Aula 6: The Operational Amplifier

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Contents

Introduction to Electric Circuits by James A. Svoboda, Richard C. Dorf, 9th Edition
Fundamentals of Electric Circuits by Alexander and Sadiku, 4th Edition

Introduction

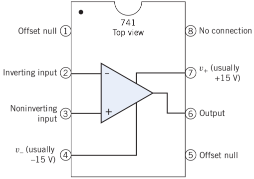
This chapter introduces another circuit element, the operational amplifier, or op amp. In particular, we will see that:

- The simplest model of the operational amplifier is the ideal operational amplifier;
- Circuits that contain ideal operational amplifiers are analyzed by writing and solving node equations;
- Operational amplifiers can be used to build circuits that perform mathematical operations.

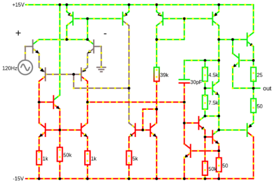
The Operational Amplifier

The operational amplifier is an electronic circuit element designed to be used with other circuit elements to perform a specified signal-processing operation.

741 Op Amp integrated circuit

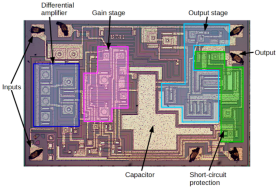


741 Op Amp Pin numbers



741 Op Amp schematic

http://www.falstad.com/circuit/

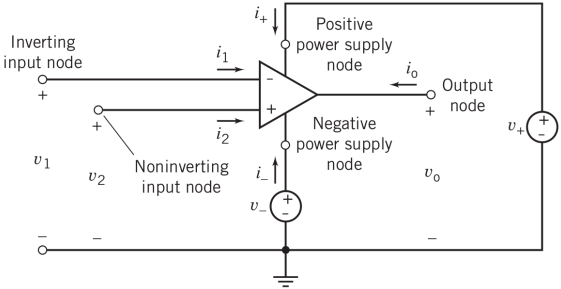


741 Op Amp inside

http://www.epanorama.net/

The Operational Amplifier

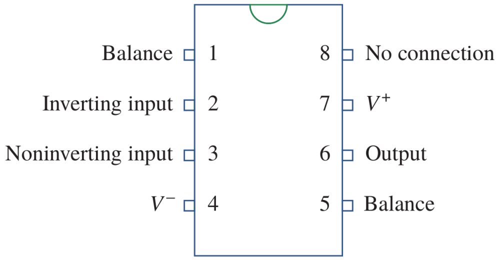
The power supplies are used to bias the operational amplifier. In other words, the power supplies cause certain conditions that are required for the operational amplifier to function properly.



- These power supplies tend to clutter drawings of operational amplifier circuits, making them harder to read;
- Consequently, the power supplies are frequently omitted from drawings that accompany explanations of the function of operational amplifier circuits.

Operational Amplifiers

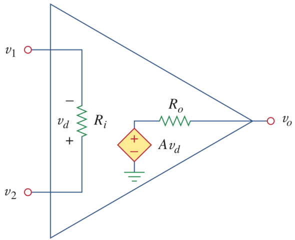
An op amp is an active circuit element designed to perform mathematical operations of addition, subtraction, multiplication, division, differentiation, and integration.



- The inverting input, pin 2;
- The noninverting input, pin 3.
- The output, pin 6.
- The positive power supply V^+, pin 7.
- The negative power supply V^-, pin 4.

Operational Amplifiers

The equivalent circuit of the nonideal op amp.



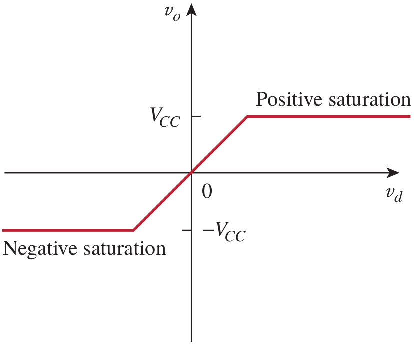
Typical ranges for op amp parameters.

Parameter	Typical range	Ideal values
Open-loop gain, A	10^5 to 10^8	∞
Input resistance, R_i	10^5 to 10^{13} Ω	$\infty\,\Omega$
Output resistance, R_o	10 to 100 Ω	$0\,\Omega$
Supply voltage, V_{CC}	5 to 24 V	

The differential input voltage v_d is given by $v_d = v_2 - v_1$. The output v_o is given by $v_o = Av_d = A(v_2 - v_1)$.

Operational Amplifiers

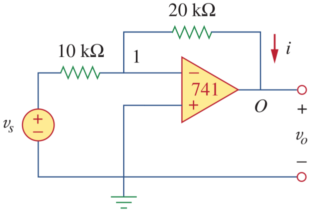
A practical limitation of the op amp is that the magnitude of its output voltage cannot exceed $|V_{CC}|$.

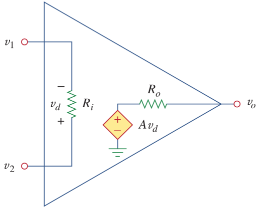


- Positive saturation, $v_o = V_{CC}$;
- Linear region, $-V_{CC} \leq v_o = Av_d \leq V_{CC}$;
- Negative saturation, $v_o = -V_{CC}$.

Operational Amplifiers

Example 5.1 - A 741 op amp has an open-loop voltage gain of 2.10^5, input resistance of $2M\Omega$, and output resistance of 50Ω. Find the closed-loop gain $\frac{v_o}{v_s}$ and determine current i when $v_s = 2V$.

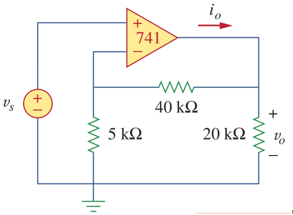


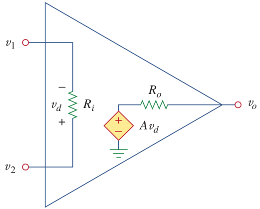


Answer: $\frac{v_o}{v_s} = -1.9999698\ and\ i = 0.19999mA$

Operational Amplifiers

Practice Problem 5.1 - If the same 741 op amp in Example 5.1 is used in the circuit below, calculate the closed-loop gain $\frac{v_o}{v_s}$. Find i_o when $v_s = 2V$.

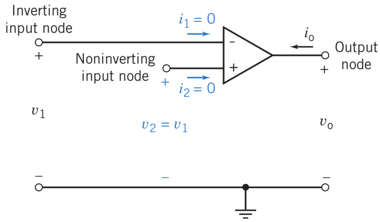




Answer: $\frac{v_o}{v_s} = 9.00041 \; and \; i = 0.657mA$

The Ideal Operational Amplifier

The ideal operational amplifier is a simple model of an operational amplifier that is linear.

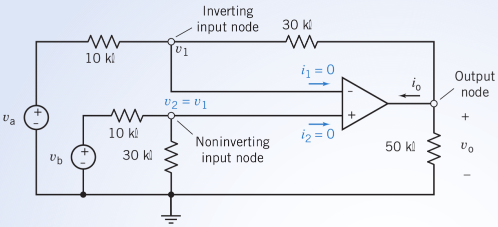


- The currents into the input terminals of an ideal operational amplifier are zero ($i_1 = i_2 = 0$).
- The node voltages at the input nodes of an ideal operational amplifier are equal ($A = \infty$ *and* $v_1 = v_2$).

The ideal operational amplifier is characterized by restrictions on its input currents and voltages.

Nodal Analysis of Circuits Containing Ideal Operational Amplifiers

EXEMPLE 6.4.1 Use node equations to analyze this circuit and determine v_o in terms of the two source voltages v_a and v_b .



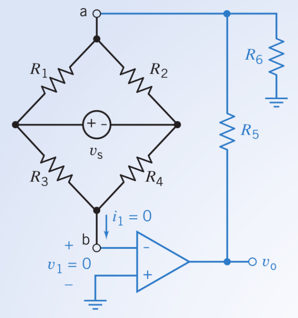
Answer: $v_o = 3(v_b - v_a)$

There are three things to remember:

- The node voltages at the input nodes of ideal operational amplifiers are equal.
- The currents in the input leads of an ideal operational amplifier are zero.
- The output current of the operational amplifier is not zero.

Analysis of a Bridge Amplifier

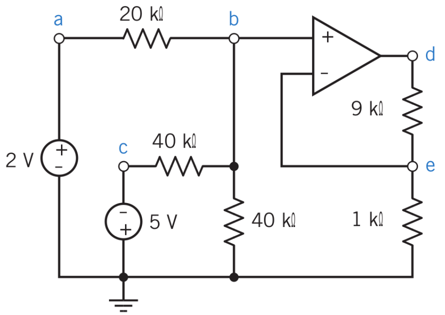
Example 6.4.2 - Determine the output voltage v_o in terms of the source voltage v_s .

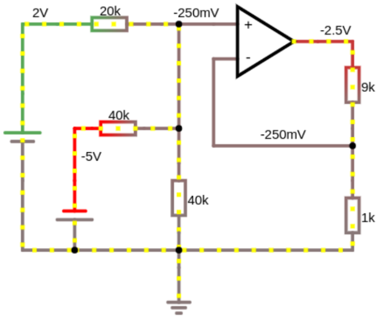


Answer: $v_o = (1 + \frac{R_5}{R_6})(\frac{R_2}{R_1+R_2} - \frac{R_4}{R_3+R_4})v_s$

Nodal Analysis

Problem 6.4.1 - Determine the node voltages for the circuit shown in Figure below.

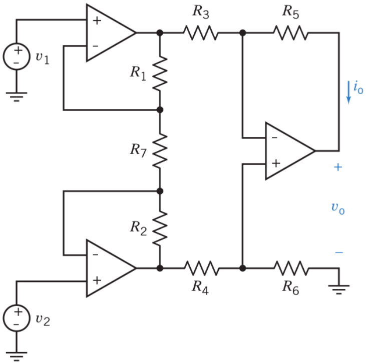




Answer: $v_a = 2V, v_b = -0.25V, v_c = -5V, v_d = -2.5V,$ and $v_e = -0.25V$. `http://www.falstad.com/circuit/`

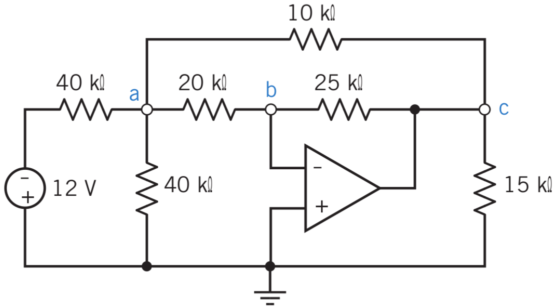
Nodal Analysis

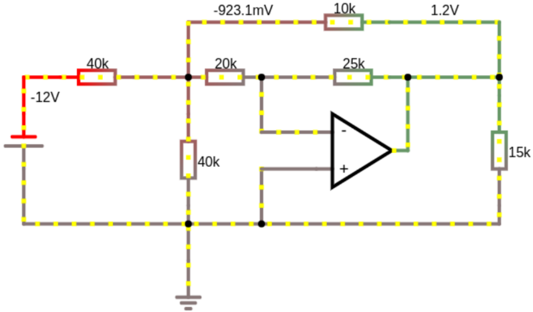
Problem 6.4.5 - Express the outputs as functions of the inputs and the resistor resistances.



Nodal Analysis

Problem 6.4.6 - Determine the node voltages for the circuit shown in Figure below.



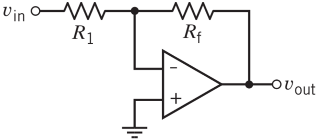


Answer: $v_a = -0.923V, v_b = 0V \text{ and } v_c = 1.154V.$

`http://www.falstad.com/circuit/`

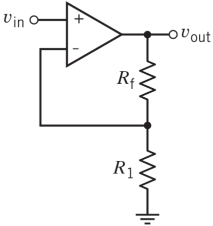
Standard Operational Amplifier Circuits

One of the early applications of operational amplifiers was to build circuits that performed mathematical operations.



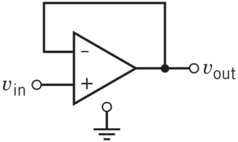
$$v_{out} = -\frac{R_f}{R_1}v_{in}$$

Inverting amplifier



$$v_{out} = -\frac{R_f}{R_1}v_{in}$$

Noninverting amplifier

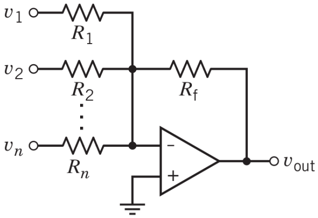


$$v_{out} = v_{in}$$

Voltage follower (buffer Amplifier)

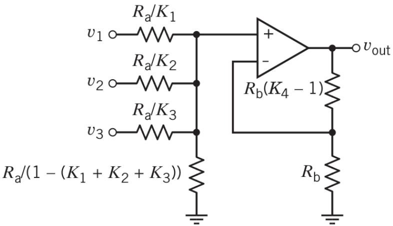
Standard Operational Amplifier Circuits

Many of the operational amplifier circuits that perform mathematical operations are used so often that they have been given names.



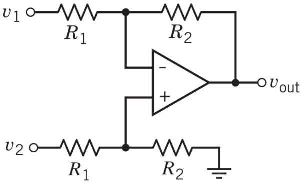
$$v_{out} = -(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \ldots + \frac{R_f}{R_n}v_n)$$

Summing amplifier



$$v_{out} = -K_4(K_1v_1 + K_2v_2 + K_3v_3)$$

Noinverting summing amplifier

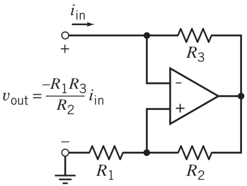


$$v_{out} = \frac{R_2}{R_1}(v_2 - v_1)$$

Difference amplifier

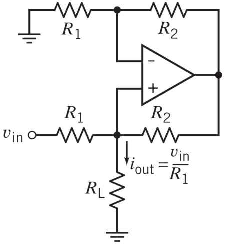
Standard Operational Amplifier Circuits

These names are part of an electrical engineer's vocabulary.



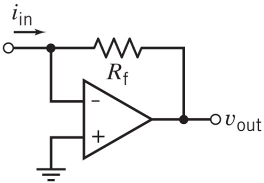
$$R_{in} = \frac{v_{in}}{i_{in}} = -\frac{R_1R_3}{R_2}$$

Negative resistanse convertor



$$v_{out} = -R_f i_{in}$$

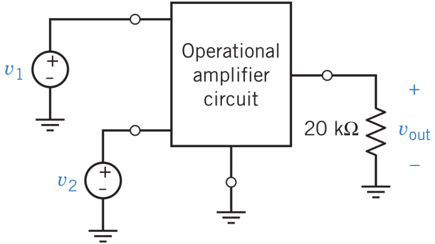
Current-to-voltage converter



$$i_{out} = \frac{v_{in}}{R_1}$$

Voltage-controlled current source (VCCS)

Design Using Operational Amplifiers

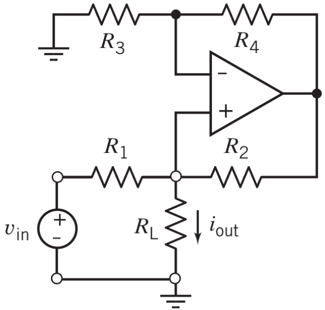


Problem 6.5-4 - Design the operational amplifier circuit in Figure above so that.
$v_{out} = 5(v_1 - v_2)$

Problem 6.5-5 - Design the operational amplifier circuit in Figure above so that.
$v_{out} = 5v_1 - 2v_2$

Design Using Operational Amplifiers

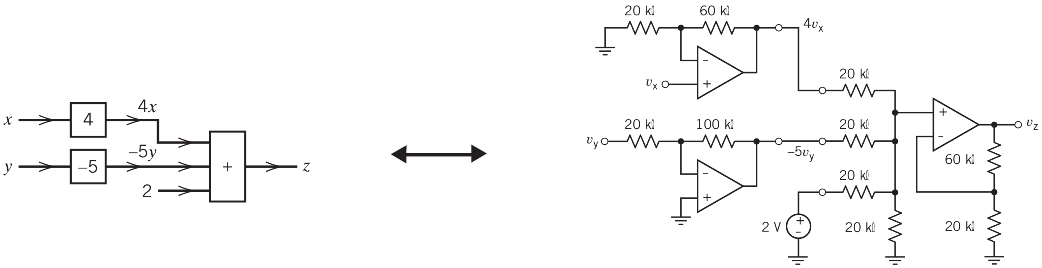
Problem 6.5-11 - The circuit shown in Figure below is called a Howland current source. It has one input, v_{in}, and one output, i_{out}.



Show that when the resistances are chosen so that $R_2R_3 = R_1R_4$, the output is related to the input by the equation $i_{out} = \frac{v_{in}}{R_1}$.

Operational Amplifier Circuits and Linear Algebraic Equations

This section describes a procedure for designing operational amplifier circuits to implement linear algebraic equations. For example, the equation $z = 4x - 5y + 2$ will be represented by $v_z = 4v_x - 5v_y + 2$, where v_z, v_x and v_y are voltages.



A voltage or current that is used to represent something is called a signal.

Operational Amplifier Circuits and Linear Algebraic Equations

Problem 6.6-1 - Design a circuit to implement the equation

$$z = 4w + \frac{x}{4} - 3y$$

The circuit should have one output corresponding to z and three inputs corresponding to w, x, and y.

Problem 6.6-2 - Design a circuit to implement the equation

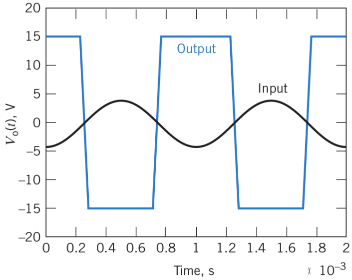
$$0 = 4w + x + 10 - (6y + 2z)$$

The output of the circuit should correspond to z.

Analysis of Op Amp Circuits Using MATLAB

When voltage saturation is included in the model of the operational amplifier, the inverting amplifier is described by equation and the corresponding graph below.

$$v_o(t) = \begin{cases} v_{sat}, \ when \ -\frac{R_2}{R_1}v_s(t) > v_{sat} \\ -\frac{R_2}{R_1}v_s(t), \ when \ -v_{sat} \leq -\frac{R_2}{R_1}v_s(t) \leq v_{sat} \\ -v_{sat}, \ when \ -\frac{R_2}{R_1}v_s(t) < -v_{sat} \end{cases}$$



The correspondence graphic: $R_1 = 2K\Omega, R_2 = 50K\Omega, v_s = -4\cos(2000\pi t) \ and \ v_s = 15V.$