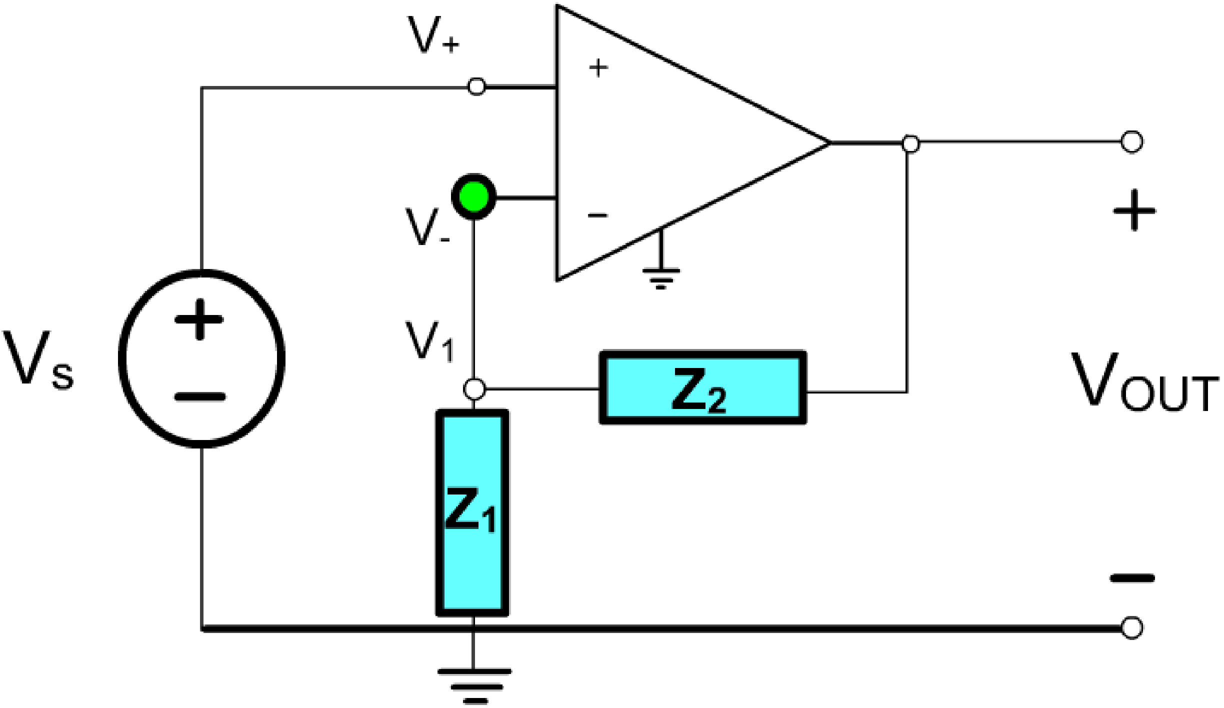


V_s and V_+ are the same node, so they are at the same potential.



$$V_s = V_+$$

According to the first ideal op-amp equation, V_+ and V_- have the same potential.



$$V_+ = V_-$$

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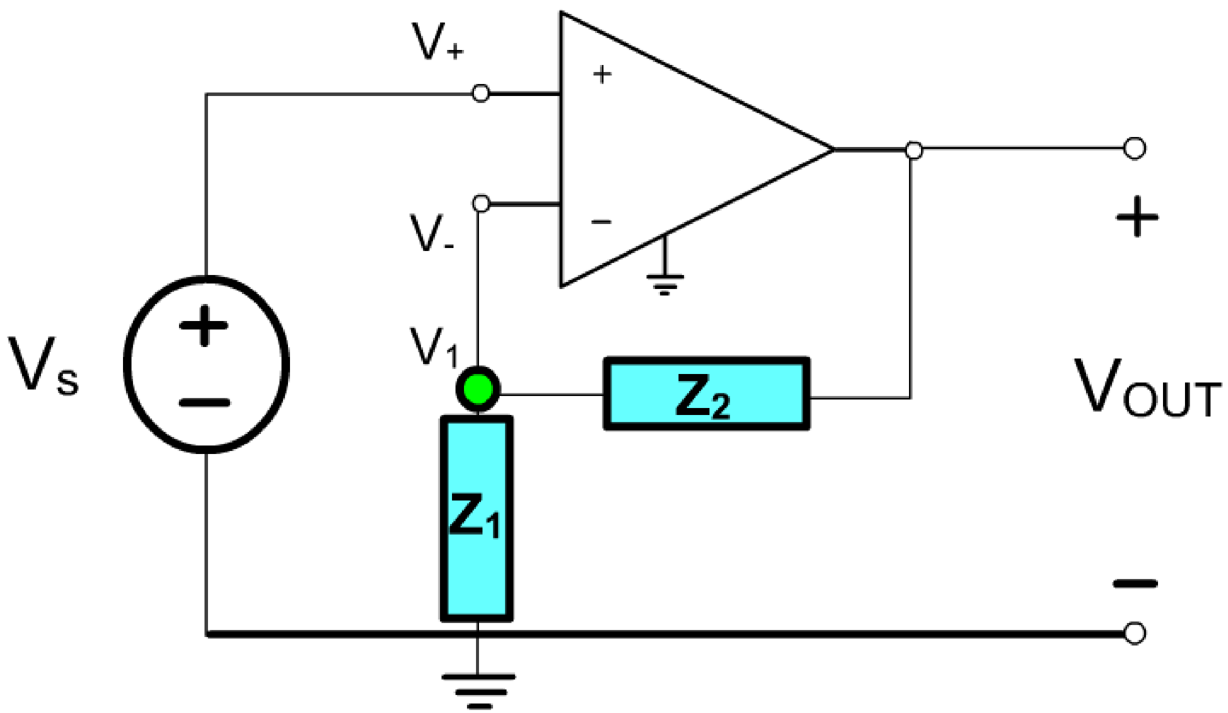
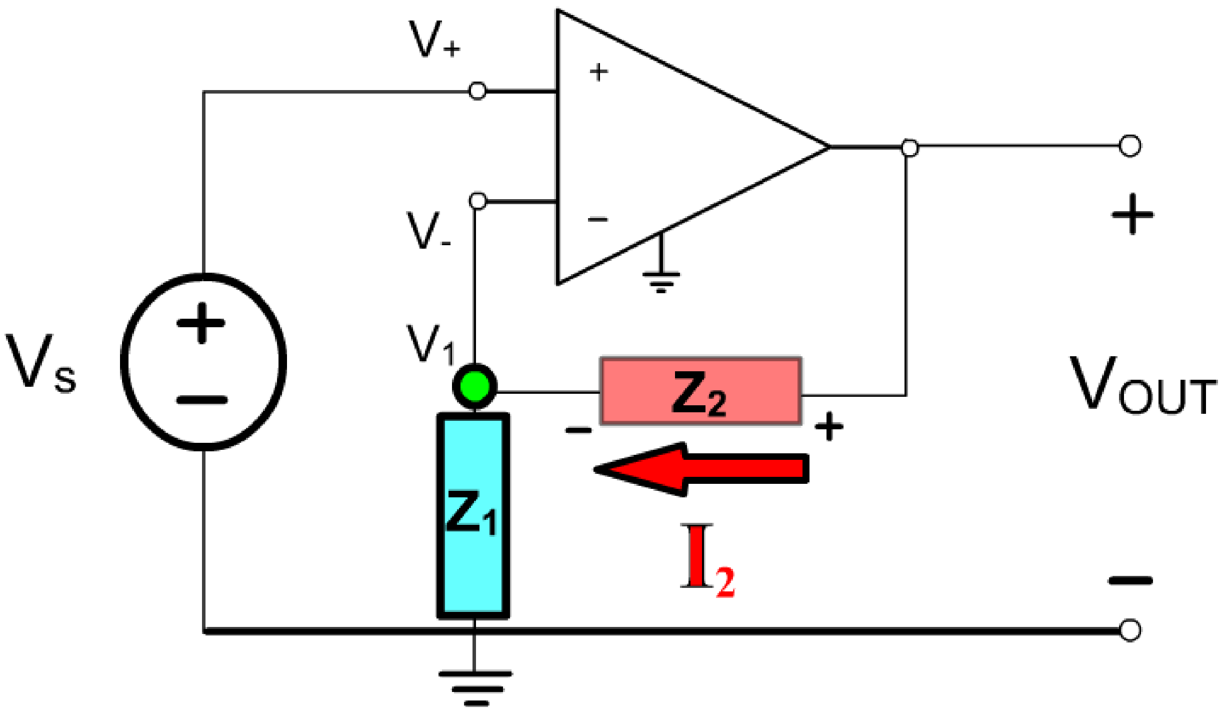
V- and V_1 are the same node, and thus have the same potential.



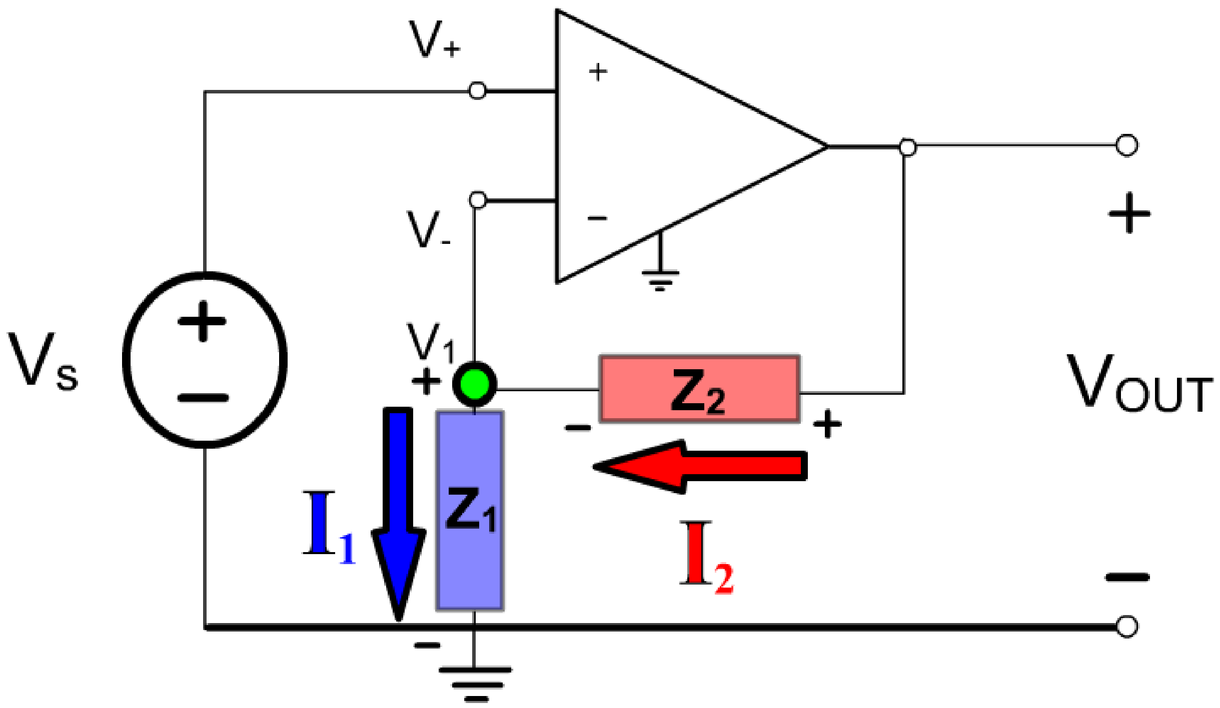
$$V_- = V_1$$

Ohm's law can now be used to find the current I_2 through element Z_2.



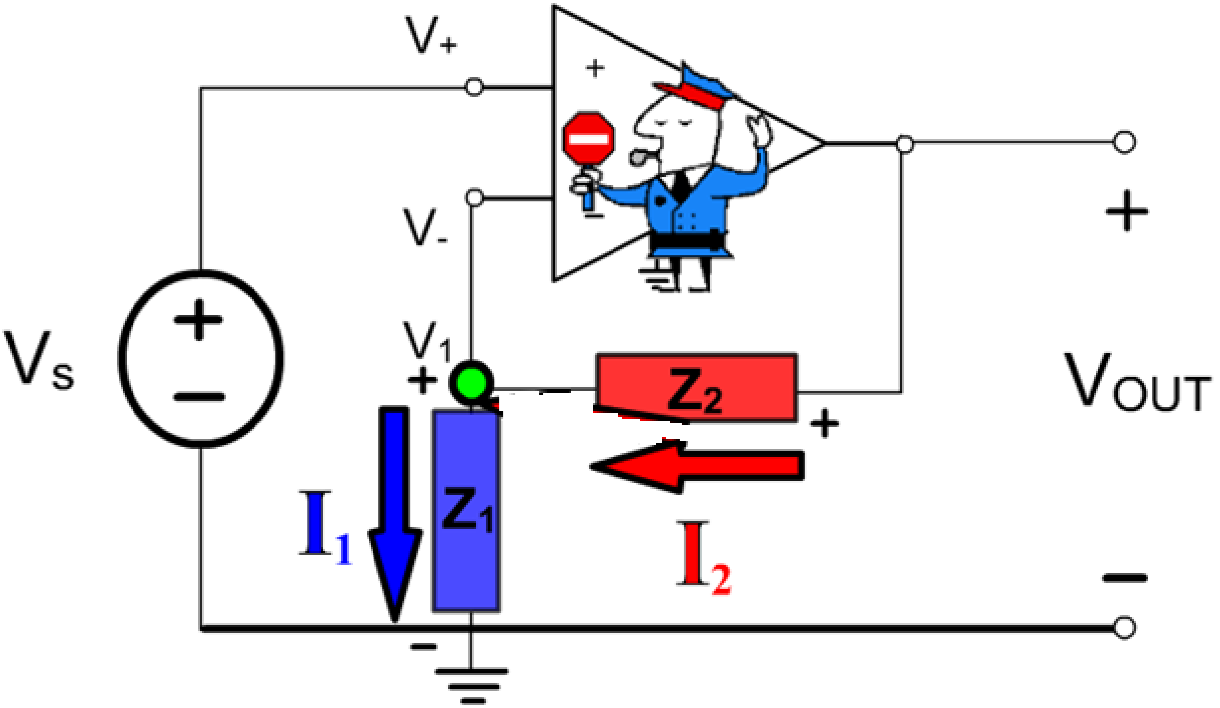
$$I_2 = \frac{V_{OUT} - \cancelto{V_S}{V_1}}{Z_2}$$

Likewise, Ohm's law yields the current I_1 through Z_1.



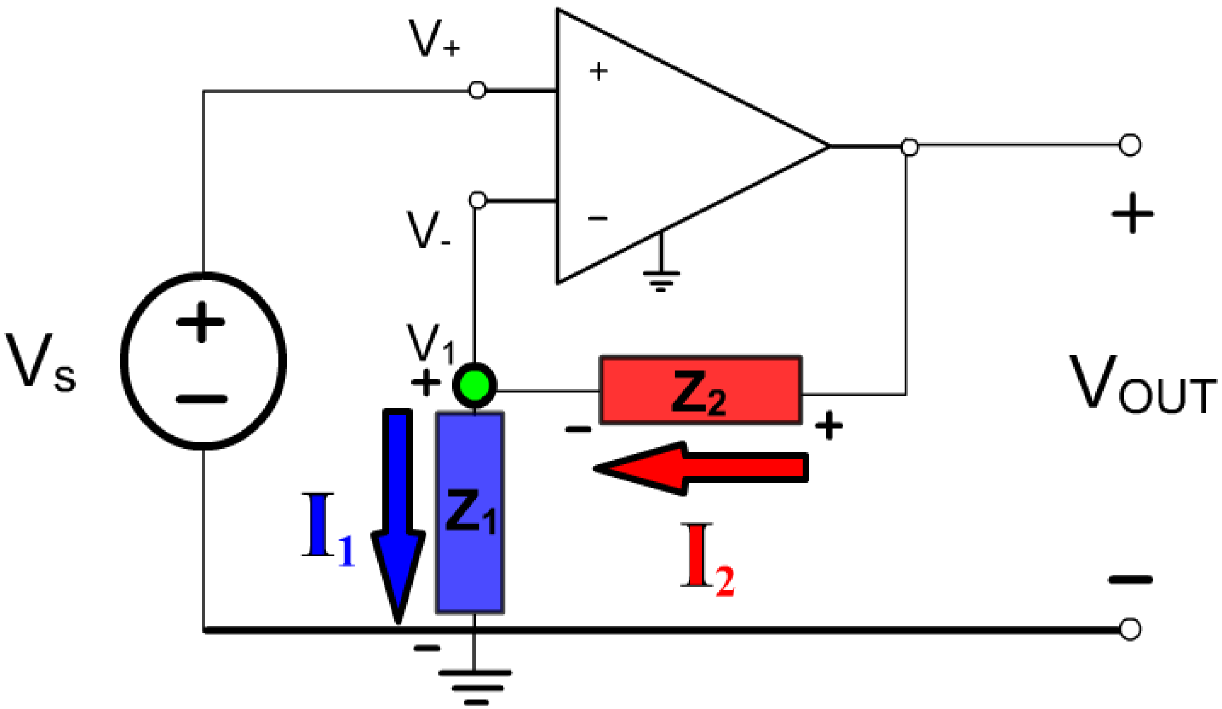
$$I_1 = \frac{\cancelto{V_S}{V_1} - 0}{Z_1}$$

Next apply KCL at node V_1. According to the second ideal op-amp equation, no current enters the negative input to the op-amp. Thus, $I_1 = I_2$.



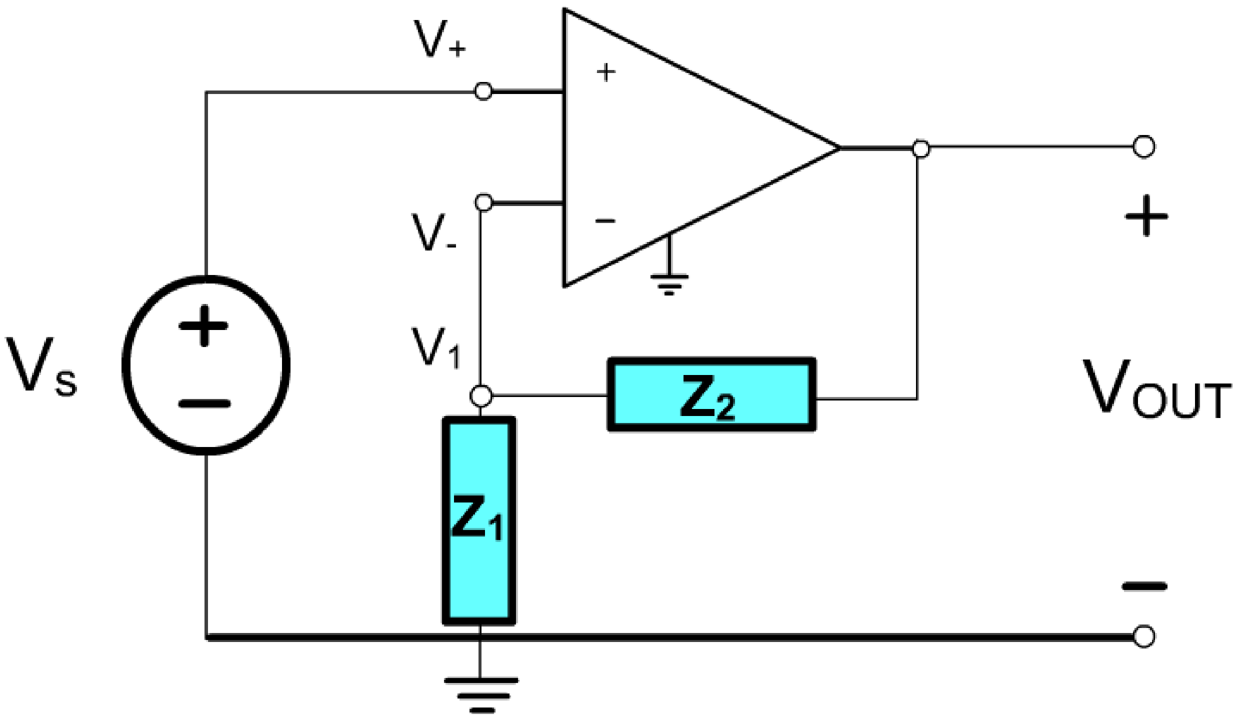
$$I_1 = I_2 + \cancel{I_-}^{\,0}$$

Now substitute for I_1 and I_2 into the KCL equation at V_1.



$$\frac{V_{OUT} - V_S}{Z_2} = \frac{V_S}{Z_1}$$

By rearranging the equation, the output is found.



solution:

$$V_{OUT} = \left(1 + \frac{Z_2}{Z_1}\right) V_S$$

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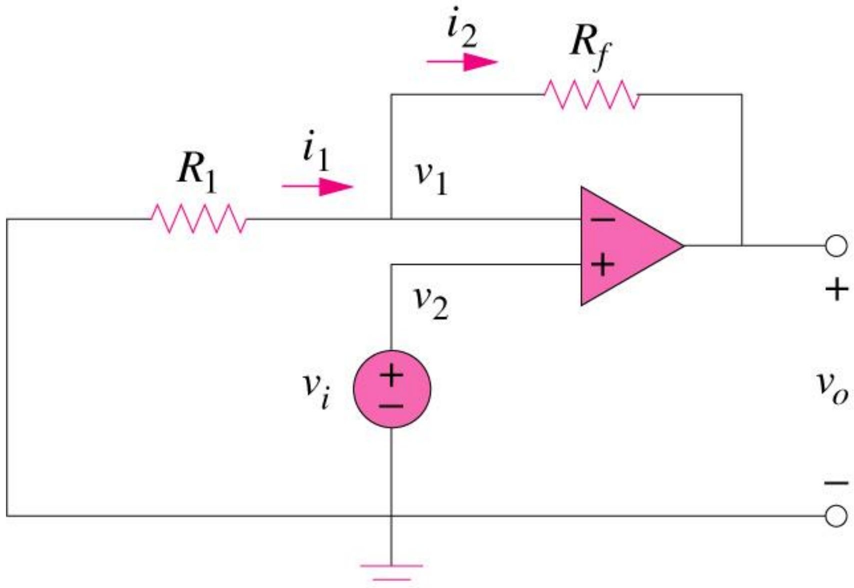
Non-inverting Op Amp

- A non-inverting amplifier is designed to produce positive transfer function

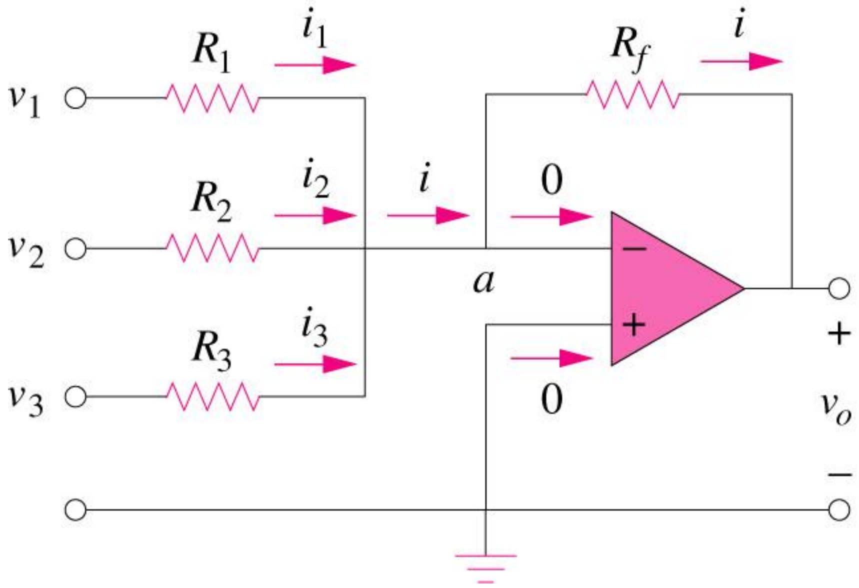


$$v_o = \left(1 + \frac{R_f}{R_1}\right) v_i$$

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

Summing Op Amp

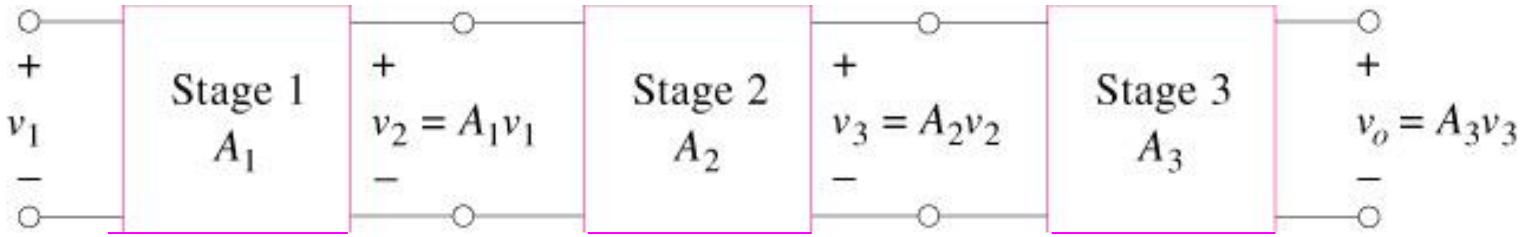
- Summing Amplifier is an op amp circuit that combines several inputs and produces an output that is the weighted sum of the inputs.



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

Cascaded Op Amp Circuit

- A head-to-tail arrangement of two or more op amp circuits such that the output of one is the input of the next.

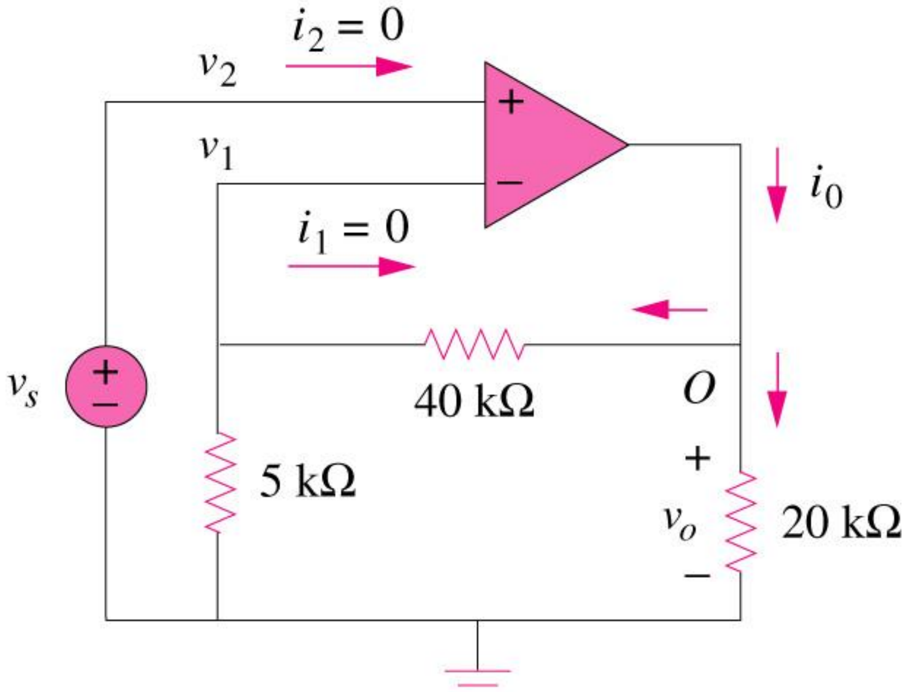


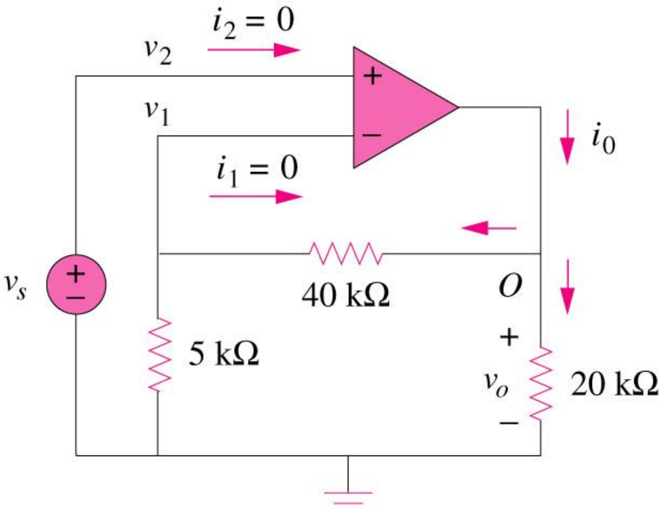
$$v_o = A_1 A_2 A_3 v_1$$

$$\frac{v_o}{v_1} = A_1 A_2 A_3$$

Example 1

Find the voltage gain and determine the value of i_o when v_s = 1 V.





$$TF = \left(1 + \frac{40}{5}\right) = 9$$

$$\therefore \frac{V_o}{V_s} = 9 = A \text{ (Gain)}$$

<u>Method 2</u>

$$V_2 = V_s$$

$$V_1 = \frac{5}{5+40} V_o = \frac{V_o}{9} = V_2.$$

$$\therefore V_s = \frac{V_o}{9} \Rightarrow \frac{V_o}{V_s} = 9$$

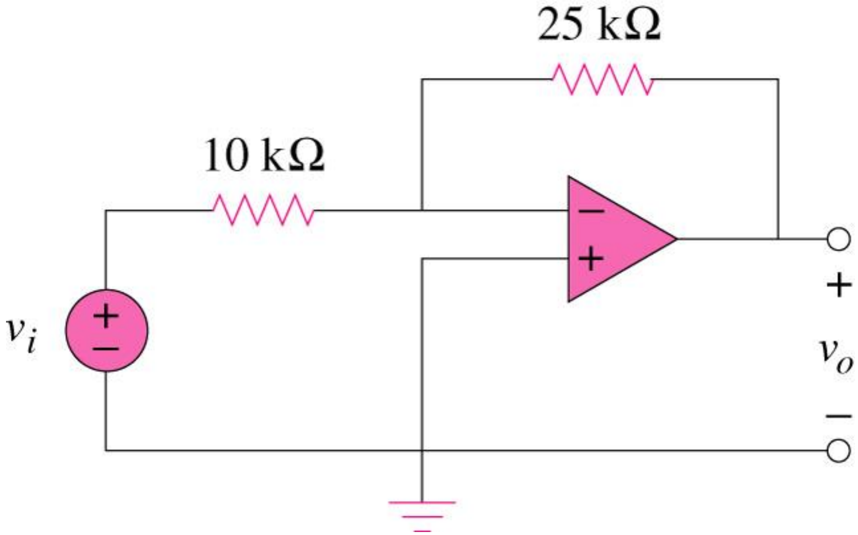
$$i_o = \frac{V_o}{40+5} + \frac{V_o}{20} \text{ mA}.$$

When $V_s = 1\,V$, $V_o = 9\,V$.

$$\therefore i_o = 0.2 + 0.45 = \underline{\underline{0.65}} \text{ mA}$$

Example 2

Refer to the op amp circuit below. If v_i = 0.5V, calculate: (a) the transfer function, (b) v_o and (c) the current in the 10kΩ resistor.



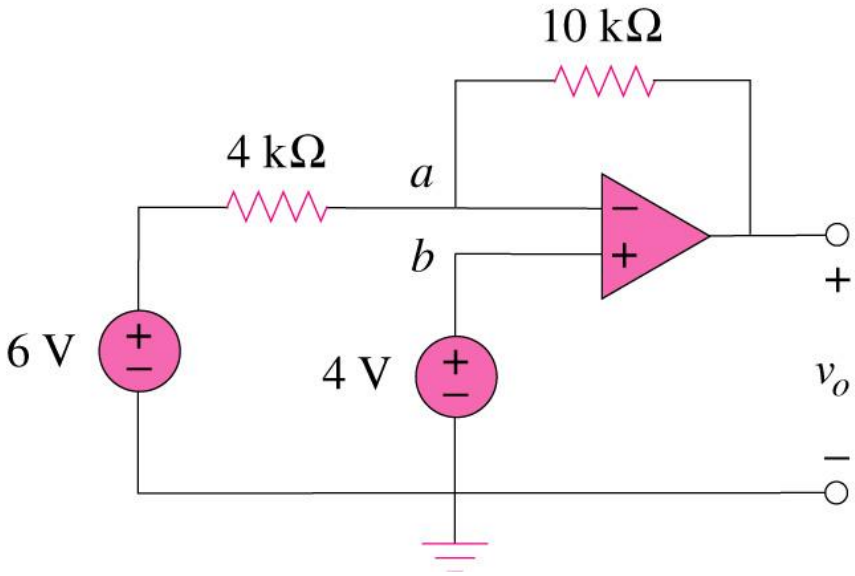
$$\frac{v_o}{v_i} = -\frac{R_f}{R_1} = -\frac{25}{10} = -2.5$$

$$v_o = -2.5v_i = -2.5(0.5) = -1.25 \text{ V}$$

$$i = \frac{v_i - 0}{R_1} = \frac{0.5 - 0}{10 \times 10^3} = 50\ \mu\text{A}$$

Example 3

For the op amp shown below, calculate the output voltage v_o.



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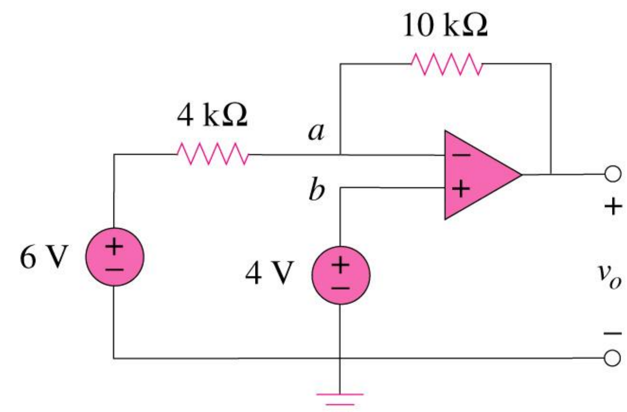
$$v_o = v_{o1} + v_{o2}$$

where v_{o1} is due to the 6-V voltage source, and v_{o2} is due to the 4-V input

$$v_{o1} = -\frac{10}{4}(6) = -15 \text{ V}$$

$$v_{o2} = \left(1 + \frac{10}{4}\right)4 = 14 \text{ V}$$

$$v_o = v_{o1} + v_{o2} = -15 + 14 = -1 \text{ V}$$



Method 2

$$\frac{6 - v_a}{4} = \frac{v_a - v_o}{10}$$

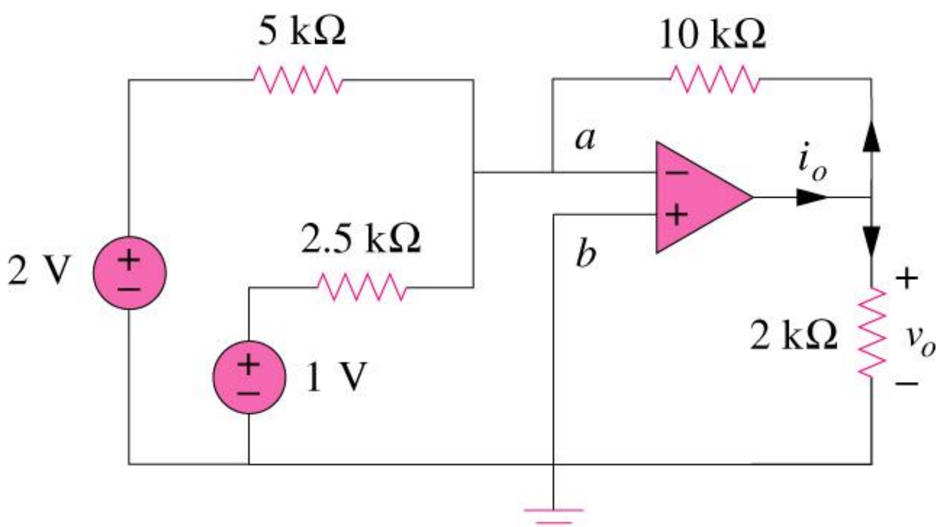
But $v_a = v_b = 4$, and so

$$\frac{6-4}{4} = \frac{4 - v_o}{10} \implies 5 = 4 - v_o$$

or $v_o = -1$ V, as before.

Example 4

Calculate v_o and i_o in the op amp circuit shown below.



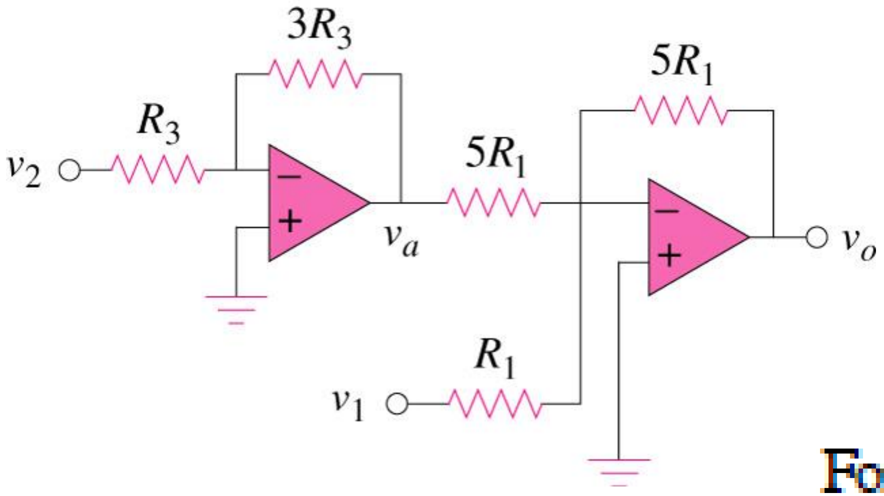
$$v_o = -\left[\frac{10}{5}(2) + \frac{10}{2.5}(1)\right] = -(4+4) = -8 \text{ V}$$

The current i_o is the sum of the currents through the 10-kΩ and 2-kΩ resistors. Both of these resistors have voltage $v_o = -8$ V across them, since $v_a = v_b = 0$. Hence,

$$i_o = \frac{v_o - 0}{10} + \frac{v_o - 0}{2} \text{ mA} = -0.8 - 4 \ = -4.8 \text{ mA}$$

Example 5

Determine v_o for the circuit shown below.



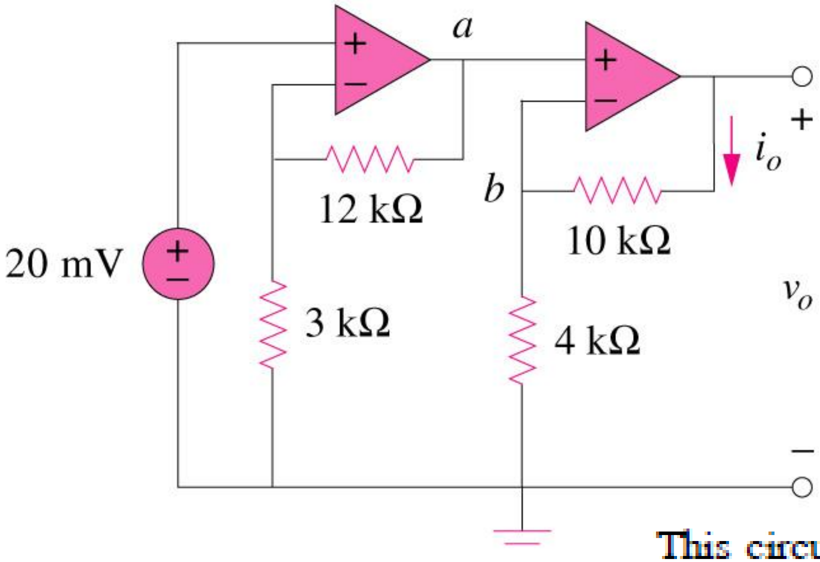
For the summer $\quad v_o = -v_a - 5v_1$

for the inverter, $\quad v_a = -3v_2$

$$v_o = 3v_2 - 5v_1$$

Example 6

Find v_o in the circuit shown below.



This circuit consists of two noninverting amplifiers cascaded. At the output of the first op amp,

$$v_a = \left(1 + \frac{12}{3}\right)(20) = 100 \text{ mV}$$

At the output of the second op amp,

$$v_o = \left(1 + \frac{10}{4}\right)v_a = (1 + 2.5)100 = 350 \text{ mV}$$

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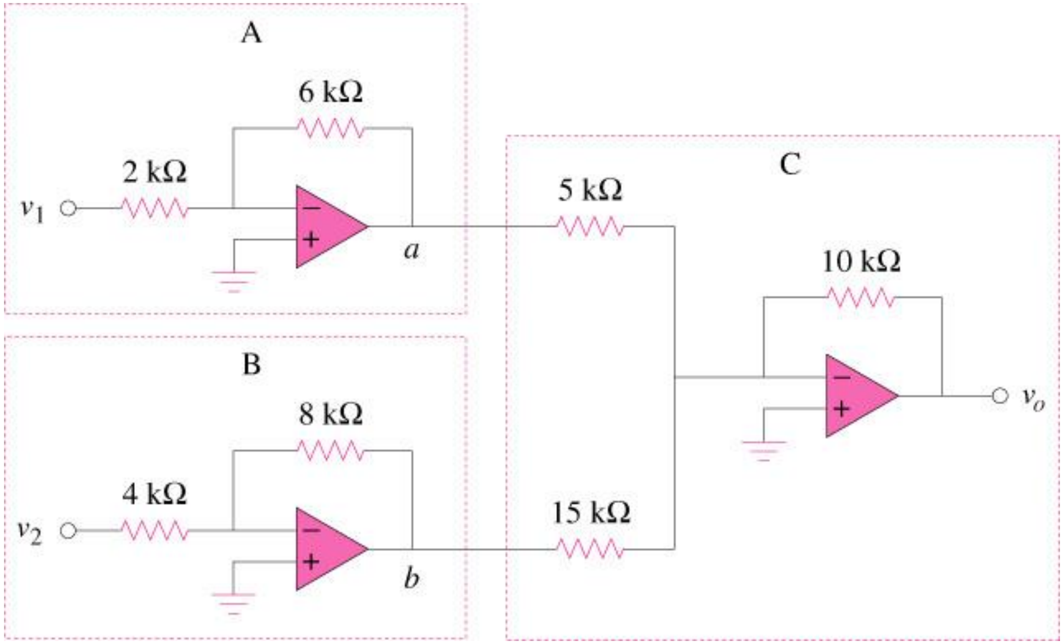
Example 7

If v_1 = 1V and v_2 = 2V, find v_o in the op-amp circuit shown below.



$$v_a = -\frac{6}{2}(v_1) = -3(1) = -3 \text{ V}, \qquad v_b = -\frac{8}{4}(v_2) = -2(2) = -4 \text{ V}$$

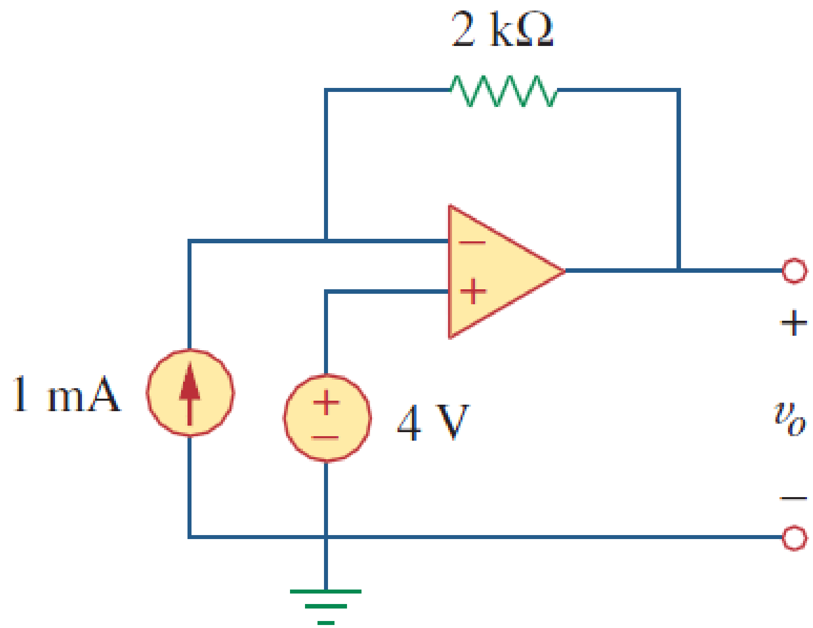
$$v_o = -\left(\frac{10}{5}v_a + \frac{10}{15}v_b\right) = -\left[2(-3) + \frac{2}{3}(-4)\right] = 8.333 \text{ V}$$

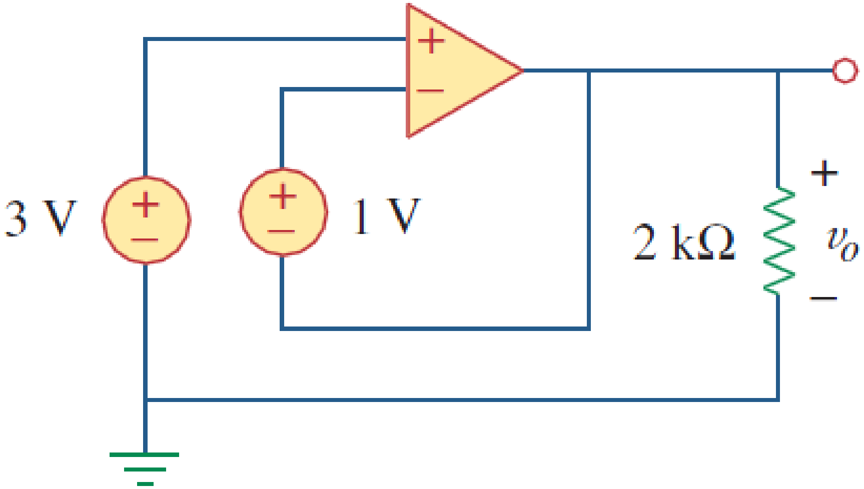
Example 8

Determine v_o for each of the op-amp circuits in following figures

Fundamentals of Electric Circuits”,

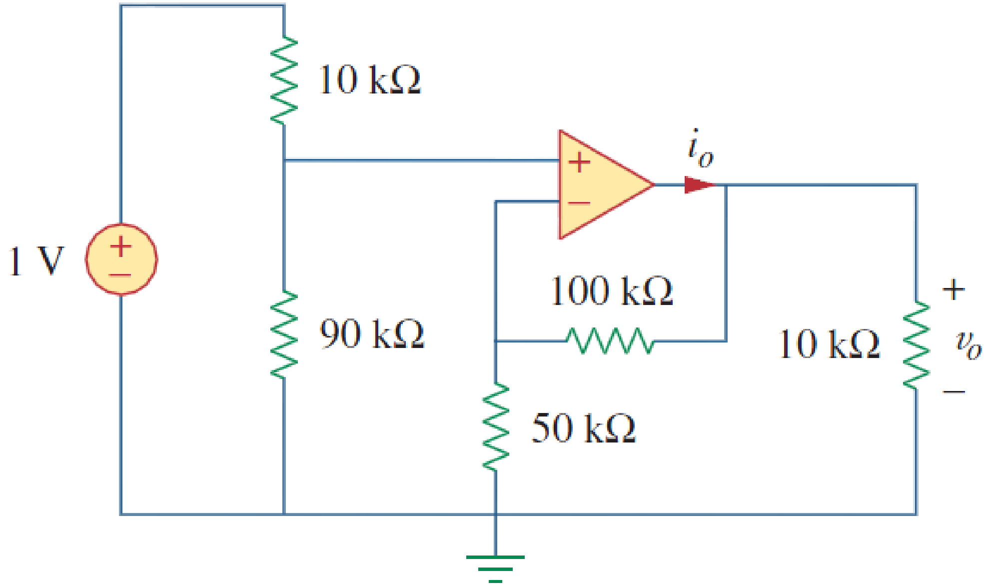
Alexander and Sadiku, McGraw-Hill.





Example 9

Find v_o in the following op-amp circuit

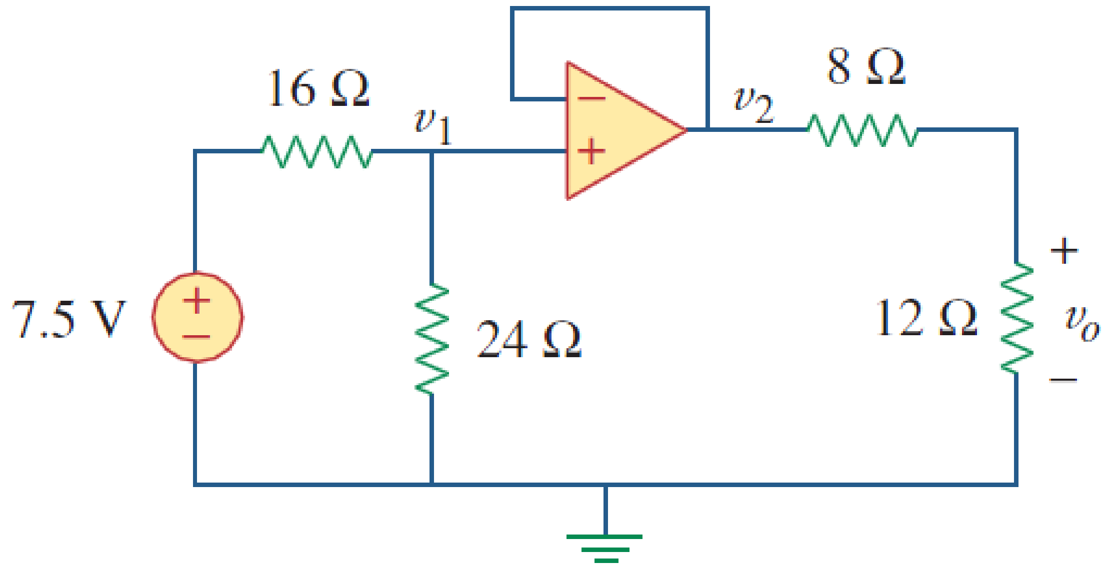


Fundamentals of Electric Circuits”,

Alexander and Sadiku, McGraw-Hill.

Example 10

Find v_o and i_o for the op-amp circuits in following figure

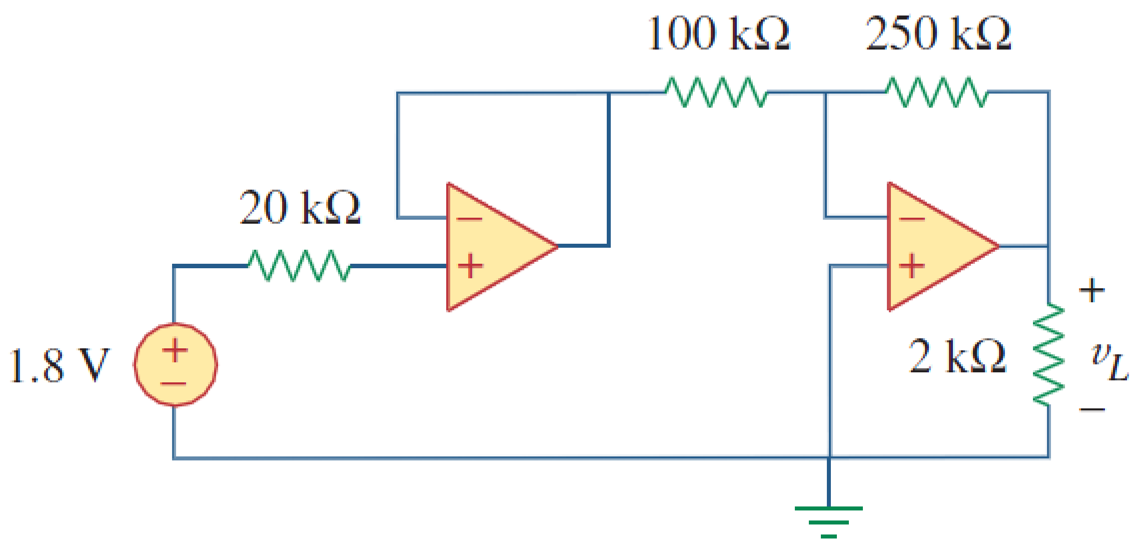


Fundamentals of Electric Circuits",

Alexander and Sadiku, McGraw-Hill.

Example 11

Find the load voltage v_L in following circuit



Fundamentals of Electric Circuits",

Alexander and Sadiku, McGraw-Hill.

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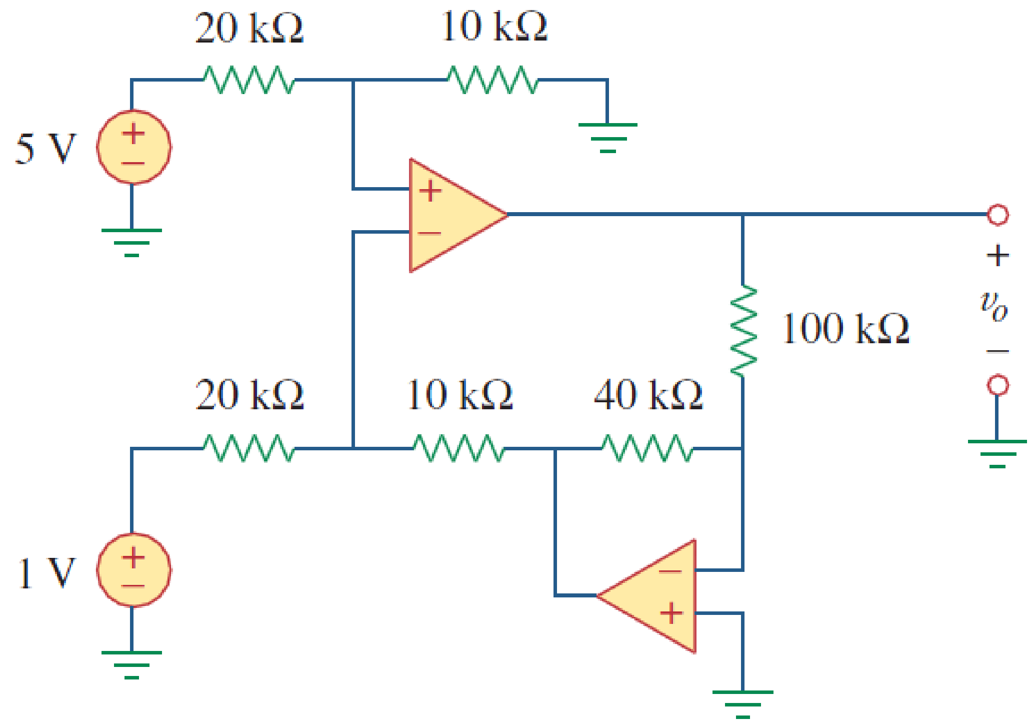
Example 12

Find the load voltage v_L in following circuit



Fundamentals of Electric Circuits",

Alexander and Sadiku, McGraw-Hill.