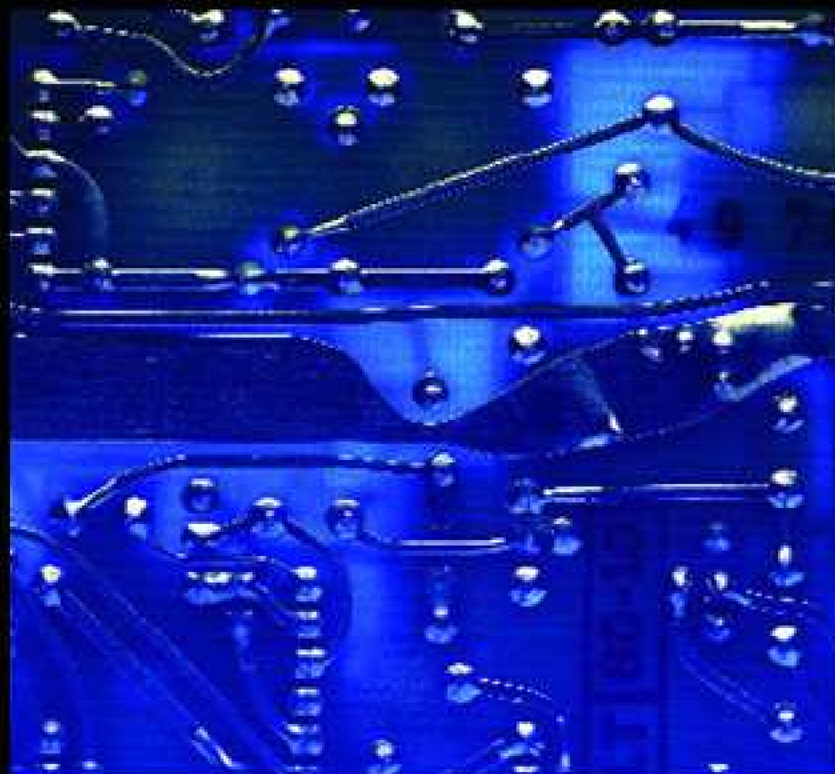
ELECTRONIC DEVICES AND CIRCUIT THEORY

TENTH EDITION



BOYLESTAD

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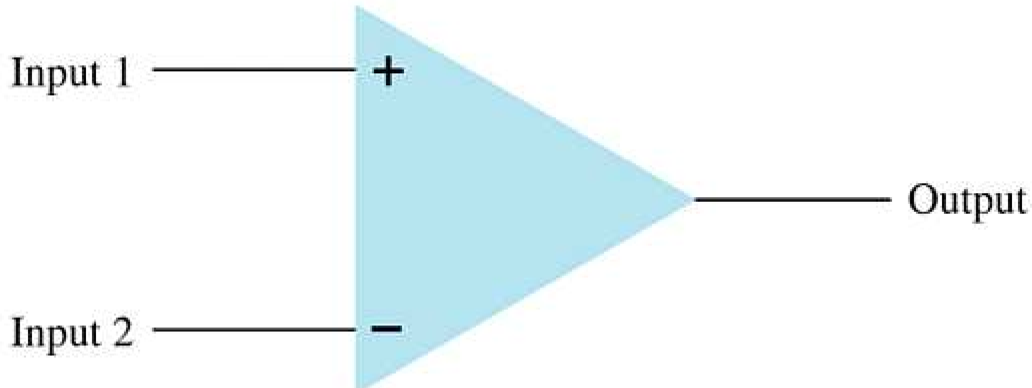
Chapter 10: Operational Amplifiers

Basic Op-Amp



Operational amplifier or op-amp, is a very high gain differential amplifier with a high input impedance (typically a few meg-Ohms) and low output impedance (less than 100 Ω).

Note the op-amp has two inputs and one output.

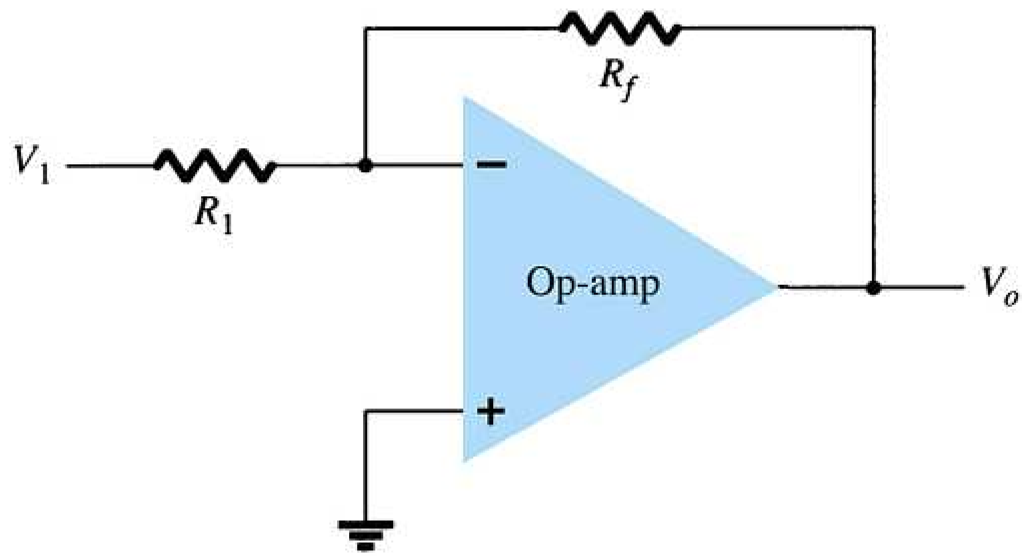
Op-Amp Gain

Op-Amps have a very high gain. They can be connected open-loop or closed-loop.

- **Open-loop** refers to a configuration where there is no feedback from output back to the input. In the open-loop configuration the gain can exceed 10,000.

- **Closed-loop** configuration reduces the gain. In order to control the gain of an op-amp it must have feedback. This feedback is a negative feedback. A **negative feedback** reduces the gain and improves many characteristics of the op-amp.

Inverting Op-Amp

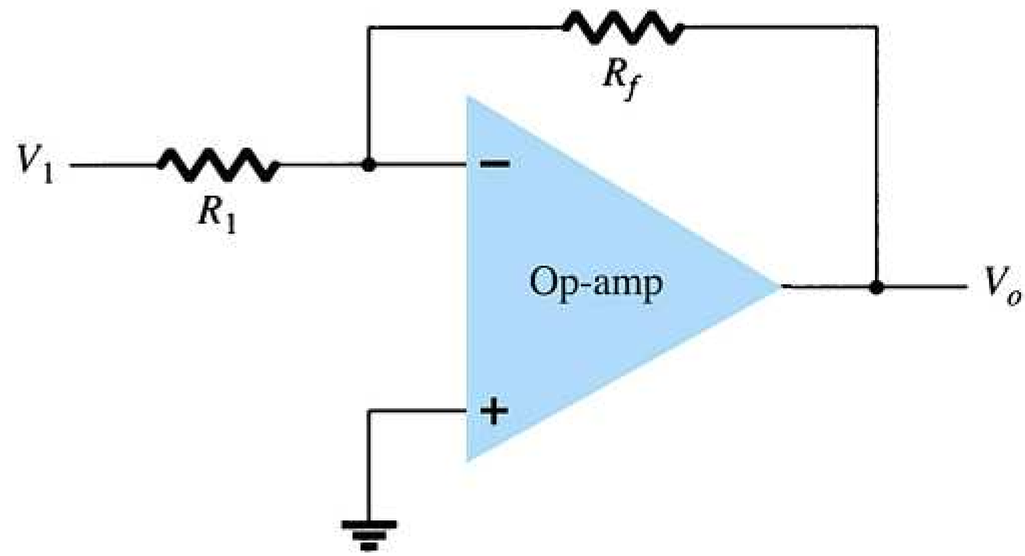


- The signal input is applied to the inverting (–) input
- The non-inverting input (+) is grounded
- The resistor R_f is the feedback resistor. It is connected from the output to the negative (inverting) input. This is *negative feedback*.

Inverting Op-Amp Gain

Gain can be determined from external resistors: R_f and R_1

$$A_v = \frac{V_o}{V_i} = \frac{R_f}{R_1}$$



Unity gain—voltage gain is 1

$$R_f = R_1$$

$$A_v = \frac{-R_f}{R_1} = -1$$

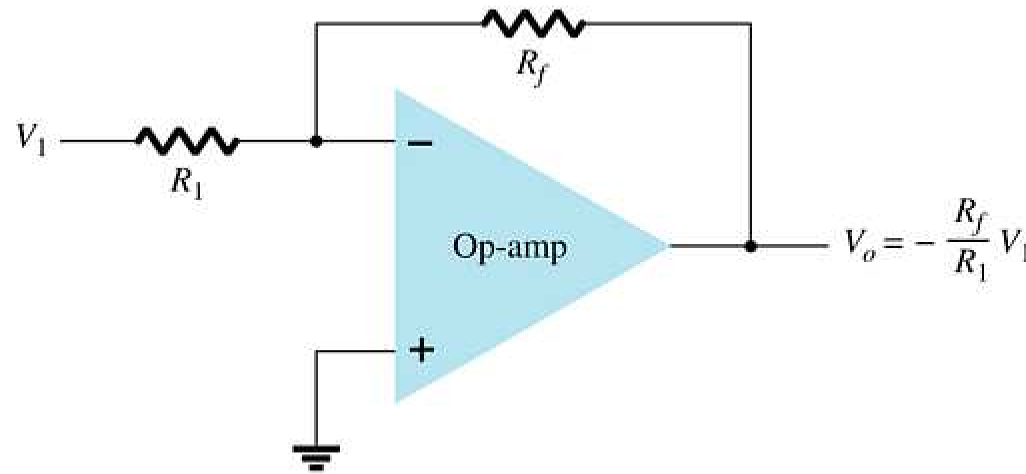
The negative sign denotes a 180° phase shift between input and output.

Constant Gain—R_f is a multiple of R_1

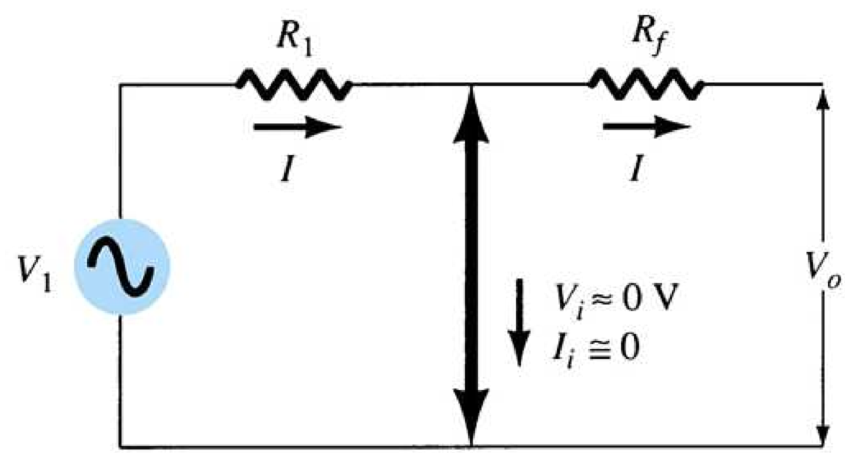
Virtual Ground

An understanding of the concept of virtual ground provides a better understanding of how an op-amp operates.

The *non-inverting* input pin is at ground. *The inverting* input pin is also at 0 V for an AC signal.



The op-amp has such high input impedance that even with a high gain there is no current from inverting input pin, therefore there is no voltage from inverting pin to ground—all of the current is through R_f.



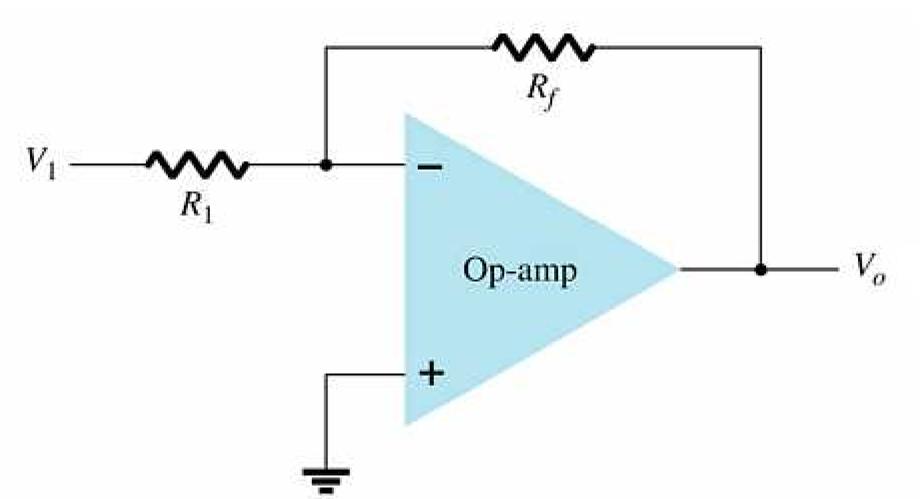
Practical Op-Amp Circuits

Inverting amplifier
Noninverting amplifier
Unity follower
Summing amplifier
Integrator
Differentiator

Inverting/Noninverting Op-Amps

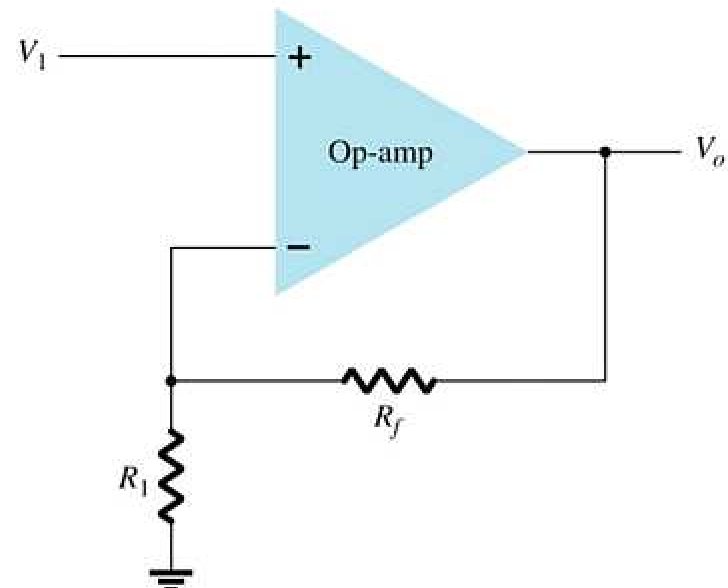
Inverting Amplifier

$$V_o = \frac{-R_f}{R_1} V_1$$



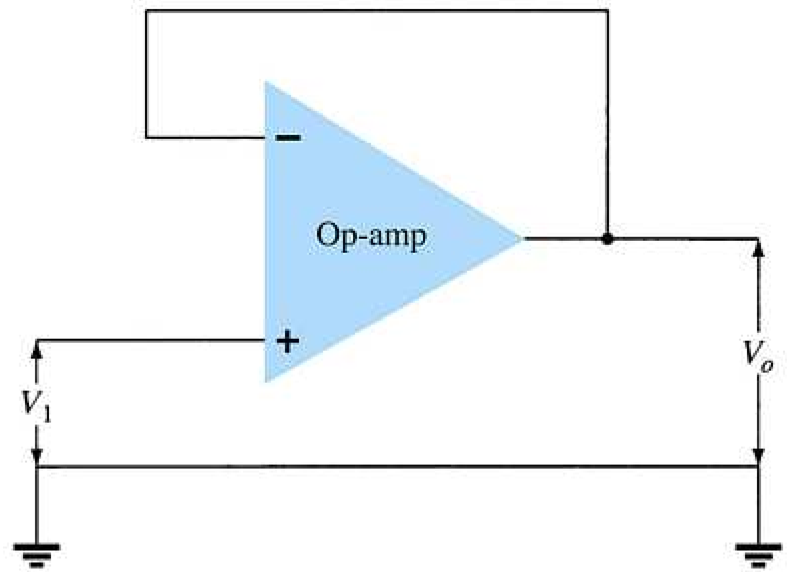
Noninverting Amplifier

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1$$



Unity Follower

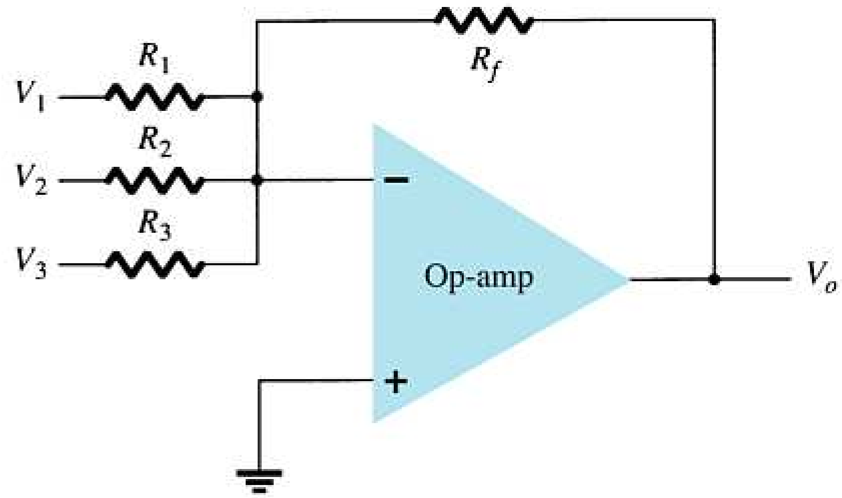
$$V_o = V_1$$



Summing Amplifier

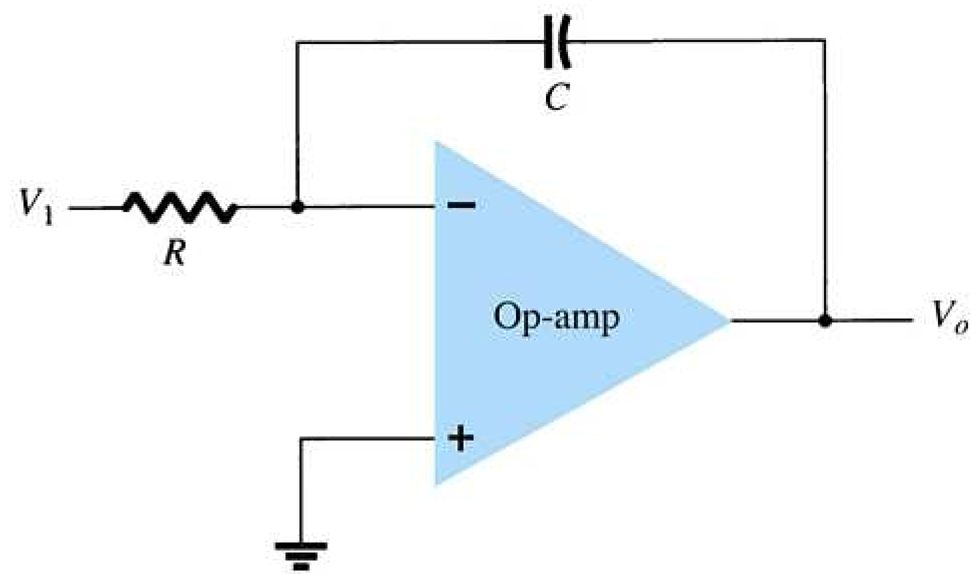
Because the op-amp has a high input impedance, the multiple inputs are treated as separate inputs.

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$



Integrator

The output is the integral of the input. Integration is the operation of summing the area under a waveform or curve over a period of time. This circuit is useful in low-pass filter circuits and sensor conditioning circuits.

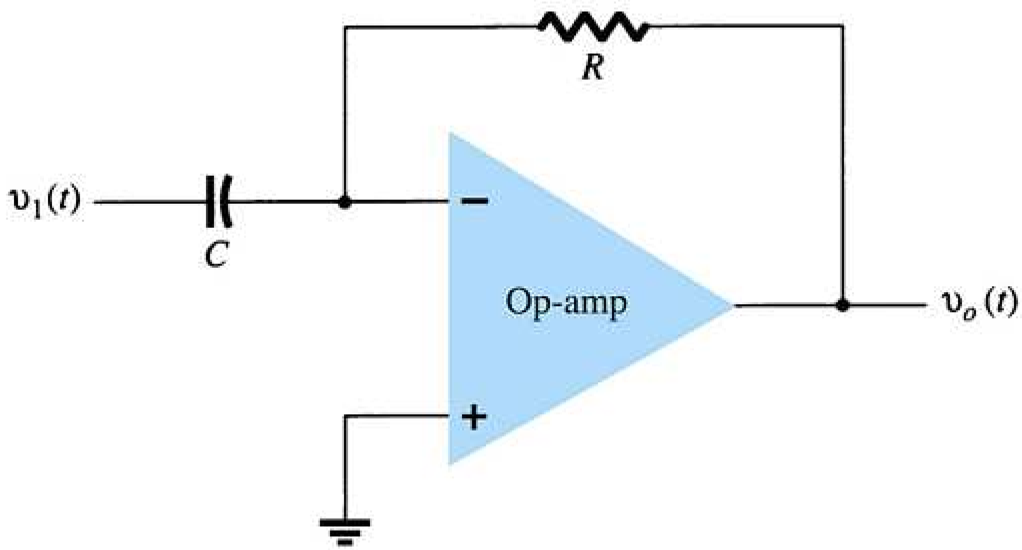


$$v_o(t) = -\frac{1}{RC}\int v_1(t)dt$$

Differentiator

The differentiator takes the derivative of the input. This circuit is useful in high-pass filter circuits.

$$v_o(t) = -RC\frac{dv_1(t)}{dt}$$



Frequency Parameters

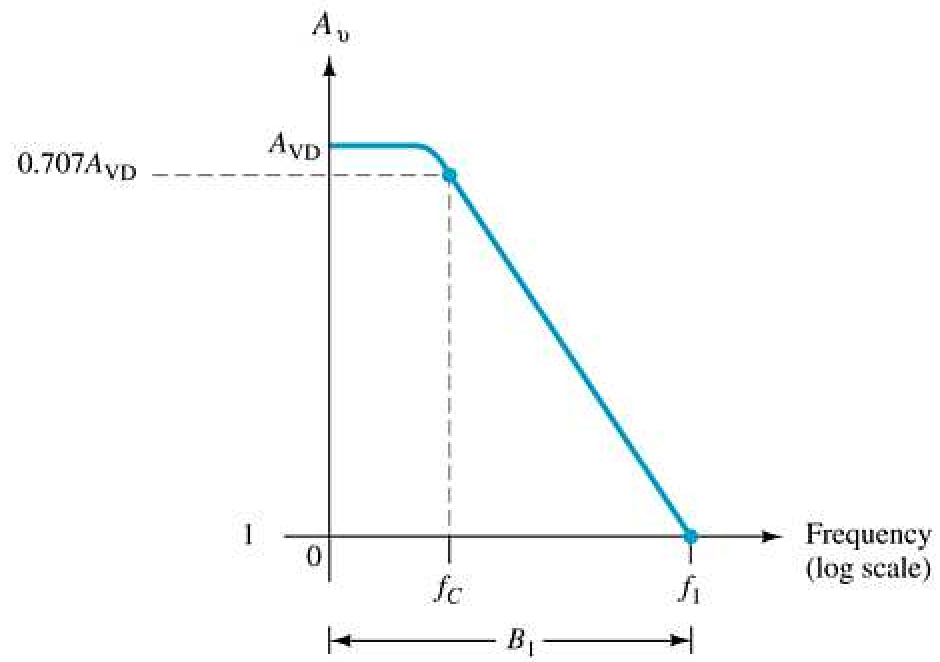
An op-amp is a wide-bandwidth amplifier. The following affect the bandwidth of the op-amp:

- **Gain**
- **Slew rate**

Gain and Bandwidth

The op-amp's high frequency response is limited by internal circuitry. The plot shown is for an open loop gain (A_{OL} or A_{VD}). This means that the op-amp is operating at the highest possible gain with no feedback resistor.

In the open loop, the op-amp has a narrow bandwidth. The bandwidth widens in closed-loop operation, but then the gain is lower.



Slew Rate (SR)

Slew rate (SR) is the maximum rate at which an op-amp can change output without distortion.

$$\mathrm{SR} = \frac{\Delta V_o}{\Delta t} \qquad \text{(in V}/\mu\text{s)}$$

The SR rating is given in the specification sheets as V/μs rating.

Maximum Signal Frequency

The slew rate determines the highest frequency of the op-amp without distortion.

$$f \le \frac{SR}{2\pi V_p}$$

where V_P is the peak voltage

General Op-Amp Specifications

Other ratings for op-amp found on specification sheets are:

- **Absolute Ratings**
- **Electrical Characteristics**
- **Performance**

Absolute Ratings

These are common maximum ratings for the op-amp.

Absolute Maximum Ratings	
Supply voltage	6 22 V
Internal power dissipation	500 mW
Differential input voltage	6 30 V
Input voltage	6 15 V

Electrical Characteristics

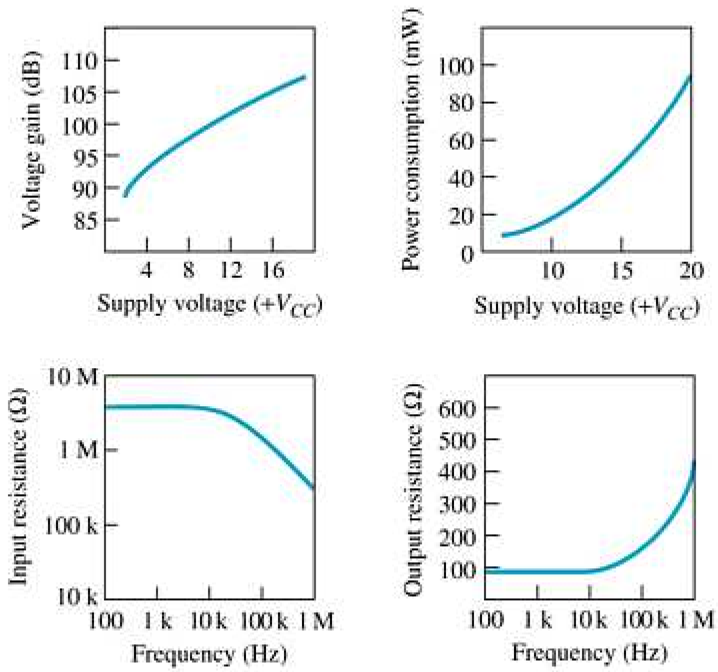
TABLE 13.2 mA741 Electrical Characteristics: $V_{CC} = \pm 15$ V, $T_A = 25°C$

Characteristic	*MIN*	*TYP*	*MAX*	*Unit*
V_{IO} Input offset voltage		1	6	mV
I_{IO} Input offset current		20	200	nA
I_{IB} Input bias current		80	500	nA
V_{ICR} Common-mode input voltage range	±12	±13		V
V_{OM} Maximum peak output voltage swing	±12	±14		V
A_{VD} Large-signal differential voltage amplification	20	200		V/mV
r_i Input resistance	0.3	2		MΩ
r_o Output resistance		75		Ω
C_i Input capacitance		1.4		pF
CMRR Common-mode rejection ratio	70	90		dB
I_{CC} Supply current		1.7	2.8	mA
P_D Total power dissipation		50	85	mW

Note: These ratings are for specific circuit conditions, and they often include minimum, maximum and typical values.

Op-Amp Performance

The specification sheets will also include graphs that indicate the performance of the op-amp over a wide range of conditions.

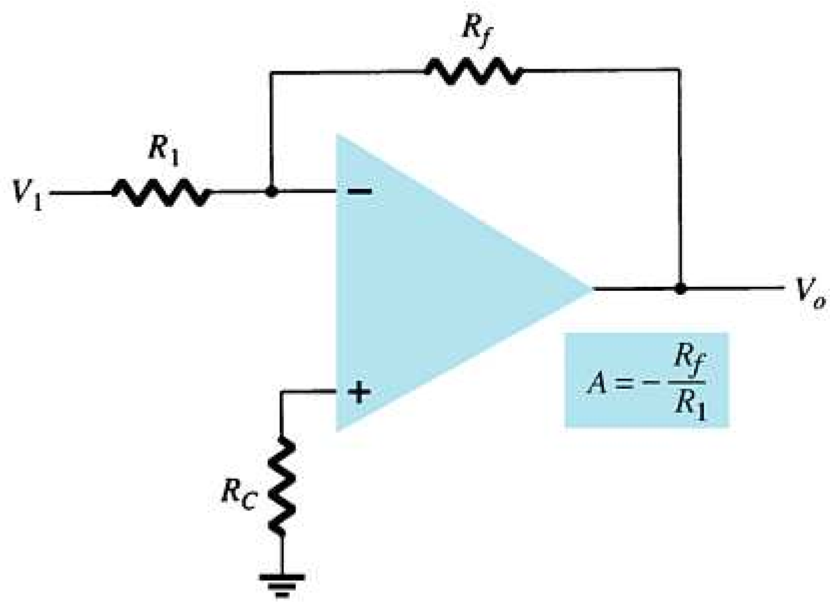


Op-Amp Applications

Constant-gain multiplier
Voltage summing
Voltage buffer
Controlled sources
Active filters

Constant-Gain Amplifier

Inverting Version



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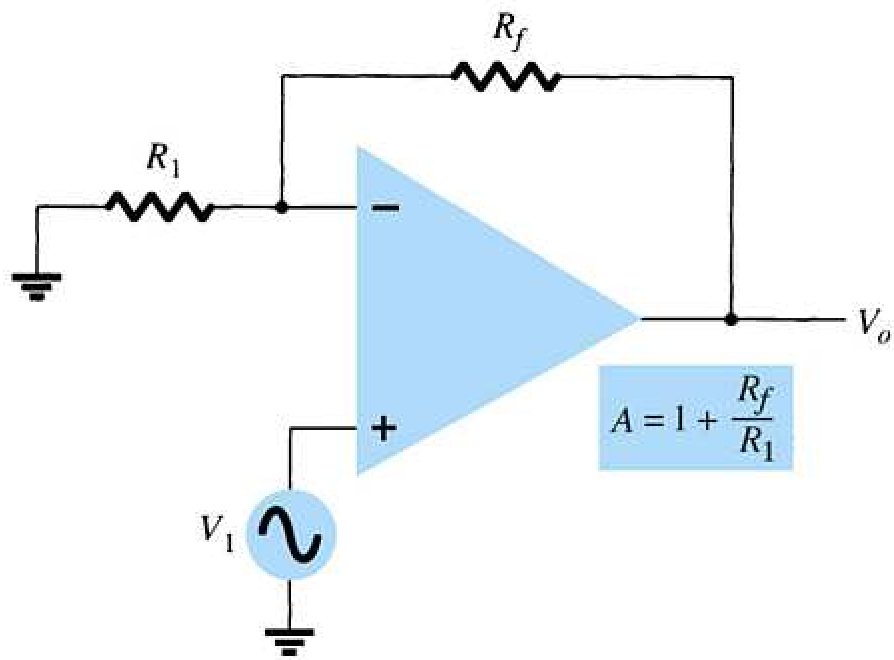
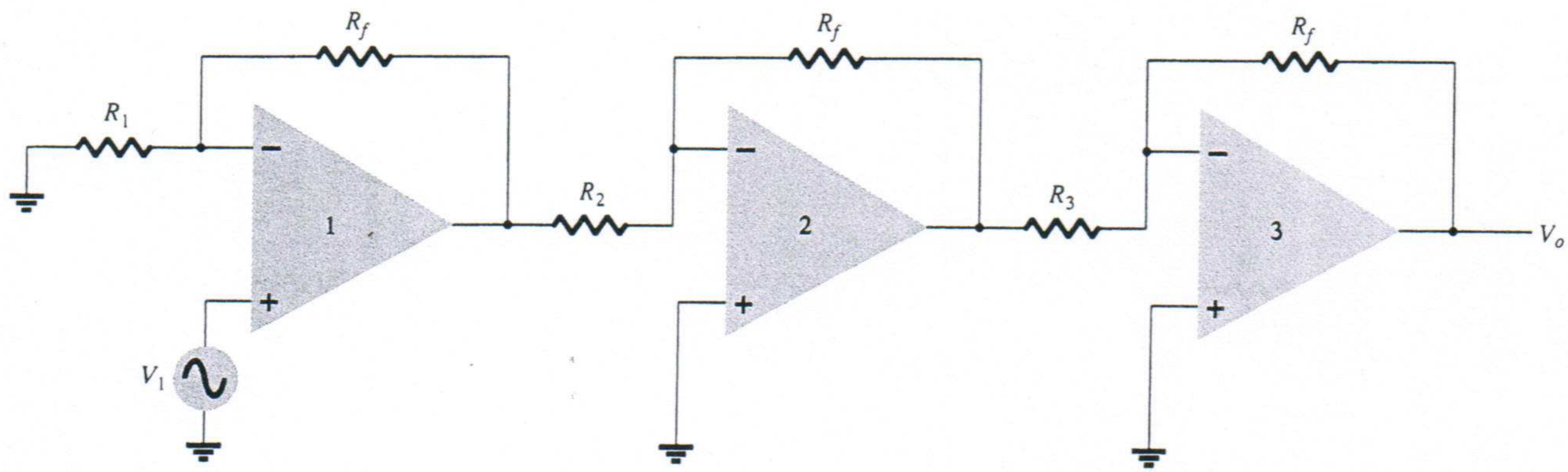
Constant-Gain Amplifier

Noninverting Version



Multiple-Stage Gains



The total gain (3-stages) is given by:

$$\mathbf{A = A_1 A_2 A_3}$$

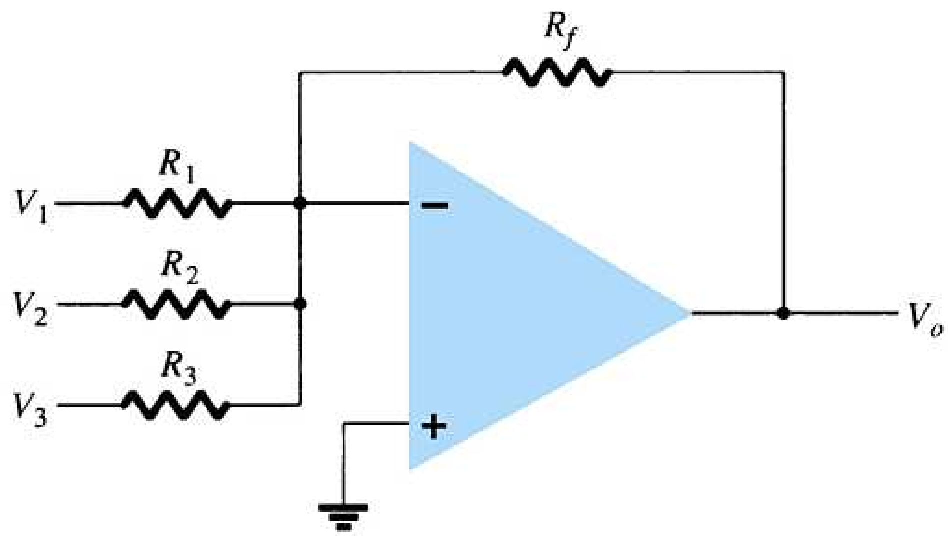
or

$$\mathbf{A = \left(1 + \frac{R_f}{R_1}\right)\left(-\frac{R_f}{R2}\right)\left(-\frac{R_f}{R3}\right)}$$

Voltage Summing

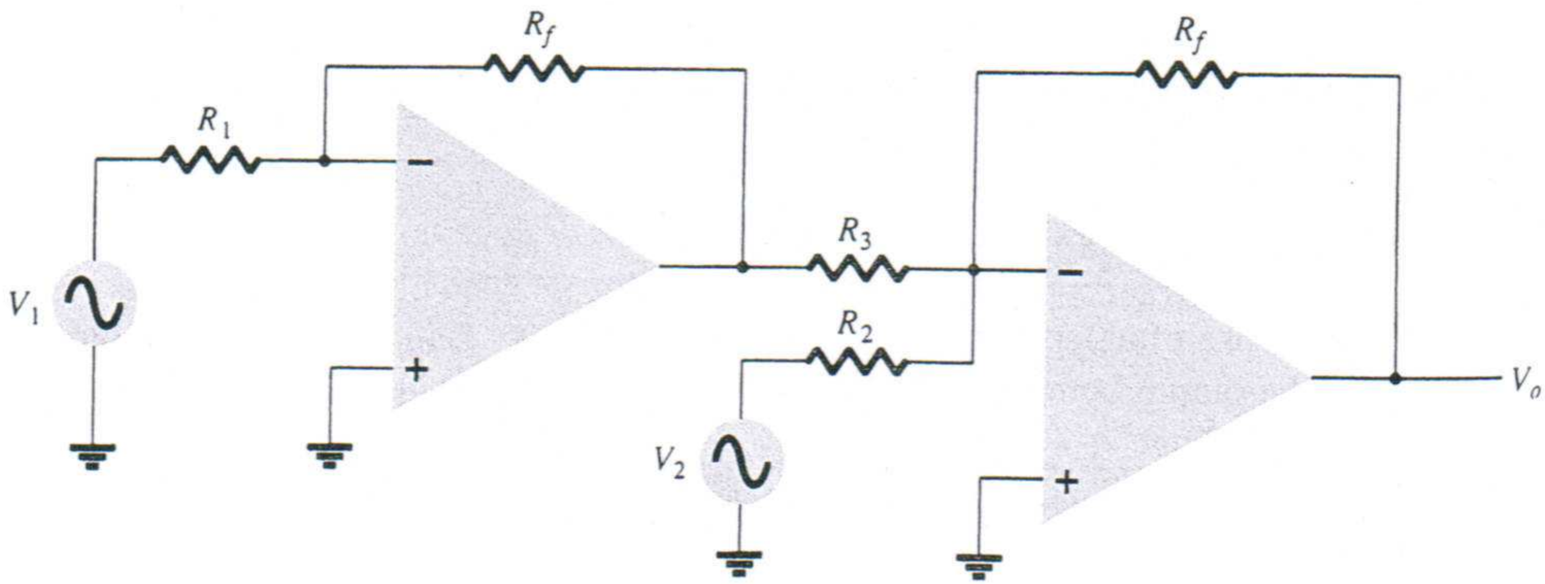
The output is the sum of individual signals times the gain:

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$



[Formula 14.3]

Voltage Subtraction



$$V_o = -\left(\frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}\frac{R_f}{R_1}V_1\right)$$

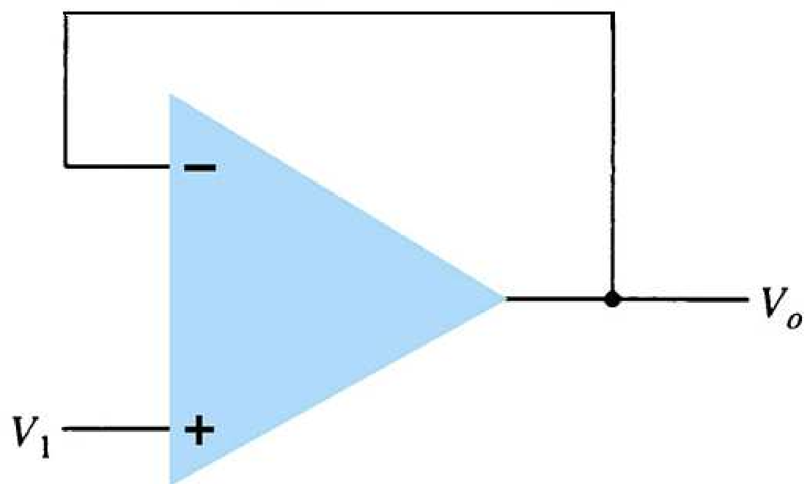
Voltage Buffer

Any amplifier with no gain or loss is called a **unity gain amplifier**.

The advantages of using a unity gain amplifier:

- Very high input impedance
- Very low output impedance

Realistically these circuits are designed using equal resistors ($R_1 = R_f$) to avoid problems with offset voltages.



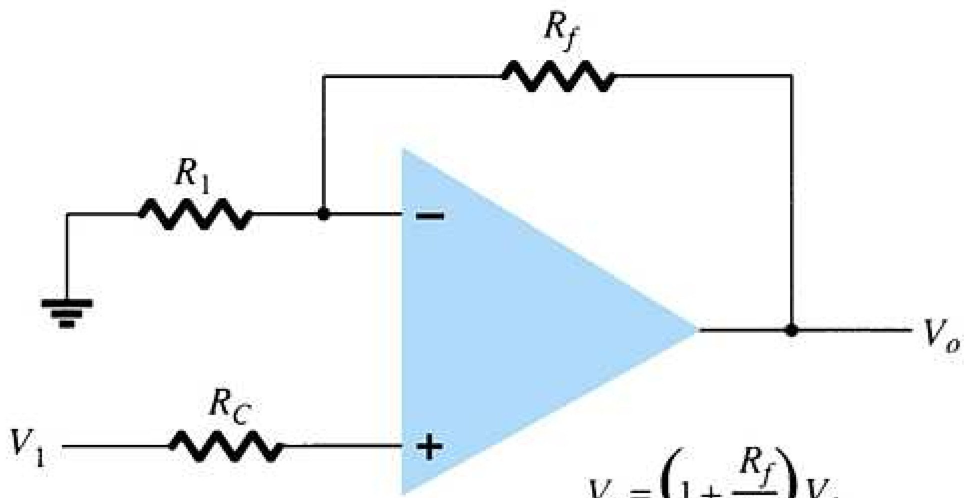
Controlled Sources

Voltage-controlled voltage source
Voltage-controlled current source
Current-controlled voltage source
Current-controlled current source

Voltage-Controlled Voltage Source

The output voltage is the gain times the input voltage. What makes an op-amp different from other amplifiers is its impedance characteristics and gain calculations that depend solely on external resistors.

Noninverting Amplifier Version



$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1$$

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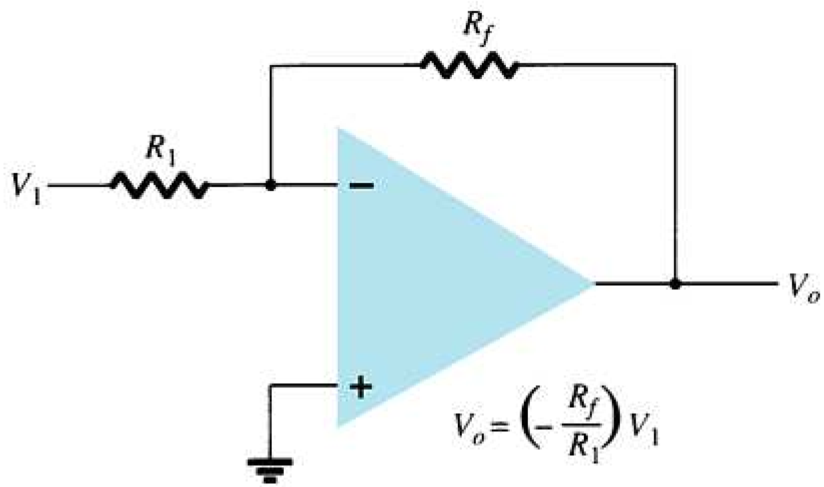
Voltage-Controlled Voltage Source

The output voltage is the gain times the input voltage. What makes an op-amp different from other amplifiers is its impedance characteristics and gain calculations that depend solely on external resistors.

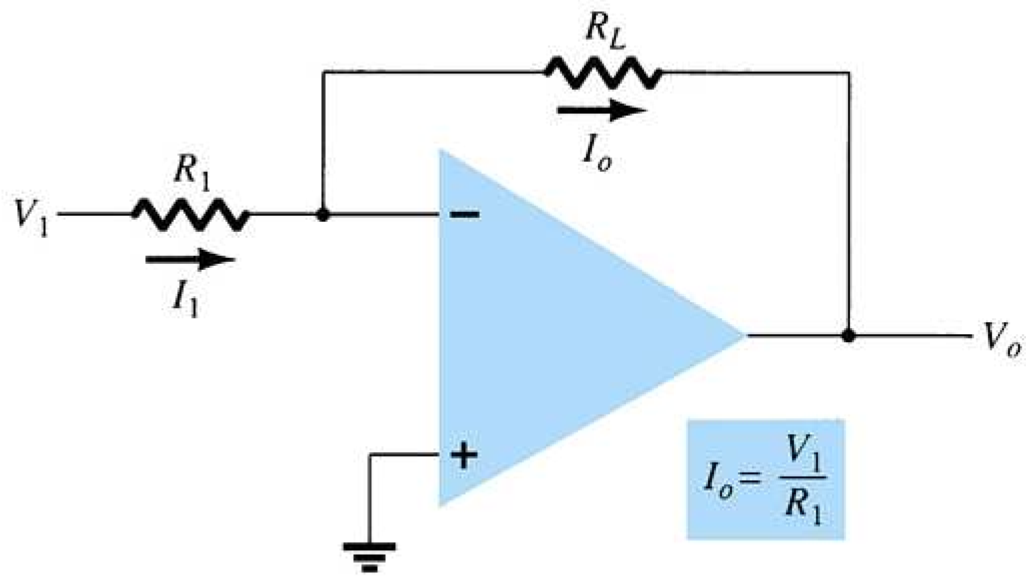
Inverting Amplifier Version



Voltage-Controlled Current Source

The output current is:

$$I_o = \frac{V_1}{R_1} = kV_1$$



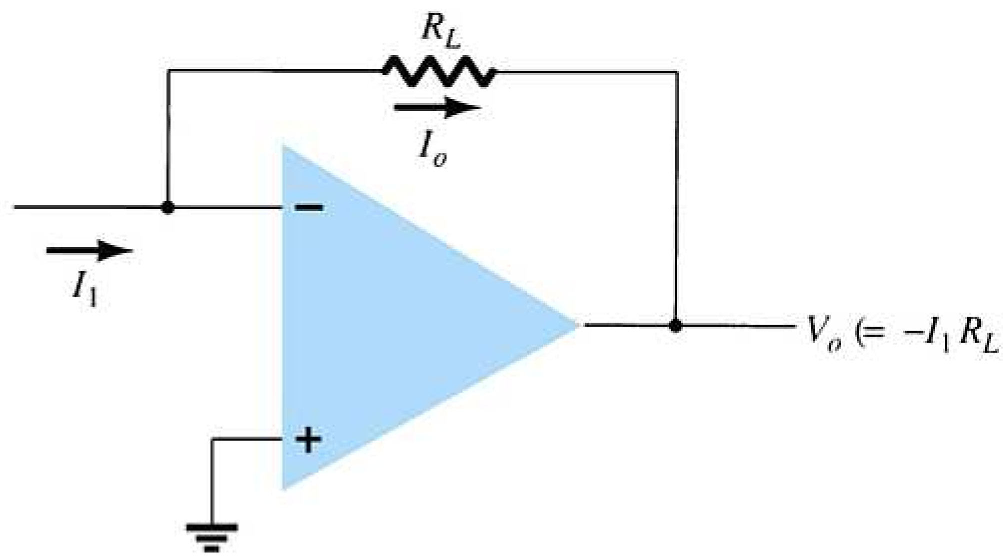
Current-Controlled Voltage Source

This is simply another way of applying the op-amp operation. Whether the input is a current determined by V_{in}/R_1 or as I_1:

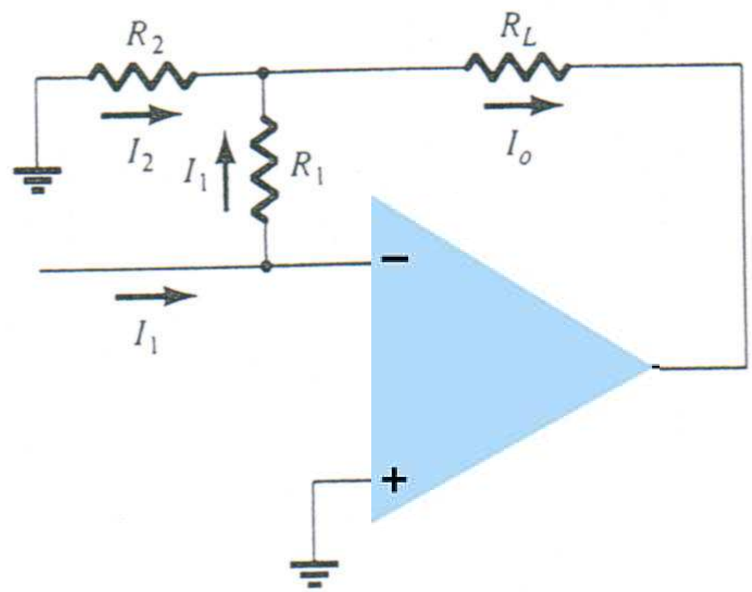
$$V_{out} = \frac{-R_f}{R_1} V_{in}$$

or

$$V_{out} = -I_1 R_L$$



Current-Controlled Current Source



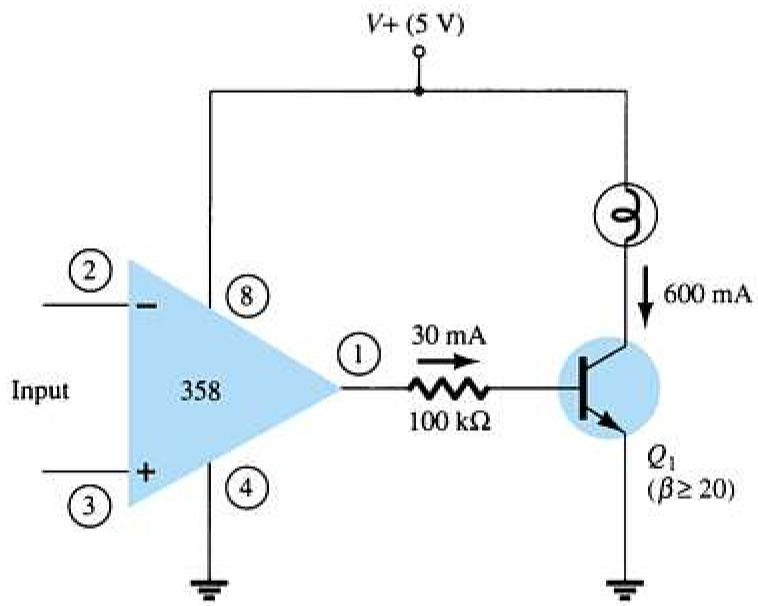
$$I_o = I_1 + I_2 = I_1 + \frac{I_1 R_1}{R_2} = \left(1 + \frac{R_1}{R_2}\right) I_1 = kI_1$$

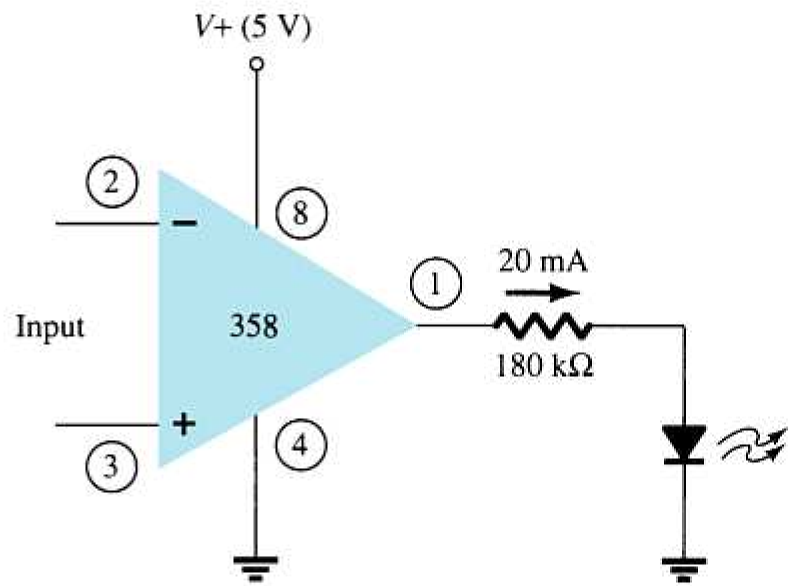
Instrumentation Circuits

Some examples of instrumentation circuits using op-amps:

- Display driver
- Instrumentation amplifier

Display Driver



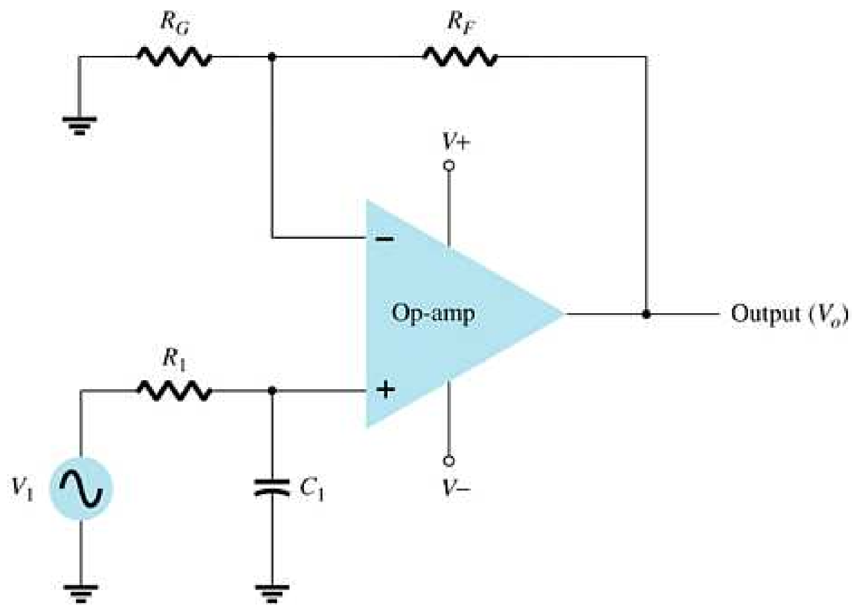


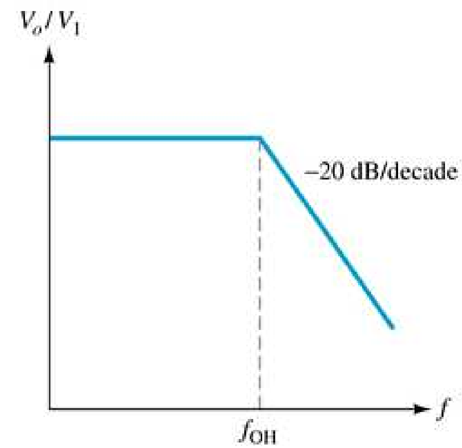
Active Filters

Adding capacitors to op-amp circuits provides external control of the cutoff frequencies. The op-amp active filter provides controllable cutoff frequencies and controllable gain.

- **Low-pass filter**
- **High-pass filter**
- **Bandpass filter**

Low-Pass Filter—First-Order

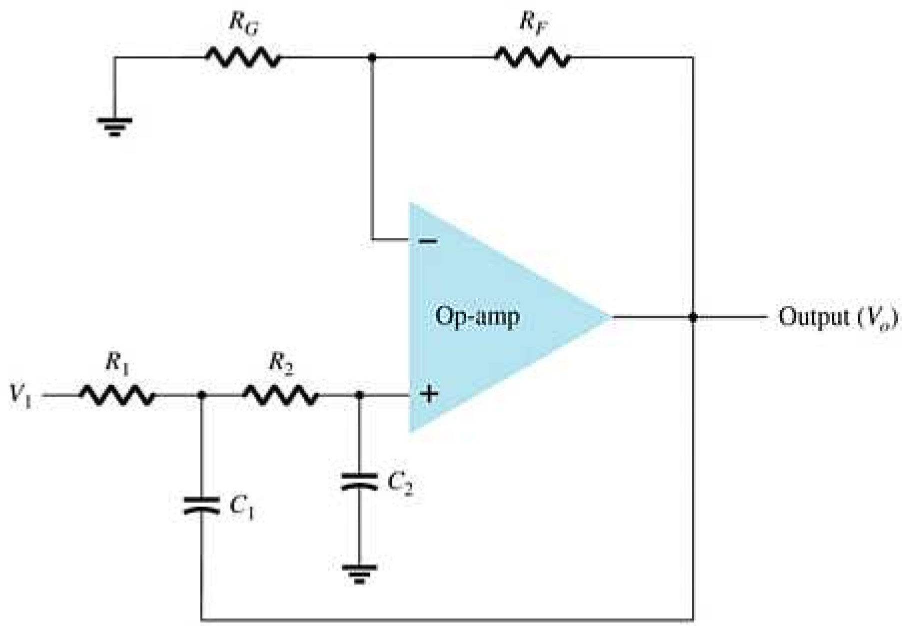


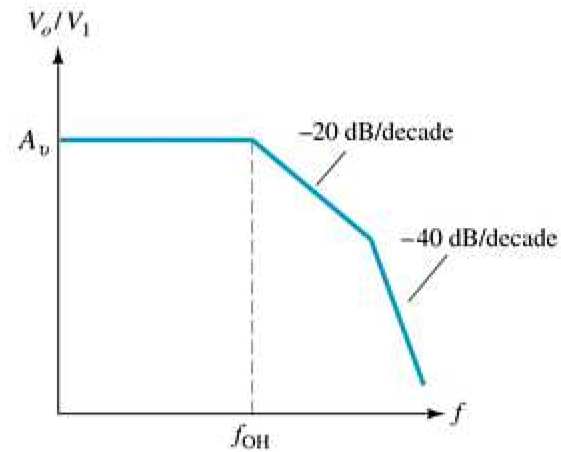


The upper cutoff frequency and voltage gain are given by:

$$f_{OH} = \frac{1}{2\pi R_1 C_1} \qquad A_v = 1 + \frac{R_f}{R_1}$$

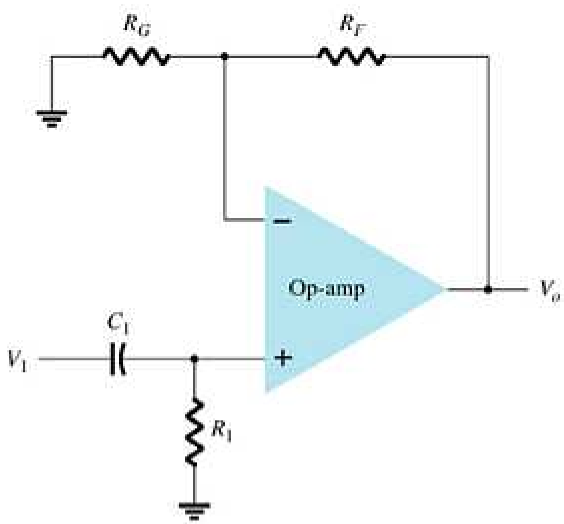
Low-Pass Filter—Second-Order

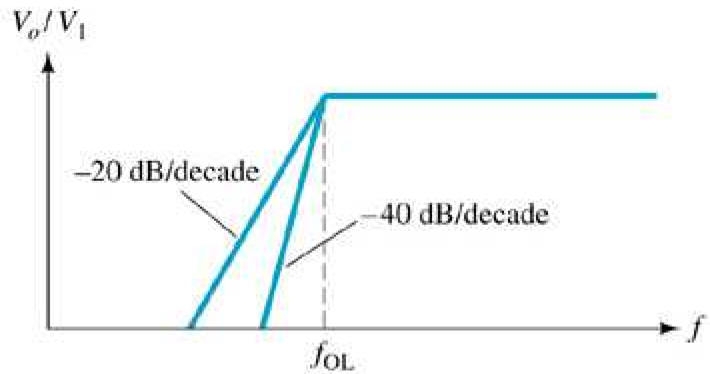




The roll-off can be made steeper by adding more RC networks.

High-Pass Filter



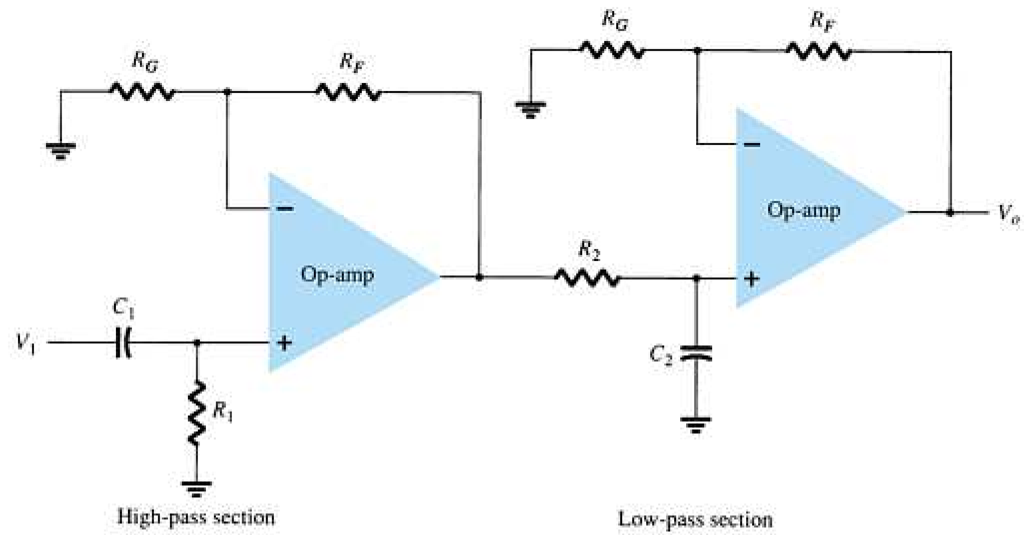


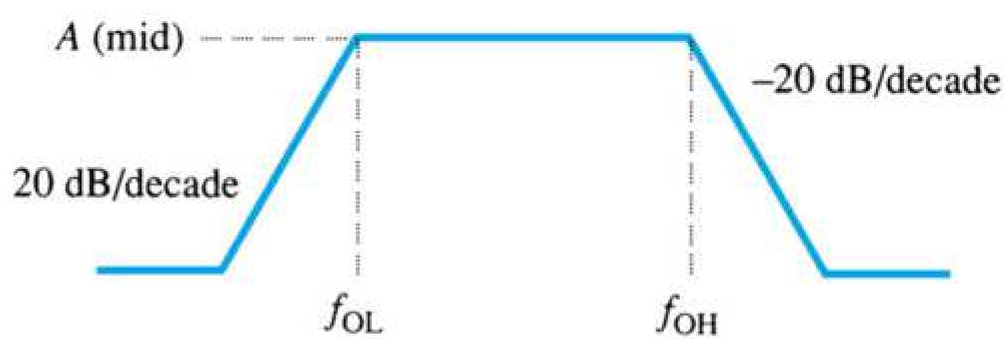
The cutoff frequency is determined by:

$$f_{OL} = \frac{1}{2\pi R_1 C_1}$$

Bandpass Filter

There are two cutoff frequencies: upper and lower. They can be calculated using the same low-pass cutoff and high-pass cutoff frequency formulas in the appropriate sections.





Homework 5

- Practical Op-Amp Circuits
  - 10.5 (2, 5, 8, 14)
- Constant-Gain Multiplier
  - 11.1 (2, 3)
- Voltage Summing
  - 11.2 (7)
- Controlled Sources
  - 11.4 (11)
- Active Filters
  - 11.6 (17)