Basic Electronics Engineering (ET10203B)(FY A&ES SEM-II)

Unit- IV: Linear Integrated Circuits

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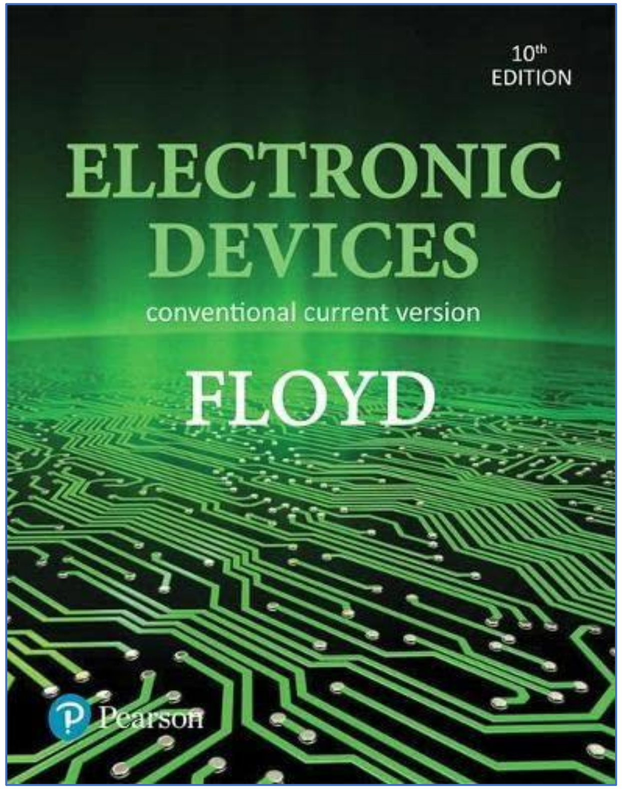
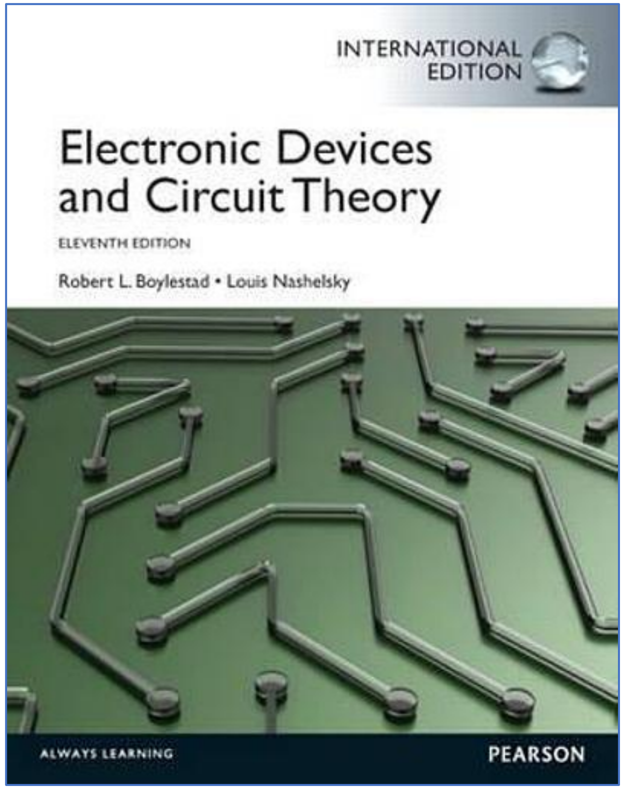
Teaching Scheme

Topics	Unit- IV: Linear Integrated Circuits
1	Introduction to operational amplifiers,
2	Block diagram of OP-AMP,
3	Ideal characteristics of OP-AMP,
4	Positive feedback, Negative feedback, Inverting Non inverting Amplifier,
5	Comparators, Summing amplifier, Difference amplifier.
6	Voltage Regulator – 3 terminal Fixed, variable

On completion of the course UNIT IV, students will be able to:
Illustrate and explain the working of simple Linear Integrated circuits using OP-AMPs

Acknowledgment





Acknowledgment

Figures and text in this presentation are taken from book “Electronic Devices – Conventional Current Version,” ,by Thomas L. Floyd.

Acknowledgment

Figures and text in this presentation are taken from book :- “Electronic Devices and Circuit Theory”, Boylestad and Nashelsky, 11th Edition

Text/Reference Books

Text Books			
Sr. No.	**Title**	**Authors**	**Publication**
T1	Electronic Devices and Circuits.	Floyd	9^{TH} Edition, Pearson Education
T2	Electronic Devices and Circuit Theory	Robert L. Boylestad, Louis Nashelsky	Prentice Hall
T3	Electronic Devices and Circuits	David A. Bell	5th Edition, Oxford press.
T4	Electronic Devices and Circuits	N.P. Deshpande	McGraw-Hill Education (India) Pvt Ltd.
Text Books			
R1	Electronic principles	Albert Malvino	7thEd,TataMc-Graw-Hill
R2	Linear Integrated Circuits	Ramakant Gaikwad	Pearson Education.
R3	Electronic Circuits Analysis and Design	Donald Neamen	3^{rd} Edition, TMH.
R4	Electronics Analog And Digital System	Jacob Millman, Christos C. Halkias	5th Edition Integrated McGraw-Hill

Introduction to operational amplifier, or op-amp

HISTORY NOTE

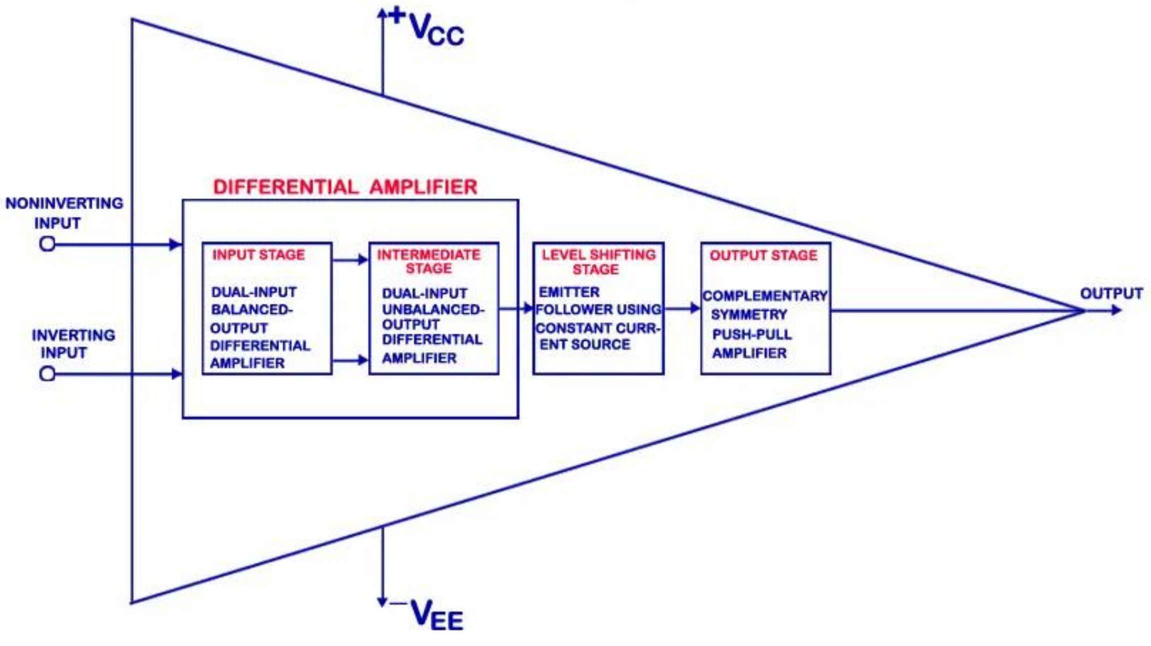
The operational amplifier concept originated around 1947. It was proposed that such a device would form an extremely useful analog building block. The first commercial op-amps used vacuum tubes, but it was not until the introduction of the integrated circuit did the op-amp start to fulfill its true potential. In 1964, the first integrated circuit op-amp, designated the 702, was developed by Fairchild Semiconductor. This was later followed by the 709 and eventually the 741, which has become an industry standard.

- An operational amplifier, or op-amp, is a very high gain differential amplifier with high input impedance and low output impedance.
- Typical uses of the operational amplifier are to provide voltage amplitude changes (amplitude and polarity), oscillators, filter circuits, and many types of instrumentation circuits.
- An op-amp contains a number of differential amplifier stages to achieve a very high voltage gain.

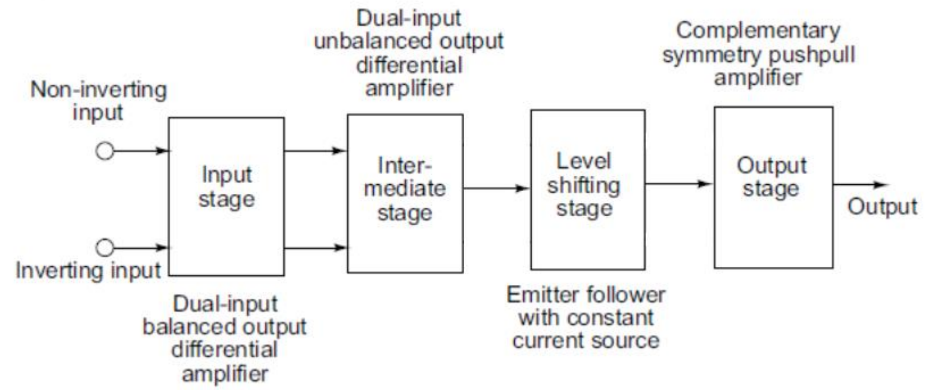
- Early operational amplifiers (op-amps) were used primarily to perform mathematical operations such as addition, subtraction, integration, and differentiation—thus the term operational.
- These early devices were constructed with vacuum tubes and worked with high voltages.
- Today's op-amps are linear integrated circuits (ICs) that use relatively low dc supply voltages and are reliable and inexpensive

Block diagram of operational amplifier, or op-amp

- The op-amp begins with a differential amplifier stage, which operates in the differential mode.
- Thus the inputs noted with ‘+’ & ‘- ‘ .
- The positive sign is for the non-inverting input and negative is for the inverting input.
- The non-inverting input is the ac signal (or dc) applied to the differential amplifier which produces the same polarity of the signal at the output of op-amp.
- The inverting signal input is the ac signal (or dc) applied to the differential amplifier. This produces a 180 degrees out of phase signal at the output.



Block Diagram of Operational Amplifier (Op-Amp)



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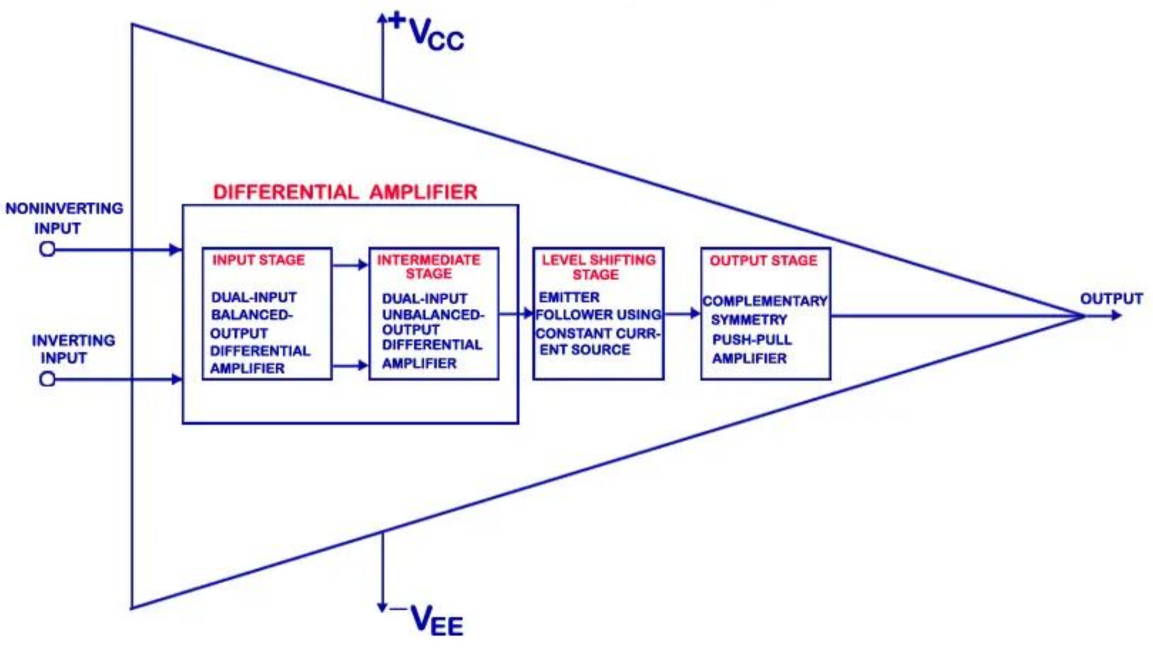
Block diagram of operational amplifier, or op-amp

- The inverting and non-inverting inputs are provided to the input stage which is a dual input, balanced output differential amplifier.
- The voltage gain required for the amplifier is provided in this stage along with the input resistance for the op-amp.
- The output of the initial stage is given to the intermediate stage, which is driven by the output of the input stage.
- In this stage direct coupling is used, which makes the dc voltage at the output of the intermediate stage above ground potential.
- Therefore, the dc level at its output must be shifted down to 0Volts with respect to the ground. For this, the level shifting stage is used where usually an emitter follower with the constant current source is applied.
- The level shifted signal is then given to the output stage where a push-pull amplifier increases the output voltage swing of the signal and also increases the current supplying capability of the op-amp.

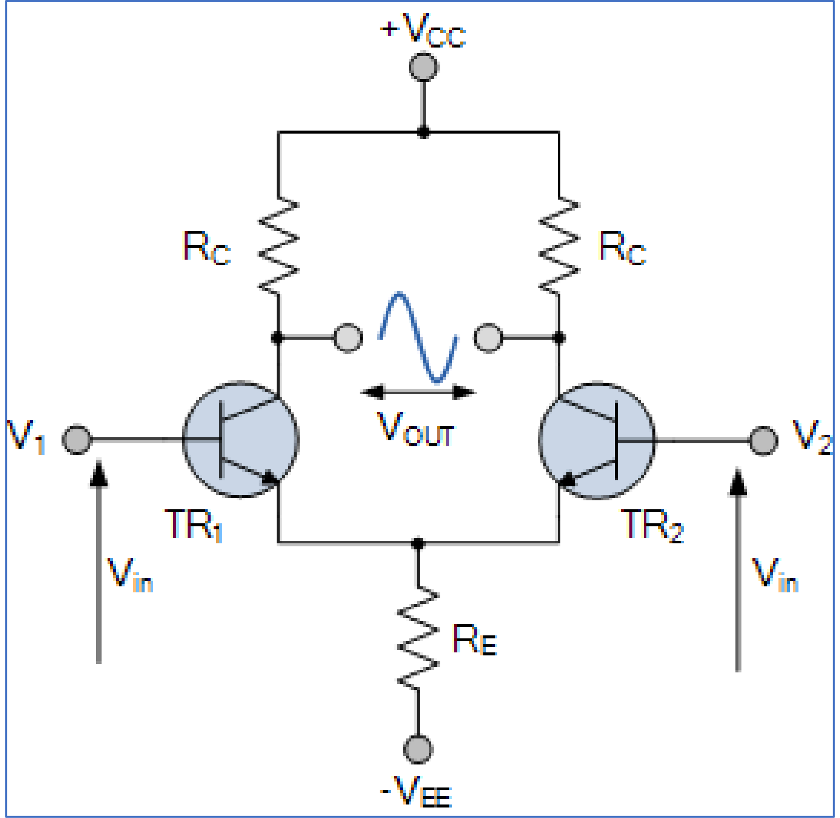


Block Diagram of Operational Amplifier (Op-Amp)

Basic operational amplifier circuits

- Differential circuits are one of the most basic circuitry used in op-amp’s.
- Shown below is a differential amplifier circuit that is modified to use an op-amp. This constitutes the basic op-amp circuit.

- The basic configuration of the circuit is shown in the figure.
- Two transistors TR1 and TR2 are provided, in which the input is provided to the base of both the transistors.
- Both the transistor emitters are connected to a common emitter RE so that the two input signals are affected by either or both input signals.
- Two supply voltages +VCC and -VEE are connected to both the collectors and emitters TR1 and TR2 .
- In the circuit diagram, there is no indication of common ground point. It must be understood that the opposite points of both positive and negative voltage supplies are connected to the ground.



Differential amplifier

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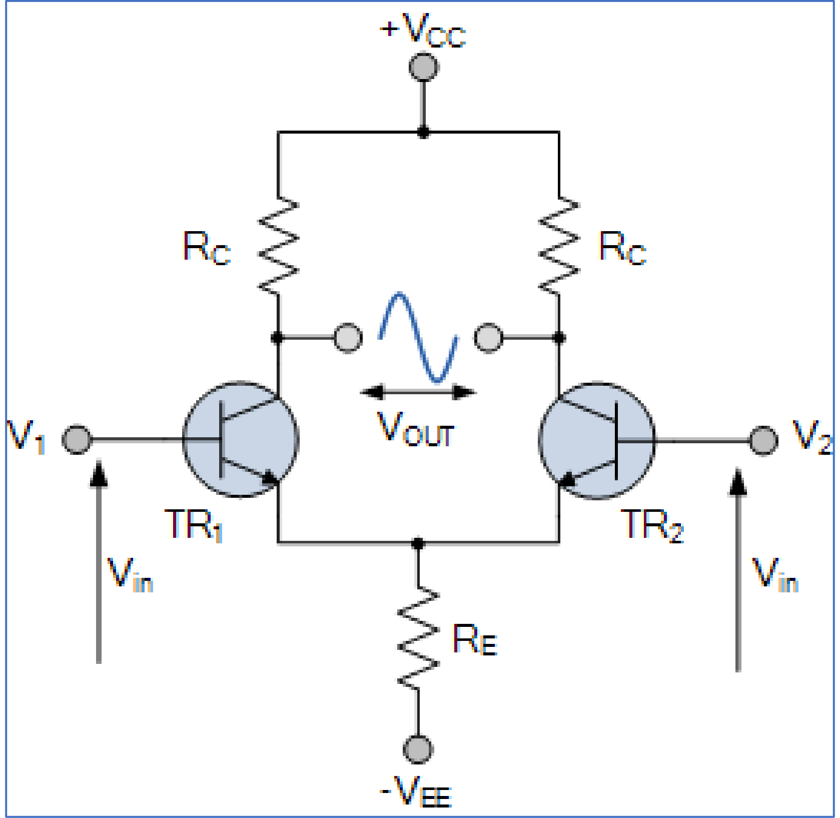
Basic operational amplifier circuits

- When input at point 1(V1) increases , the emitter current of transistor TR1 increases, and thus causes an increase of voltage at top of the emitter resistance RE.
- Thus it decreases the base-emitter voltage VBE of transistor TR2.
- Thus, when VBE of TR2 decreases, there is less current flow in the transistor TR2.
- This brings a voltage drop in the collector resistance RC and an increase in the output voltage VOUT as it is the difference between the collector supply voltage VCC and voltage drop in collector resistance RC (ICRC).
- This brings us to the conclusion that there is will be an increase in output voltage when there is an increase in input voltage V1.
- This why V1 is considered as the non-inverting input. Vout is in phase with V1.

- In another instant, when the voltage V2 increases, the collector current of TR2 increases, and makes way for a voltage drop in collector resistance and thus a decreased output voltage VOUT. This is why V2 is considered as the inverting input. VOUT is 180 degrees out of phase with V2.



Differential amplifier

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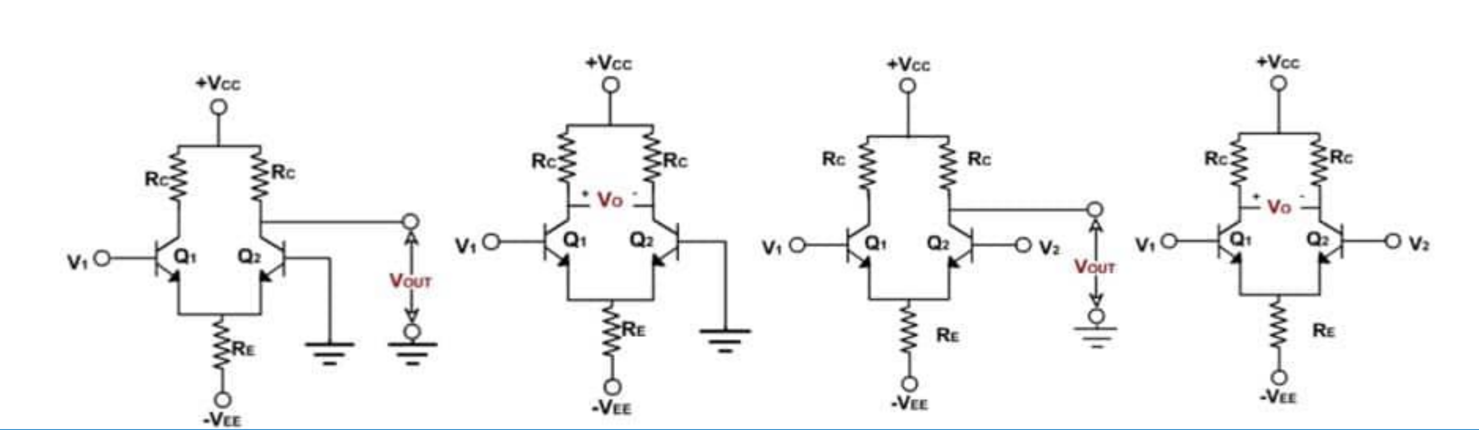
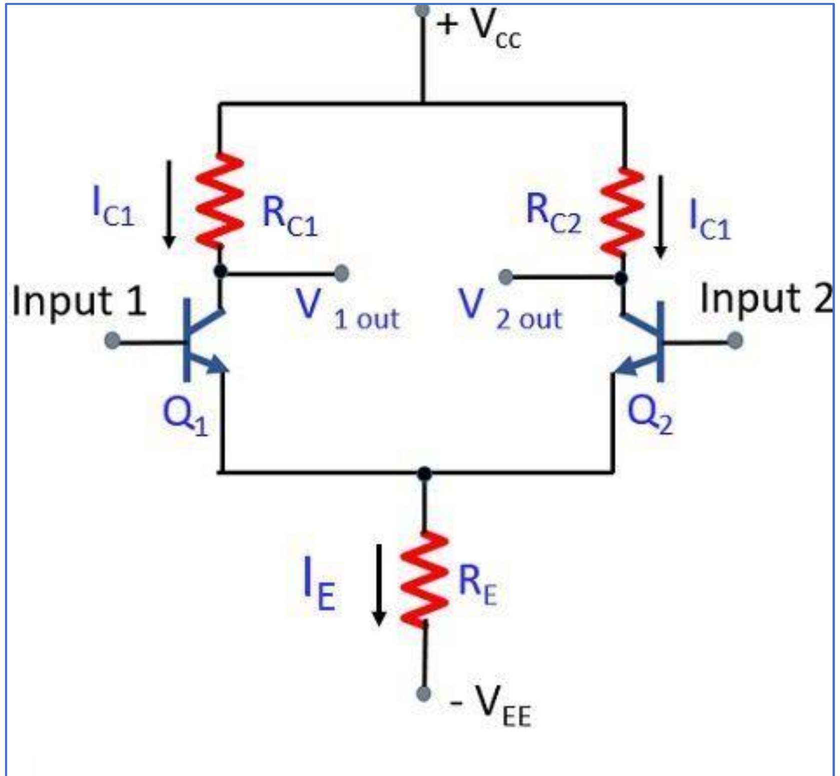
Basic operational amplifier circuits

There are mainly four configurations:

- **Dual Input Balanced Output-** In this configuration two inputs are given an output is taken from both the transistors.
- **Dual Input Unbalanced Output-** The input is given to both the transistors but the output is taken from a single transistor.
- **Single Input Balanced Output-** Here, by providing single input we take the output from two separate transistors.
- **Single Input Unbalance Output-** It is a type of configuration in which a single input is given an output is taken from only a single transistor.



1. Single input unbalanced output 2. Single input balanced output 3. Dual input unbalanced output 4. Dual input balanced output



Differential amplifier

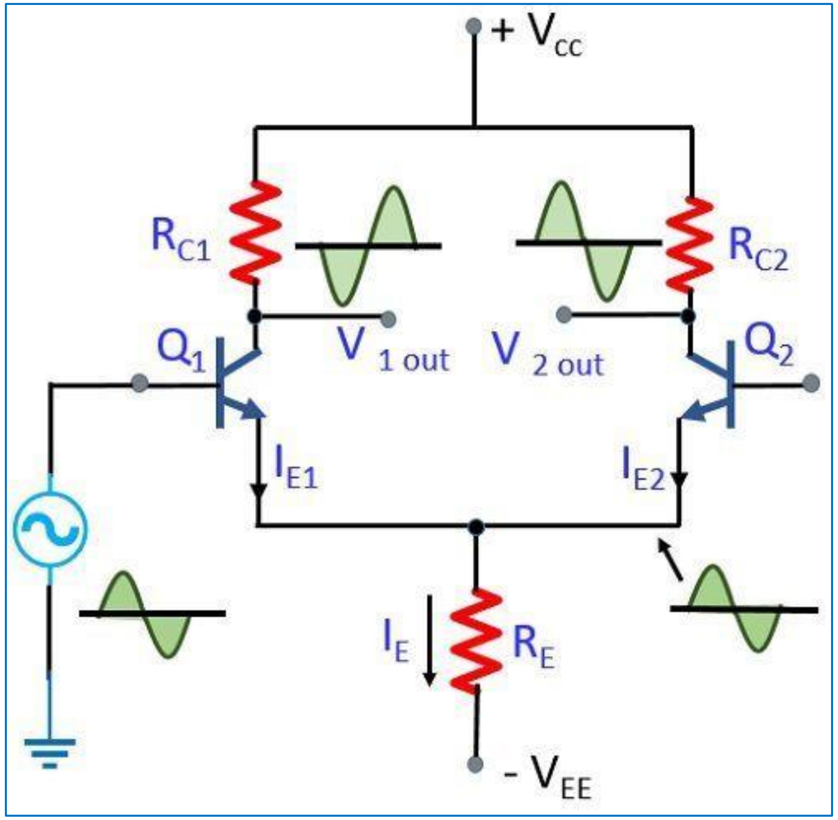
Basic operational amplifier circuits

Working of Differential Amplifier

- Let us see the **First** case where

A signal is applied at the base of transistor Q_1 and no any signal is applied at the base of transistor Q_2.

- Here, Q_1 acts in two ways: firstly, as common emitter amplifier, by which applied input at Q_1 will provide an amplified inverted signal at output 1.
- Secondly, as common collector amplifier, in which the signal appears at the emitter of Q_1 which is in phase with the input and slightly smaller.
- So, the input signal at the base of Q_1 drives the transistor i.e., Q_1 turns ON by the positive input signal. The voltage drop across R_{C1} will be more resulting the collector of Q_1 to be less positive.
- When the input signal is negative, transistor Q_1 will get OFF resulting in less voltage drop across R_{C1} causing collector of Q_1 to be more positive.
- In this way, an inverted output appears at the collector of Q_1 by applying the signal at input 1.
- At the time when Q_1 gets ON by positive half of input, the current through R_E will increase as we know $\mathbf{I_C \approx I_E}$. So, the voltage drop at R_E will be more thus causing the emitters of both the transistors to go in the positive direction.
- This Q_2 emitter positive will cause the base of Q_2 to be negative. This negative half will cause less current in Q_2. Resultantly voltage drop at R_{C2} will also be less thus the collector goes in the positive direction.
- In this way, we will have a non-inverting output at the collector of Q_2 for positive input at the base of Q_1.



Differential amplifier

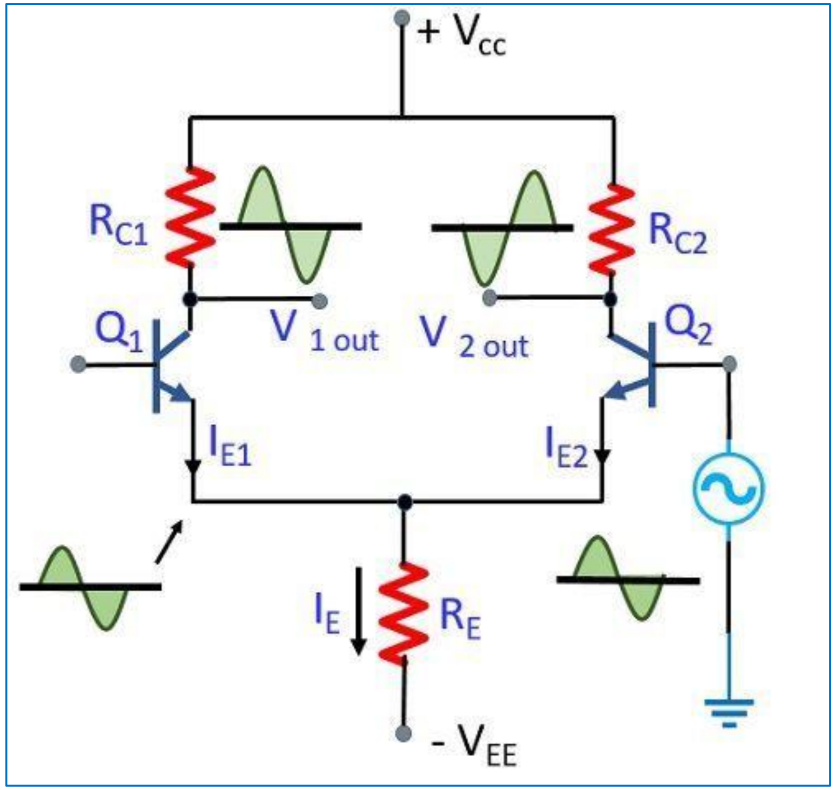
Basic operational amplifier circuits

Working of Differential Amplifier

- Now, moving further to our **Second** case-

Suppose the signal is now applied to the base of transistor Q_2 and transistor Q_1 is grounded.

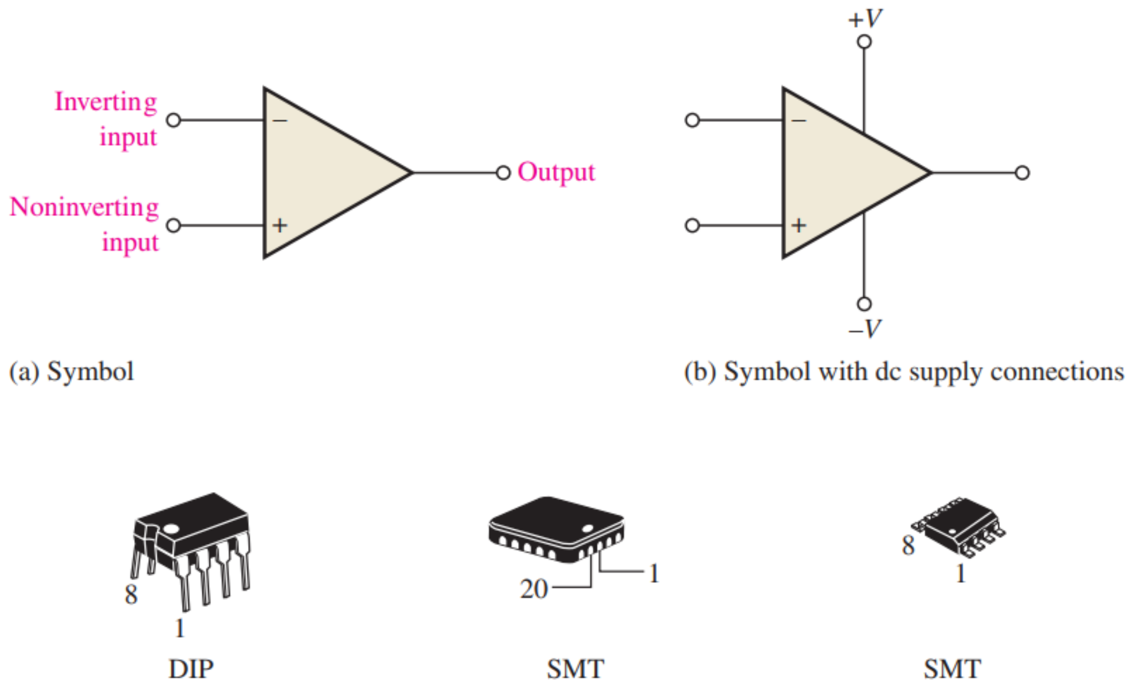
- So, in this condition the above-discussed case will get interchanged i.e., now Q2 will behave as common emitter and common amplifier and Q1 will act as a common base amplifier.
- Hence, an inverted and amplified output will be received at the output of Q1 and at the output of Q2 we will have a non-inverted amplified output.



Differential amplifier

The standard operational amplifier (op-amp) symbol

- The standard operational amplifier (op-amp) symbol is shown in Figure (a).
- It has two input terminals, the inverting (-) input and the noninverting (+) input, and one output terminal.
- Most op-amps operate with two dc supply voltages, one positive and the other negative, as shown in Figure (b), although some have a single dc supply.
- Usually these dc voltage terminals are left off the schematic symbol for simplicity but are understood to be there.
- Some typical op-amp IC packages are shown in Figure (c).



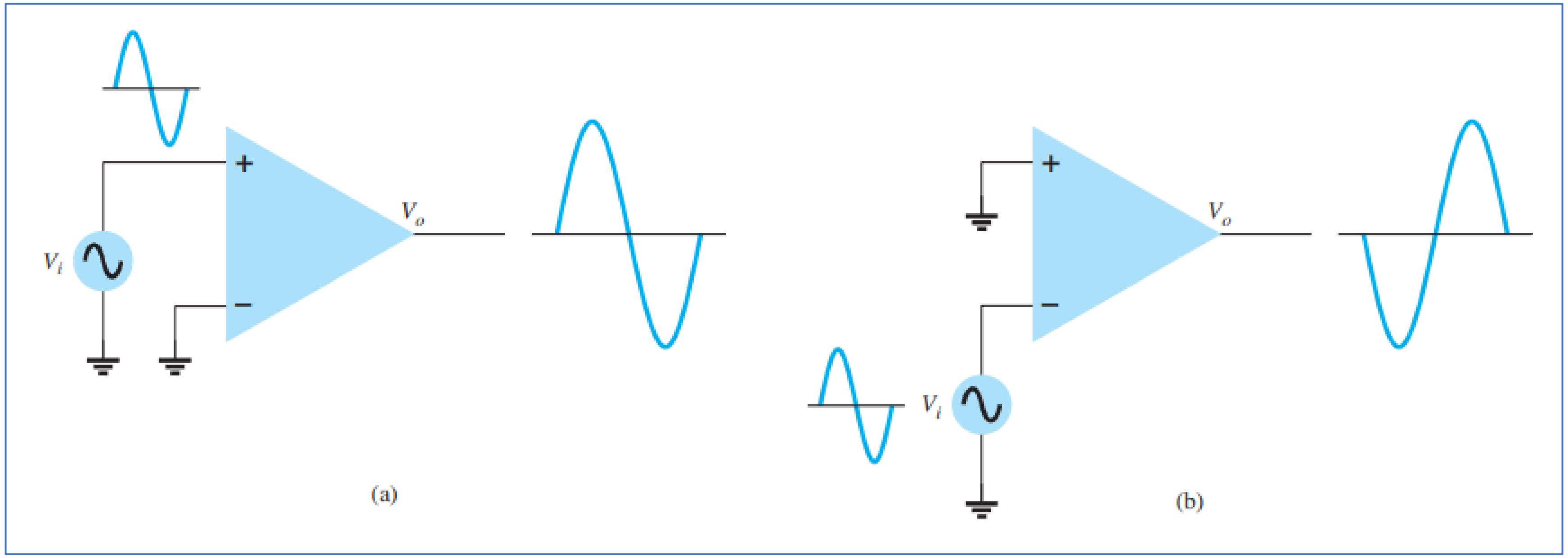
(c) Typical packages. Pin 1 is indicated by a notch or dot on dual in-line (DIP) and surface-mount technology (SMT) packages, as shown.

Op-amp symbols and packages

The standard operational amplifier (op-amp) symbol

Single-Ended Input

- Single-ended input operation results when the input signal is connected to one input with the other input connected to ground.
- Figure shows the signals connected for this operation.
- In Fig. a, the input is applied to the plus input (with minus input at ground), which results in an output having the same polarity as the applied input signal.
- Figure b shows an input signal applied to the minus input, the output then being opposite in phase to the applied signal.



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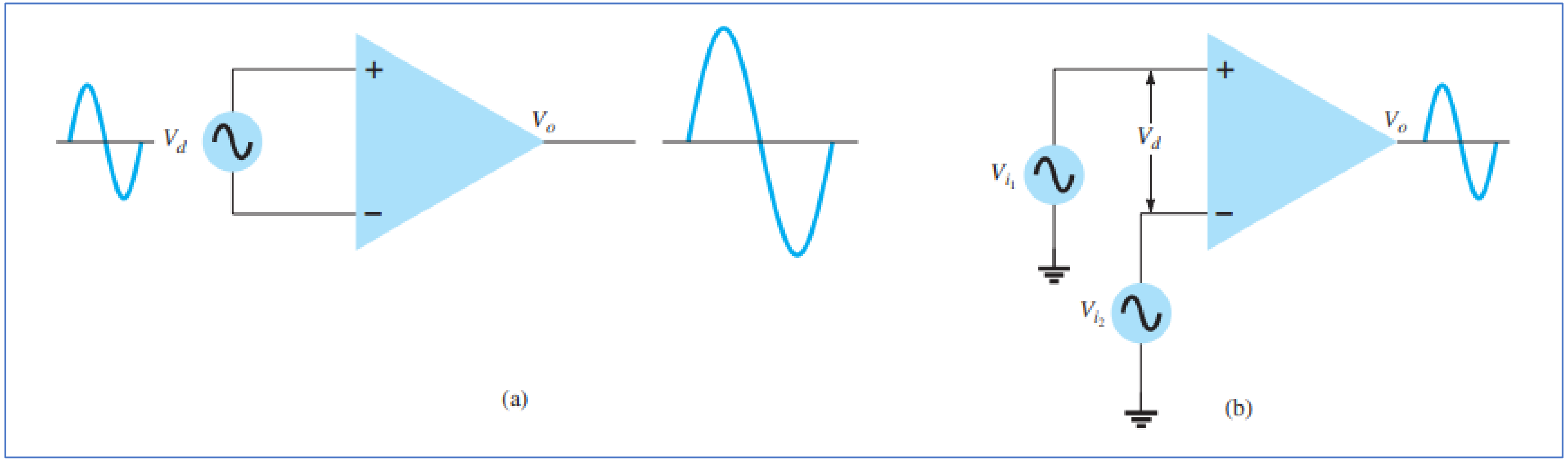
The standard operational amplifier (op-amp) symbol

Double-Ended (Differential) Input

- In addition to using only one input, it is possible to apply signals at each input—this being a double-ended operation.
- Figure a shows an input, V d , applied between the two input terminals (recall that neither input is at ground), with the resulting amplified output in phase with that applied between the plus and minus inputs.
- Figure b shows the same action resulting when two separate signals are applied to the inputs, the difference signal being Vi1 - Vi2 .



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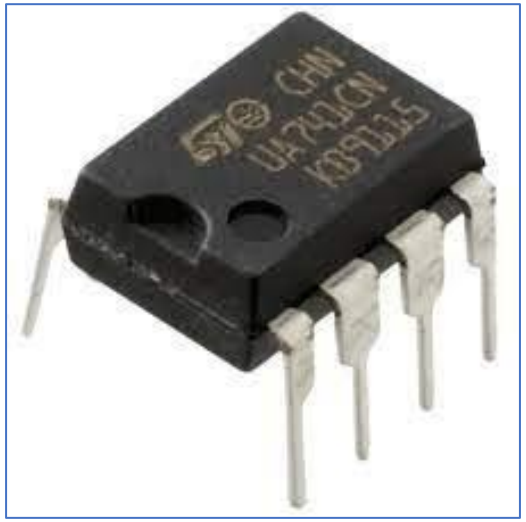
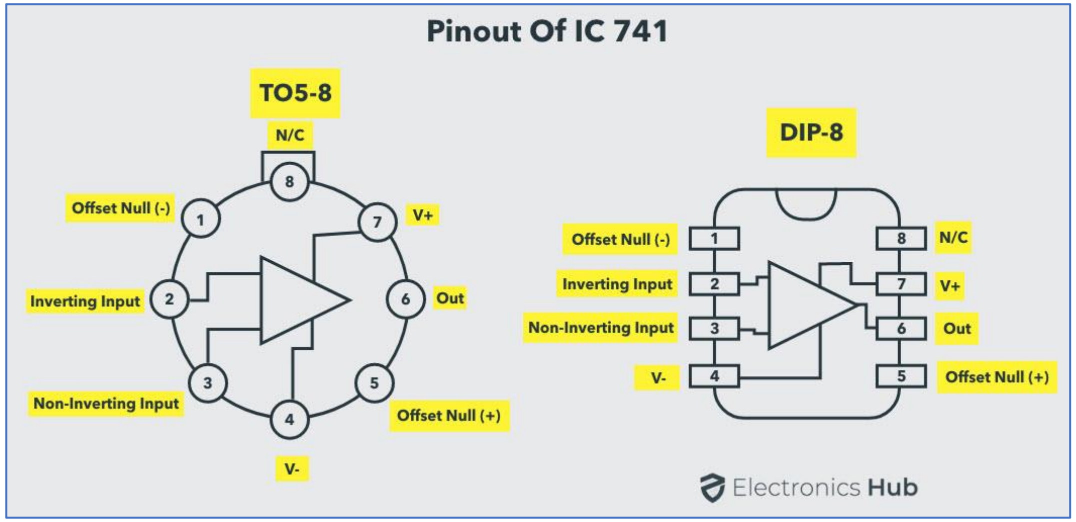
µA 741 A Classic Op-Amp

- Designed by David Fullagar of Fairchild Semiconductor in 1968.
- First commercial very successful operational amplifier IC.
- The µA741 is still in production, and has become universal in electronics.
- Several companies produce a version of this classic chip, recognizable by part numbers containing *741*.



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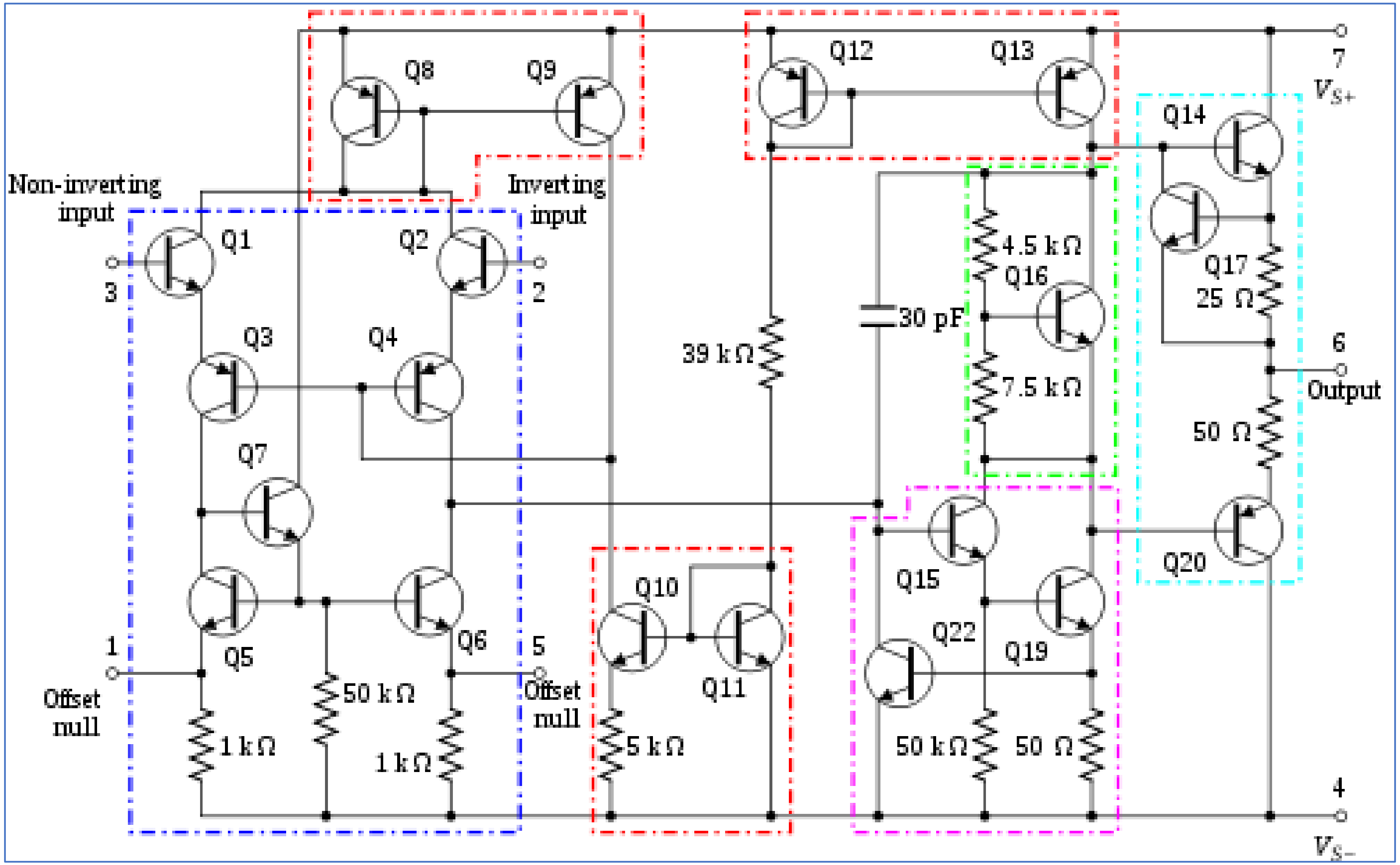
Op-Amp Architecture

- Differential Amp.
- Current mirror
- Class A amplifier
- Voltage level shifter
- Output stage



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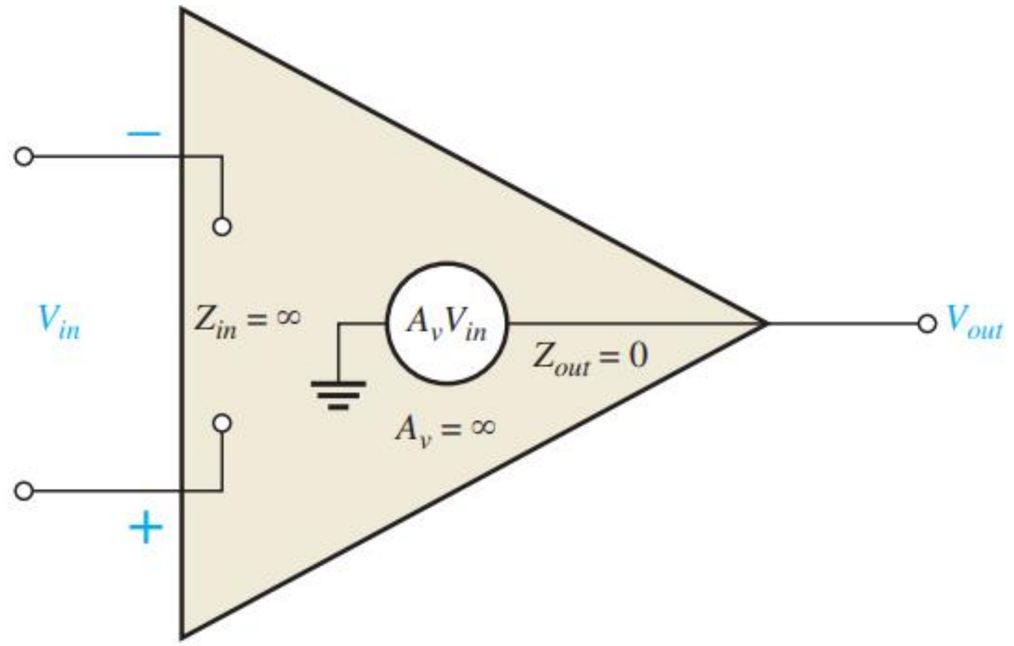
The Ideal Op-Amp

- **The Ideal Op-Amp**
- To illustrate what an op-amp is, let's consider its ideal characteristics. A practical op-amp, of course, falls short of these ideal standards, but it is much easier to understand and analyze the device from an ideal point of view.

- First, the ideal op-amp has **infinite voltage gain and infinite bandwidth.**
- Also, it has an **infinite input impedance** (open) so that it does not load the driving source.
- Finally, it has a **zero output impedance**.
- Op-amp characteristics are illustrated in Figure (a).
- The input voltage, Vin, appears between the two input terminals, and the output voltage is AvVin, as indicated by the internal voltage source symbol.



(a) Ideal op-amp representation

Ideal op-amp representation

The Ideal Op-Amp parameters

- **The characteristics of an ideal op-amp are as follows:**

  (i) Infinite input resistance, Ri = ∞

  (ii) Zero output resistance, Ro = 0

  (iii) Infinite voltage gain, Av = ∞

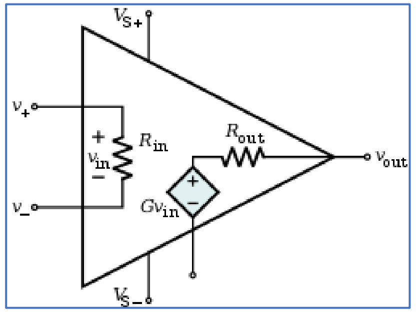
  (iv) Infinite bandwidth, BW = ∞

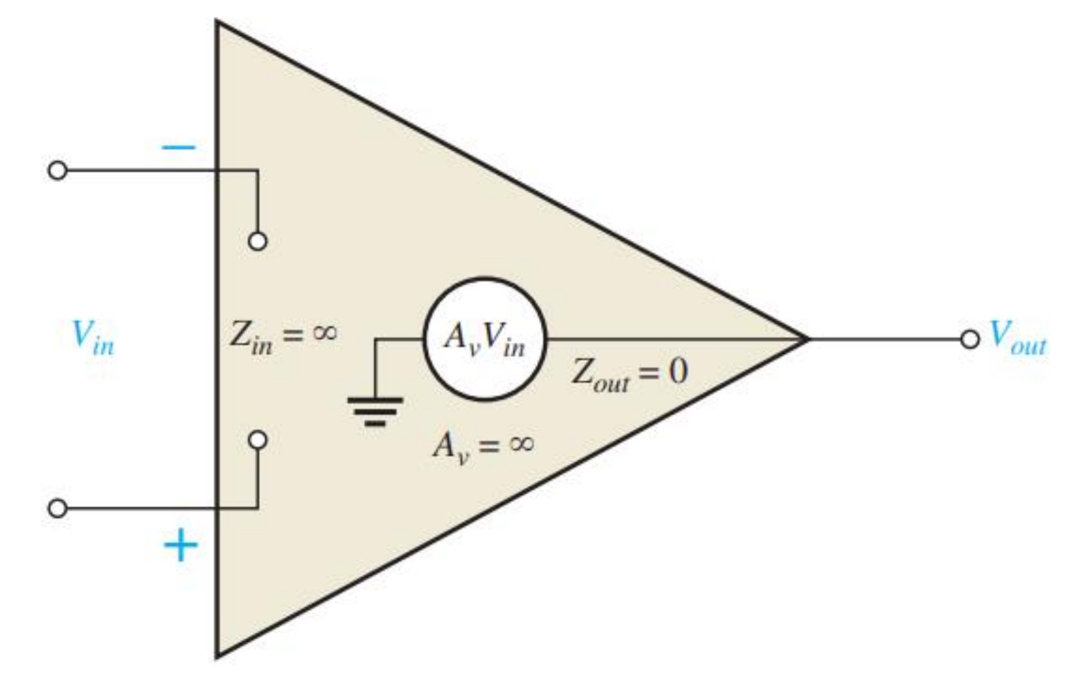
  (v) Infinite common-mode rejection ratio,CMRR = ∞

  (vi) Infinite slew rate, SR = ∞

  (vii) Zero offset, i.e. when v1 = v2, vo = 0

  (viii) Characteristics do not drift with temperature



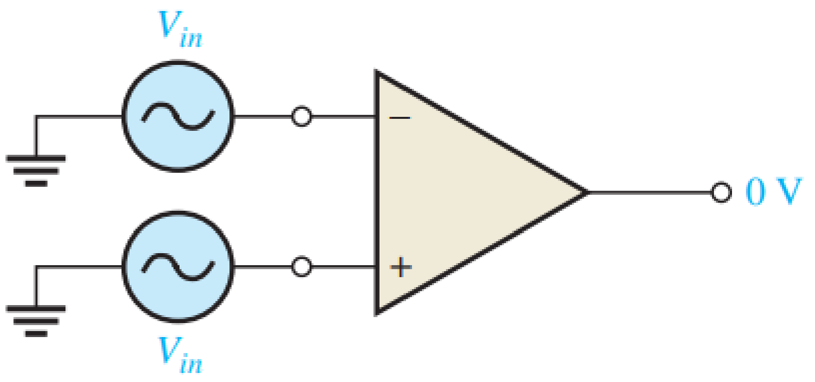


(a) Ideal op-amp representation

Ideal op-amp representation

The Ideal Op-Amp parameters

- **Common-Mode**
- Two signal voltages of the same phase, frequency and amplitude are applied to the two inputs as shown is figure 12-6.
- This results in a zero output voltage (as difference is 0V).
- This action is called common-mode rejection.



Common-mode operation.

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The Ideal Op-Amp parameters

- **<u>Common-Mode Rejection Ratio</u>** (CMRR = ∞)
- Desired signals can appear on only one input or with opposite polarities on both input lines.
- These desired signals are amplified and appear on the output.
- Unwanted signals (noise) appearing with the same polarity on both input lines are essentially cancelled by the op-amp and do not appear on the output.
- The measure of an amplifier's ability to reject common-mode signals is a parameter called the ***CMRR (common-mode rejection ratio)***

This suggests that a good measure of the op-amp's performance in rejecting unwanted common-mode signals is the ratio of the open-loop differential voltage gain, A_{ol}, to the common-mode gain, A_{cm}. This ratio is the common-mode rejection ratio, CMRR.

$$\mathrm{CMRR} = \frac{A_{ol}}{A_{cm}}$$

- The higher the CMRR, the better. A very high value of CMRR means that the open-loop gain, A_{ol}, is high and the common-mode gain, A_{cm}, is low.
- The CMRR is often expressed in decibels (dB) as : $\mathrm{CMRR} = 20 \log\left(\frac{A_{ol}}{A_{cm}}\right)$

The Ideal Op-Amp parameters

- **<u>Slew Rate</u>** (SR = ∞)
- The maximum rate of change of the output voltage in response to a step input voltage is the slew rate of an op-amp.
- The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp.

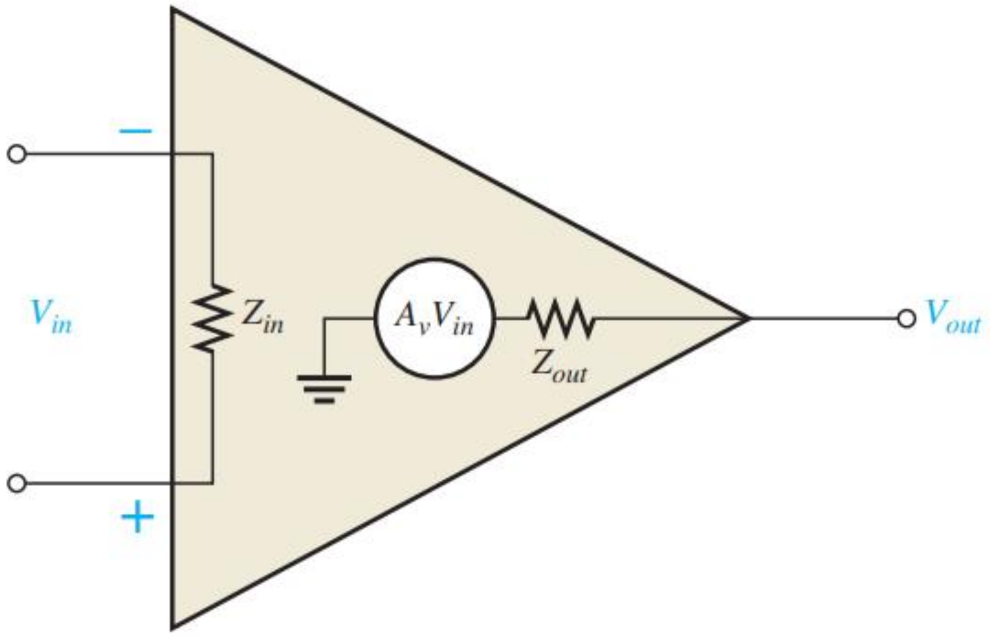
$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

- When the SR is too slow for the input, distortion results.
- For example when a input sine wave is applied to a voltage follower it produces a triangular output waveform.
- The triangular waveform results because the op-amp simply cannot move fast enough to follow the sine wave input.
- This happens because voltage change in the second stage (Voltage Amplifier(s)) is limited by the charging and discharging of capacitors.

The Practical Op-Amp parameters

- **The Practical Op-Amp**
- Although integrated circuit (IC) op-amps approach parameter values that can be treated as ideal in many cases, the ideal device can never be made.
- Any device has limitations, and the IC op-amp is no exception.
- Op-amps have both voltage and current limitations.
- Peak-to-peak output voltage, for example, is usually limited to slightly less than the two supply voltages.
- Output current is also limited by internal restrictions such as power dissipation and component ratings.

- Characteristics of a practical op-amp are **very high voltage gain, very high input impedance, and very low output impedance**.
- These are labelled in Figure (b).



(b) Practical op-amp representation

Practical op-amp representation

- Another practical consideration is that there is always noise generated within the op-amp.
- Noise is an undesired signal that affects the quality of a desired signal.
- Today, circuit designers are using smaller voltages that require high accuracy, so low-noise components are in greater demand.

Op-Amp configurations

- Configuration of op-amp means the ways in which an op-amp is connected in circuit.
- Based on the connection, the op-amp can work in two different modes.

  1. Open loop mode

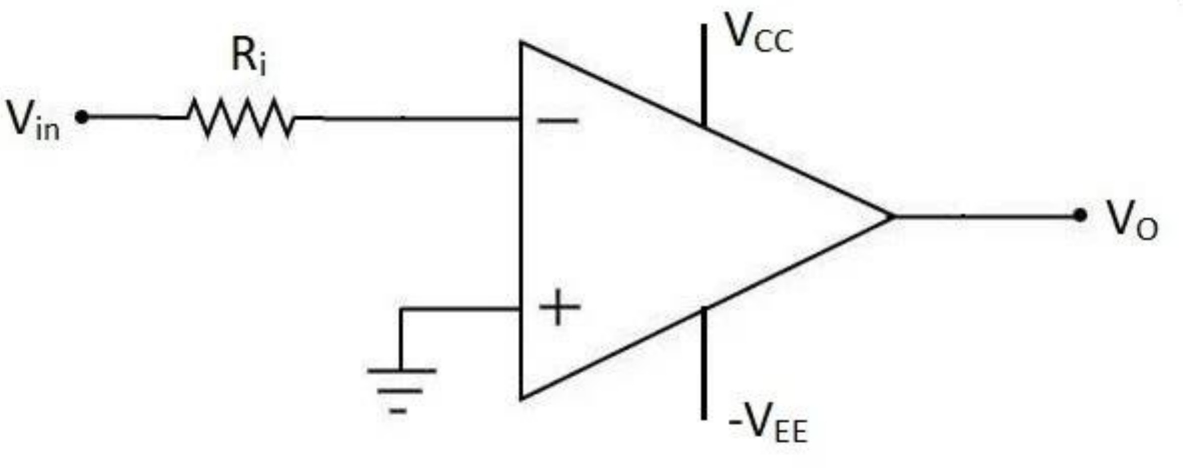
  2. Closed loop mode

Open Loop Configuration of Op-amp

- When no part of output is connected to input, it is known as open loop configuration. It means that there is absolutely no feedback present from output to Input.
- The output assumes one of the two possible output states, that is +Vsat or –Vsat and the amplifier acts as a switch only.

- The voltage transfer curve indicates the inability of op-amp to work as a linear small signal amplifier in the open loop mode
- Such an open loop behavior of the op-amp finds some rare applications like voltage amplifier, zero crossing detector etc.

Following figure shows an open loop configuration of op-amp.



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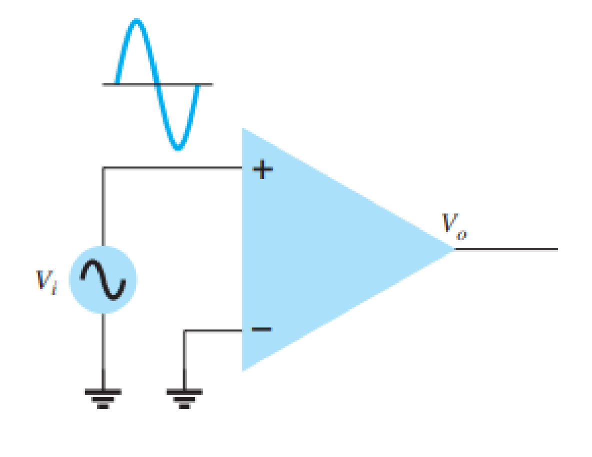
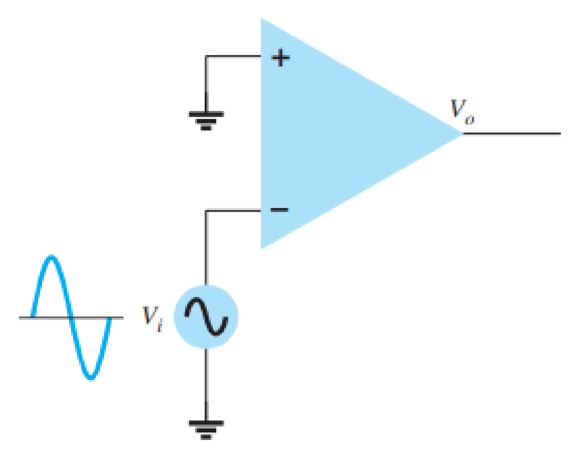
Open Loop Configuration of Op-amp

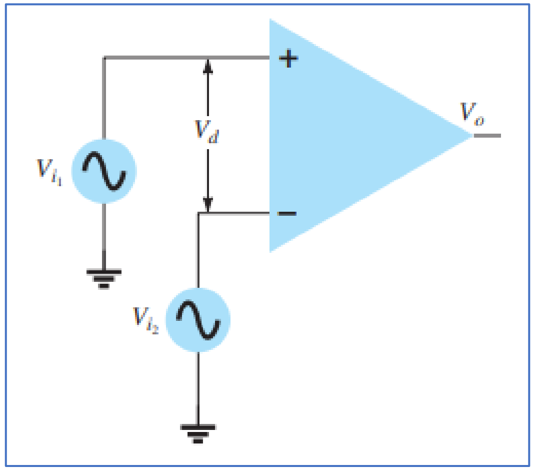
- The configuration in which output depends on input, but output has no effect on the input is called open loop configuration.
- No feedback from output to input is used in such configuration.
- **The op-amp works as high gain amplifier**

- The op-amp can be used in three modes in open loop configuration they are:

1. Differential amplifier
2. Inverting amplifier
3. Non-inverting amplifier







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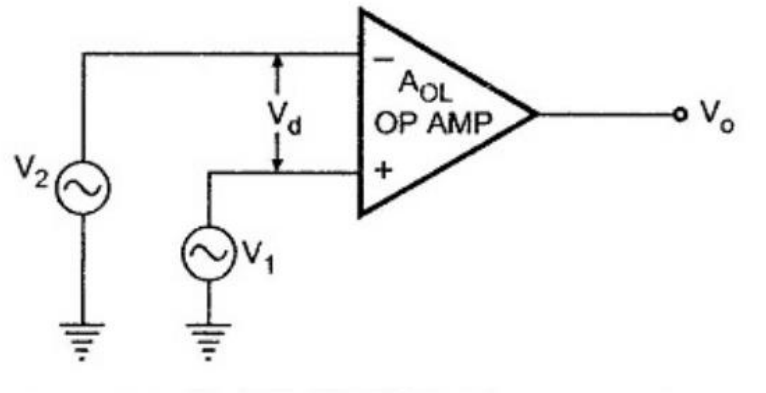
Open Loop Configuration of Op-amp

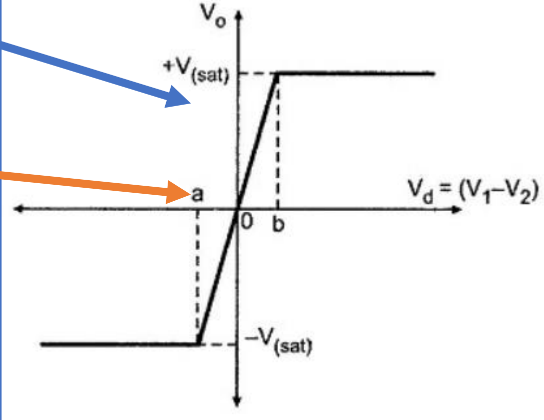
- The simplest possible way to use an operational amplifier is in the open loop mode. The Fig. shows an Open Loop Configuration of Op amp.

- We know that the d.c. supply voltages applied to the op-amp are V_{CC} and -V_{EE} and the output varies linearly only between V_{CC} and -$V_{EE.}$
- Since gain is very large in open loop condition, the output voltage V_o is either at its positive saturation voltage (+ V_{sat}) or negative saturation voltage (- V_{sat}) as $V_1 > V_2$ or $V_2 > V_1$ respectively. This is shown in the Fig.



Open loop operation of an op-amp

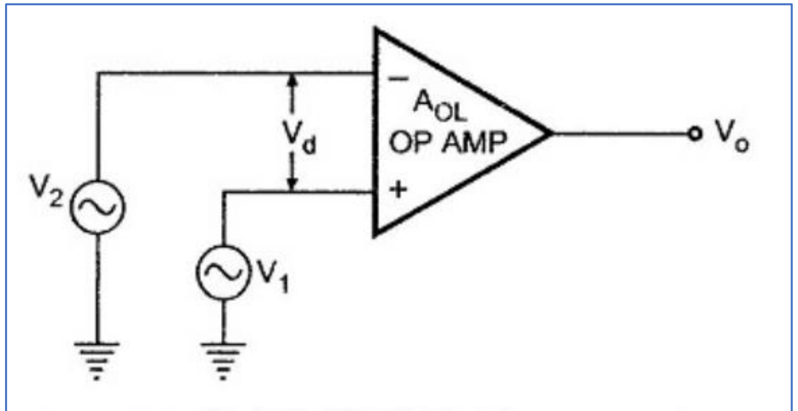
- Thus very small noise voltage present at the input also gets amplified due to its high open loop gain and operational amplifier gets saturated.
- It can be seen from the Fig., only for small range of input signal (from point a to b), it behaves linearly.
- This range is very small and practically due to high open loop gain, op-amp either shows + V_{sat} or – V_{sat} level.
- This indicates the inability of op-amp to work as a linear small signal amplifier in the <u>open loop mode</u>.
- Hence, the op-amp is generally not used in the open loop configurations.
- Such an open loop behavior of the operational amplifier finds some rare applications like voltage comparator, zero crossing detector etc.



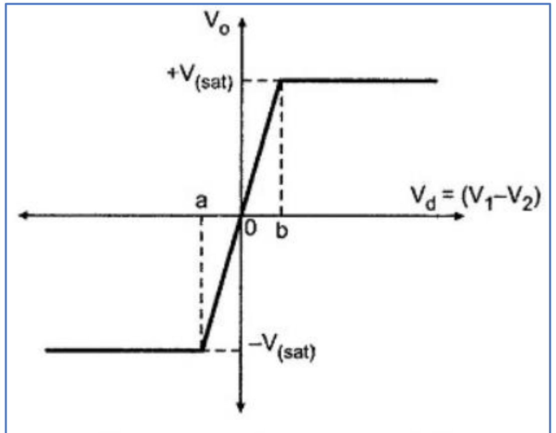
Voltage transfer characteristics

Open Loop Configuration of Op-amp

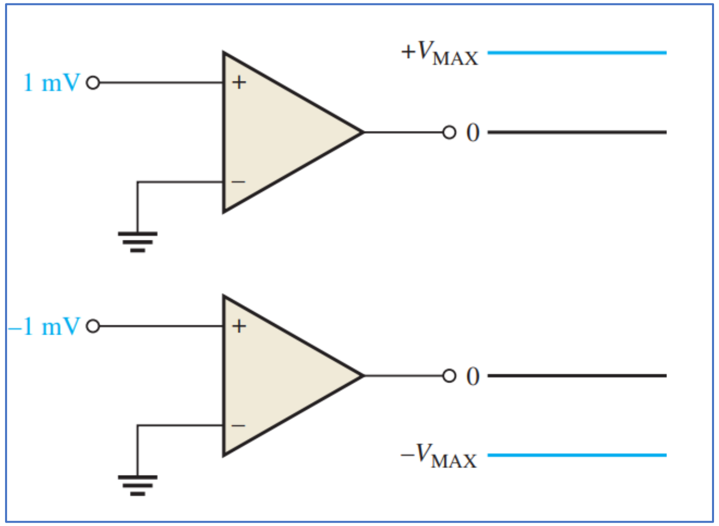
- **Why op-amp is generally not used in open loop mode?**
- As open loop gain is very large, very small input voltage drives the op-amp voltage to the saturation level.
- Thus in open loop configuration, the output is at its positive saturation voltage (+V sta) or negative saturation voltage (-Vsat) depending on which input V1 or V2 is more than the other.
- For A.C. input voltages, output may switch between positive and negative saturation voltages.



Open loop operation of an op-amp



Voltage transfer characteristics



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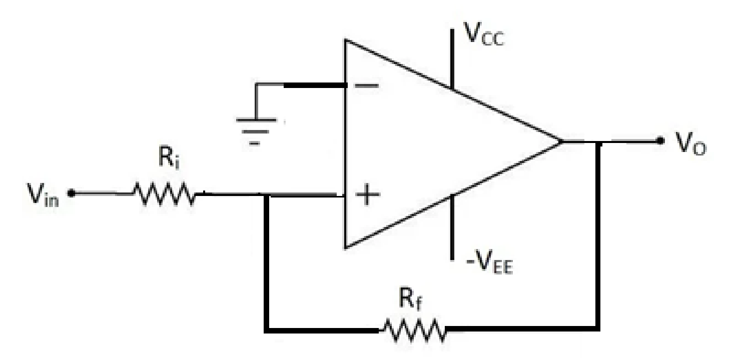
Close Loop Configuration of Op-amp

- When a part of output is connected to (or fed back to) the input, it is called as closed loop configuration.
- It means that, some kind of feedback is present in the circuit.

Types of feedback: 1. Positive feedback or regenerative feedback. 2. Negative feedback or degenerative feedback

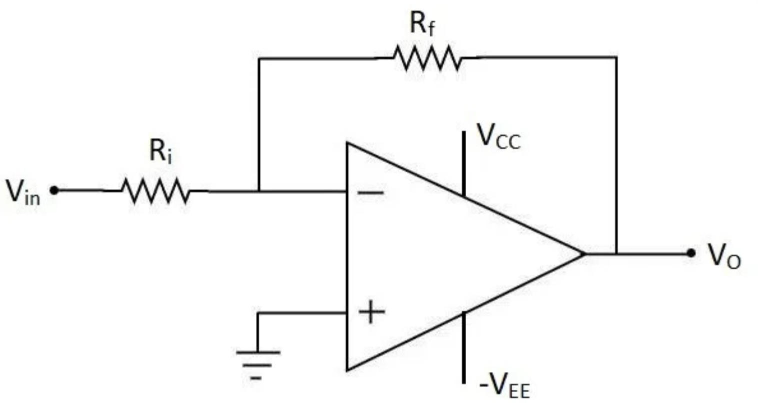
Positive Feedback

- In positive feedback, the feedback signal and the original input signal are **in phase** with each.
- Here, the feedback is present between **non-inverting terminal** (+) through resistor Rf.
- It is used in oscillators and Schmitt triggers.



Negative Feedback

- If the feedback signal and the original input signal are **180° out of phase**, then it is called as negative feedback. Here the feedback is present between output and **inverting terminal** (-) through resistor Rf. Negative feedback is used in almost every circuit using op-amp.
- For example, circuits like inverting op-amp, adder, subtractor and integrator use negative feedback.



Comparison of Open Loop and Closed Loop

Sr. No.	Parameter	Open Loop	Closed Loop
1	Type of feedback	No feedback	Positive or negative feedback
2	Voltage gain	Very high	Low
3	Input resistance	Very high	Depends on the circuit
4	Output resistance	Low	Very low
5	Bandwidth	High	Very high
6	Drawback	Waveform distortion	Low gain
7	Configuration	Differential, Inverting, Non-inverting	Inverting, Non-inverting, Summing
8	Application	Comparator	Amplifier, Oscillator

Advantages Of Negative Feedback

1. Reduces the distortion.
2. Reduces and stabilizes the gain.
3. Increases the bandwidth.
4. Changes values of input and output resistance.
5. Reduces the effects of variations in temperature and supply voltage on the output of Op-amp.

	VOLTAGE GAIN	INPUT Z	OUTPUT Z	BANDWIDTH
Without negative feedback	A_{ol} is too high for linear amplifier applications	Relatively high	Relatively low	Relatively narrow (because the gain is so high)
With negative feedback	A_{cl} is set to desired value by the feedback circuit	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider

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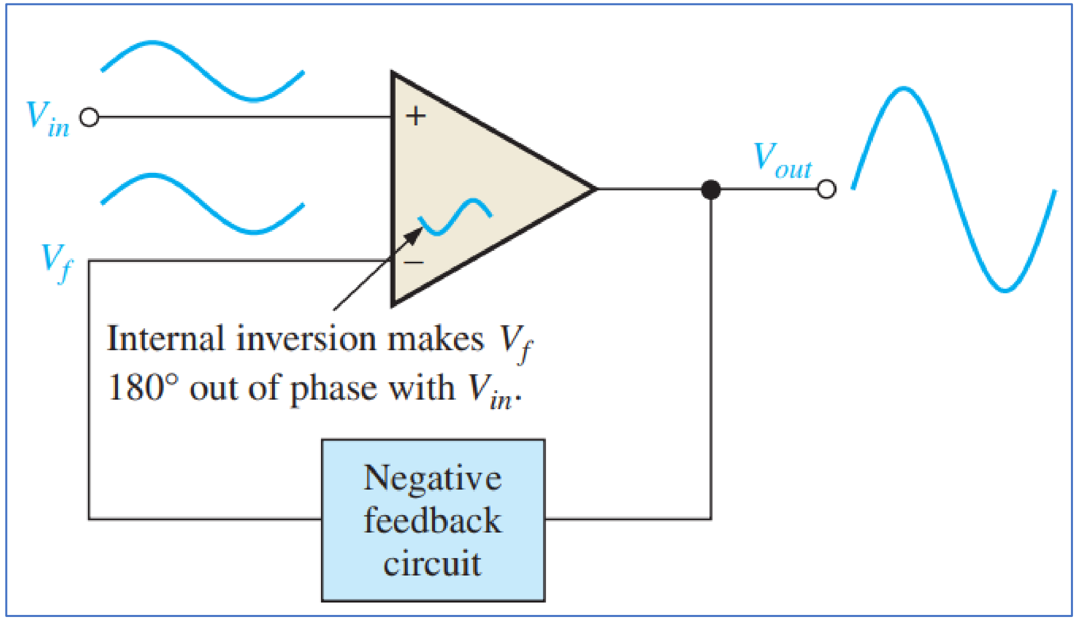
Negative feedback in OP-AMP

- Negative feedback is one of the most useful concepts in electronics, particularly in op-amp applications.
- Negative feedback is the process whereby a portion of the output voltage of an amplifier is returned to the input with a phase angle that opposes (or subtracts from) the input signal.

- Negative feedback is illustrated in Figure .
- The inverting input effectively makes the feedback signal 180° out of phase with the input signal.



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Why Use Negative Feedback?

- Typical op-amps have an open-loop gain on the order of 10^5 (100 dB).
- Without feedback, op-amps make circuit design difficult because of high gain sensitivity.
- Negative feedback makes it possible to set the gain and cut-off frequency to the desired values, thereby improving their stability and reducing performance variation, part-to-part variation, and sensitivity to temperature and other environmental parameters.

- Open-loop voltage gain of a typical op-amp is very high (usually greater than 100,000).
- Therefore, an extremely small input voltage drives the op-amp into its saturated output states.
- In fact, even the input offset voltage of the op-amp can drive it into saturation. For example, assume V_{IN} =1 mV and A_{ol} =100,000. Then,

$$V_{IN} A_{ol} = (1 \text{ mV})(100{,}000) = 100 \text{ V}$$

Since the output level of an op-amp can never reach 100 V, it is driven deep into saturation and the output is limited to its maximum output levels

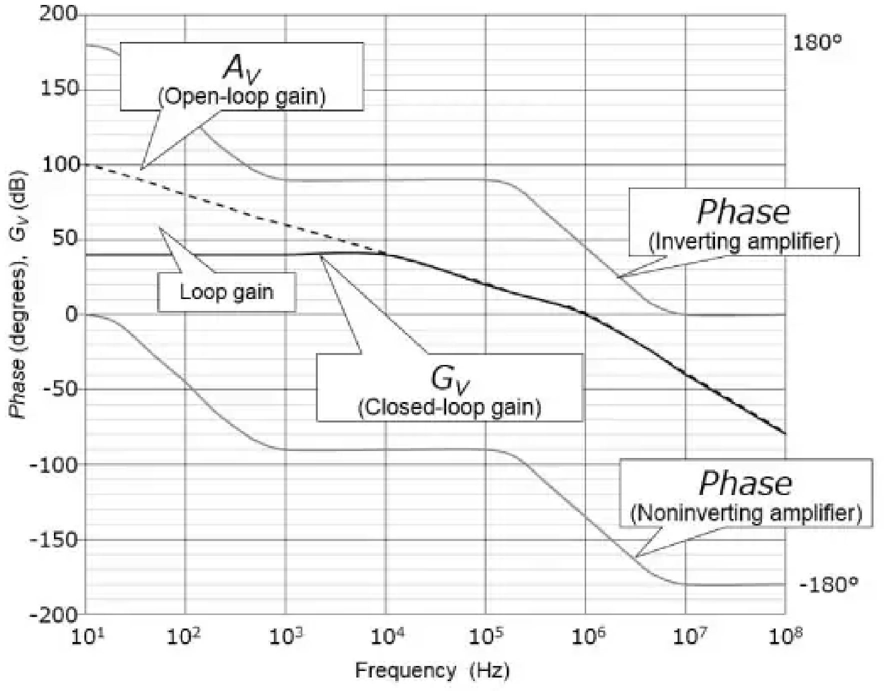

Figure: Bode plot of an op-amp

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Op-Amps with negative feedback

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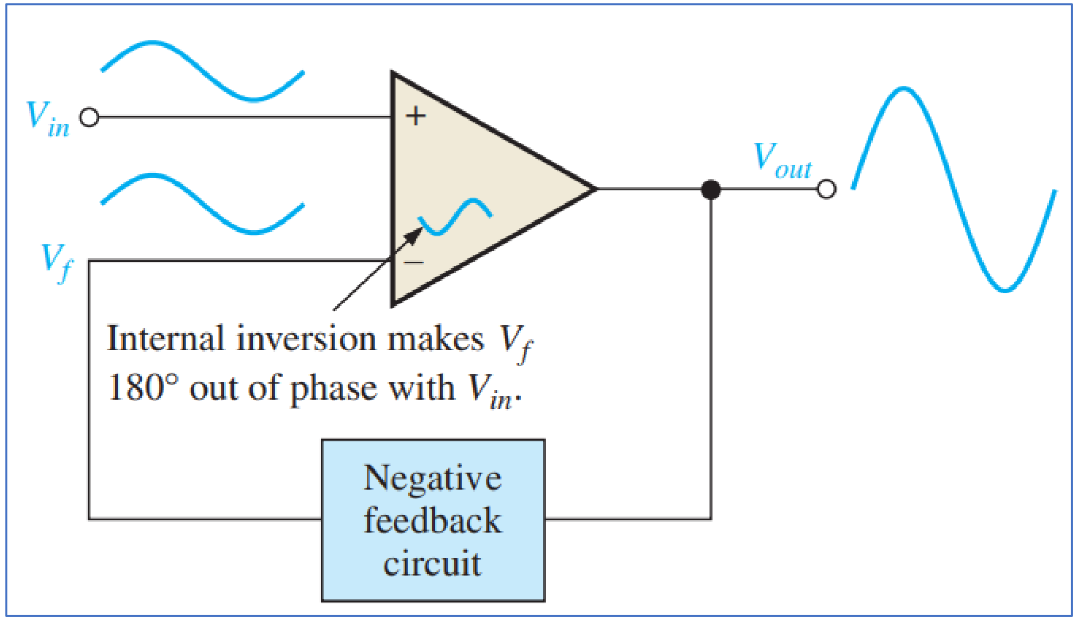

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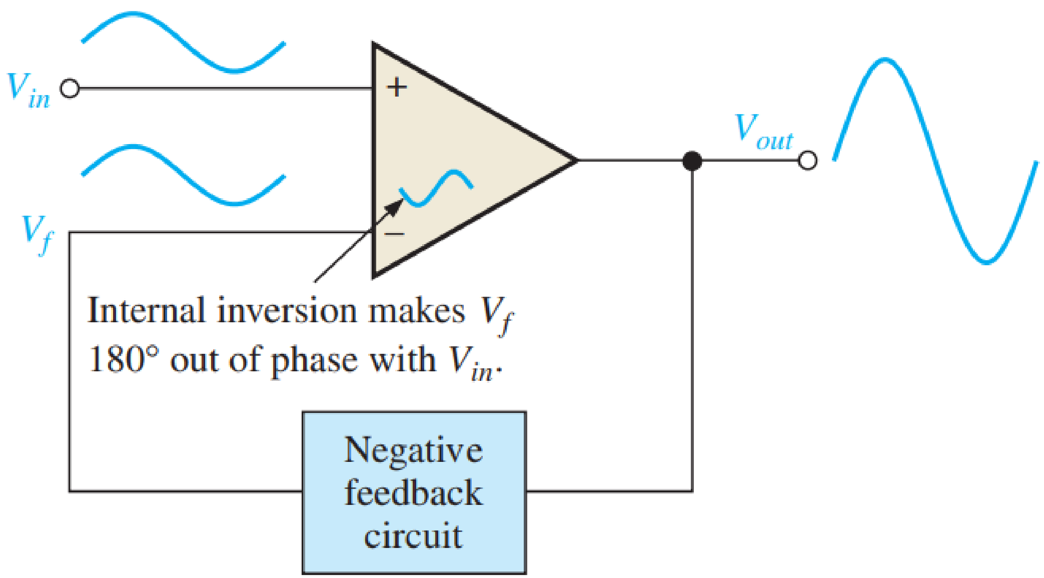
Op-Amps with negative feedback *(From:-Thomas L. Floyd)*

- An op-amp can be connected using negative feedback to stabilize the gain and increase frequency response.
- Negative feedback takes a portion of the output and applies it back out of phase with the input, creating an effective reduction in gain.
- This closed-loop gain is usually much less than the open-loop gain and independent of it.

<u>Closed-Loop Voltage Gain, Acl</u>

- The closed-loop voltage gain is the voltage gain of an op-amp with external feedback.
- The amplifier configuration consists of the op-amp and an external negative feedback circuit that connects the output to the inverting input.
- The closed-loop voltage gain is determined by the external component values and can be precisely controlled by them.



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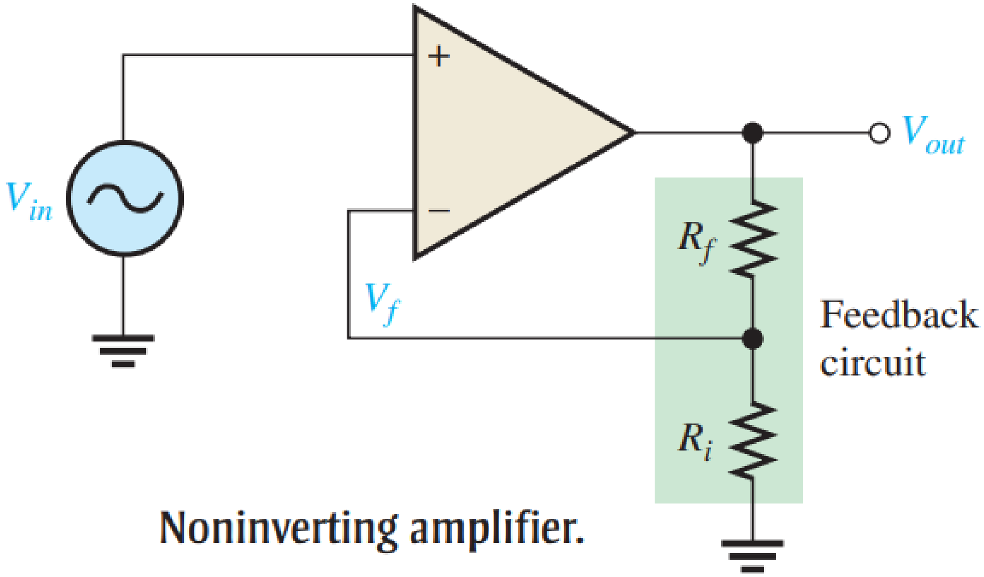
Op-Amps with negative feedback *(From:-Thomas L. Floyd)*

- **Noninverting Amplifier**
- An op-amp connected in a **closed-loop** configuration as a noninverting amplifier with a controlled amount of voltage gain is shown in Figure. ***The input signal is applied to the noninverting (+) input.***
- The output is applied back to the inverting input through the feedback circuit (closed loop) formed by the input resistor Ri and the feedback resistor Rf.
- This creates negative feedback as follows. Resistors Ri and Rf form a voltage-divider circuit, which reduces Vout and connects the reduced voltage Vf to the inverting input.



Noninverting amplifier.

The feedback voltage is expressed as

$$V_f = \left(\frac{R_i}{R_i + R_f}\right)V_{out}$$

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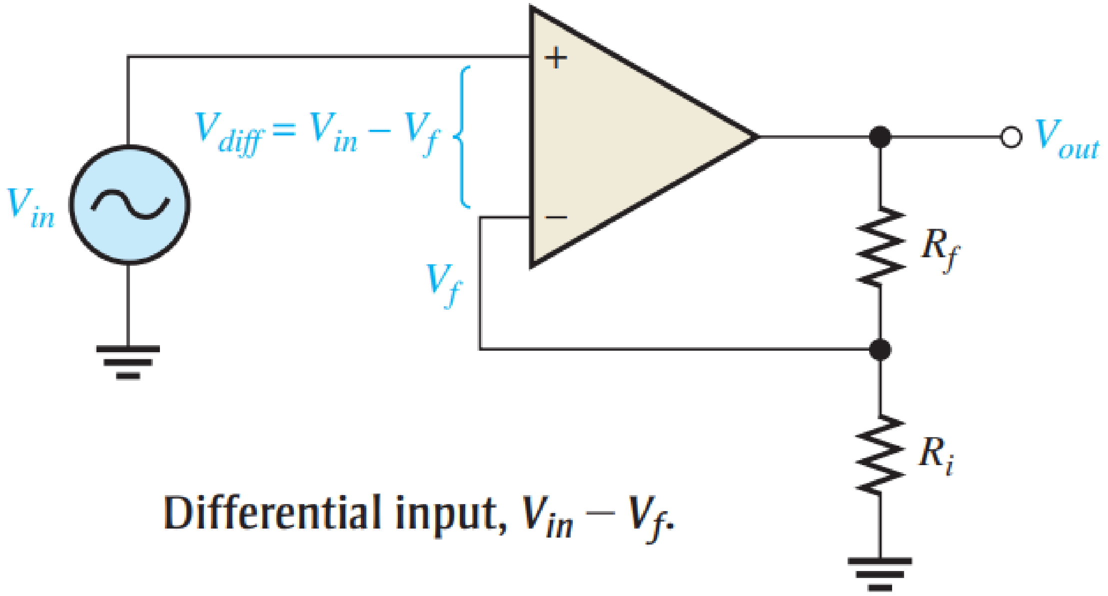
- **Noninverting Amplifier**

The difference of the input voltage, *Vin*, and the feedback voltage, *Vf*, is the differential input to the op-amp, as shown in Figure. This differential voltage is amplified by the open-loop voltage gain of the op-amp *(Aol)* and produces an output voltage expressed as



Differential input, $V_{in} - V_f$.

$$V_{out} = A_{ol}(V_{in} - V_f)$$

The attenuation, B, of the feedback circuit is

$$B = \frac{R_i}{R_i + R_f}$$

Substituting *BVout* for *Vf* in the *Vout* equation,

$$V_{out} = A_{ol}(V_{in} - BV_{out})$$

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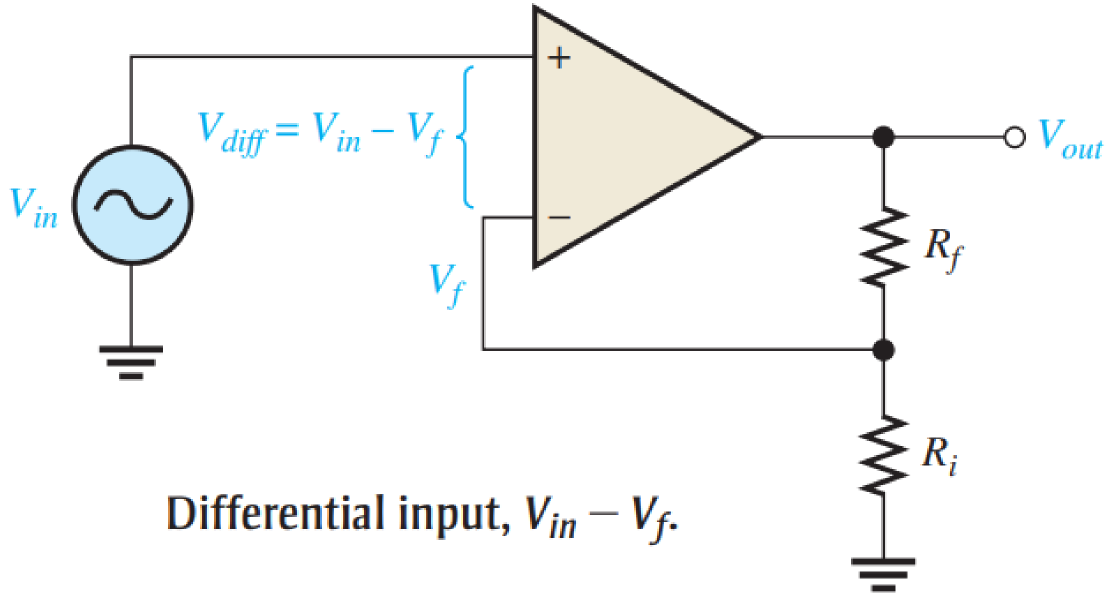
- **Noninverting Amplifier**



Differential input, $V_{in} - V_f$.

Substituting *BVout* for *Vf* in the *Vout* equation,

$$V_{out} = A_{ol}(V_{in} - BV_{out})$$

Then applying basic algebra,

$$V_{out} = A_{ol}V_{in} - A_{ol}BV_{out}$$

$$V_{out} + A_{ol}BV_{out} = A_{ol}V_{in}$$

$$V_{out}(1 + A_{ol}B) = A_{ol}V_{in}$$

Since the overall voltage gain of the amplifier in Figure is, it can be expressed as:

$$\frac{V_{out}}{V_{in}} = \frac{A_{ol}}{1 + A_{ol}B}$$

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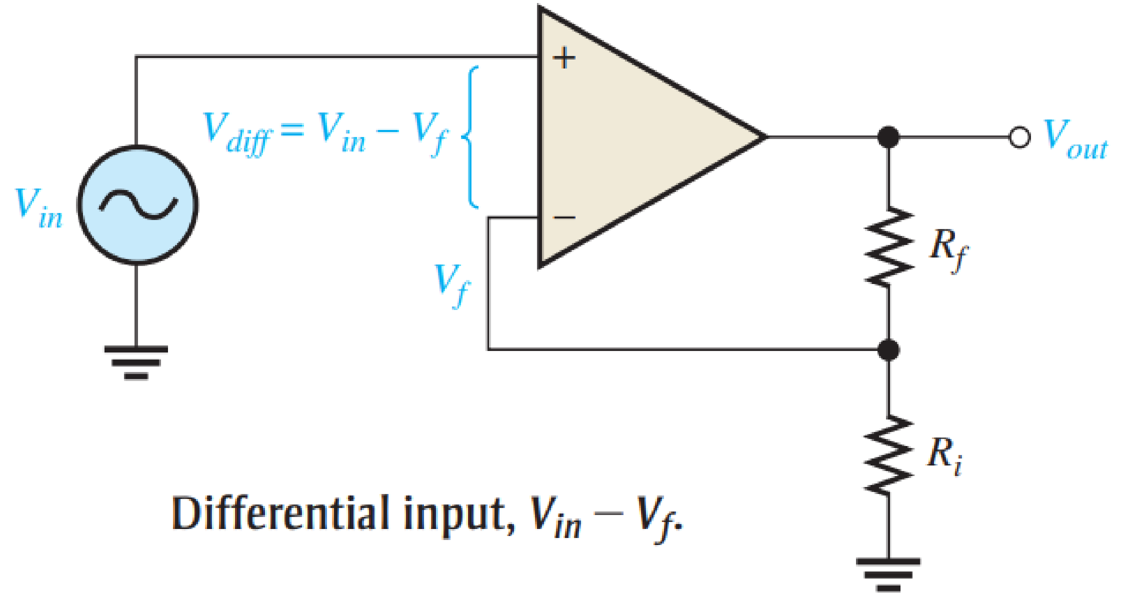
- **Noninverting Amplifier**



Differential input, $V_{in} - V_f$.

Since the overall voltage gain of the amplifier in Figure is, it can be expressed as:

$$\frac{V_{out}}{V_{in}} = \frac{A_{ol}}{1 + A_{ol}B}$$

The product AolB is typically much greater than 1, so the equation simplifies to

$$\frac{V_{out}}{V_{in}} \cong \frac{A_{ol}}{A_{ol}B} = \frac{1}{B}$$

The closed-loop gain of the noninverting (NI) amplifier is the reciprocal of the attenuation (B) of the feedback circuit (voltage-divider).

$$A_{cl(\mathrm{NI})} = \frac{V_{out}}{V_{in}} \cong \frac{1}{B} = \frac{R_i + R_f}{R_i}$$

Therefore,

$$A_{cl(\mathrm{NI})} = 1 + \frac{R_f}{R_i}$$

The closed-loop gain can be set by selecting values of Ri and Rf

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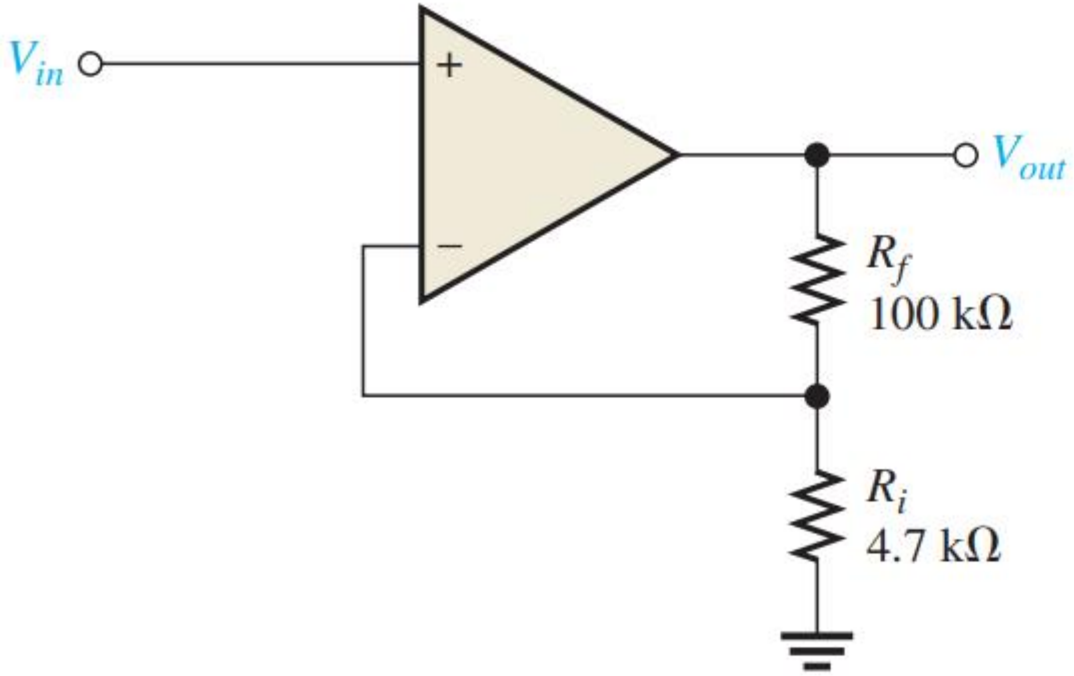
- **Noninverting Amplifier**

EXAMPLE Determine the closed-loop voltage gain of the amplifier in Figure



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- **Noninverting Amplifier**

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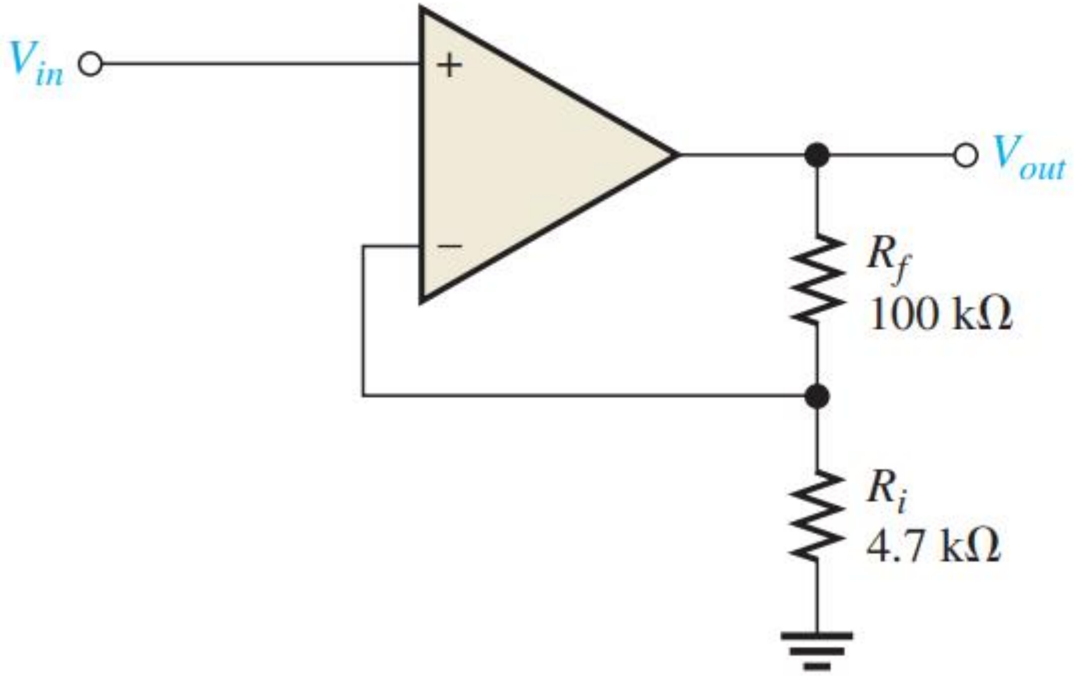

Solution

This is a noninverting op-amp configuration.

Therefore, the closed-loop voltage gain is

$$A_{cl(NI)} = 1 + \frac{R_f}{R_i}$$

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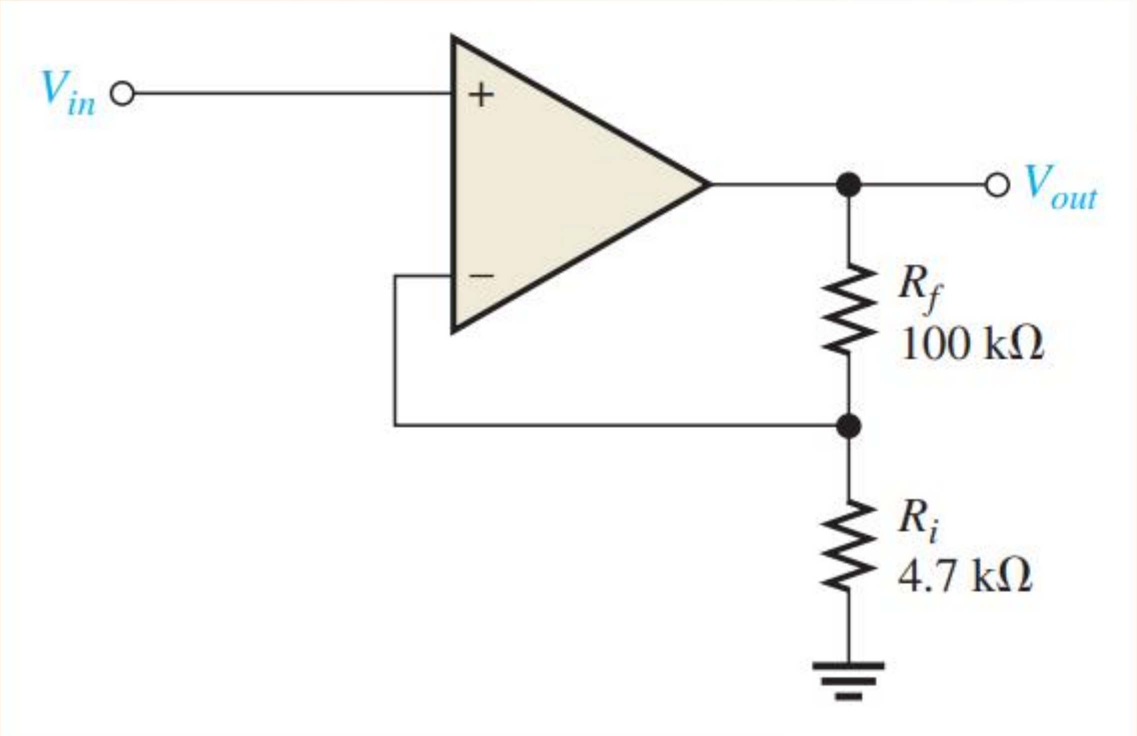
- **Noninverting Amplifier**

EXAMPLE Determine the closed-loop voltage gain of the amplifier in Figure



Solution

This is a noninverting op-amp configuration.

Therefore, the closed-loop voltage gain is

$$A_{cl(NI)} = 1 + \frac{R_f}{R_i} = 1 + \frac{100\ \text{k}\Omega}{4.7\ \text{k}\Omega} = \mathbf{22.3}$$

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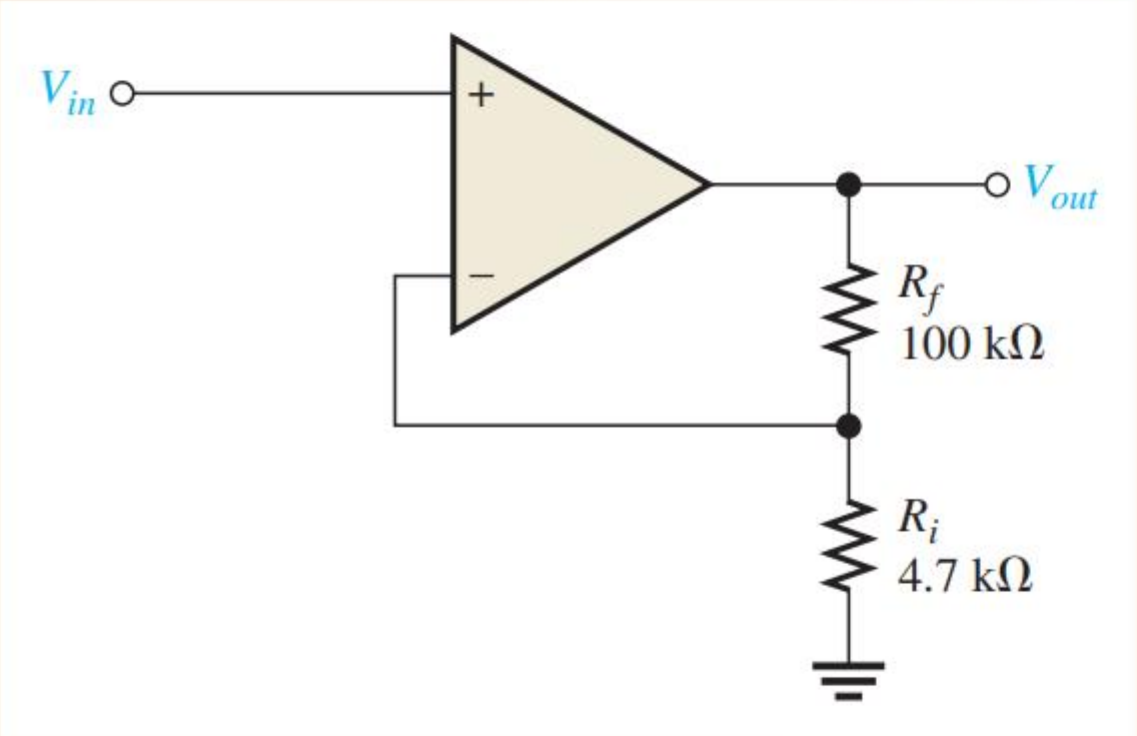
- **Noninverting Amplifier**

EXAMPLE Determine the closed-loop voltage gain of the amplifier in Figure



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Related Problem If R_f in Figure is increased to 150 kΩ, determine the closed-loop gain.

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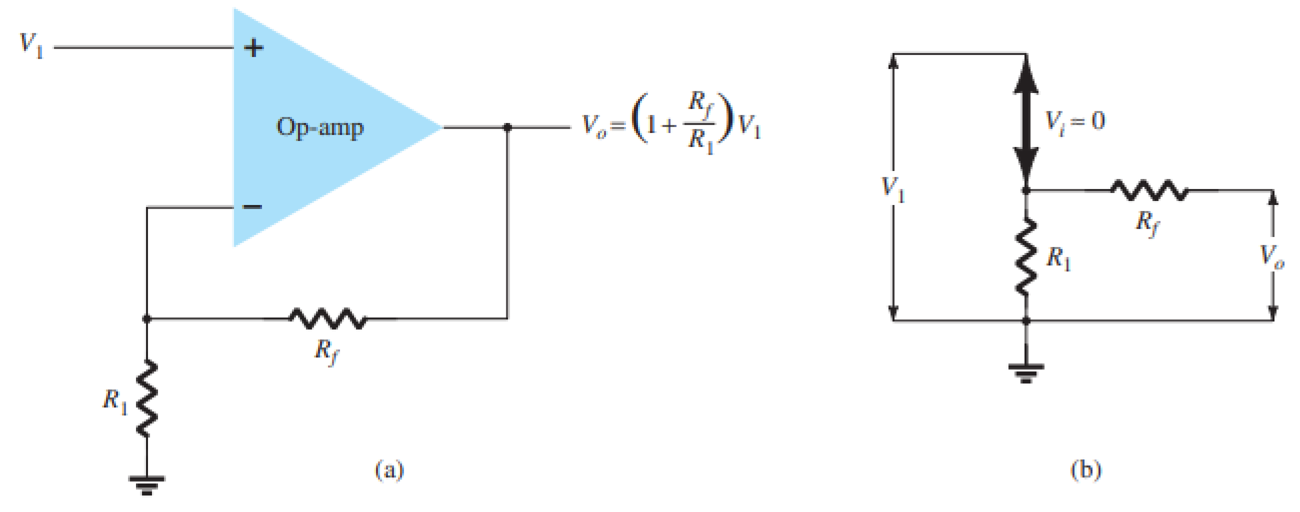
- **Noninverting Amplifier**

- The connection of Fig (a). a shows an op-amp circuit that works as a noninverting amplifier or constant-gain multiplier.
- It should be noted that the inverting amplifier connection is more widely used because it has better frequency stability.
- To determine the voltage gain of the circuit, we can use the equivalent representation shown in Fig. (b).
- Note that the voltage across R_1 is V_1 since $Vi \approx 0$ V.
- This must be equal to the output voltage, through a voltage divider of R_1 and R_f, so that



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

which results in

$$\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

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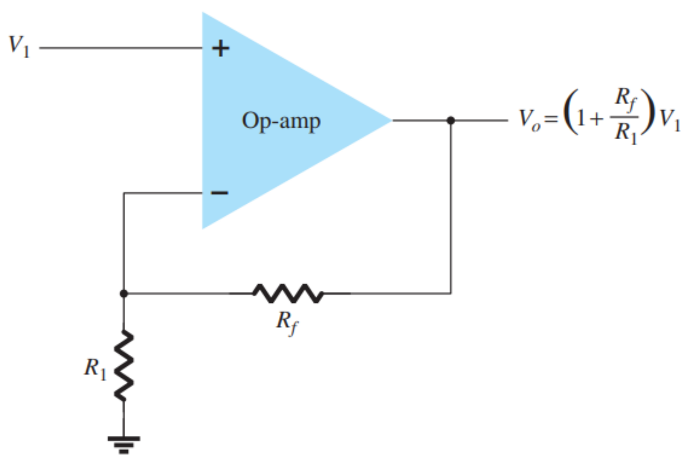
Op-Amps with negative feedback *(From:-* Boylestad*)*

- **Noninverting Amplifier**

EXAMPLE Calculate the output voltage of a noninverting amplifier (as in Fig.) for values of $V_1 = 2$ V, $R_f = 500$ kΩ, and $R_1 = 100$ kΩ.



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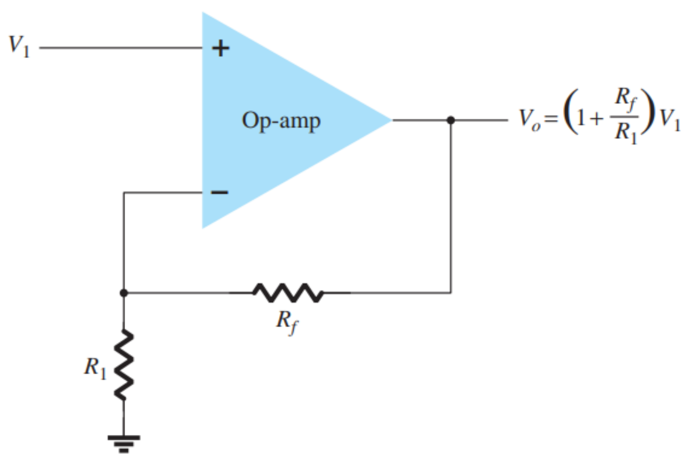
Solution:

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



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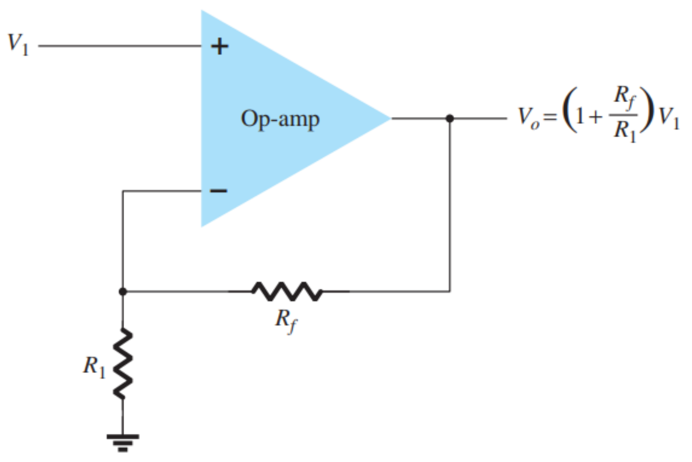
Solution:

$$V_o = \left(1 + \frac{R_f}{R_1}\right)V_1 = \left(1 + \frac{500\text{ k}\Omega}{100\text{ k}\Omega}\right)(2\text{ V}) =$$



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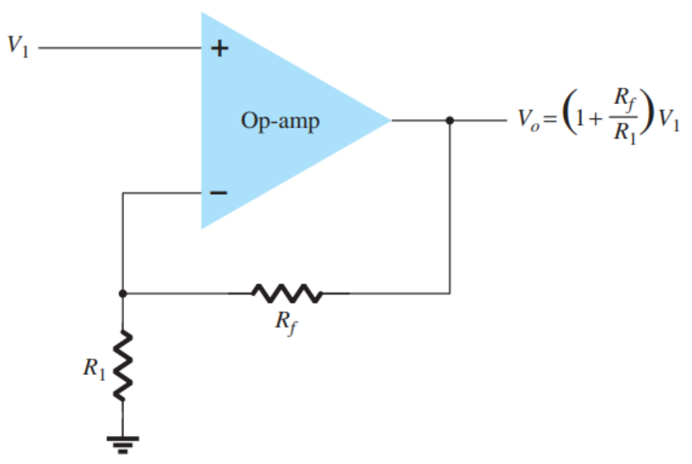
Solution:

$$V_o = \left(1 + \frac{R_f}{R_1}\right)V_1 = \left(1 + \frac{500\text{ k}\Omega}{100\text{ k}\Omega}\right)(2\text{ V}) = 6(2\text{ V}) = \mathbf{+12\text{ V}}$$



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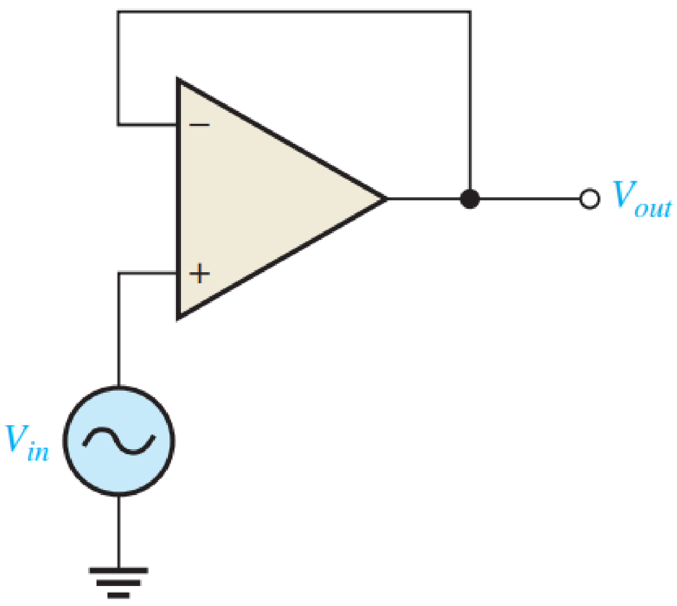
- **Unity Follower** (Voltage-Follower)

- The voltage-follower configuration is a special case of the noninverting amplifier where all of the output voltage is fed back to the inverting input by a straight connection, as shown in Figure .
- As you can see, the straight feedback connection has a voltage gain of 1 (which means there is no gain).

Op-amp voltage-follower.



for a voltage-follower, the closed-loop voltage gain of the voltage-follower is

$$A_{cl(VF)} = 1$$

- The most important features of the voltage-follower configuration are its very high input impedance and its very low output impedance.
- These features make it a nearly ideal buffer amplifier for interfacing high-impedance sources and low-impedance loads.

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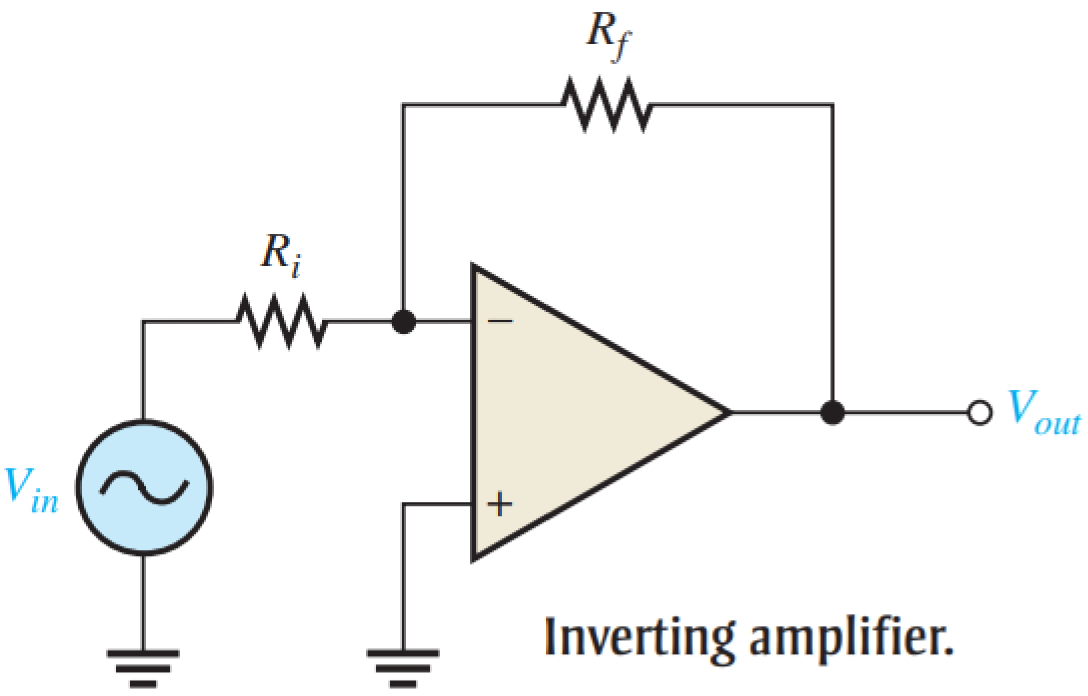
- **Inverting Amplifier**

- An op-amp connected as an inverting amplifier with a controlled amount of voltage gain is shown in Figure.
- The input signal is applied through a series input resistor Ri to the inverting input.
- Also, the output is fed back through Rf to the same input. The noninverting (+) input is grounded



Inverting amplifier.

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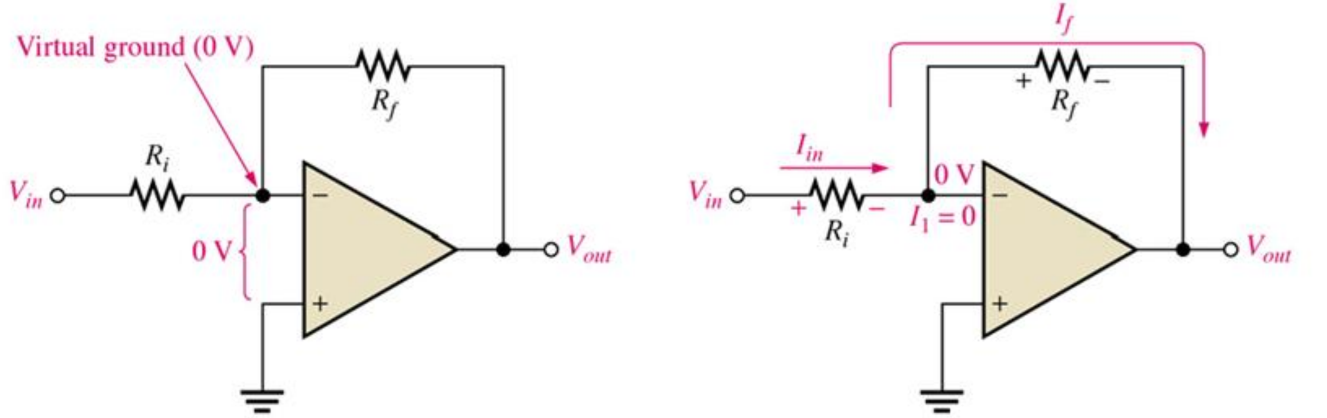
• Inverting Amplifier

- At this point, the ideal op-amp parameters mentioned earlier are useful in simplifying the analysis of this circuit.
- In particular, the concept of infinite input impedance is of great value.
- An infinite input impedance implies zero current at the inverting input.
- If there is zero current through the input impedance, then there must be no voltage drop between the inverting and noninverting inputs.
- This means that the voltage at the inverting (-) input is zero because the noninverting (+) input is grounded.
- This zero voltage at the inverting input terminal is referred to as virtual ground.
- This condition is illustrated in Figure (a).



(a) Virtual ground

(b) $I_{in} = I_f$ and current into the inverting input (I_1) is 0.

Virtual ground concept and closed-loop voltage gain development for the inverting amplifier.

Since there is no current at the inverting input, the current through Ri and the current through Rf are equal, as shown in Figure (b)

$$I_{in} = I_f$$

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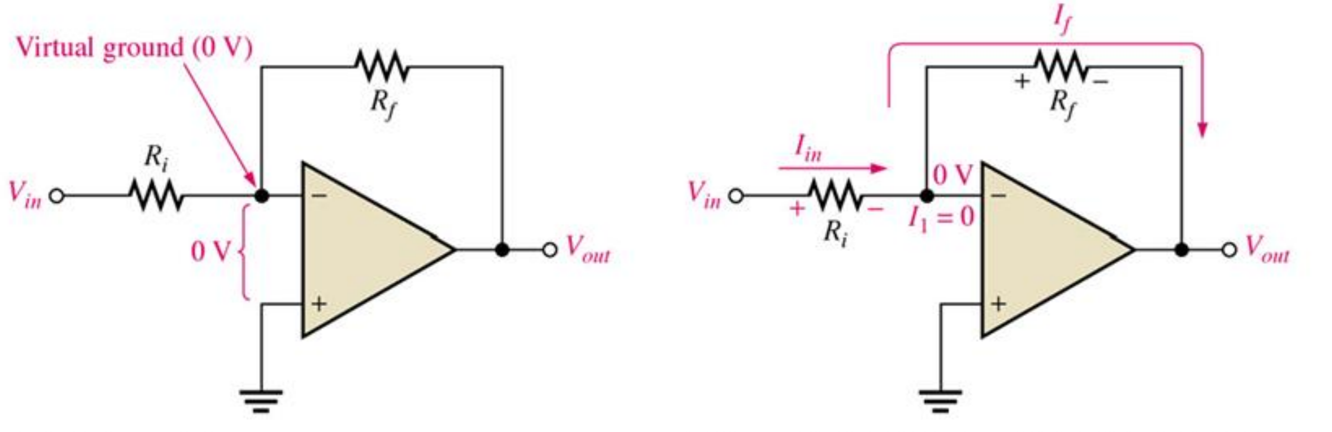
- **Inverting Amplifier**

The voltage across Ri equals Vin because the resistor is connected to virtual ground at the inverting input of the op-amp. Therefore

$$I_{in} = \frac{V_{in}}{R_i}$$



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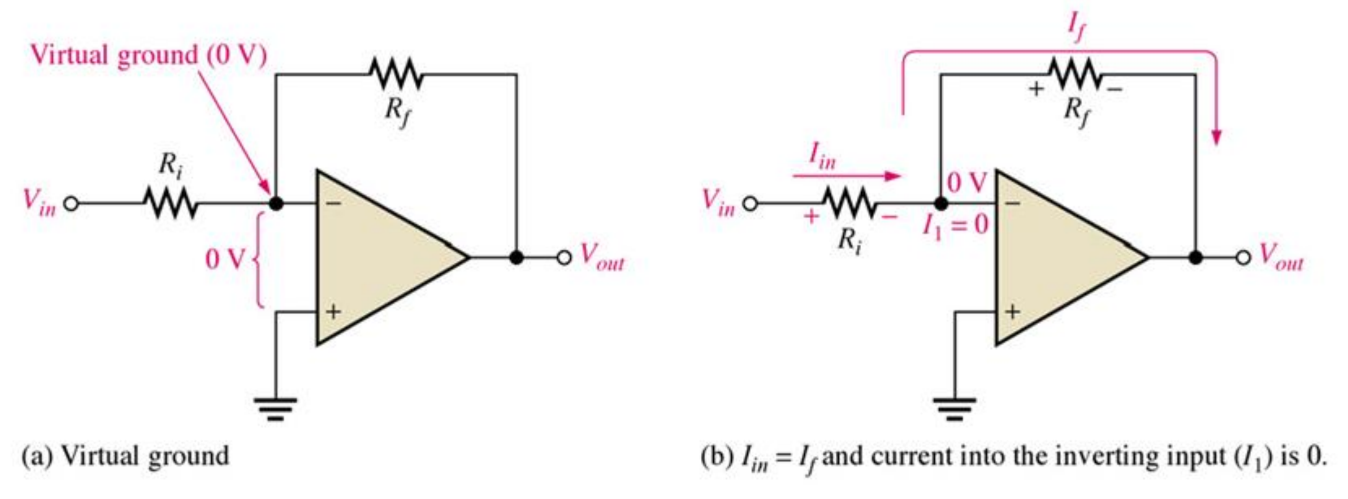
- **Inverting Amplifier**

The voltage across Ri equals Vin because the resistor is connected to virtual ground at the inverting input of the op-amp. Therefore

$$I_{in} = \frac{V_{in}}{R_i}$$

Also, the voltage across *Rf* equals – *Vout* because of virtual ground, and therefore,

$$I_f = \frac{-V_{out}}{R_f}$$



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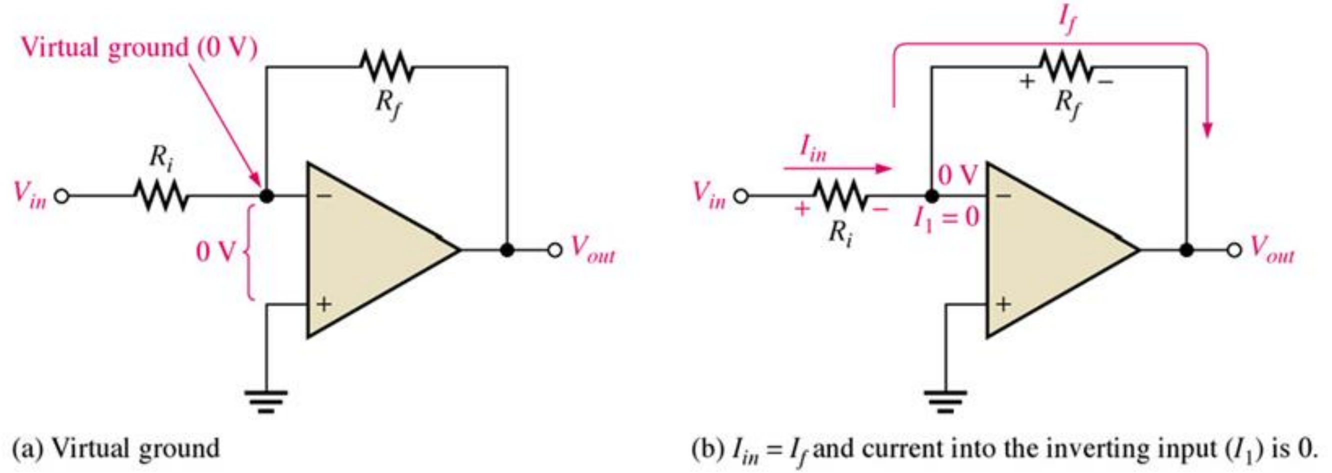
$$I_f = \frac{-V_{out}}{R_f}$$

Since $I_f = I_{in}$



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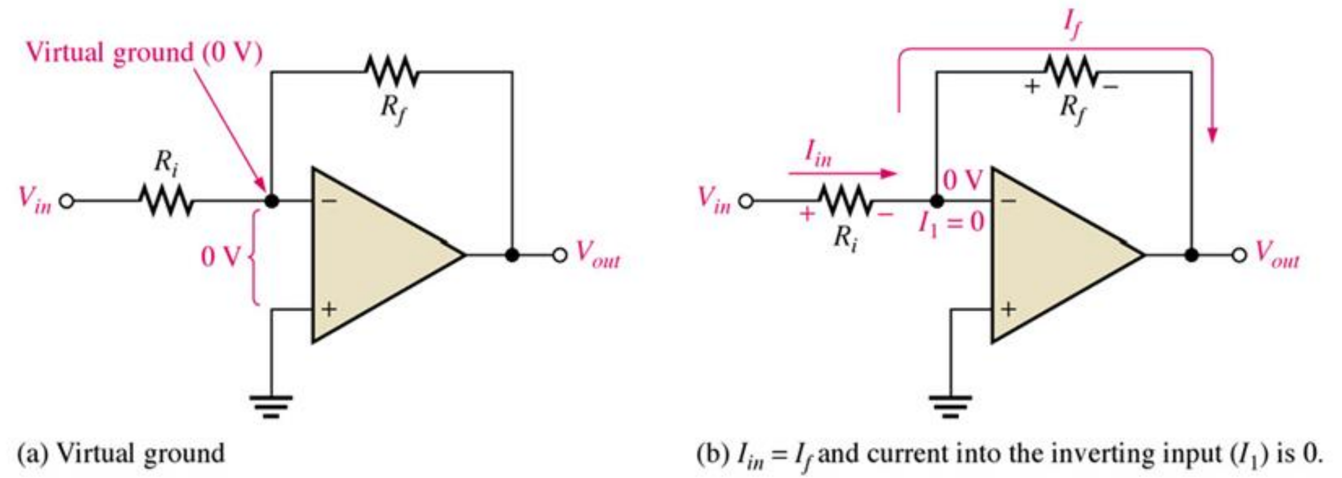
$$I_{in} = \frac{V_{in}}{R_i}$$

Also, the voltage across *Rf* equals – *Vout* because of virtual ground, and therefore,

$$I_f = \frac{-V_{out}}{R_f}$$

Since $I_f = I_{in}$

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



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$$I_{in} = \frac{V_{in}}{R_i}$$

Also, the voltage across *Rf* equals – *Vout* because of virtual ground, and therefore,

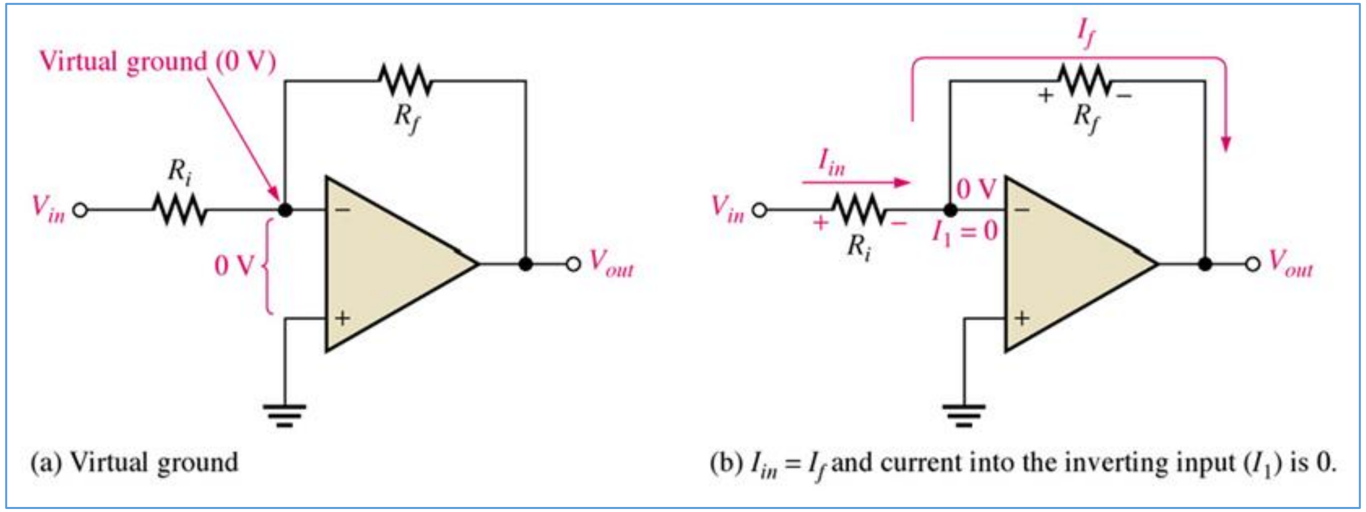
$$I_f = \frac{-V_{out}}{R_f}$$

$Since \;\; I_f = I_{in}$

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

Rearranging the terms,

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



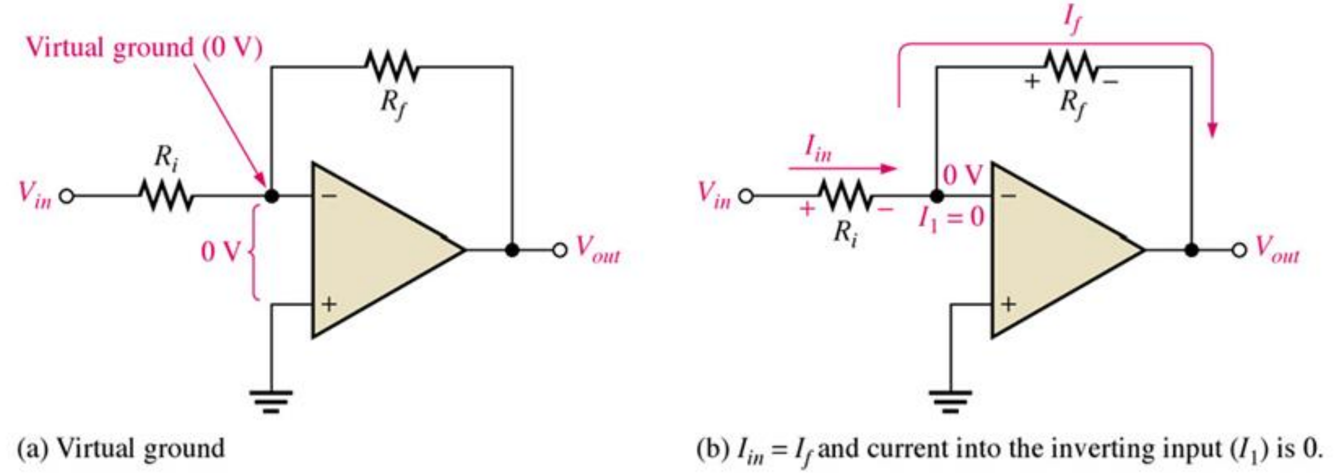
Virtual ground concept and closed-loop voltage gain development for the inverting amplifier.

Acknowledgment:-**Thomas L. Floyd** *Electronic Devices, Electron Flow Version,* Ninth Edition

• Inverting Amplifier

The voltage across Ri equals Vin because the resistor is connected to virtual ground at the inverting input of the op-amp. Therefore

$$I_{in} = \frac{V_{in}}{R_i}$$



Virtual ground concept and closed-loop voltage gain development for the inverting amplifier.

Also, the voltage across *Rf* equals – *Vout* because of virtual ground, and therefore,

$$I_f = \frac{-V_{out}}{R_f}$$

$Since \;\; I_f = I_{in}$

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

Rearranging the terms,

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

$$A_{cl(I)} = -\frac{R_f}{R_i}$$

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Op-Amps with negative feedback (From:-Thomas L. Floyd)

• Inverting Amplifier

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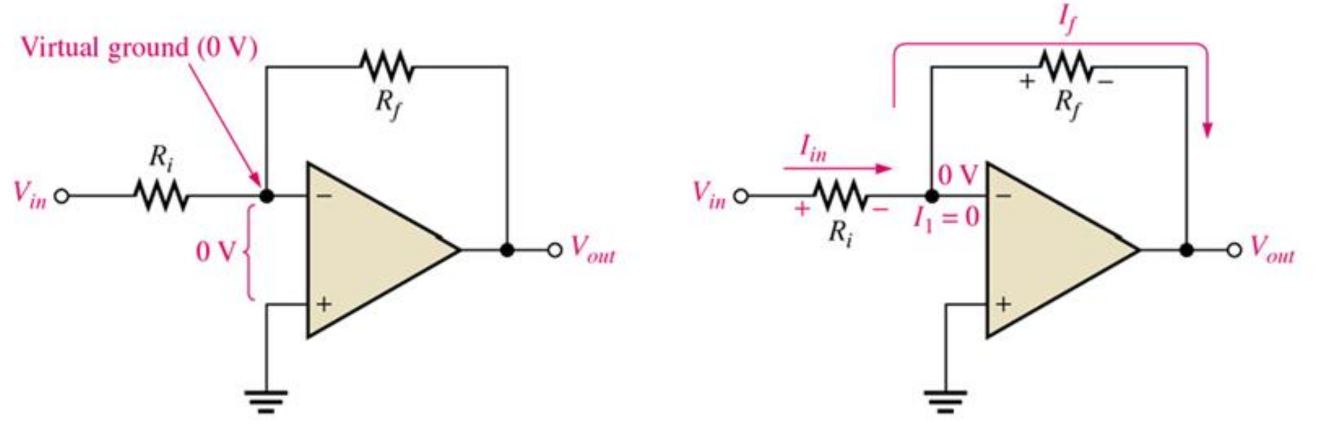
Vout/Vin is the overall gain of the inverting (I) amplifier.



(a) Virtual ground

(b) $I_{in} = I_f$ and current into the inverting input (I_1) is 0.

Virtual ground concept and closed-loop voltage gain development for the inverting amplifier.

- Equation shows that the closed-loop voltage gain of the inverting amplifier (*Acl(I)*) is the ratio of the feedback resistance (*Rf*) to the input resistance (*Ri*). The closed-loop gain is independent of the op-amp's internal open-loop gain.
- Thus, the negative feedback stabilizes the voltage gain. The negative sign indicates inversion.

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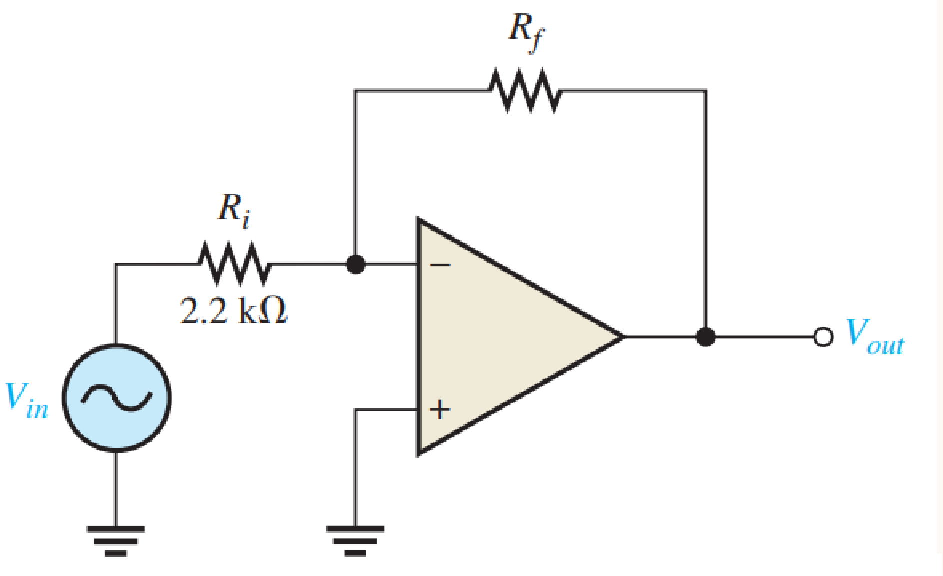
Op-Amps with negative feedback *(From:-Thomas L. Floyd)*

- **Inverting Amplifier**

EXAMPLE Given the op-amp configuration in Figure, determine the value of R_f required to produce a closed-loop voltage gain of -100.



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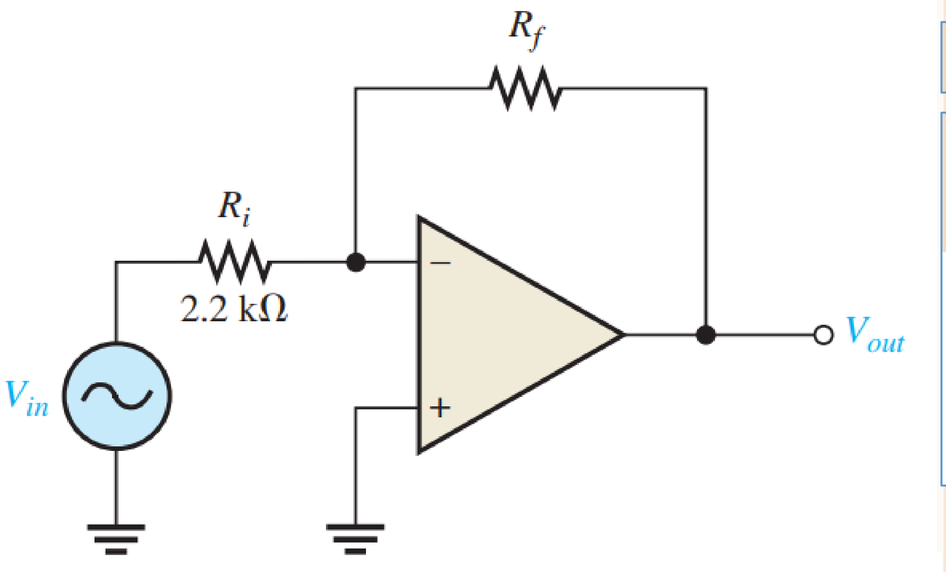

Solution

Knowing that $R_i = 2.2\ \text{k}\Omega$ and the absolute value of the closed-loop gain is $|A_{cl(\mathrm{I})}| = 100$, calculate R_f as follows:

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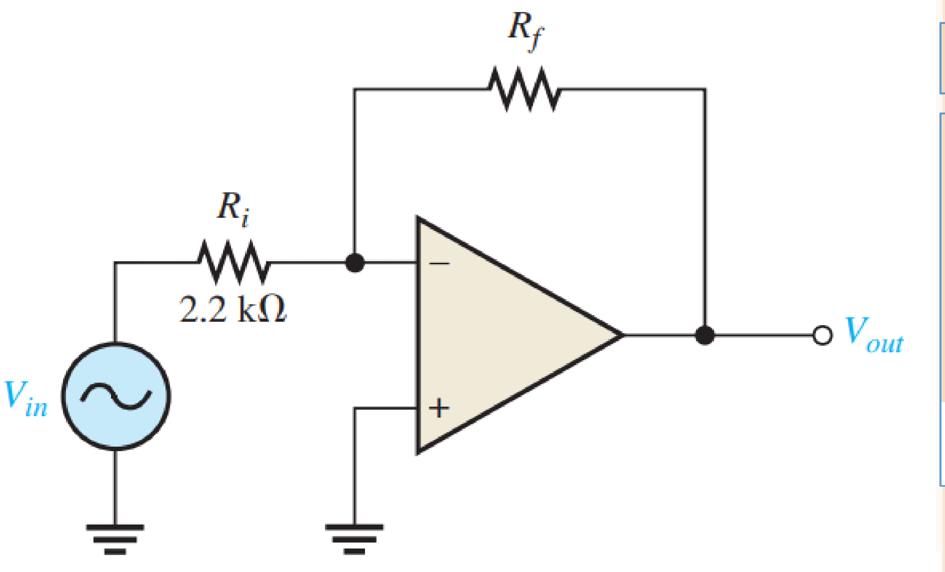

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$$|A_{cl(\text{I})}| = \frac{R_f}{R_i}$$

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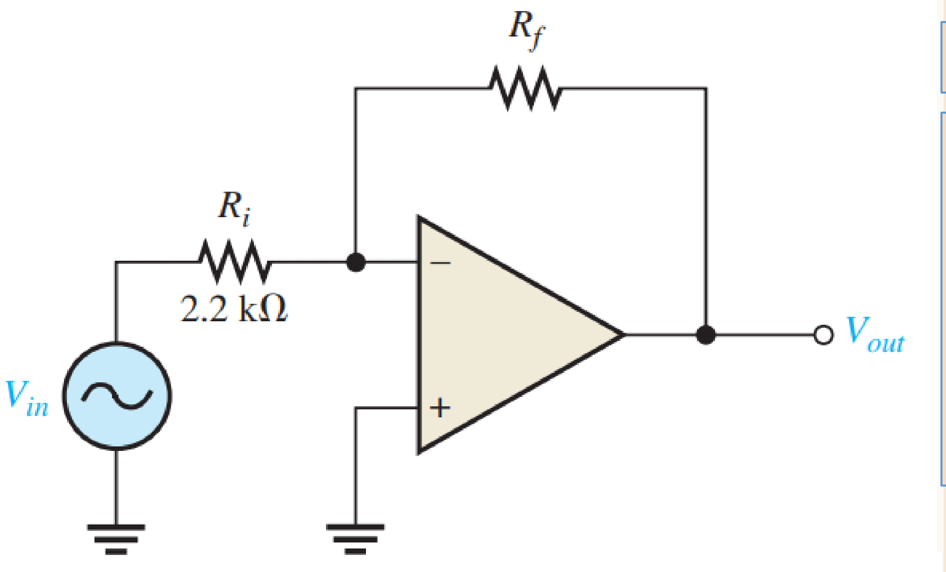

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Knowing that $R_i = 2.2\ \text{k}\Omega$ and the absolute value of the closed-loop gain is $|A_{cl(\text{I})}| = 100$, calculate R_f as follows:

$$|A_{cl(\text{I})}| = \frac{R_f}{R_i}$$

$$R_f = |A_{cl(\text{I})}|R_i = (100)(2.2\ \text{k}\Omega) = \mathbf{220\ k\Omega}$$

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Op-Amps with negative feedback *(From:-Thomas L. Floyd)*

- **Inverting Amplifier**

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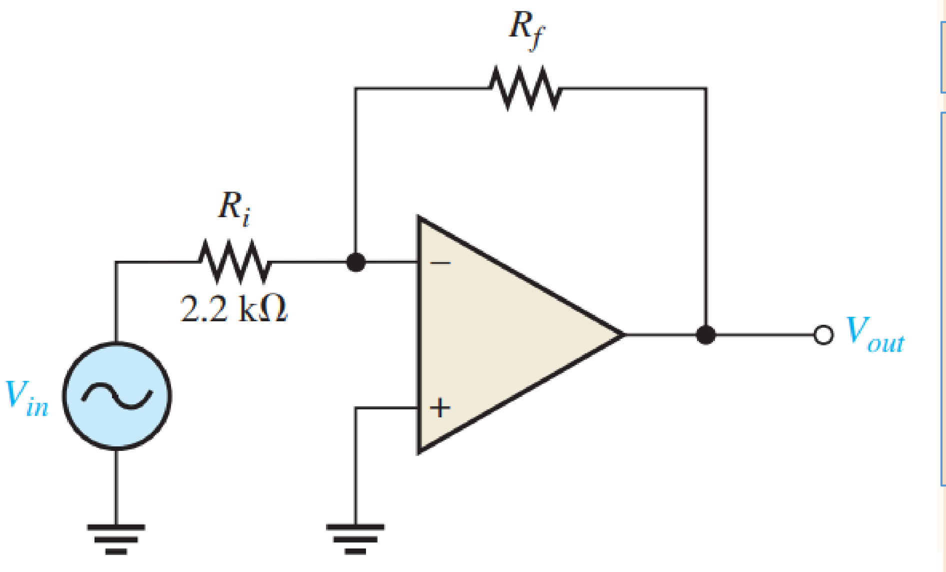

Solution

Knowing that $R_i = 2.2\ \text{k}\Omega$ and the absolute value of the closed-loop gain is $|A_{cl(\text{I})}| = 100$, calculate R_f as follows:

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$$R_f = |A_{cl(\text{I})}|R_i = (100)(2.2\ \text{k}\Omega) = \mathbf{220\ k\Omega}$$

Related Problem If R_i is changed to 2.7 kΩ in Figure what value of R_f is required to produce a closed-loop gain with an absolute value of 25?

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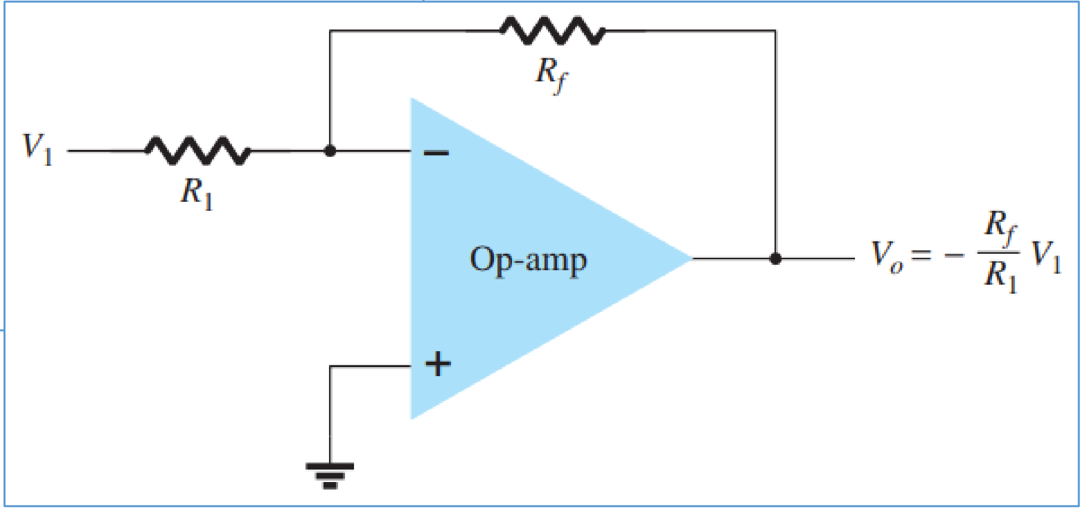
Op-Amps with negative feedback *(From:-* Boylestad*)*

- **Inverting Amplifier**

EXAMPLE If the circuit of Fig. has $R_1 = 100\,\text{k}\Omega$ and $R_f = 500\,\text{k}\Omega$, what output voltage results for an input of $V_1 = 2\text{ V}$?



Op-Amps with negative feedback (*From:-* Boylestad)

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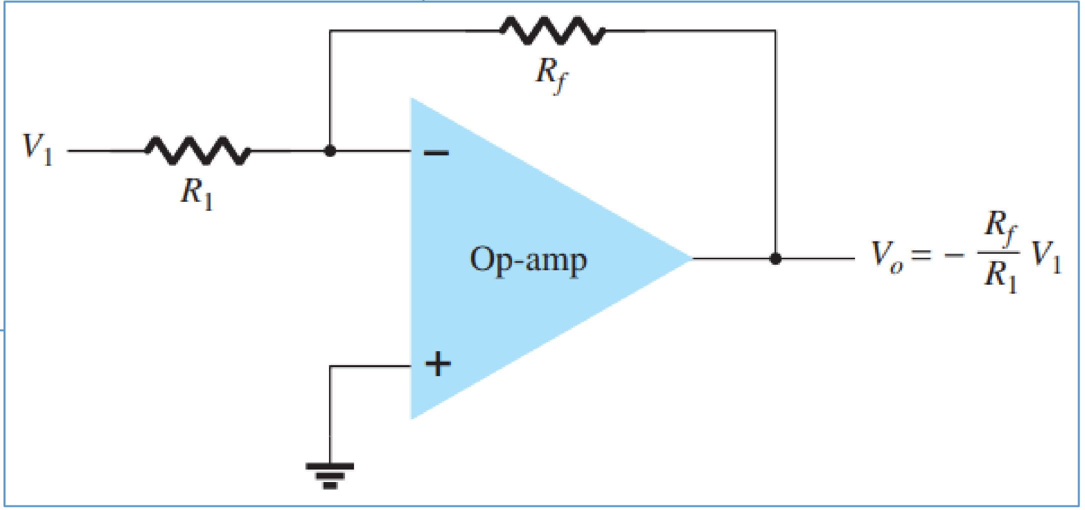
Solution:

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



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Acknowledgment:-Electronic Devices and Circuit Theory, Boylestad and Nashelsky, 11th Edition

Op-Amps with negative feedback *(From:- Boylestad)*

- **Inverting Amplifier**

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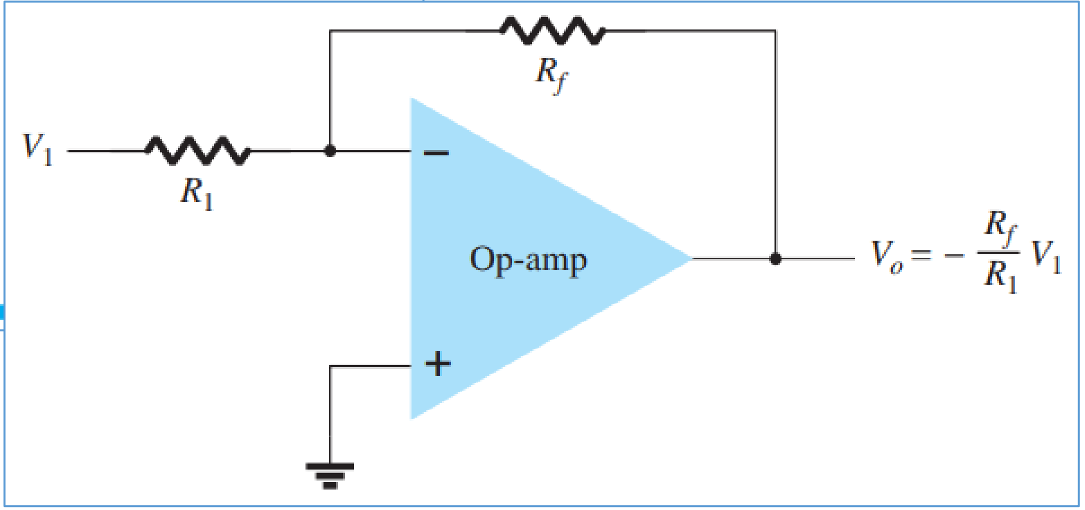
Solution:

$$V_o = -\frac{R_f}{R_1}V_1 = -\frac{500\,\text{k}\Omega}{100\,\text{k}\Omega}(2\text{ V}) = \mathbf{-10\text{ V}}$$



Op-Amp Applications

- Amplifiers
- Oscillators and waveform generators
- Differentiators and Integrators
- Filters
- Precision rectifiers
- Precision peak detectors
- Voltage and current regulators
- Analog calculators
- Clippers and clampers
- ADCs and DACs
- Buffers
- And many more…….

Basic OP-AMP circuit: Comparator

- Operational amplifiers are often used as comparators to compare the amplitude of one voltage with another.
- In this application, the op-amp is used in the open-loop configuration, with the input voltage on one input and a reference voltage on the other

- For less critical applications, an op-amp running without negative feedback (open-loop) is often used as a comparator

- Because the output is always in one of two states, comparators are often used to interface between an analog and digital circuit.

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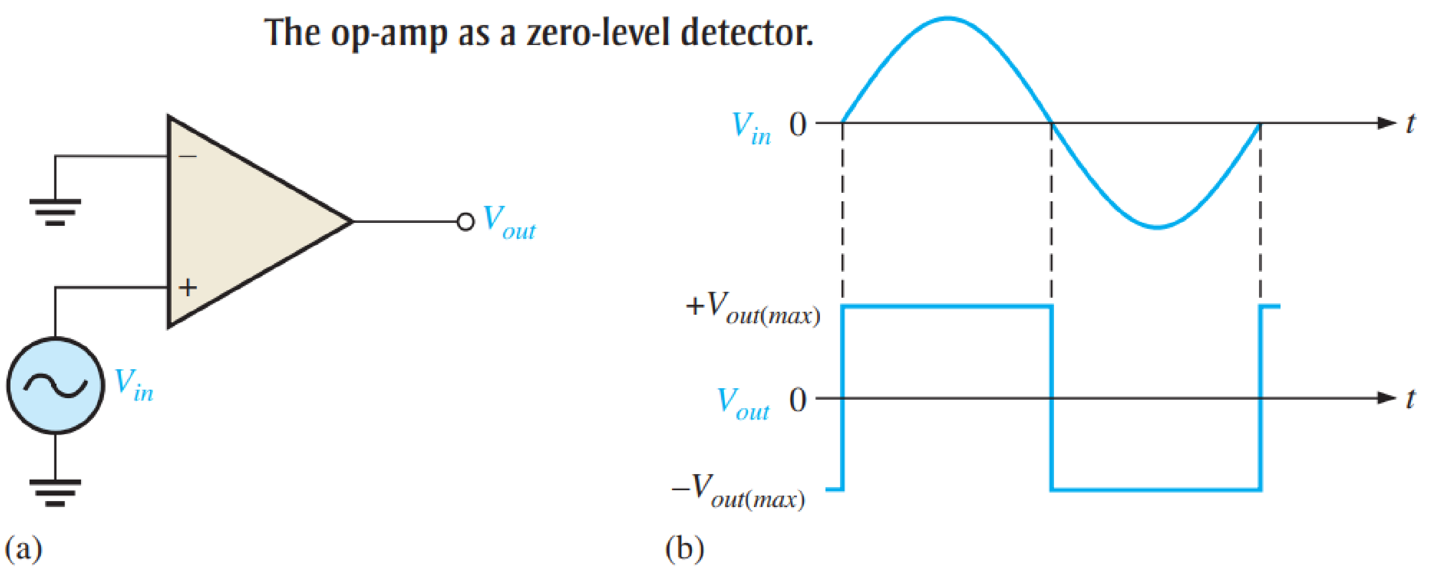
Basic OP-AMP circuit: Comparator

- **Zero-Level Detection**

- One application of an op-amp used as a comparator is to determine when an input voltage exceeds a certain level.
- Figure (a) shows a zero-level detector. Notice that the inverting input is grounded to produce a zero level and that the input signal voltage is applied to the noninverting input.
- Because of the high open-loop voltage gain, a very small difference voltage between the two inputs drives the amplifier into saturation, causing the output voltage to go to its limit.



The op-amp as a zero-level detector.

- Figure (b) shows the result of a sinusoidal input voltage applied to the noninverting input of the zero-level detector.
- When the sine wave is positive, the output is at its maximum positive level.
- When the sine wave crosses 0, the amplifier is driven to its opposite state and the output goes to its maximum negative level, as shown. the zerolevel detector can be used as a squaring circuit to produce a square wave from a sine wave.

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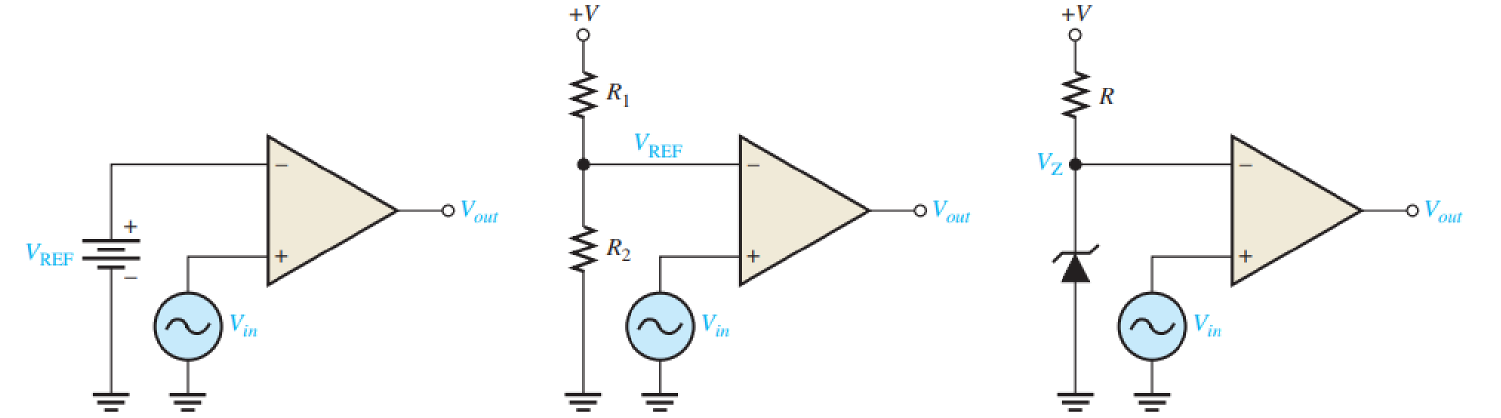
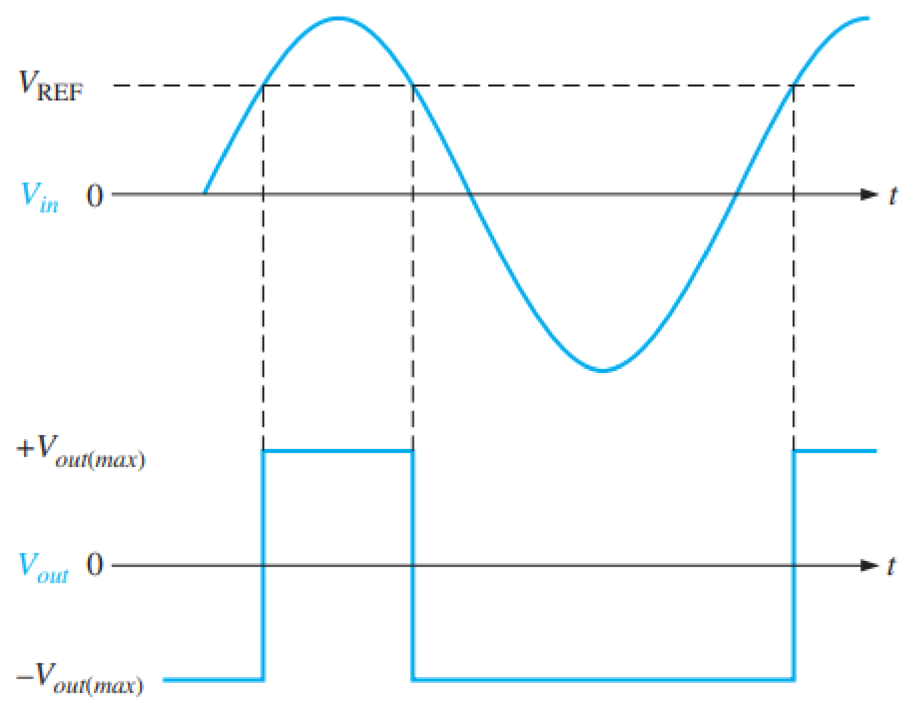
Basic OP-AMP circuit: Comparator

- **Nonzero-Level Detection**



(a) Battery reference (b) Voltage-divider reference (c) Zener diode sets reference voltage



(d) Waveforms

- The zero-level detector can be modified to detect positive and negative voltages by connecting a fixed reference voltage source to the inverting input, as shown in Figure (a). A more practical arrangement is shown in Figure (b) using a voltage divider to set the reference voltage, V_{REF}, as follows:

$$V_{REF} = \frac{R_2}{R_1 + R_2}(+V)$$

- The circuit in Figure(c) uses a zener diode to set the reference voltage ($V_{REF} = V_Z$)

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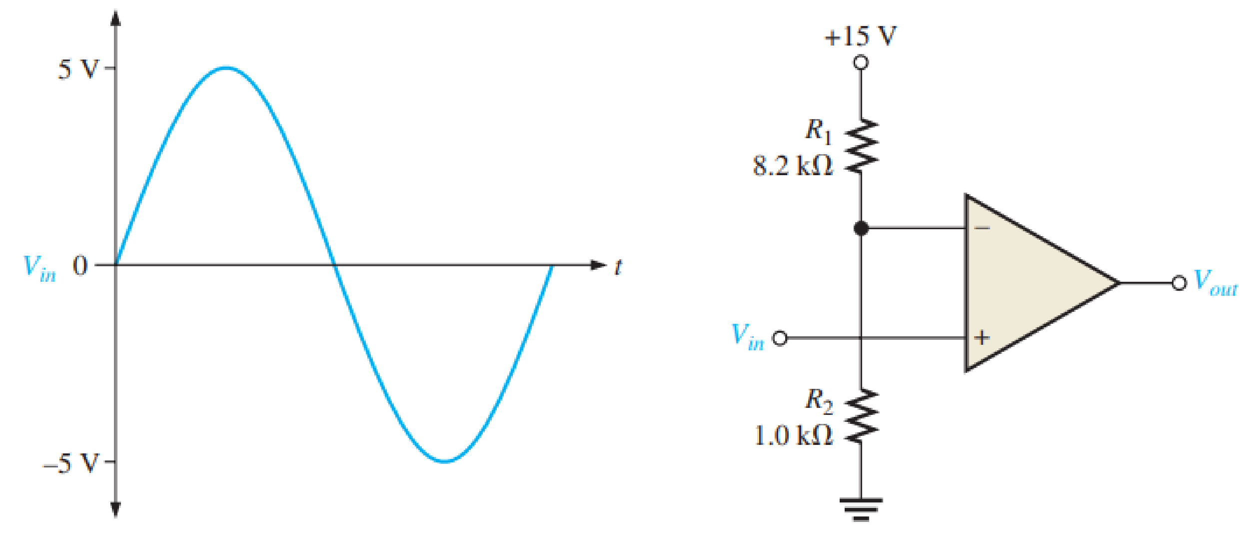
Basic OP-AMP circuit: Comparator

- **Nonzero-Level Detection**

EXAMPLE

The input signal in Figure (a) is applied to the comparator in Figure (b). Draw the output showing its proper relationship to the input signal. Assume the maximum output levels of the comparator are ±14 V.



(a) (b)

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Basic OP-AMP circuit: Comparator

- **Nonzero-Level Detection**

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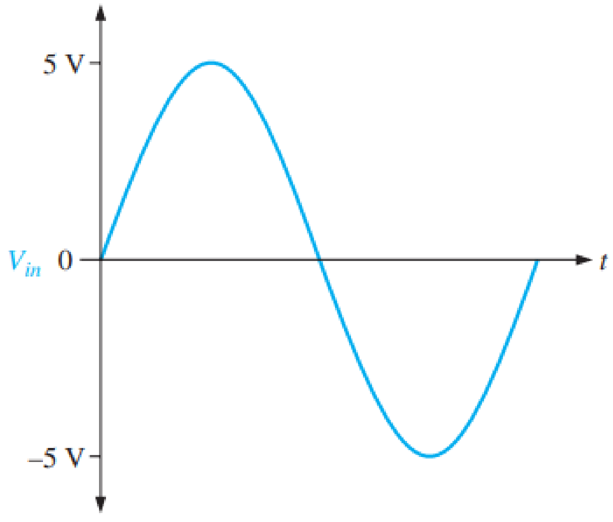
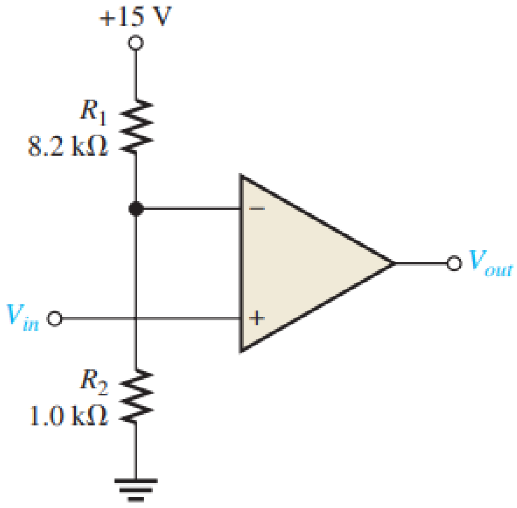


(a)



(b)

Solution

The reference voltage is set by R_1 and R_2 as follows:

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Basic OP-AMP circuit: Comparator

- **Nonzero-Level Detection**

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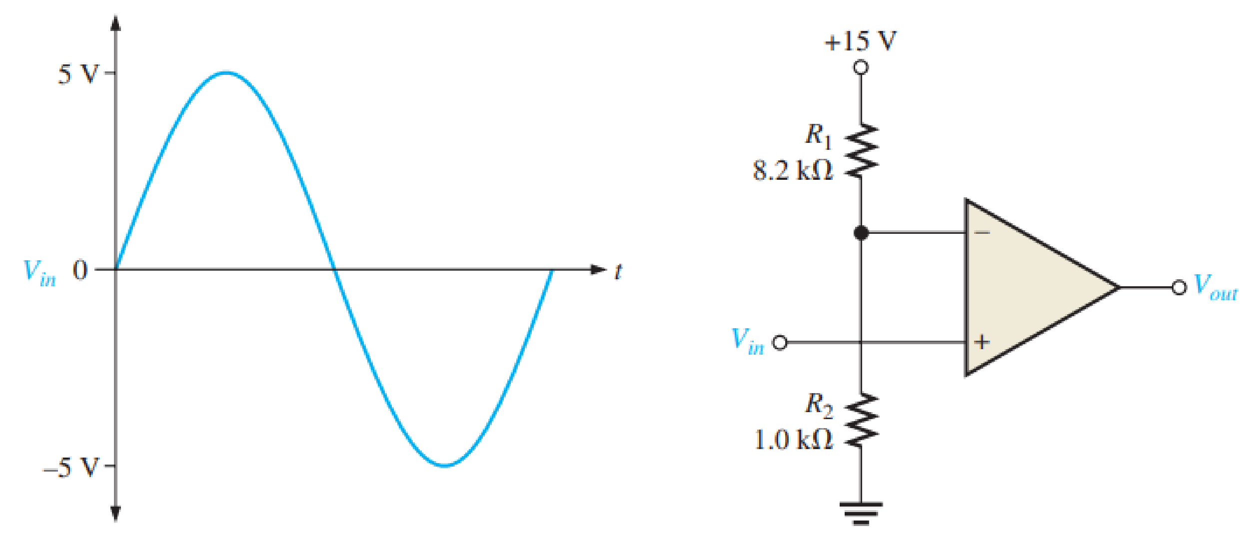

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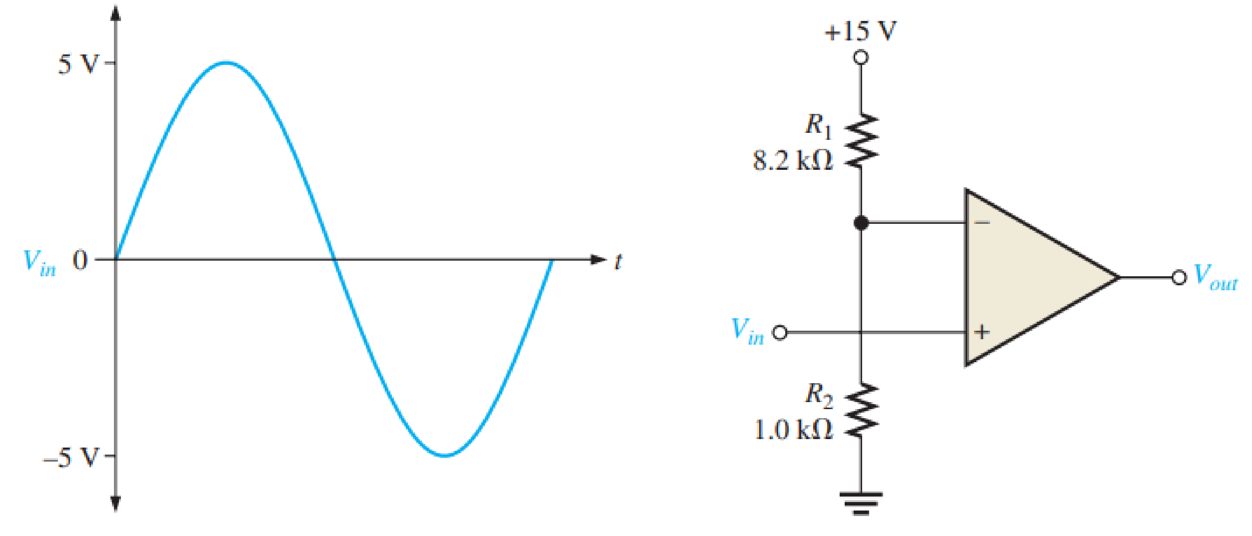

(a) (b)

Solution

The reference voltage is set by R_1 and R_2 as follows:

$$V_{REF} = \frac{R_2}{R_1 + R_2}(+V) = \frac{1.0\,\text{k}\Omega}{8.2\,\text{k}\Omega + 1.0\,\text{k}\Omega}(+15\text{ V}) = 1.63\text{ V}$$

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Basic OP-AMP circuit: Comparator

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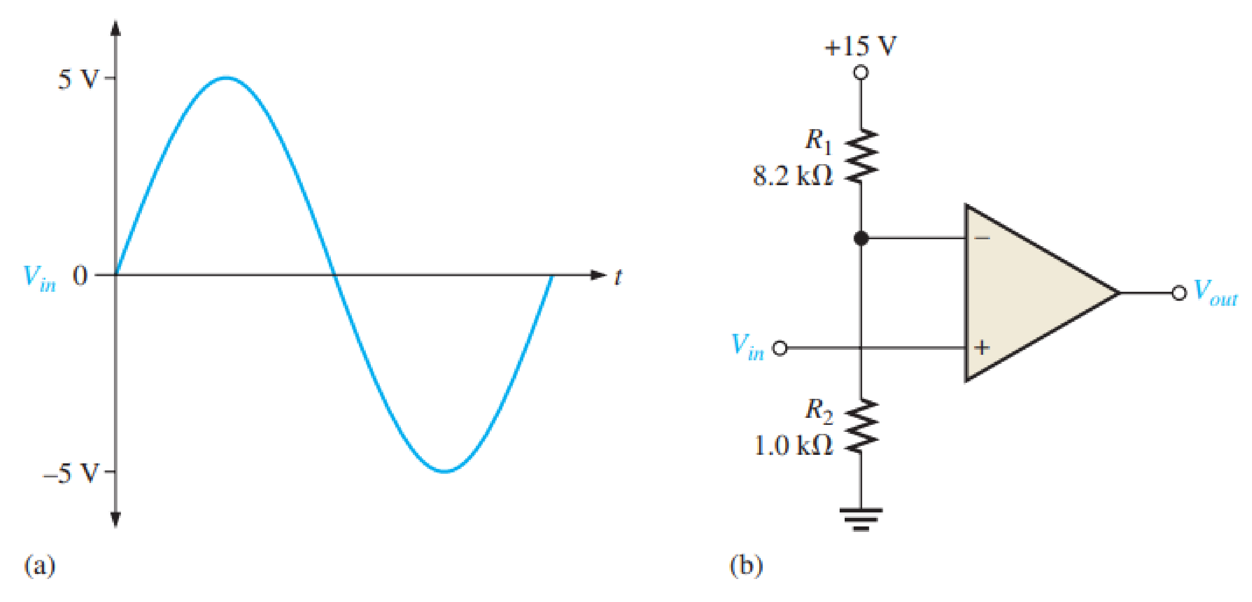

Solution

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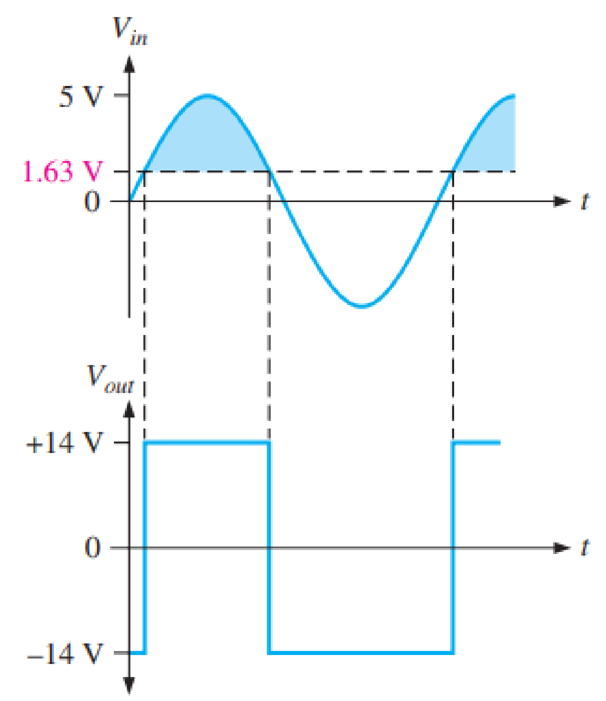
- As shown in Figure, each time the input exceeds +1.63 V, the output voltage switches to its +14 V level, and each time the input goes below +1.63 V, the output switches back to its -14 V level.



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Basic OP-AMP circuit: Comparator

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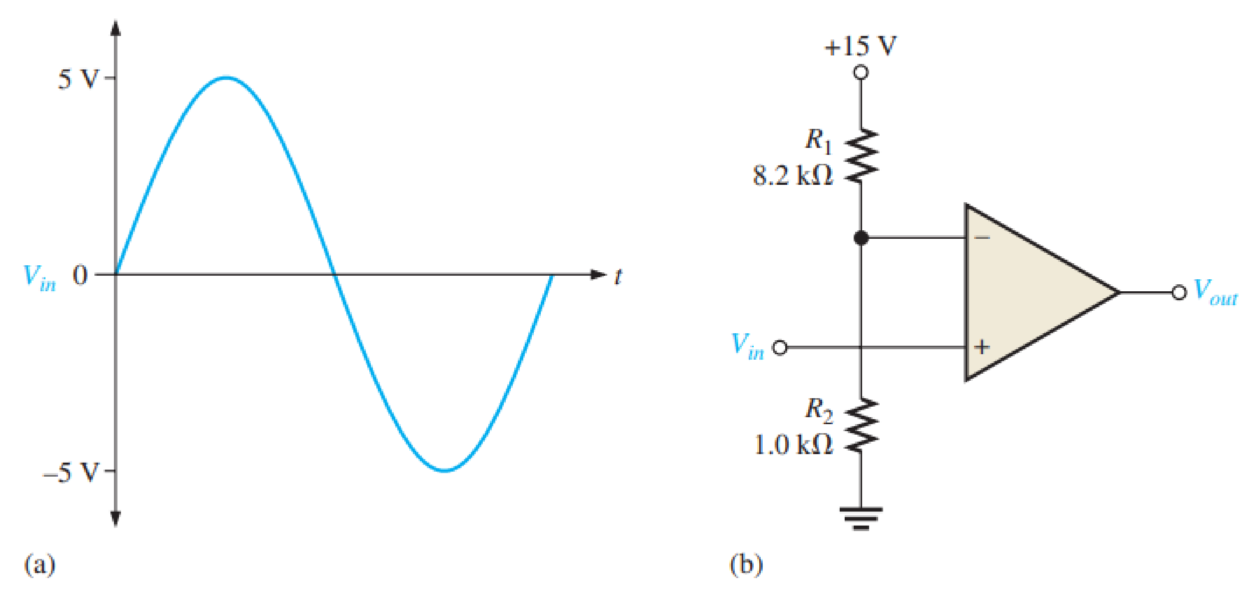

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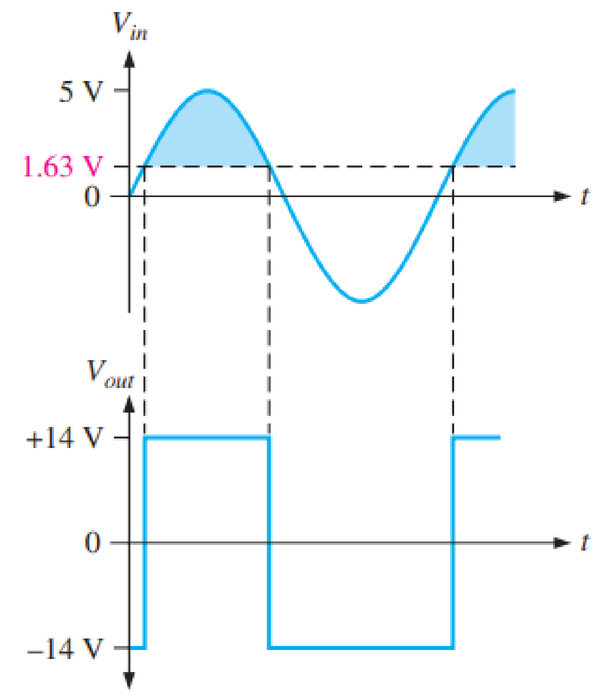

Related Problem Determine the reference voltage in Figure if $R_1 = 22\,\text{k}\Omega$ and $R_2 = 3.3\,\text{k}\Omega$.

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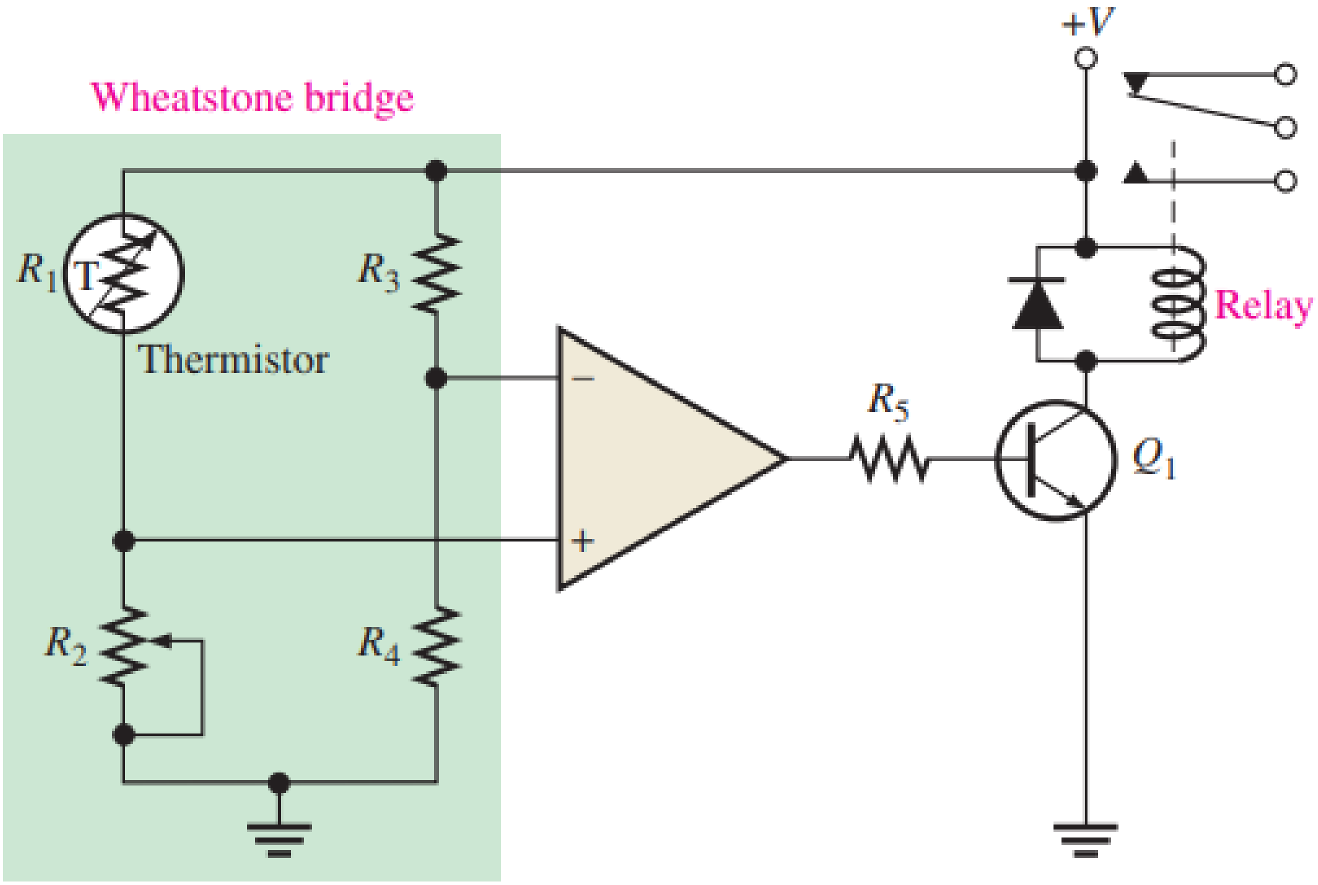
Basic OP-AMP circuit: Comparator

- **Application : Over-Temperature Sensing Circuit**



- Figure shows an op-amp comparator used in a precision over-temperature sensing circuit to determine when the temperature reaches a certain critical value.
- The circuit consists of a Wheatstone bridge with the op-amp used to detect when the bridge is balanced.
- One leg of the bridge contains a thermistor (R1), which is a temperature-sensing resistor with a negative temperature coefficient (its resistance decreases as temperature increases).
- The potentiometer (R2) is set at a value equal to the resistance of the thermistor at the critical temperature.
- At normal temperatures (below critical), R1 is greater than R2, thus creating an unbalanced condition that drives the op-amp to its low saturated output level and keeps transistor Q1 off.

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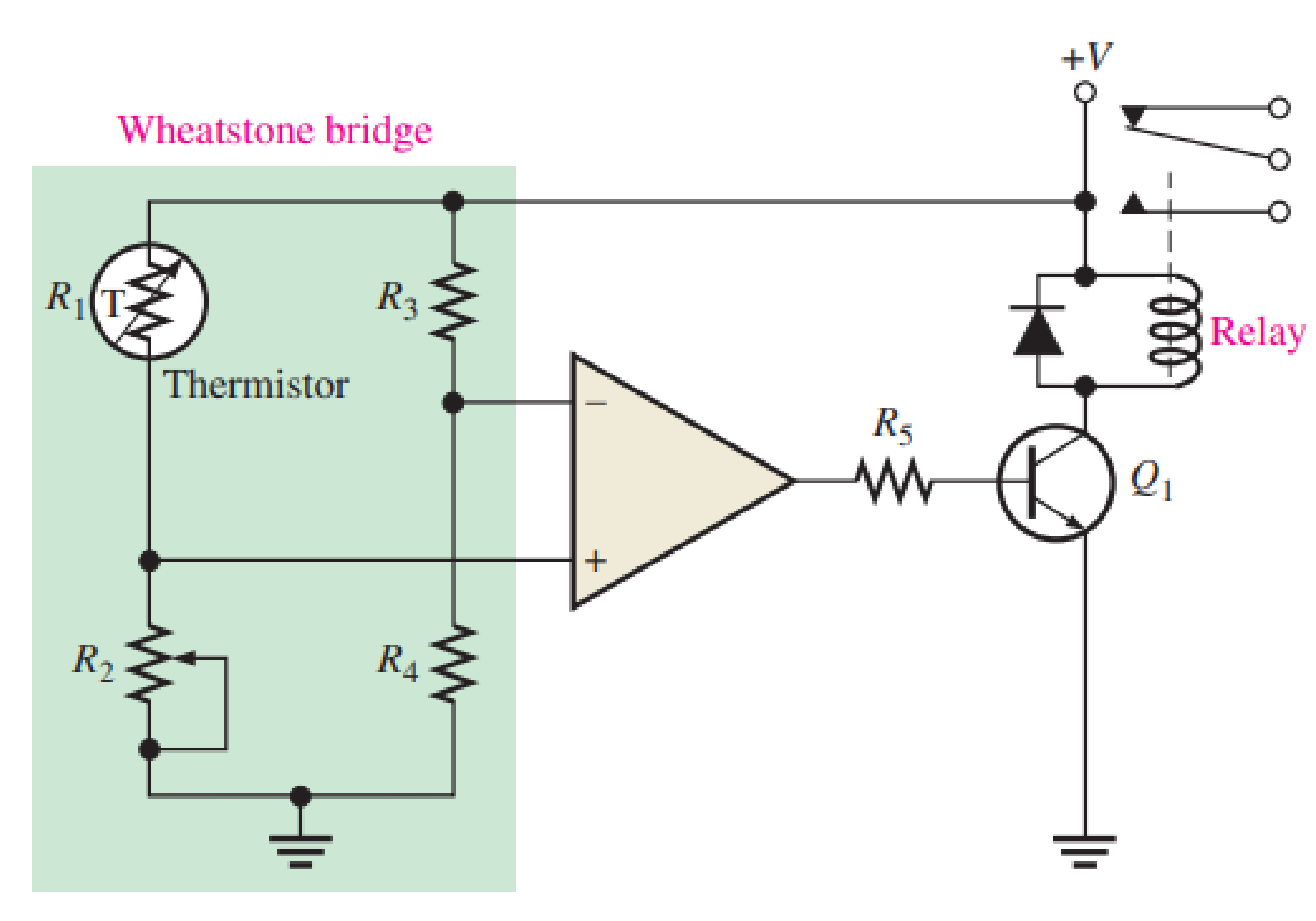
Basic OP-AMP circuit: Comparator

- **Application : Over-Temperature Sensing Circuit**



- As the temperature increases, the resistance of the thermistor decreases.
- When the temperature reaches the critical value, R1 becomes equal to R2, and the bridge becomes balanced (since R3 = R4).
- At this point the op-amp switches to its high saturated output level, turning Q1 on.
- This energizes the relay, which can be used to activate an alarm or initiate an appropriate response to the over-temperature condition.

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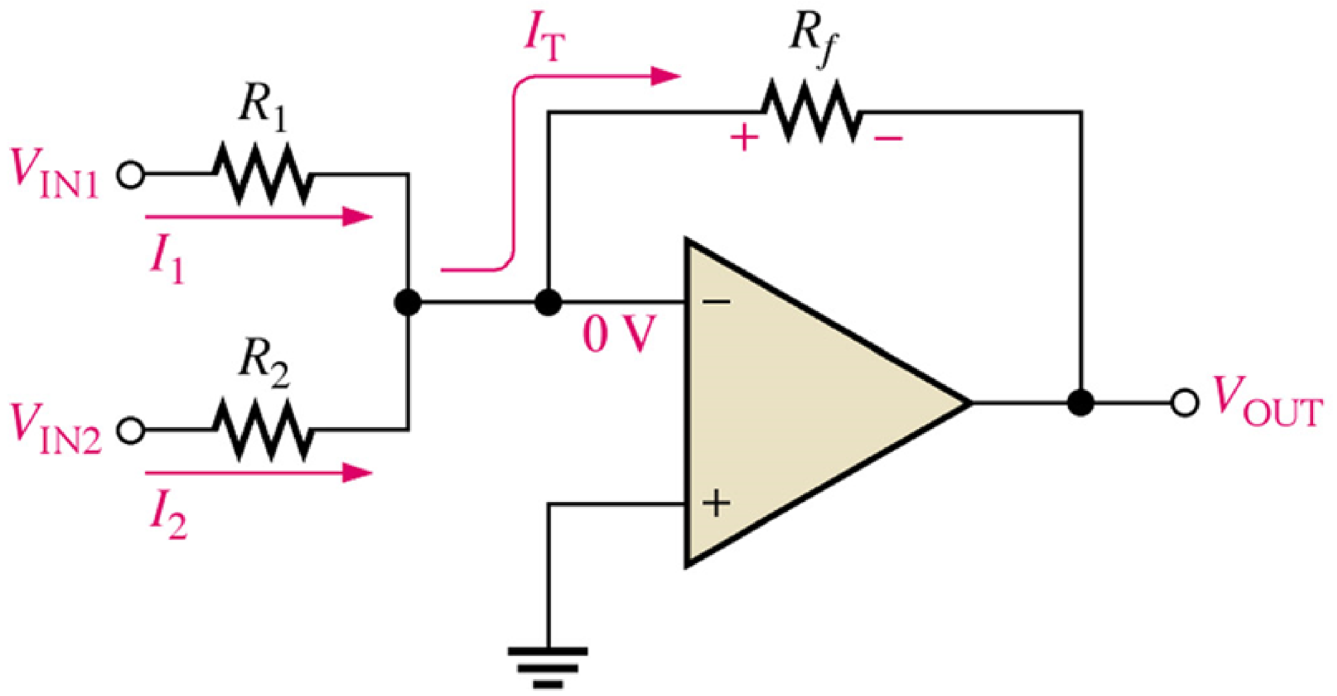
Basic OP-AMP circuit: Summing amplifiers

- **Summing Amplifier with Unity Gain**



Two-input inverting summing amplifier

- A summing amplifier has two or more inputs, and its output voltage is proportional to the negative of the algebraic sum of its input voltages.
- A two-input summing amplifier is shown in Figure, but any number of inputs can be used.
- The operation of the circuit and derivation of the output expression are as follows.
- Two voltages, V_{IN1} and V_{IN2}, are applied to the inputs and produce currents I_1 and I_2, as shown.
- Using the concepts of infinite input impedance and virtual ground, you can determine that the inverting(-) input of the op-amp is approximately 0 V and has no current through it.
- This means that the total current I_T, which goes through R_f divides into I_1 and I_2 at summing point A, as indicated in Figure.

$$I_T = I_1 + I_2$$

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Basic OP-AMP circuit: Summing amplifiers

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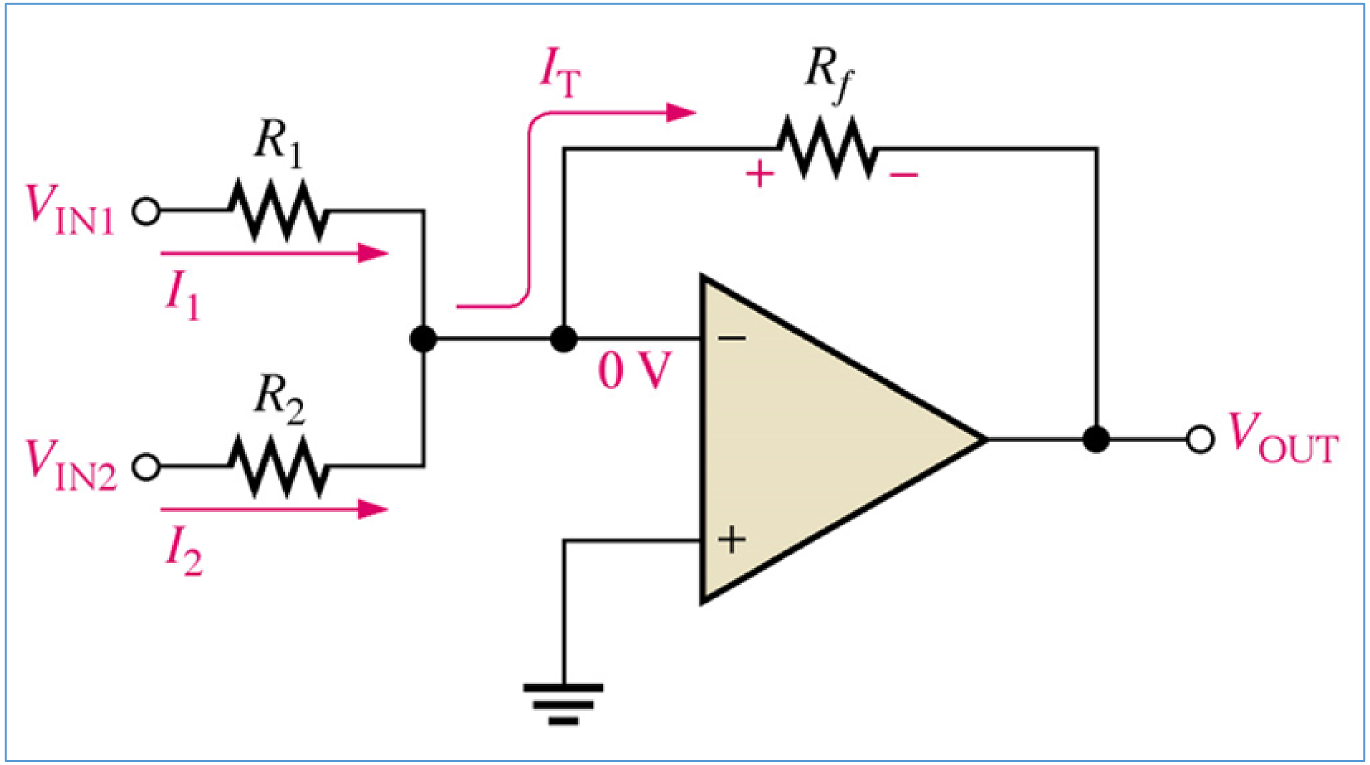

Two-input inverting summing amplifier

$$I_T = I_1 + I_2$$

Since $V_{out} = -I_T R_f$ the following steps apply:

$$V_{OUT} = -(I_1 + I_2)R_f = -\left(\frac{V_{IN1}}{R_1} + \frac{V_{IN2}}{R_2}\right)R_f$$

If all three of the resistors are equal (R1 = R2 = Rf = R), then

$$V_{OUT} = -\left(\frac{V_{IN1}}{R} + \frac{V_{IN2}}{R}\right)R = -(V_{IN1} + V_{IN2})$$

The equation shows that the output voltage has the same *magnitude* as the sum of the two input voltages but with a negative sign, indicating inversion.

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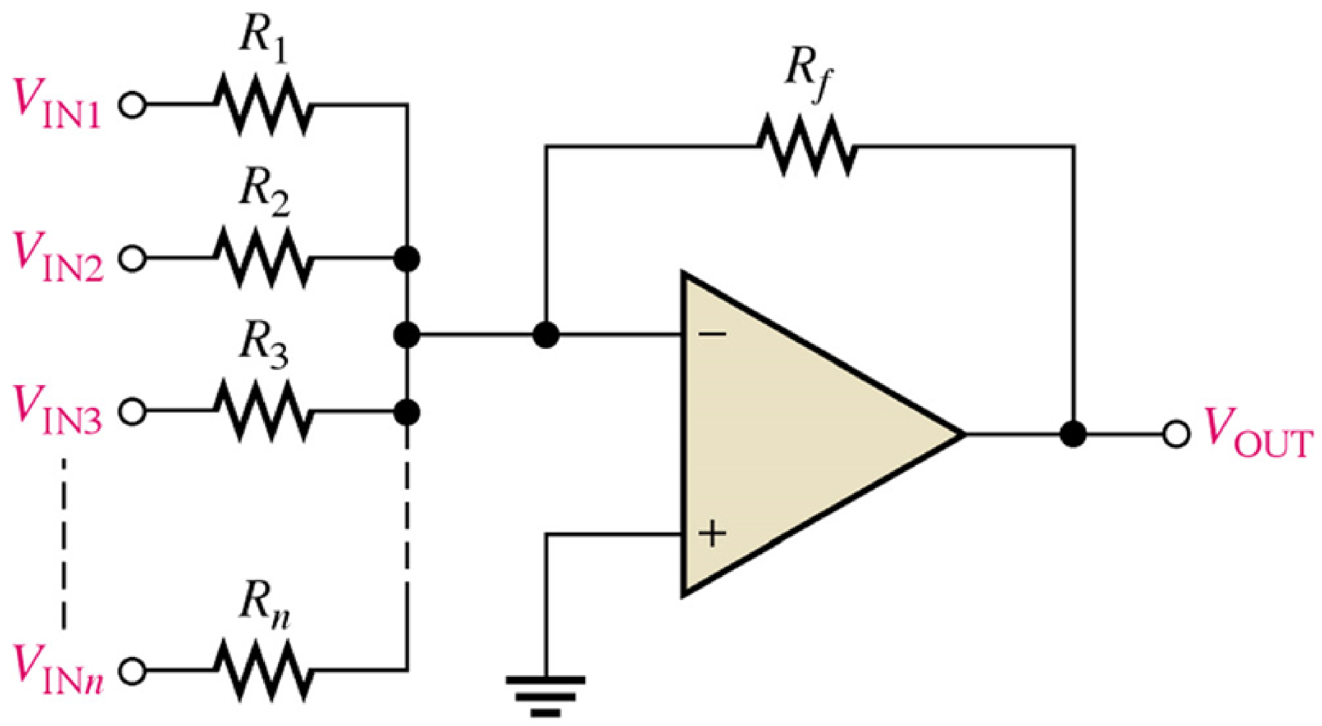
Basic OP-AMP circuit: Summing amplifiers

- **Summing Amplifier with Unity Gain**



n-input inverting summing amplifier

A general expression is given in Equation for a unity-gain summing amplifier with n inputs, as shown in Figure where all resistors are equal in value

$$V_{OUT} = -(V_{IN1} + V_{IN2} + V_{IN3} + \cdots + V_{INn})$$

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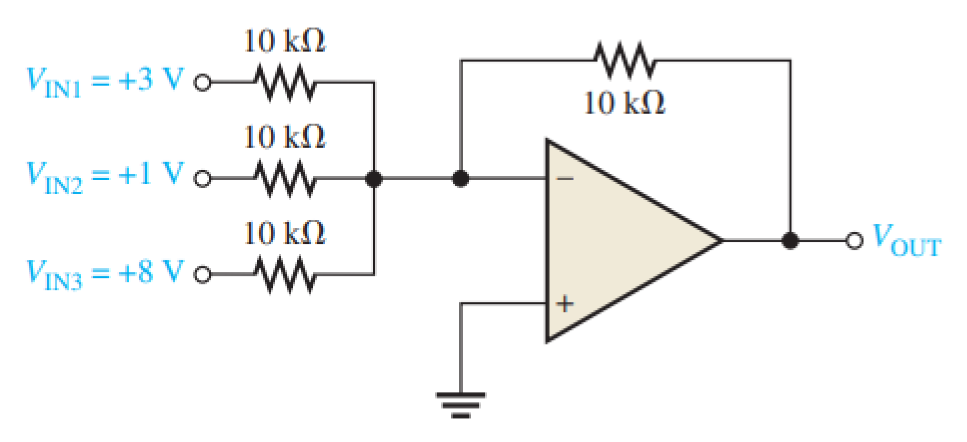
Basic OP-AMP circuit: Summing amplifiers

- **Summing Amplifier with Unity Gain**

EXAMPLE

Determine the output voltage in Figure



Solution

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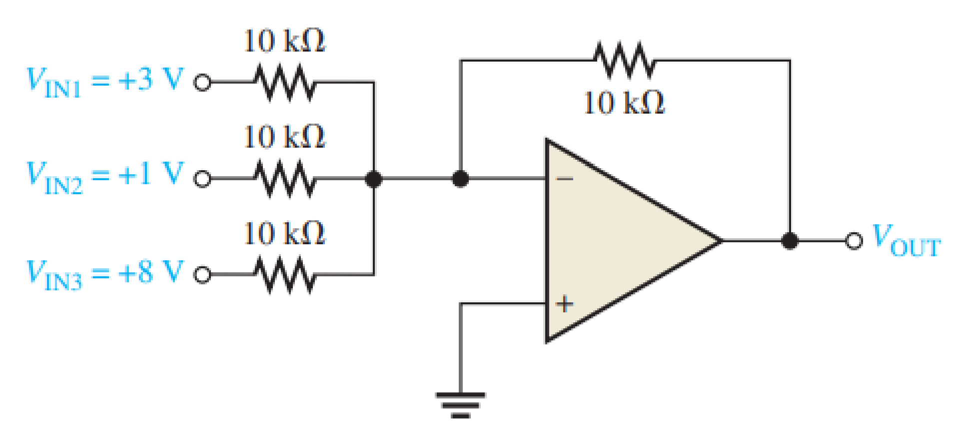
Basic OP-AMP circuit: Summing amplifiers

- **Summing Amplifier with Unity Gain**

EXAMPLE

Determine the output voltage in Figure



Solution

$$V_{OUT} = -(V_{IN1} + V_{IN2} + V_{IN3})$$

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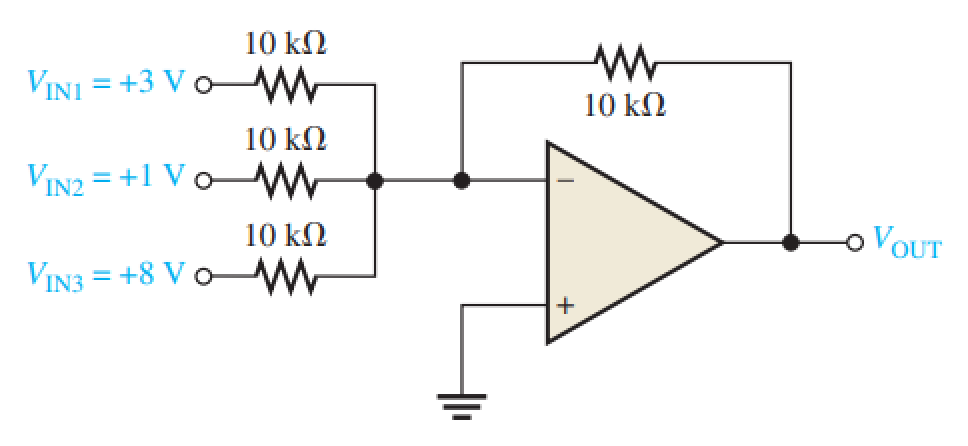
Basic OP-AMP circuit: Summing amplifiers

- **Summing Amplifier with Unity Gain**

EXAMPLE

Determine the output voltage in Figure



Solution

$$V_{OUT} = -(V_{IN1} + V_{IN2} + V_{IN3})$$
$$= -(3\text{ V} + 1\text{ V} + 8\text{ V}) = \mathbf{-12\text{ V}}$$
$$= \mathbf{-12\text{ V}}$$

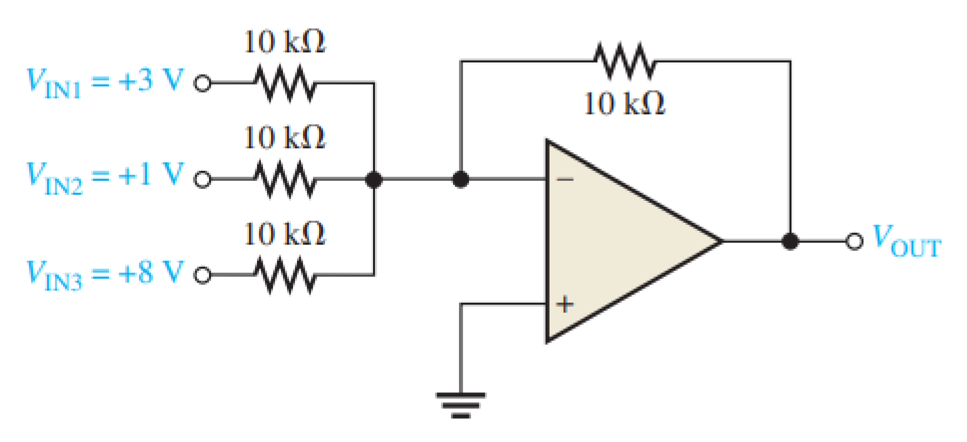
*Acknowledgment:-*Thomas L. Floyd *Electronic Devices, Electron Flow Version,* Ninth Edition

Basic OP-AMP circuit: Summing amplifiers

- **Summing Amplifier with Unity Gain**

EXAMPLE

Determine the output voltage in Figure



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Related Problem If a fourth input of −0.5 V is added to Figure with a 10 kΩ resistor, what is the output voltage? = -11.5

Acknowledgment:-Thomas L. Floyd *Electronic Devices, Electron Flow Version,* Ninth Edition

Basic OP-AMP circuit: Summing amplifiers

- **Summing Amplifier with Gain Greater Than Unity**

When Rf is larger than the input resistors, the amplifier has a gain of Rf /R, where R is the value of each equal-value input resistor. The general expression for the output is

$$V_{OUT} = -\frac{R_f}{R}(V_{IN1} + V_{IN2} + \cdots + V_{INn})$$

As you can see, the output voltage has the same magnitude as the sum of all the input voltages multiplied by a constant determined by the ratio -(Rf /R)

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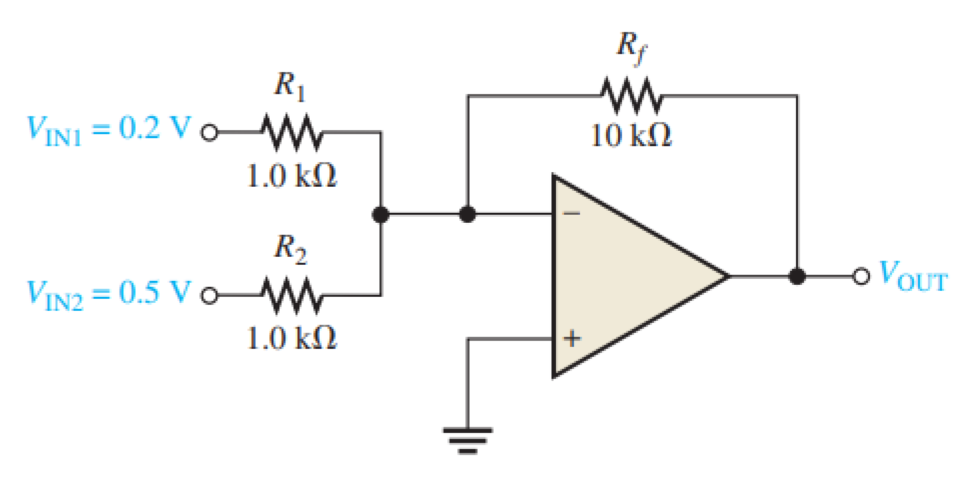
Basic OP-AMP circuit: Summing amplifiers

- **Summing Amplifier with Gain Greater Than Unity**

EXAMPLE

Determine the output voltage for the summing amplifier in Figure



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Basic OP-AMP circuit: Summing amplifiers

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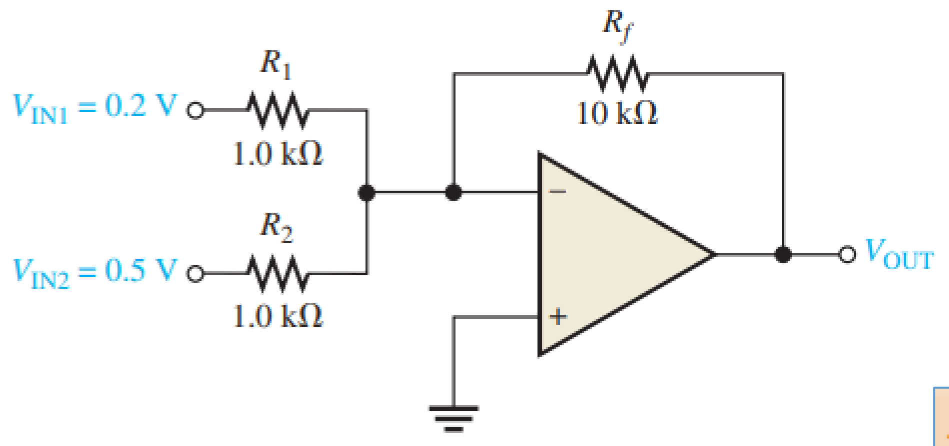

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$R_f = 10\,k\Omega$ and $R = R_1 = R_2 = 1.0\,k\Omega$. Therefore,

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Basic OP-AMP circuit: Summing amplifiers

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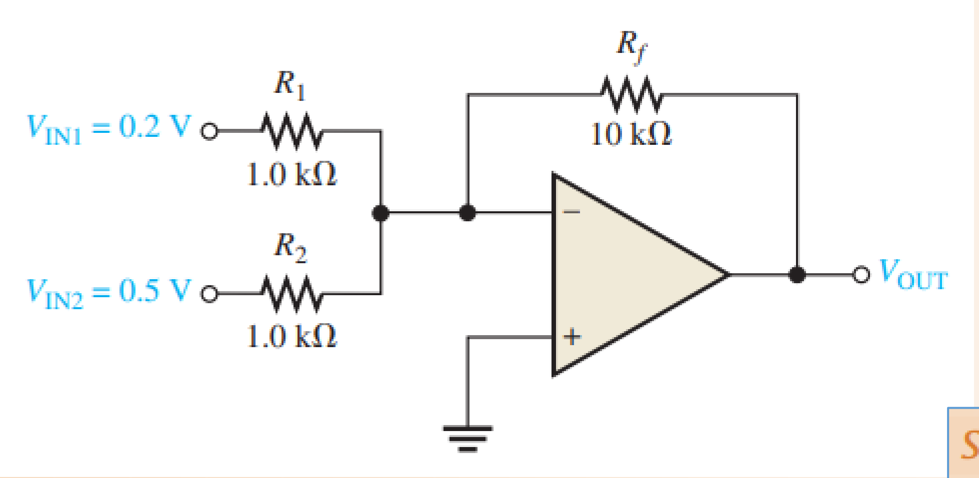

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Solution

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$$V_{OUT} = -\frac{R_f}{R}(V_{IN1} + V_{IN2}) = -\frac{10\,\text{k}\Omega}{1.0\,\text{k}\Omega}(0.2\text{ V} + 0.5\text{ V}) = -10(0.7\text{ V}) = \mathbf{-7\text{ V}}$$

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Basic OP-AMP circuit: Summing amplifiers

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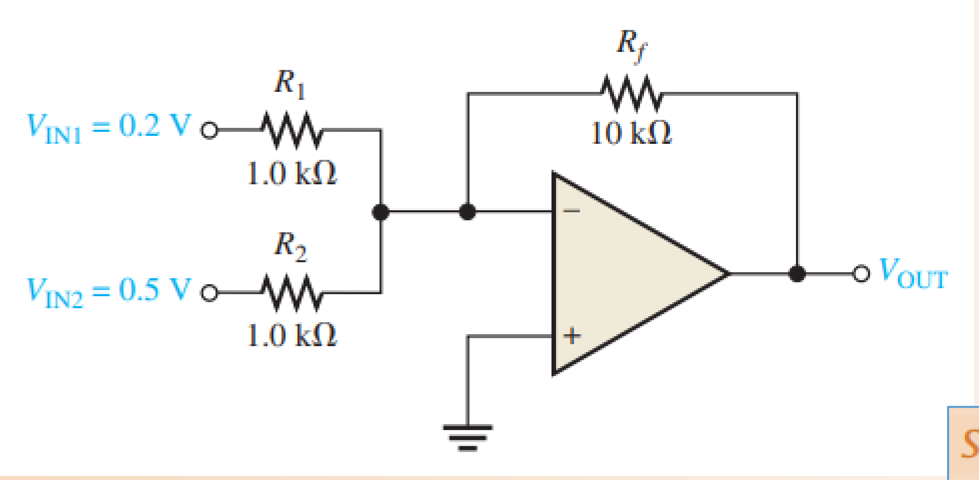

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Related Problem Determine the output voltage in Figure if the two input resistors are 2.2 kΩ and the feedback resistor is 18 kΩ. = -5.73

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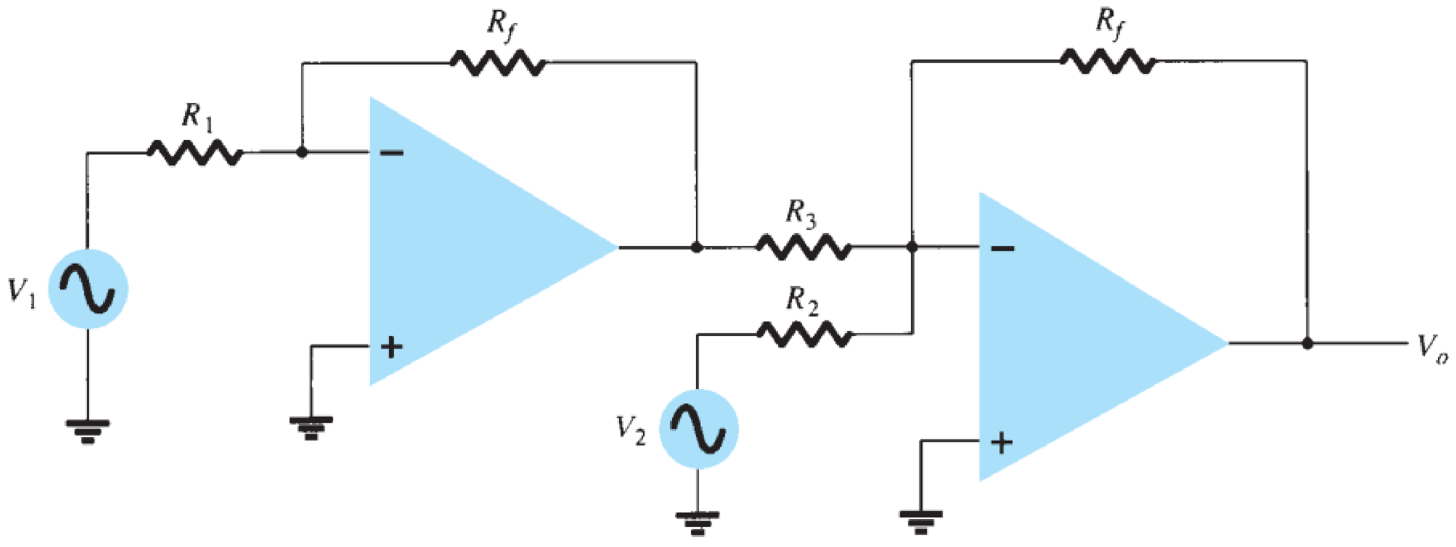
Basic OP-AMP circuit: Difference amplifiers (subtractor)

- **Voltage Subtraction**

Two signals can be subtracted from one another in a number of ways. Figure shows two op-amp stages used to provide subtraction of input signals. The resulting output is given by



Circuit for subtracting two signals.

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

Acknowledgment:-Electronic Devices and Circuit Theory, Boylestad and Nashelsky, 11th Edition

Basic OP-AMP circuit: Difference amplifiers (subtractor)

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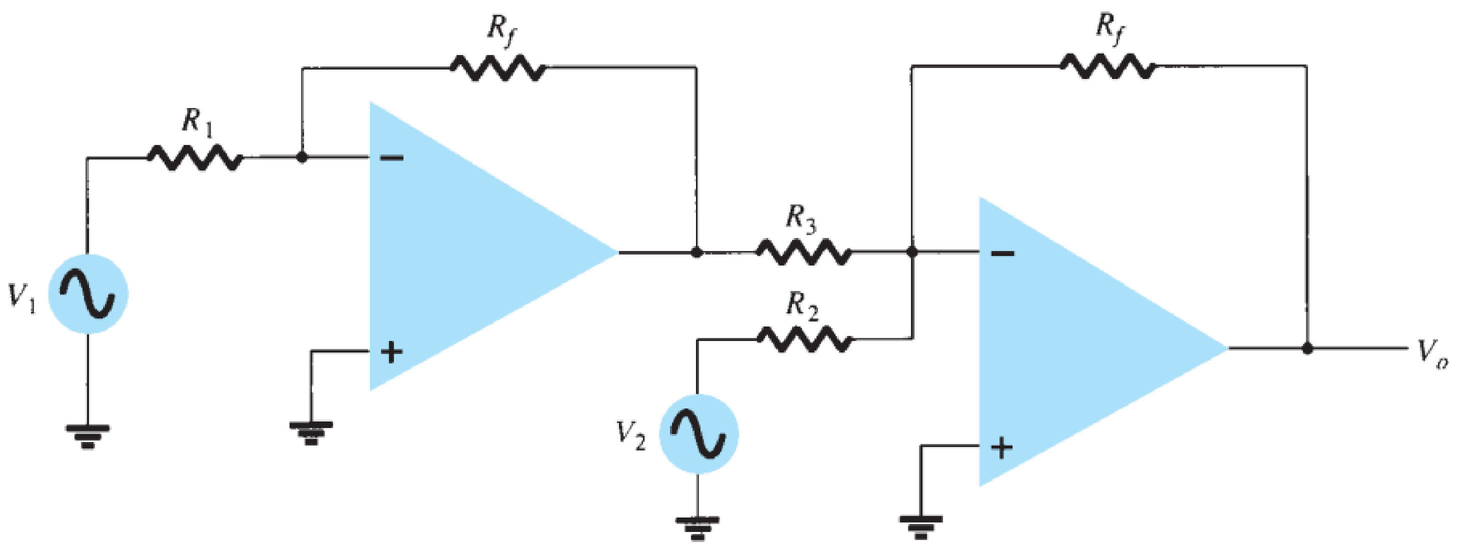

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$$V_o = -\left[\frac{R_f}{R_3}\left(-\frac{R_f}{R_1}V_1\right) + \frac{R_f}{R_2}V_2\right]$$

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

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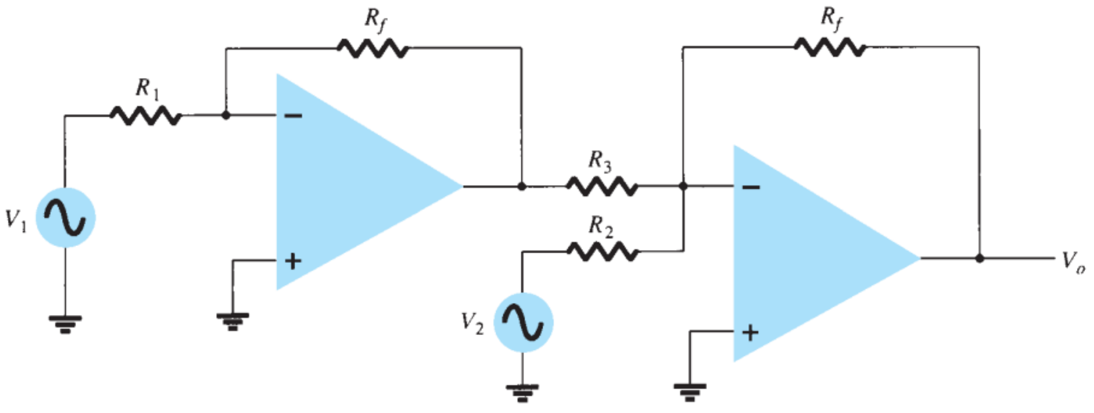
Basic OP-AMP circuit: Difference amplifiers (subtractor)

- **Voltage Subtraction**



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EXAMPLE Determine the output for the circuit of Fig. with components $R_f = 1\,\text{M}\Omega$, $R_1 = 100\,\text{k}\Omega$, $R_2 = 50\,\text{k}\Omega$, and $R_3 = 500\,\text{k}\Omega$.

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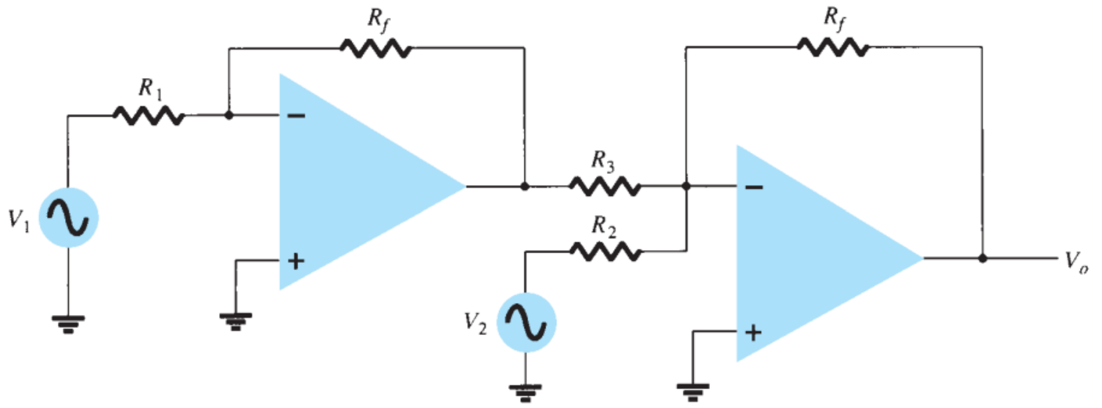
Basic OP-AMP circuit: Difference amplifiers (subtractor)

- **Voltage Subtraction**



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Solution: The output voltage is calculated to be

$$V_o = -\left(\frac{1\ \text{M}\Omega}{50\ \text{k}\Omega}V_2 - \frac{1\ \text{M}\Omega}{500\ \text{k}\Omega}\,\frac{1\ \text{M}\Omega}{100\ \text{k}\Omega}V_1\right) = -(20\ V_2 - 20\ V_1) = \mathbf{-20(V_2 - V_1)}$$

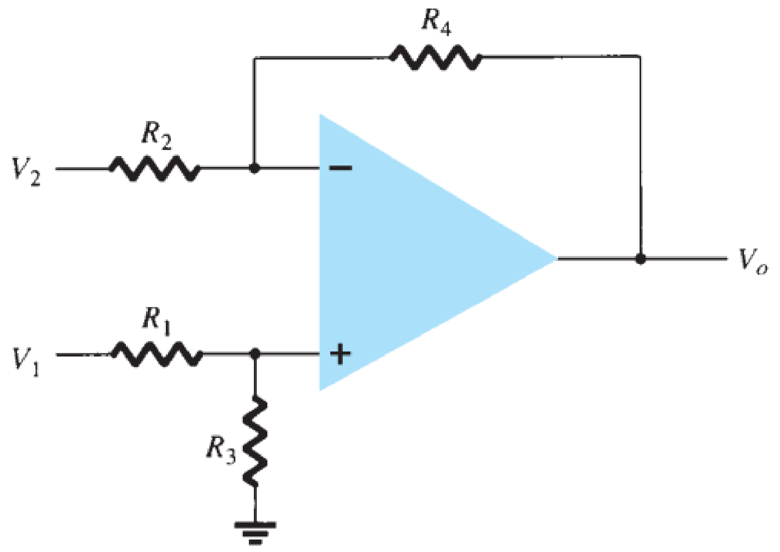
The output is seen to be the difference of V_2 and V_1 multiplied by a gain factor of -20.

Acknowledgment:-Electronic Devices and Circuit Theory, Boylestad and Nashelsky, 11th Edition

Basic OP-AMP circuit: Difference amplifiers (subtractor)

- **Voltage Subtraction**

- Another connection to provide subtraction of two signals is shown in Fig.
- This connection uses only one op-amp stage to provide subtracting two input signals.
- Using superposition, we can show the output to be



Subtraction circuit.

$$V_o = \frac{R_3}{R_1 + R_3} \frac{R_2 + R_4}{R_2} V_1 - \frac{R_4}{R_2} V_2$$

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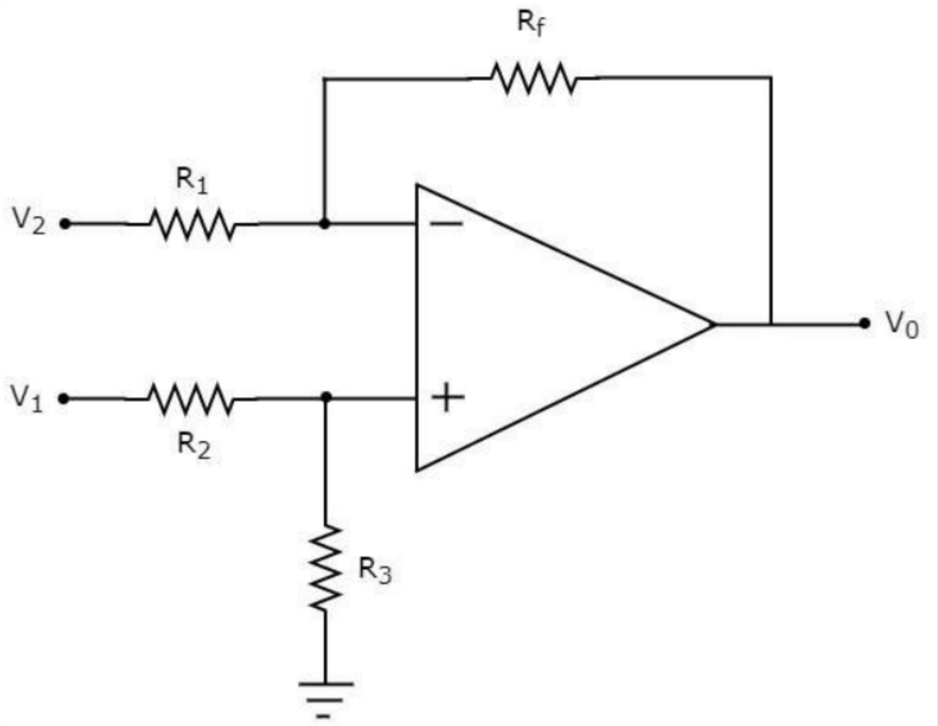
Basic OP-AMP circuit: Difference amplifiers (subtractor)

- **A subtractor** is an electronic circuit that produces an output, which is equal to the difference of the applied inputs.
- An op-amp based subtractor produces an output equal to the difference of the input voltages applied at its inverting and non-inverting terminals.
- It is also called as a **difference amplifier**, since the output is an amplified one.

The **circuit diagram** of an op-amp based subtractor is shown in the following figure −



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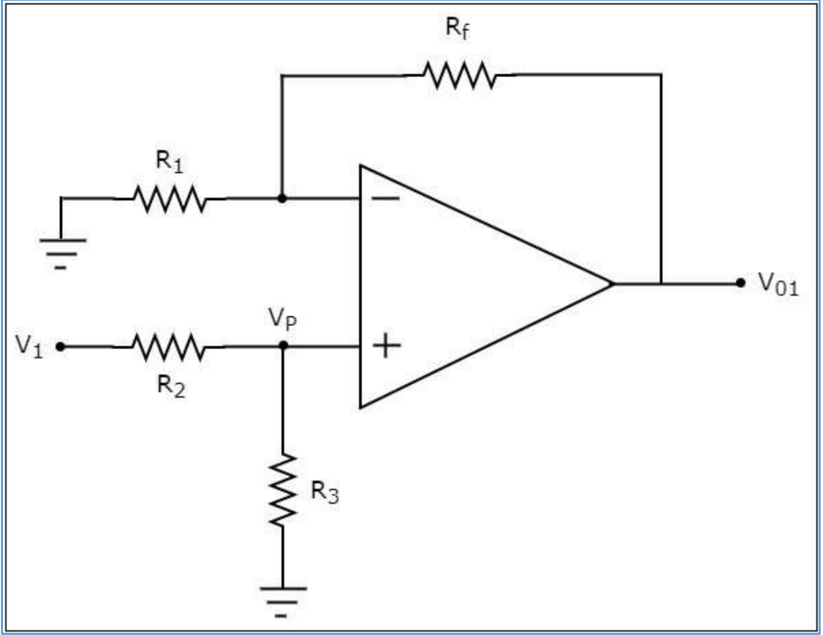
Basic OP-AMP circuit: Difference amplifiers (subtractor)

- Now, let us find the expression for output voltage Vo of the above circuit using **superposition theorem** using the following steps −

Step 1
Firstly, let us calculate the output voltage V_{01} by considering only V_1

For this, eliminate V_2 by making it short circuit. Then we obtain the **modified circuit diagram** as shown in the following figure −



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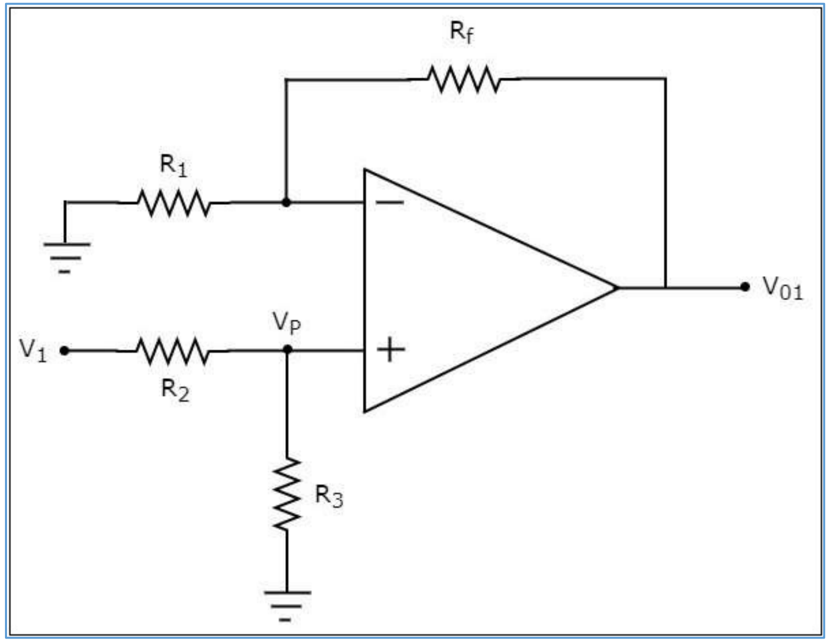

Now, using the **voltage division principle**, calculate the voltage at the non-inverting input terminal of the op-amp.

$$=> V_p = V_1 \left(\frac{R_3}{R_2 + R_3} \right)$$

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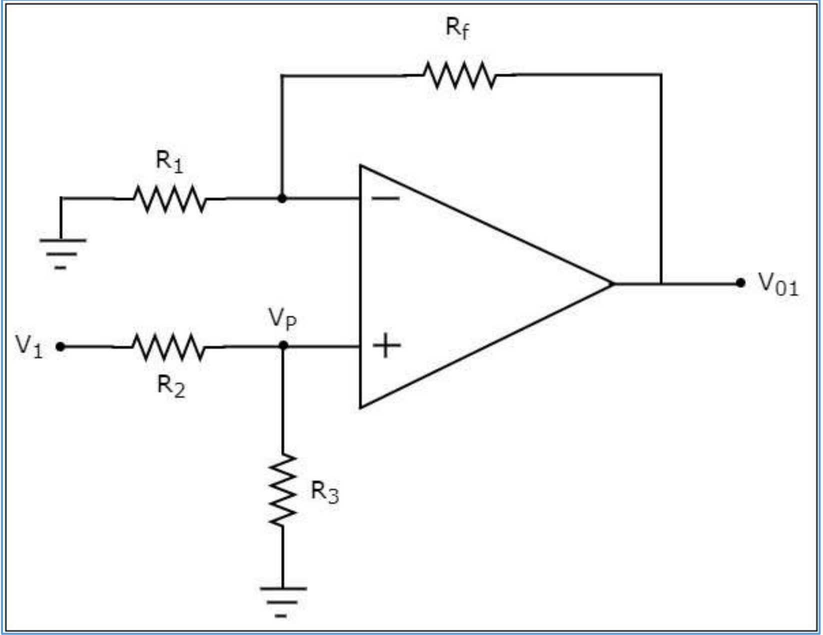

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Now, the above circuit looks like a non-inverting amplifier having input voltage V_p. Therefore, the output voltage V_{01} of above circuit will be

$$V_{01} = V_p \left(1 + \frac{R_f}{R_1} \right)$$

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Basic OP-AMP circuit: Difference amplifiers (subtractor)

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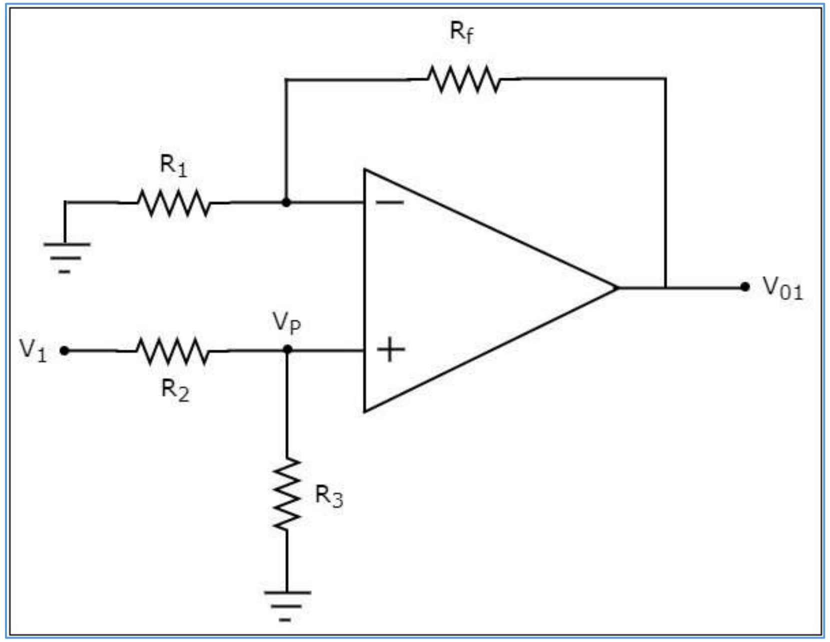

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$$V_{01} = V_p \left(1 + \frac{R_f}{R_1} \right)$$

Substitute, the value of V_p in above equation, we obtain the output voltage V01 by considering only V_1 as-

$$V_{01} = V_1 \left(\frac{R_3}{R_2 + R_3} \right) \left(1 + \frac{R_f}{R_1} \right)$$

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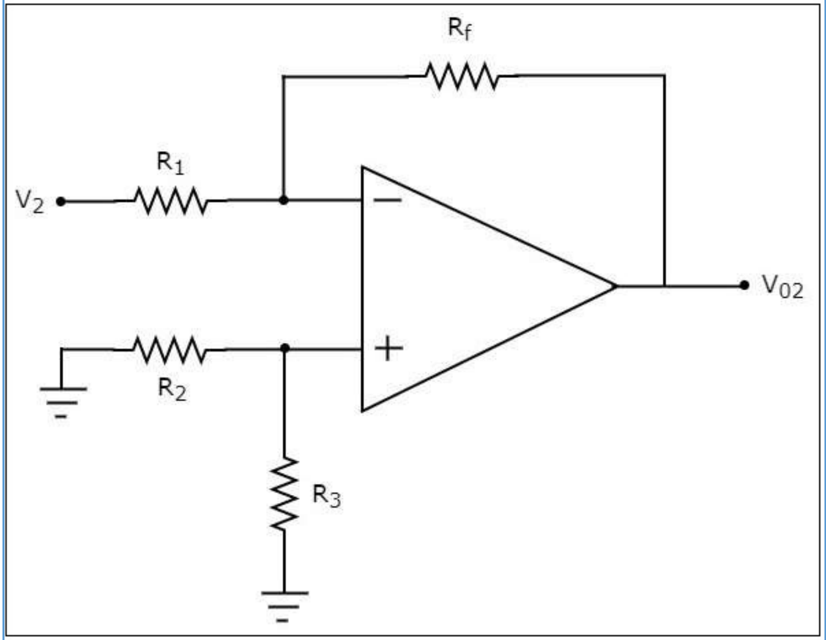
Basic OP-AMP circuit: Difference amplifiers (subtractor)

- Now, let us find the expression for output voltage Vo of the above circuit using **superposition theorem** using the following steps −

Step 2
In this step, let us find the output voltage, V_{02} by considering only V_2

For this, eliminate V_1 by making it short circuit. Then we obtain the **modified circuit diagram** as shown in the following figure −



- Observe that the voltage at the non-inverting input terminal of the op-amp will be zero volts.
- It means, the above circuit is simply an inverting op-amp. Therefore, the output voltage V_{02} of above circuit will be -

$$V_{02} = \left(-\frac{R_f}{R_1}\right) V_2$$

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Basic OP-AMP circuit: Difference amplifiers (subtractor)

- Now, let us find the expression for output voltage Vo of the above circuit using **superposition theorem** using the following steps −

Step 3

In this step, we will obtain the output voltage, V_O of the subtractor circuit by ***adding the output voltages*** obtained in ***Step1*** and ***Step2***. Mathematically, it can be written as

$$V_0 = V_{01} + V_{02}$$

Substituting the values of V_{01} ***and*** V_{02} in the above equation, we get-

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If ***$R_f=R_1=R_2=R_3=R$***, then the output voltage Vo will be -

$$V_0 = V_1\left(\frac{R}{R+R}\right)\left(1+\frac{R}{R}\right) - \left(\frac{R}{R}\right)V_2$$

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Basic OP-AMP circuit: Difference amplifiers (subtractor)

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$$=> V_0 = V_1\left(\frac{R}{2R}\right)(2)-(1)V_2$$

$$V_0 = V_1 - V_2$$

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$$=> V_0 = V_1\left(\frac{R}{2R}\right)(2) - (1)V_2$$

$$V_0 = V_1 - V_2$$

Thus, the op-amp based subtractor circuit discussed above will produce an output, which is the difference of two input voltages V_1 and V_2 when all the resistors present in the circuit are of same value.

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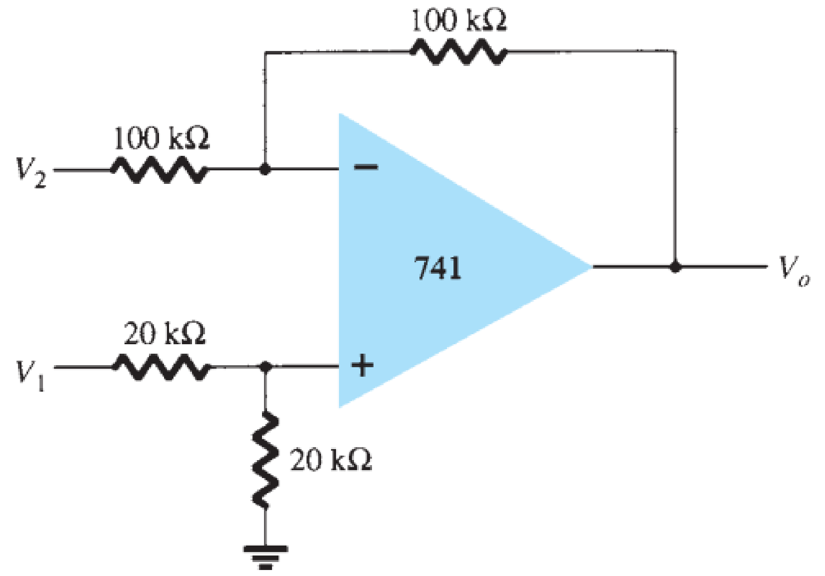
Basic OP-AMP circuit: Difference amplifiers (subtractor)

EXAMPLE Determine the output voltage for the circuit of Fig.



Basic OP-AMP circuit: Difference amplifiers (subtractor)

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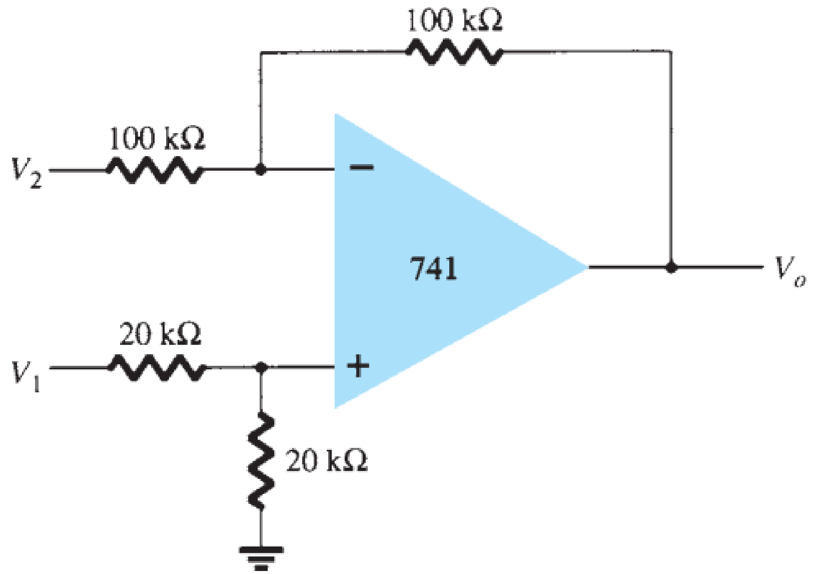


$$V_o = \frac{R_3}{R_1 + R_3}\frac{R_2 + R_4}{R_2}V_1 - \frac{R_4}{R_2}V_2$$

Solution: The resulting output voltage can be expressed as

$$V_o = \left(\frac{20\text{ k}\Omega}{20\text{ k}\Omega + 20\text{ k}\Omega}\right)\left(\frac{100\text{ k}\Omega + 100\text{ k}\Omega}{100\text{ k}\Omega}\right)V_1 - \frac{100\text{ k}\Omega}{100\text{ k}\Omega}V_2$$

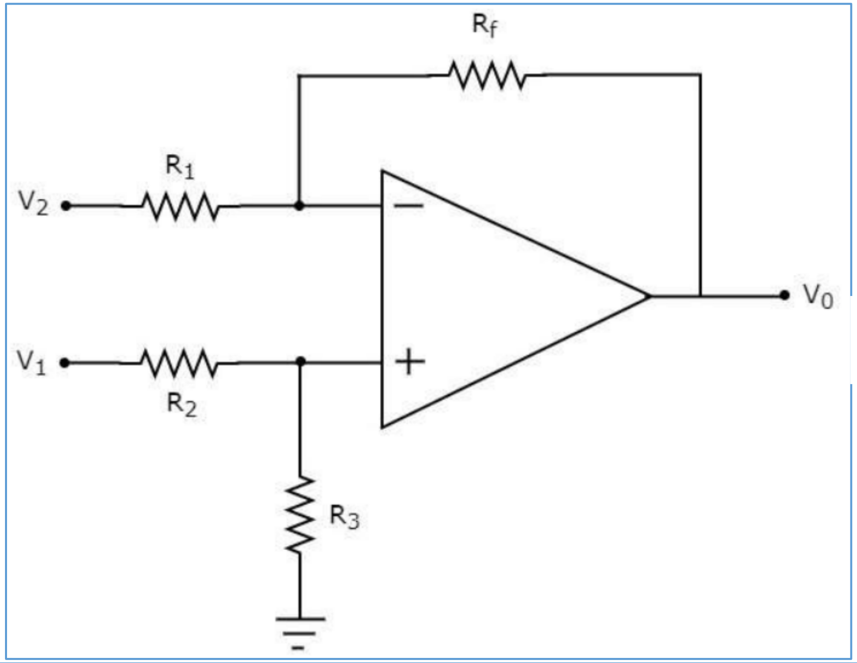
$$= V_1 - V_2$$

The resulting output voltage is seen to be the difference of the two input voltages.

Acknowledgment:-Electronic Devices and Circuit Theory, Boylestad and Nashelsky, 11th Edition

Basic OP-AMP circuit: Difference amplifiers (subtractor)

EXAMPLE Determine the output voltage for the circuit of Fig.



Find output voltage using superposition theorem.

- The values given are
- V1=5,V2=2
- R1=2 Kohm, R2=2 Kohm,
- Rf=10 Kohm, R3=4 Kohm

Basic OP-AMP circuit: Difference amplifiers (subtractor)

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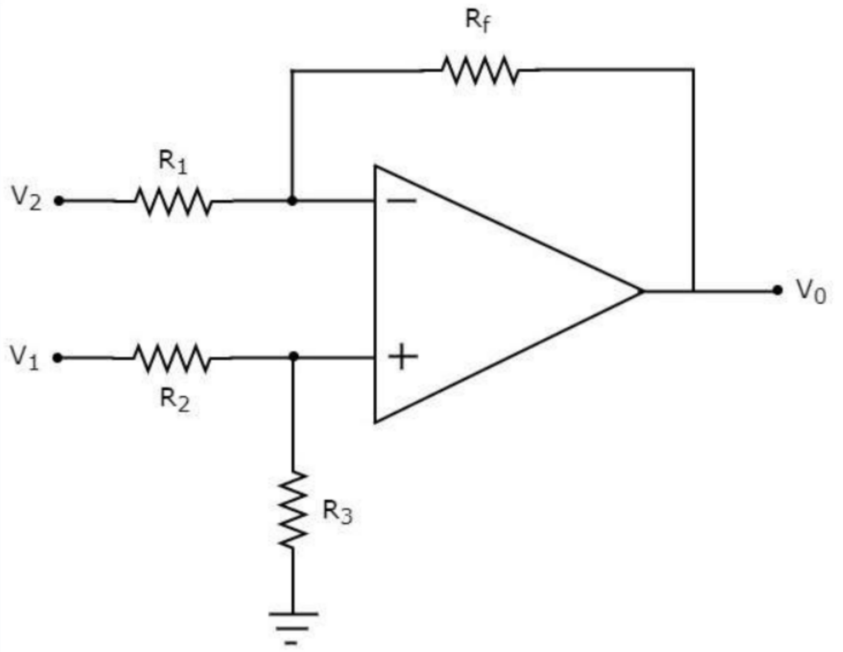

Find output voltage using superposition theorem.

- The values given are
- V1=5,V2=2
- R1=2 Kohm, R2=2 Kohm,
- Rf=10 Kohm, R3=4 Kohm

Solution:

$$V_{01} = V_1 \left(\frac{R_3}{R_2 + R_3}\right)\left(1 + \frac{R_f}{R_1}\right)$$

When V_1 is active ;V_{01}=20

$$V_0 = V_1 - V_2$$

$$V_{02} = \left(-\frac{R_f}{R_1}\right) V_2$$

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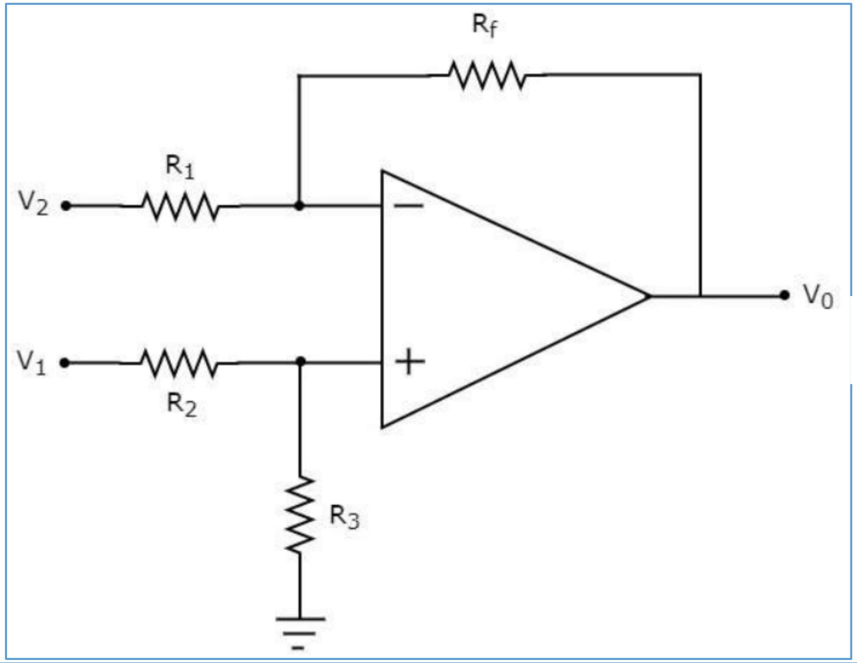
Basic OP-AMP circuit: Difference amplifiers (subtractor)

EXAMPLE Determine the output voltage for the circuit of Fig.



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Basic OP-AMP circuit: Difference amplifiers (subtractor)

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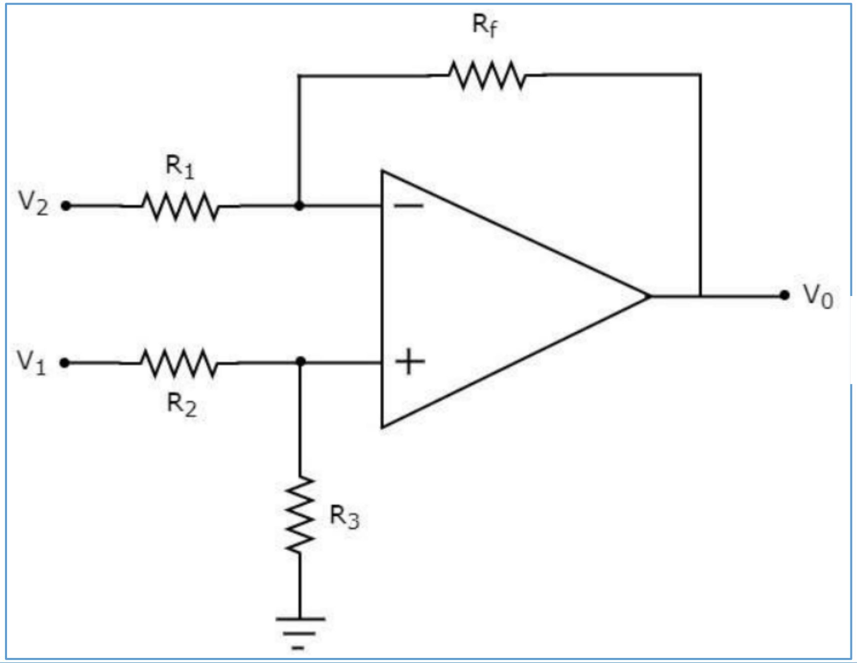

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Basic OP-AMP circuit: Difference amplifiers (subtractor)

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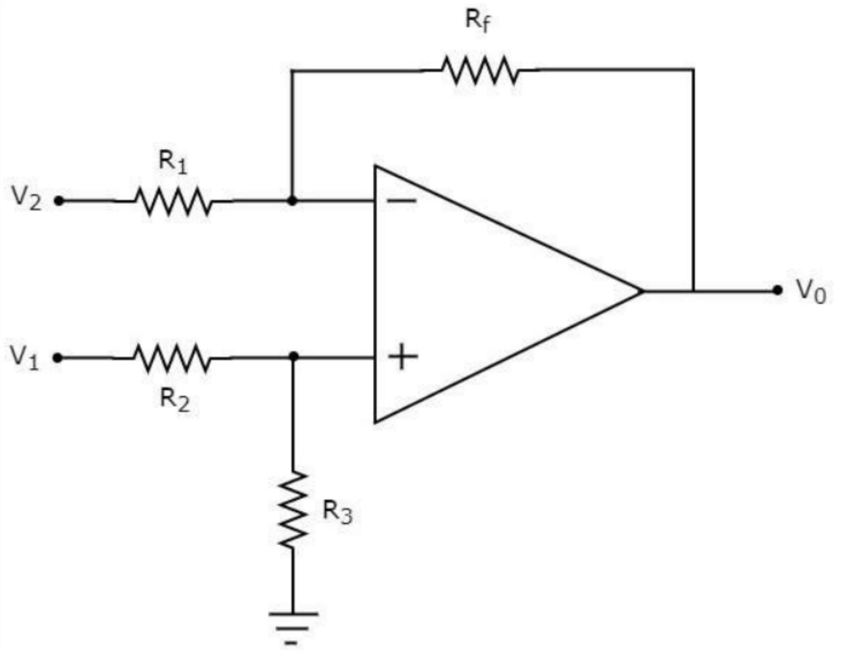

Find output voltage using superposition theorem.

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- V1=5,V2=2
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Solution:

When V_1 is active

$$V_{01} = V_1\left(\frac{R_3}{R_2+R_3}\right)\left(1+\frac{R_f}{R_1}\right)$$

When V_1 is active ;V_{01}=20

When V_2 is active

$$V_{02} = \left(-\frac{R_f}{R_1}\right)V_2$$

When V_2 is active ;V_{02}= -10

Using superposition theorem $V_0 = V_{01} + V_{02}$ **= 20+ (-10) =10**

Basic OP-AMP circuit: Difference amplifiers (subtractor)

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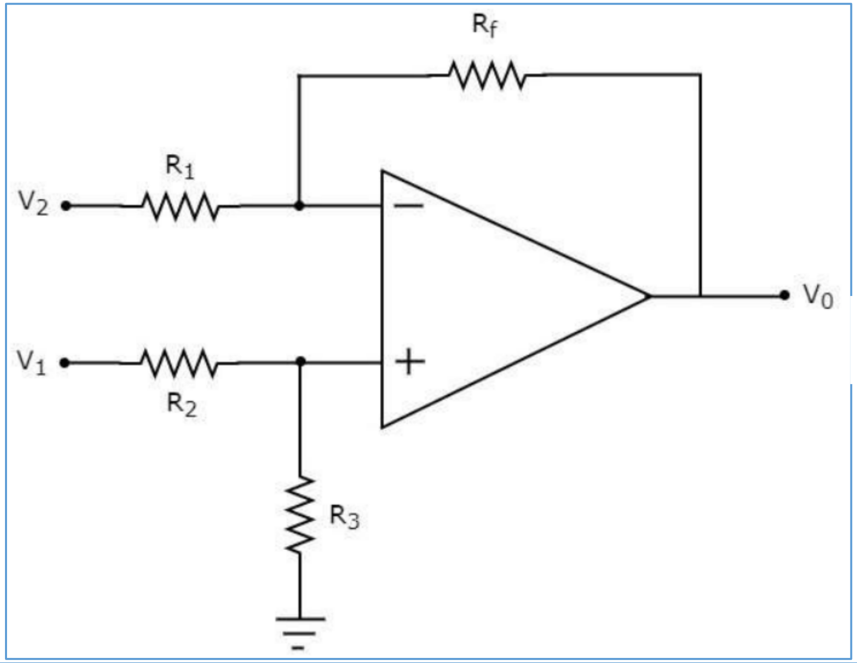

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Solution:

When V_1 is active

$$V_{01} = V_1 \left(\frac{R_3}{R_2 + R_3}\right)\left(1 + \frac{R_f}{R_1}\right)$$

When V_1 is active ;V_{01}=20

When V_2 is active

$$V_{02} = \left(-\frac{R_f}{R_1}\right) V_2$$

When V_2 is active ;V_{02}= -10

Using superposition theorem $V_0 = V_{01} + V_{02}$ **= 20+ (-10) =10**

When all the resistances are made equal then $V_0 = V_1 - V_2$

$\boldsymbol{Vo = 5 - 2 = 3}$

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Voltage Regulator

- A voltage regulator provides a constant **dc** output voltage that is essentially independent of the input voltage, output load current, and temperature.
- The voltage regulator is one part of a power supply.
- Its input voltage comes from the filtered output of a rectifier derived from an ac voltage or from a battery in the case of portable systems.

- Most voltage regulators fall into two broad categories: ***linear regulators and switching regulators.***
- In the ***linear regulator*** category, two general types are the ***series regulator and the shunt regulator.***
- These are normally available for either ***positive or negative output voltages***.
- A dual regulator provides both positive and negative outputs.

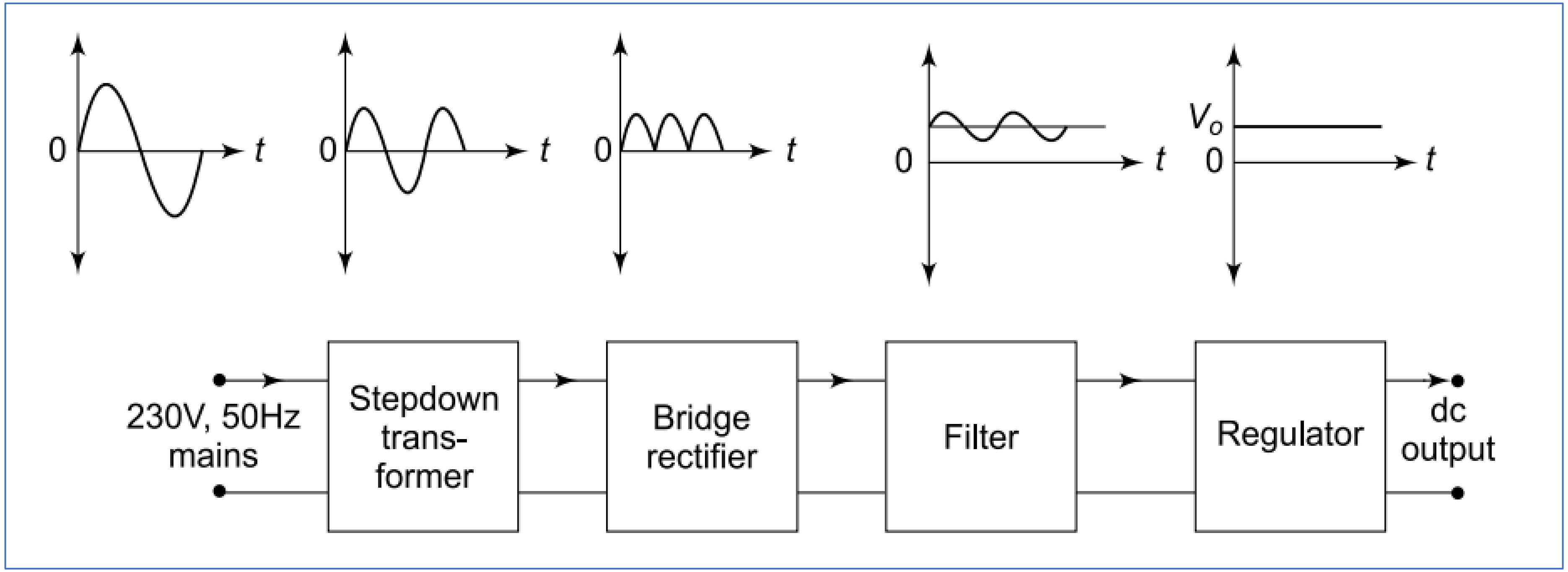
- In the ***switching regulator*** category, three general configurations are step-down, step-up, and inverting.

- Many types of integrated circuit (IC) regulators are available.
- The most popular types of linear regulator are the ***three-terminal fixed voltage regulator*** and the ***three-terminal adjustable voltage regulator***

Acknowledgment:-**Thomas L. Floyd** *Electronic Devices, Electron Flow Version,* Ninth Edition

Voltage Regulator

- The basic building blocks of a linear power supply



- The basic building blocks of a linear power supply are shown in Fig.
- A transformer supplies ac voltage at the required level. This bidirectional ac voltage is converted into a unidirectional and pulsating dc using a rectifier. The unwanted ripple contents of this pulsating dc are removed by a filter to get a pure dc voltage. The output of the filter is fed to a voltage regulator which gives a steady dc output, independent of load variations and input supply fluctuations.

Acknowledgment:-Linear Integrated Circuits by S Salivahanan

Voltage Regulator

- Two basic categories of voltage regulation are ***line regulation and load regulation***.
- The purpose of line regulation is to maintain a nearly constant output voltage when the input voltage varies.
- The purpose of load regulation is to maintain a nearly constant output voltage when the load varies.

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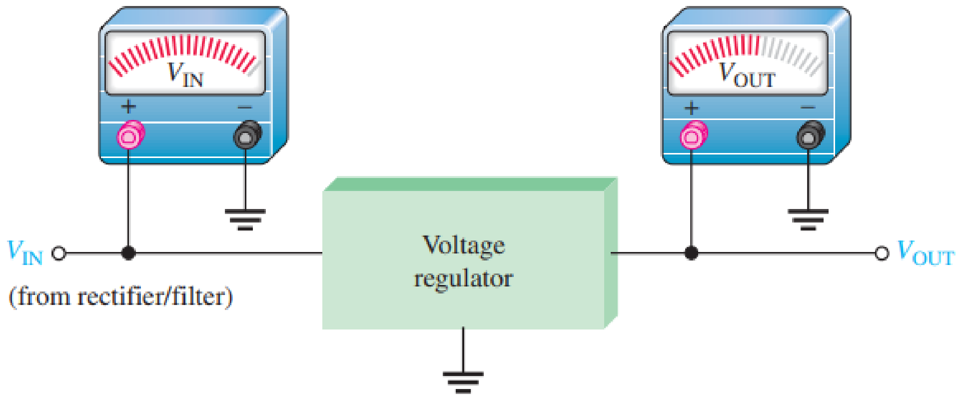
Voltage Regulator

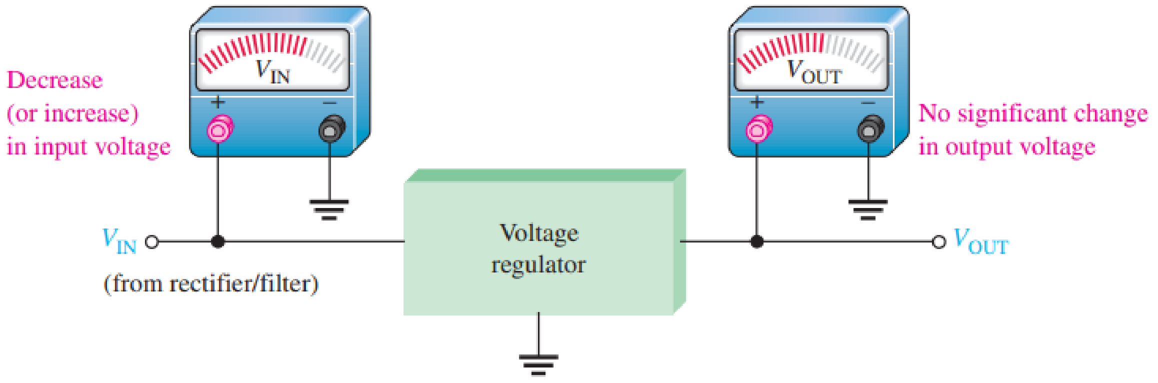
- **Line Regulation**

- When the ac input (line) voltage of a power supply changes, an electronic circuit called a regulator maintains a nearly constant output voltage, as illustrated in Figure.
- Line regulation can be defined as the percentage change in the output voltage for a given change in the input voltage.
- When taken over a range of input voltage values, line regulation is expressed as a percentage by the following formula (Line regulation can also be expressed in units of %/V)

$$\textbf{Line regulation} = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right)100\%$$

$$\textbf{Line regulation} = \frac{(\Delta V_{OUT}/V_{OUT})100\%}{\Delta V_{IN}}$$





Line regulation. A change in input (line) voltage does not significantly affect the output voltage of a regulator (within certain limits).

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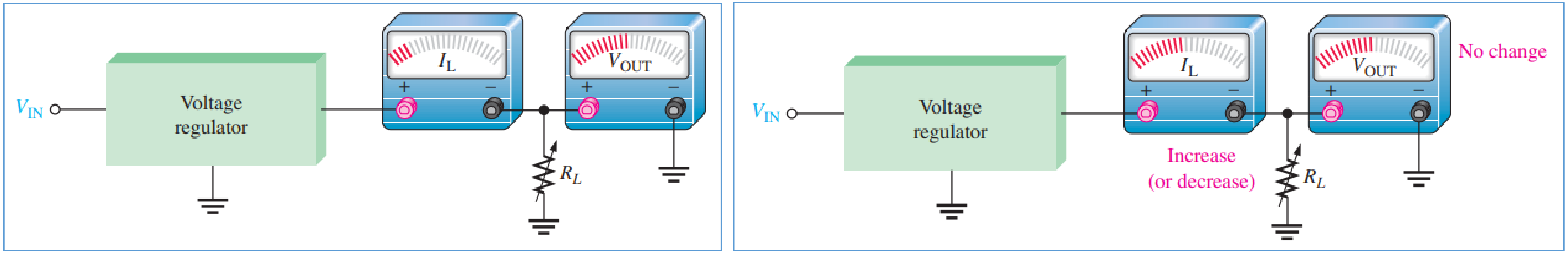
Voltage Regulator

- **Load Regulation**

- When the amount of current through a load changes due to a varying load resistance, the
- voltage regulator must maintain a nearly constant output voltage across the load, as illustrated in Figure

- Load regulation can be defined as the percentage change in output voltage for a given change in load current. One way to express load regulation is as a percentage change in output voltage from no-load (NL) to full-load (FL).

$$\textbf{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\%$$



Load regulation. A change in load current has practically no effect on the output voltage of a regulator (within certain limits).

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Voltage Regulator

- **Linear series regulators**

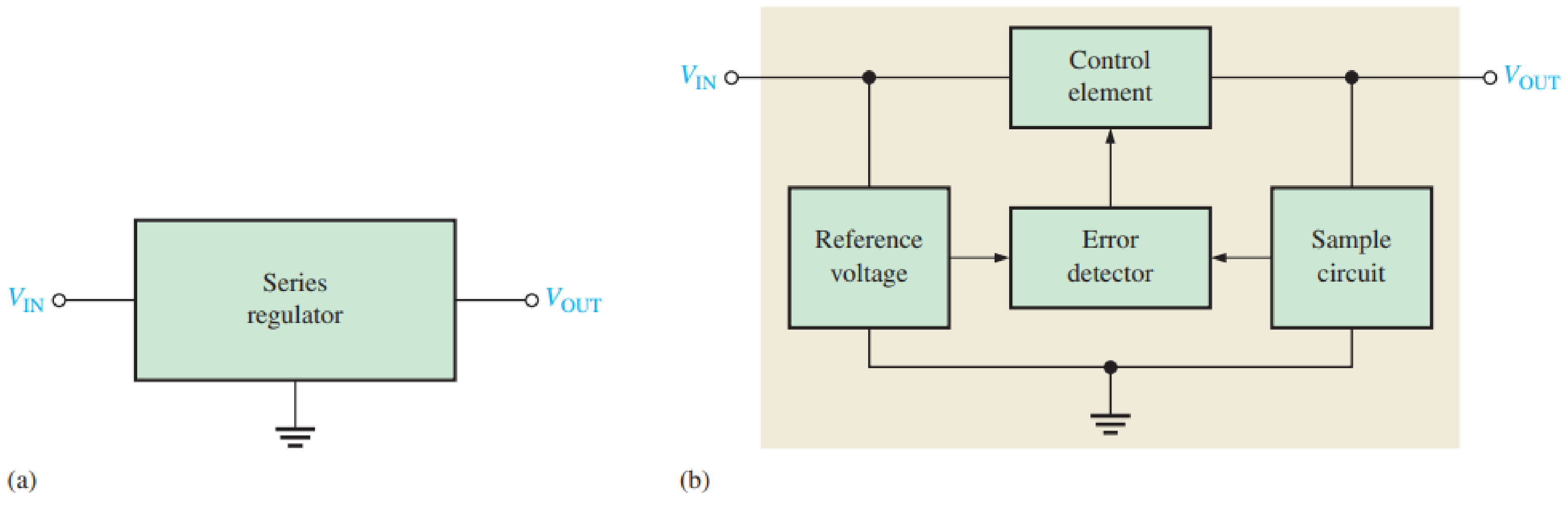
- If the control element of a voltage regulator operates in its linear region, then the regulator is called a linear voltage regulator.
- Linear voltage regulators are generally of series mode type.
- The voltage regulator circuit using Zener diode is vulnerable to the variations in supply voltage since the current through the Zener diode also changes correspondingly.
- Hence the linear voltage regulator uses an op-amp as an error amplifier, and a pass transistor as a control element.
- The error output from the op-amp drives the control element, which allows current to the load accordingly and keeps the output voltage constant.

Acknowledgment:-Linear Integrated Circuits by S Salivahanan

Voltage Regulator

- **Linear series regulators**

- A simple representation of a series type of linear regulator is shown in Figure (a), and the basic components are shown in the block diagram in Figure (b).
- The control element is a pass transistor in series with the load between the input and output.
- The output sample circuit senses a change in the output voltage.
- The error detector compares the sample voltage with a reference voltage and causes the control element to compensate in order to maintain a constant output voltage.



Simple series voltage regulator and block diagram.

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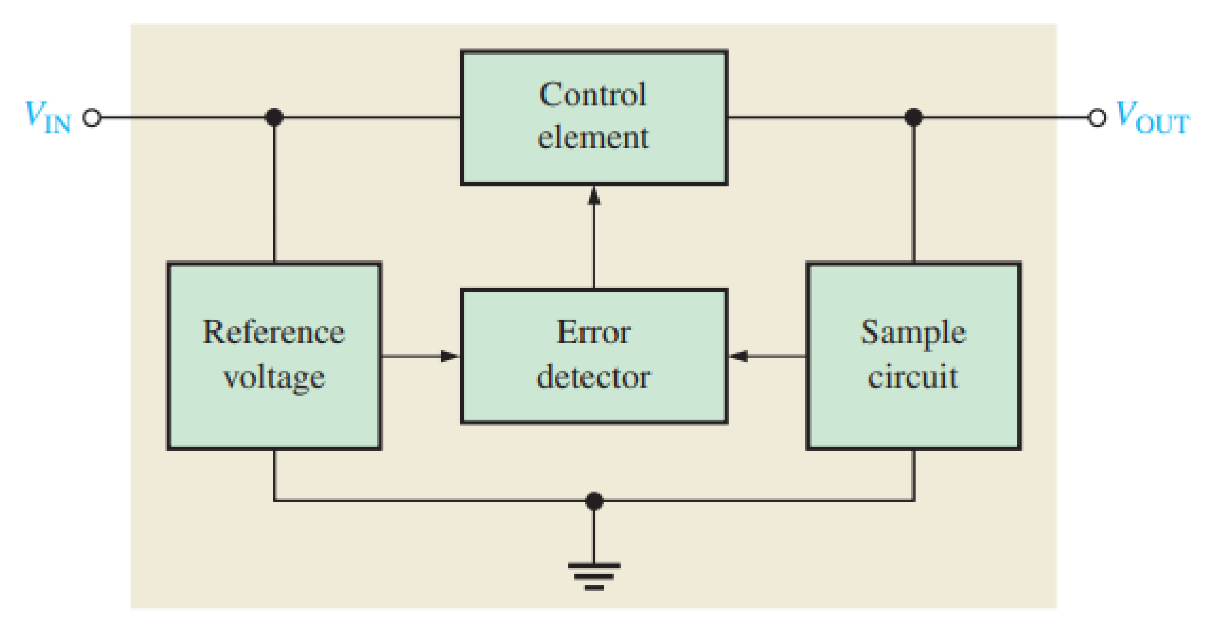
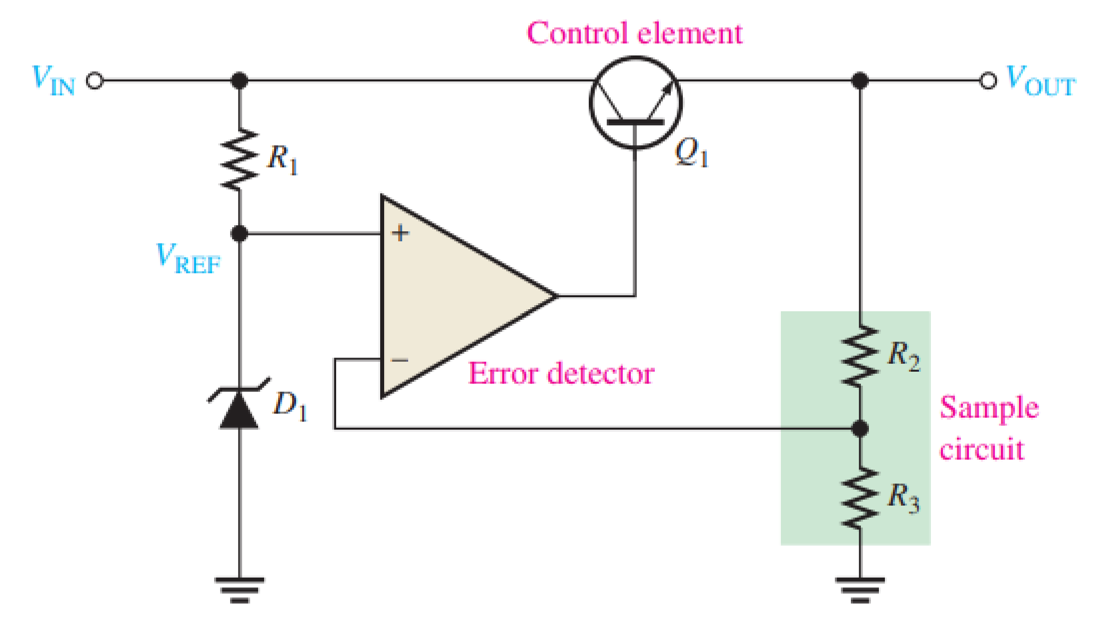
Voltage Regulator

- **Linear series regulators**

- A basic op-amp series regulator is shown in Figure



Simple series voltage regulator and block diagram.



Basic op-amp series regulator.

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Voltage Regulator

- **Linear series regulator-Regulating Action**

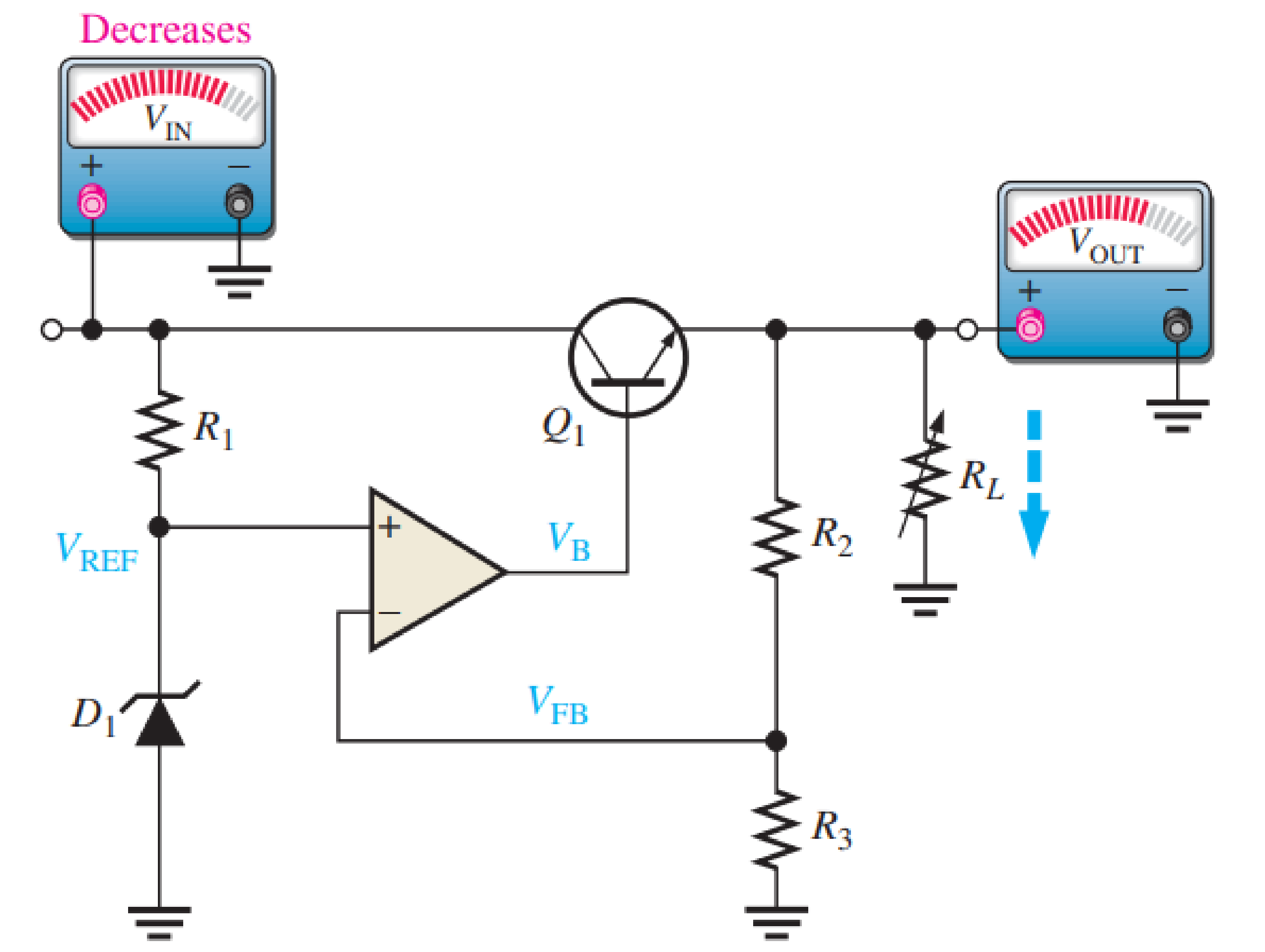

Illustration of series regulator action that keeps VOUT constant when VIN or RL changes.

- When V_{IN} or R_L decreases, V_{OUT} attempts to decrease.
- The feedback voltage, V_{FB}, also attempts to decrease, and as a result, the op-amp's output voltage V_B attempts to increase, thus compensating for the attempted decrease in V_{OUT} by increasing the Q_1 emitter voltage.
- Changes in V_{OUT} are exaggerated for illustration.
- When V_{IN} (or R_L) stabilizes at its new lower value, the voltages return to their original values, thus keeping V_{OUT} constant as a result of the negative feedback.

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Voltage Regulator

- **Linear series regulator-Regulating Action**

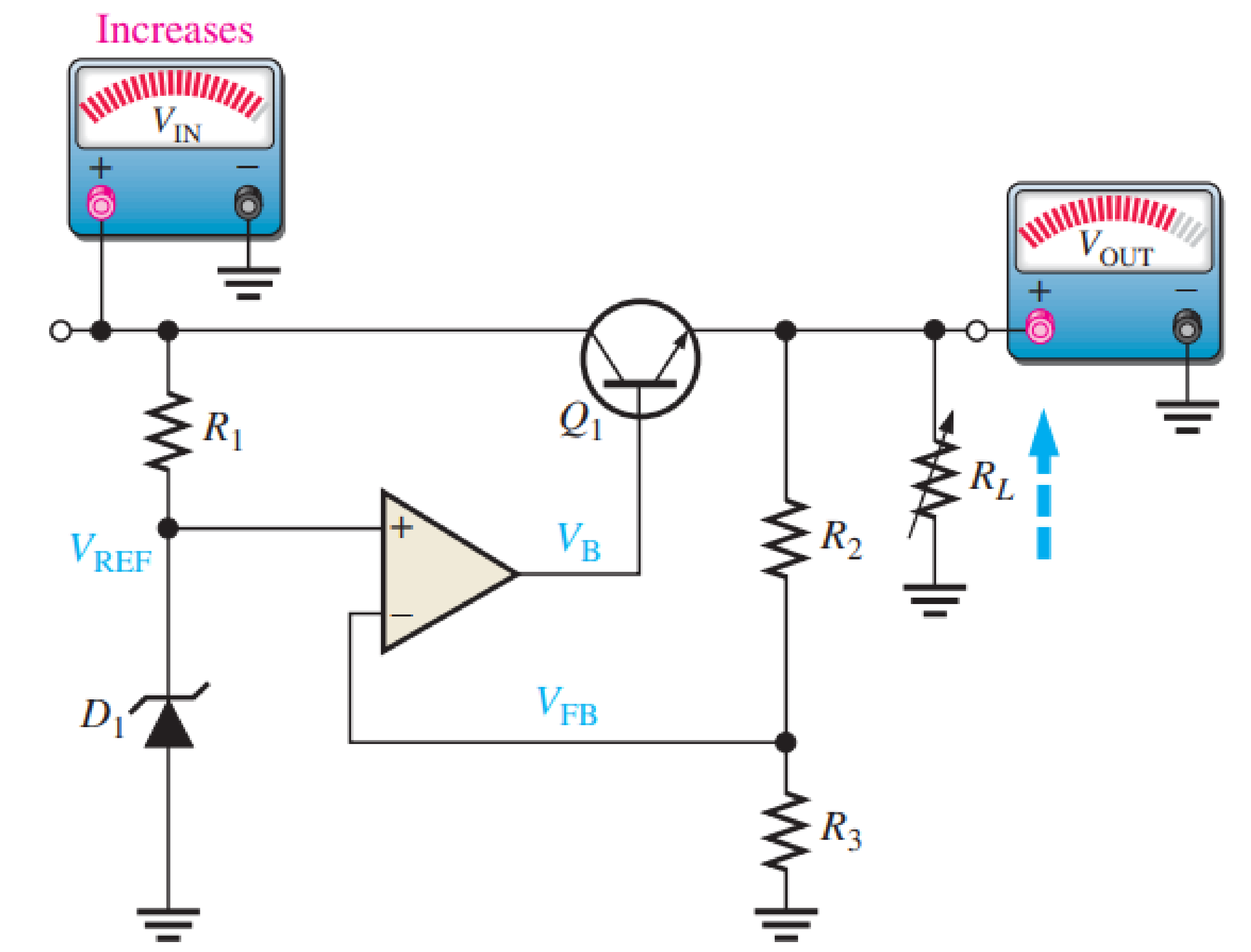

Illustration of series regulator action that keeps VOUT constant when VIN or RL changes.

- When V_{IN} or R_L increases, V_{OUT} attempts to increase.
- The feedback voltage, V_{FB}, also attempts to increase, and as a result, V_B, applied to the base of the control transistor, attempts to decrease, thus compensating for the attempted increase in V_{OUT} by decreasing the Q_1 emitter voltage.
- When V_{IN} (or R_L) stabilizes at its new higher value, the voltages return to their original values, thus keeping V_{OUT} constant as a result of the negative feedback.

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Voltage Regulator

- **Linear series regulator-Regulating Action**

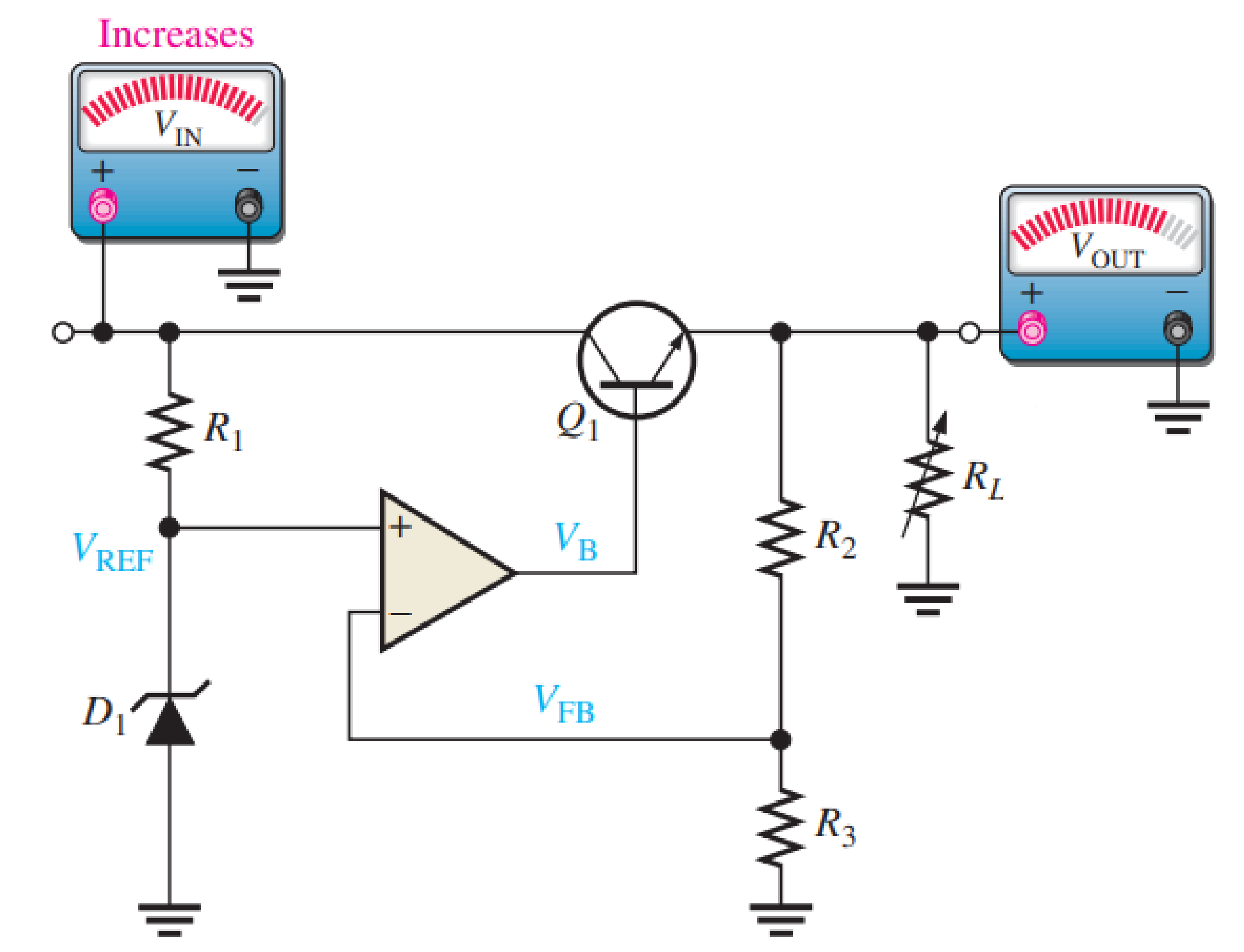

Illustration of series regulator action that keeps VOUT constant when VIN or RL changes.

- Therefore, the regulated output voltage of the series regulator (neglecting the base-emitter voltage of Q_1) is

$$V_{OUT} \cong \left(1 + \frac{R_2}{R_3}\right) V_{REF}$$

- From this analysis, you can see that the output voltage is determined by the zener voltage and the resistors R_2 and R_3.
- It is relatively independent of the input voltage, and therefore, regulation is achieved (as long as the input voltage and load current are within specified limits).

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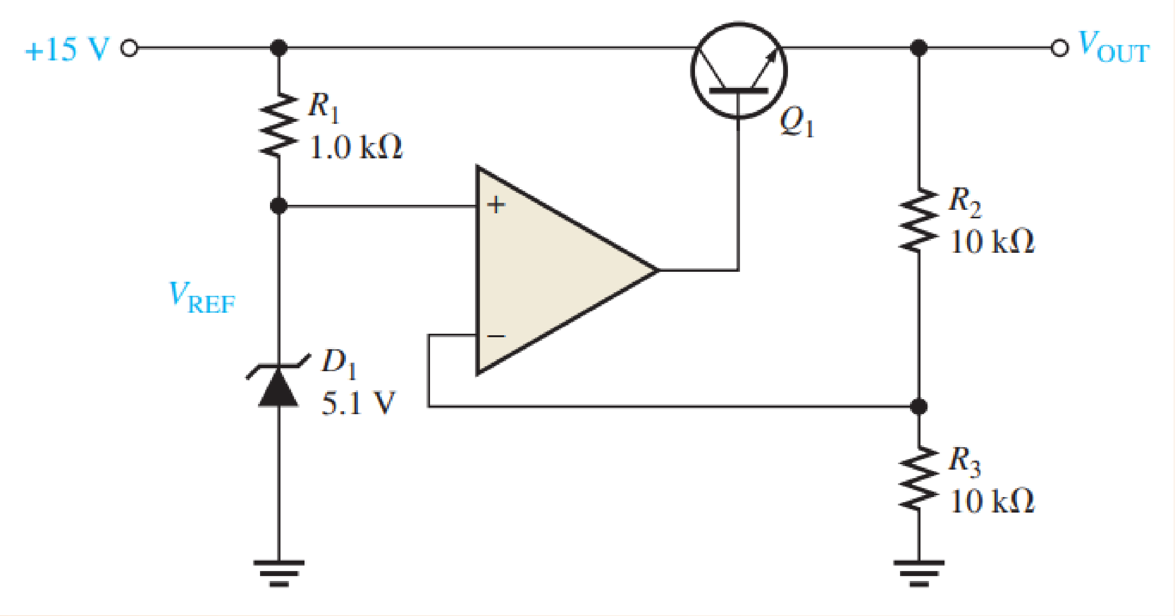
Voltage Regulator

- **Linear series regulator-Regulating Action**

EXAMPLE

Determine the output voltage for the regulator in Figure

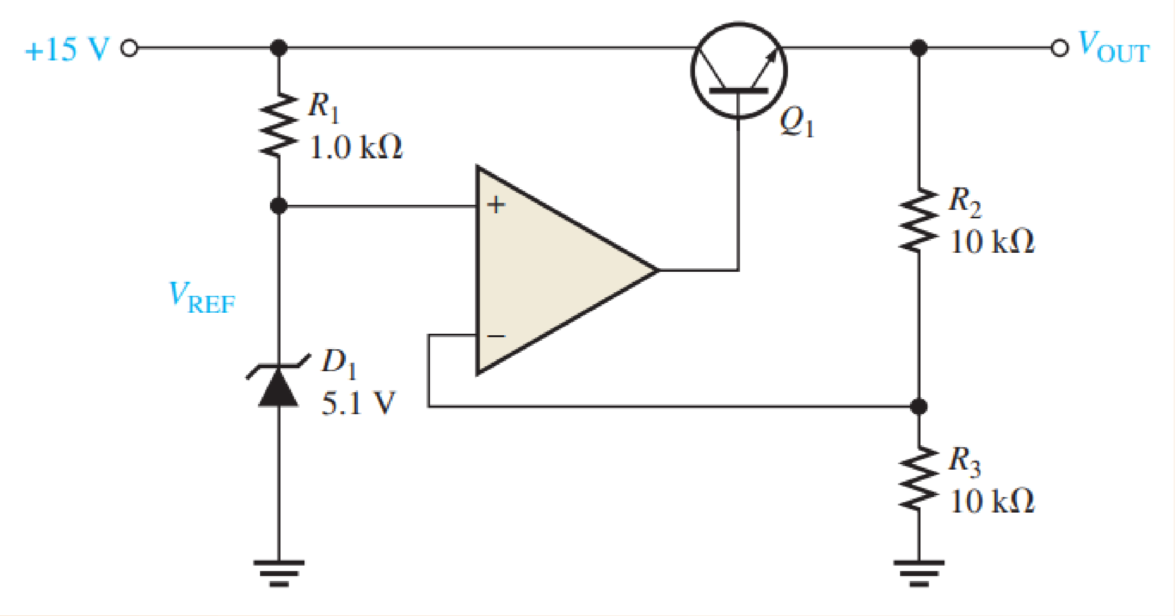


Voltage Regulator

- **Linear series regulator-Regulating Action**

EXAMPLE

Determine the output voltage for the regulator in Figure



Solution $V_{REF} = 5.1$ V, the zener voltage. The regulated output voltage is therefore

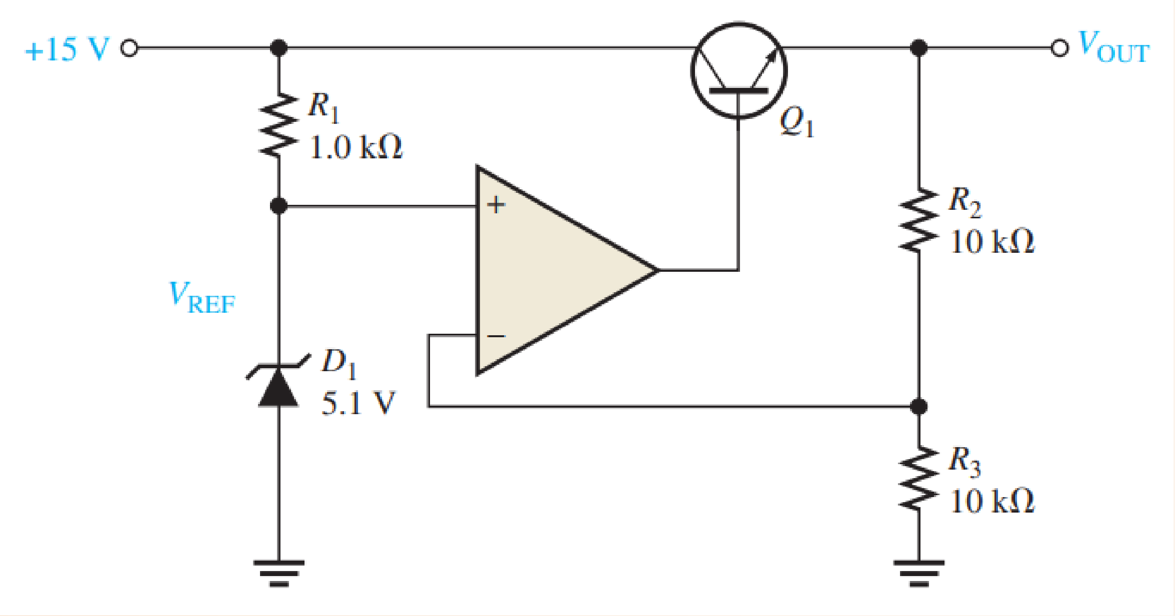
$$V_{OUT} = \left(1 + \frac{R_2}{R_3}\right)V_{REF} = \left(1 + \frac{10\text{ k}\Omega}{10\text{ k}\Omega}\right)5.1\text{ V} = (2)5.1\text{ V} = \mathbf{10.2\text{ V}}$$

Voltage Regulator

- **Linear series regulator-Regulating Action**

EXAMPLE

Determine the output voltage for the regulator in Figure



Related Problem The following changes are made in the circuit in Figure : A 3.3 V zener replaces the 5.1 V zener, $R_1 = 1.8\ \text{k}\Omega$, $R_2 = 22\ \text{k}\Omega$, and $R_3 = 18\ \text{k}\Omega$. What is the output voltage? 7.39

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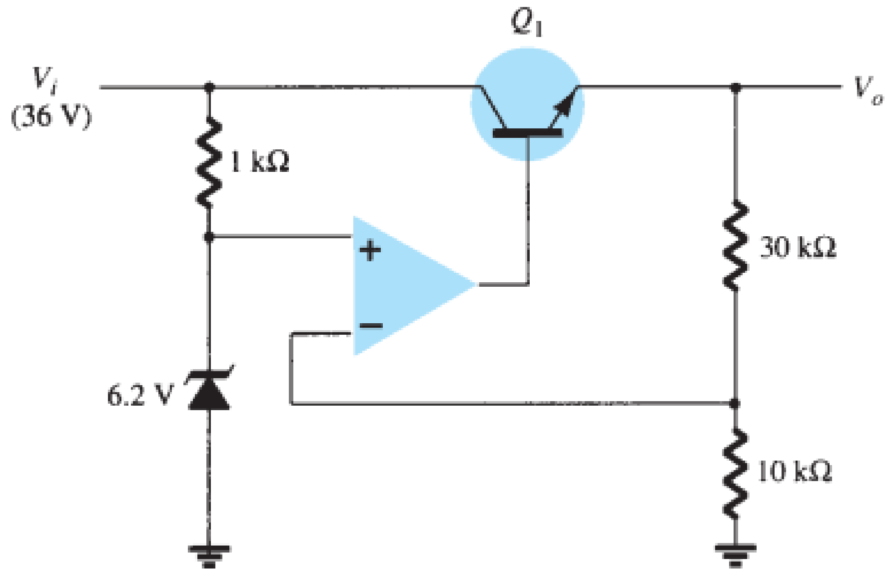
Voltage Regulator

- **Linear series regulator-Regulating Action**

EXAMPLE Calculate the regulated output voltage in the circuit of Fig.



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Voltage Regulator

- **Linear series regulator-Regulating Action**

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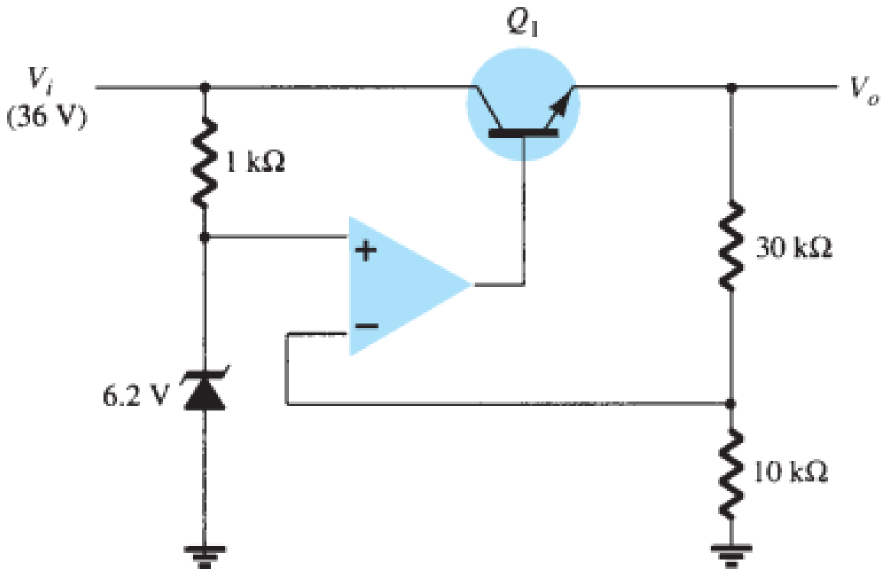

Solution:

$$\boxed{V_o = \left(1 + \frac{R_1}{R_2}\right)V_Z}$$

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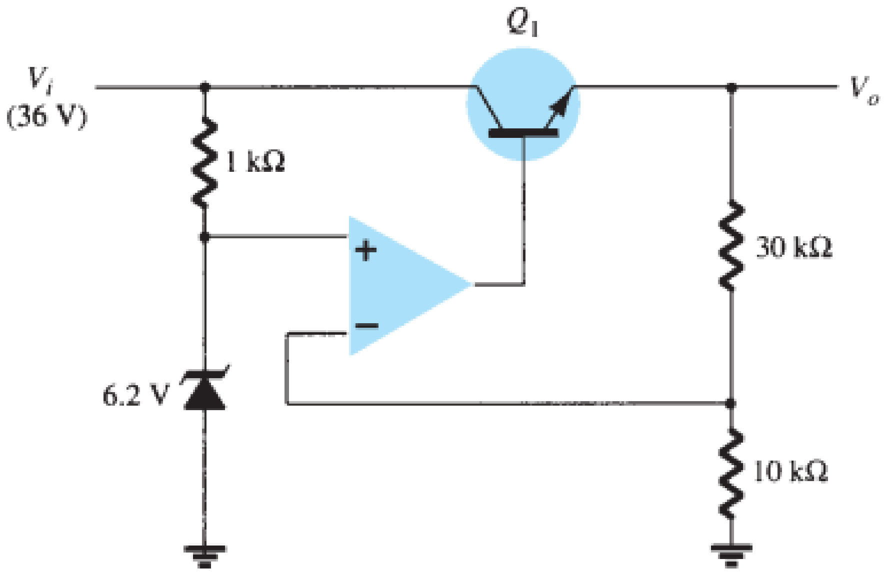
Voltage Regulator

- **Linear series regulator-Regulating Action**

EXAMPLE Calculate the regulated output voltage in the circuit of Fig.



Solution:

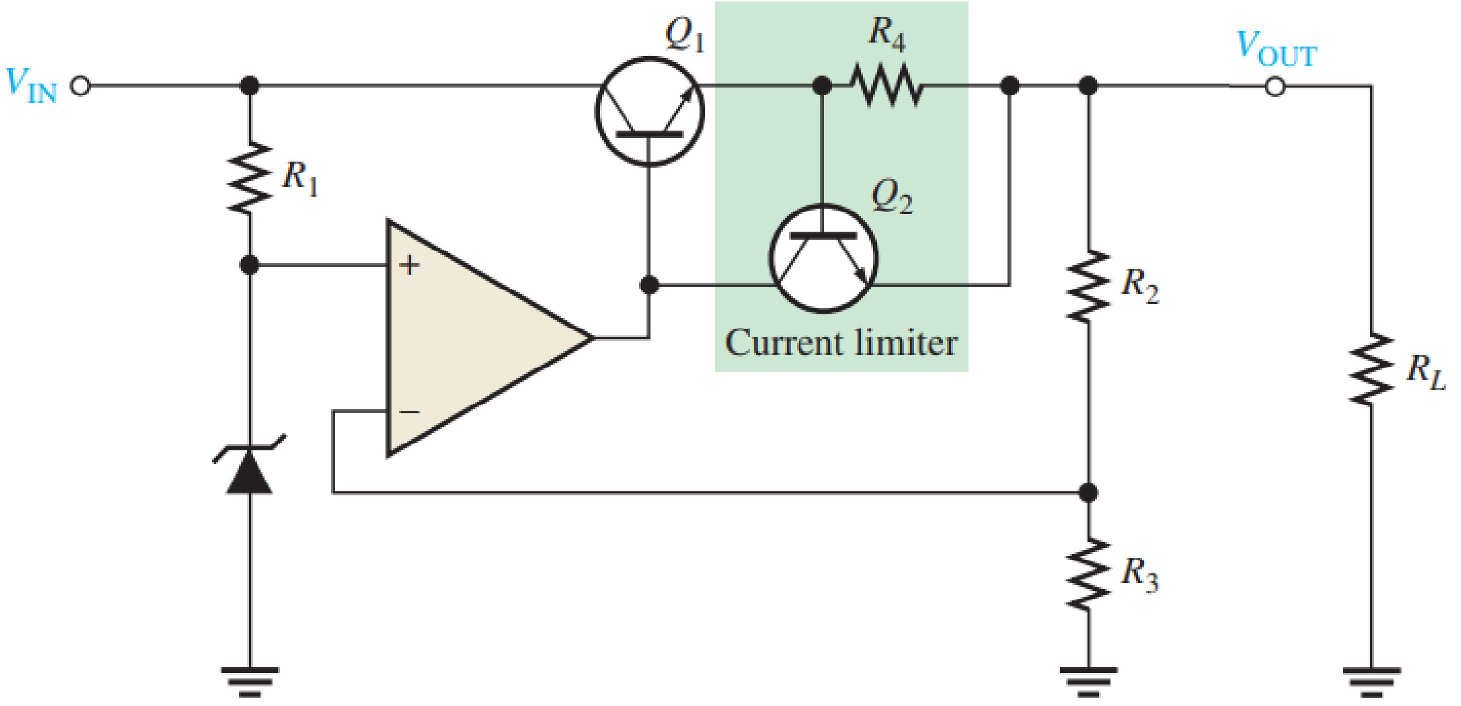
$$\boxed{V_o = \left(1 + \frac{R_1}{R_2}\right)V_Z}$$

$$V_o = \left(1 + \frac{30\ \text{k}\Omega}{10\ \text{k}\Omega}\right)6.2\ \text{V} = \mathbf{24.8\ V}$$

Acknowledgment:-Electronic Devices and Circuit Theory, Boylestad and Nashelsky, 11th Edition

Voltage Regulator

- **Linear series regulator: Short-Circuit or Overload Protection**



Series regulator with constant-current limiting.

- If an excessive amount of load current is drawn, the series-pass transistor can be quickly damaged or destroyed.
- Most regulators use some type of excess current protection in the form of a current-limiting mechanism.
- Figure shows one method of current limiting to prevent overloads called constant-current limiting.
- The current-limiting circuit consists of transistor Q2 and resistor R4.

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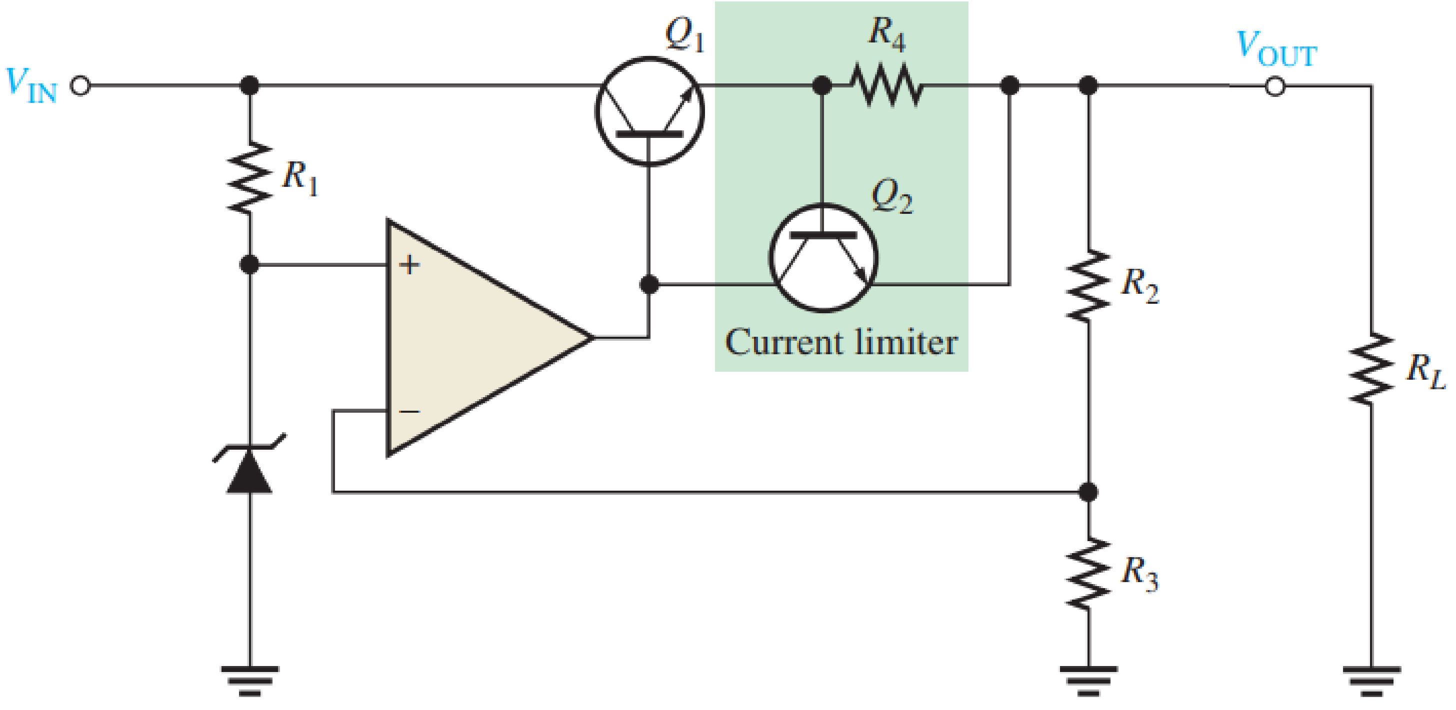
Voltage Regulator

- **Linear series regulator: Short-Circuit or Overload Protection**



Series regulator with constant-current limiting.

- The load current through R4 produces a voltage from base to emitter Q2.
- When I_L reaches a predetermined maximum value, the voltage drop across R4 is sufficient to forward-bias the base-emitter junction of Q2 thus causing it to conduct.
- Enough op-amp output current is diverted through Q2 to reduce the Q1 base current, so that I_L is limited to its maximum value $I_{L(MAX)}$,
- Since the base-to-emitter voltage of Q2 cannot exceed approximately 0.7 V, the voltage across R4 is held to this value, and the load current is limited to

$$I_{L(max)} = \frac{0.7\ V}{R_4}$$

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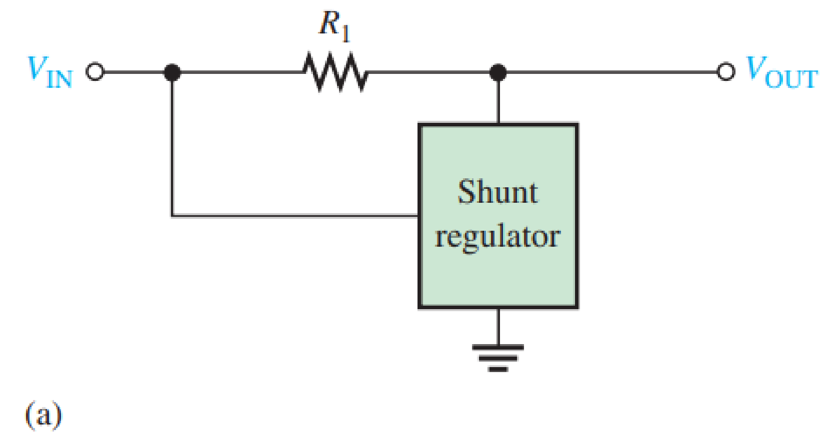
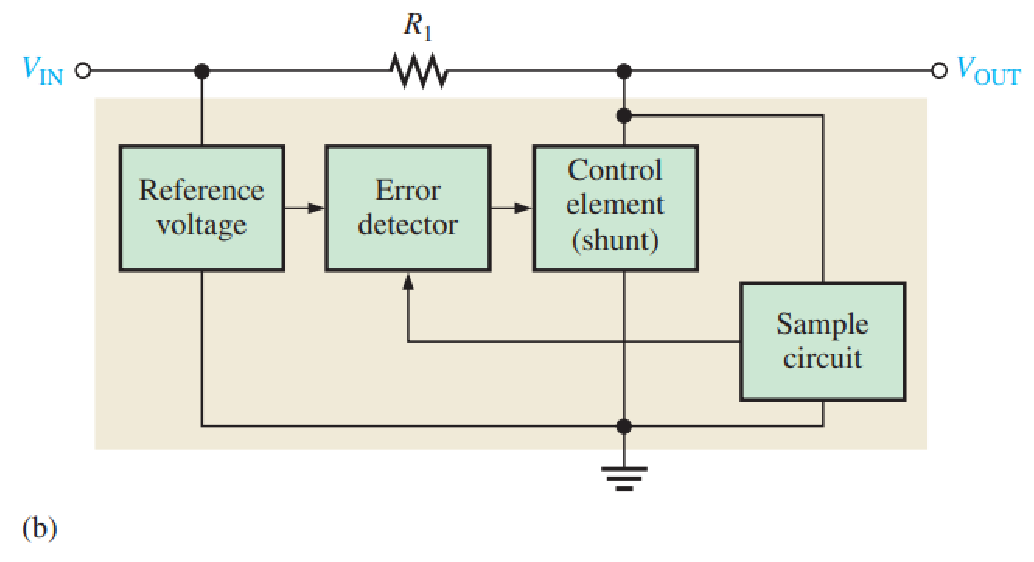
Voltage Regulator

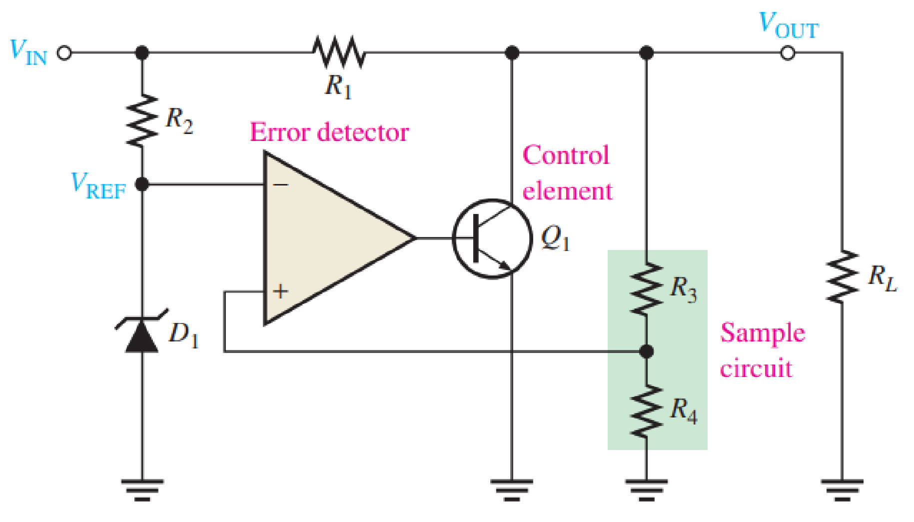
- **Linear Shunt regulator**



- The second basic type of linear voltage regulator is the shunt regulator.
- As you have learned, the control element in the series regulator is the series-pass transistor.
- In the shunt regulator, the control element is a transistor in parallel (shunt) with the load.

A simple representation of a shunt type of linear regulator is shown in Figure (a), and the basic components are shown in the block diagram in part (b).





Basic op-amp shunt regulator with load resistor.

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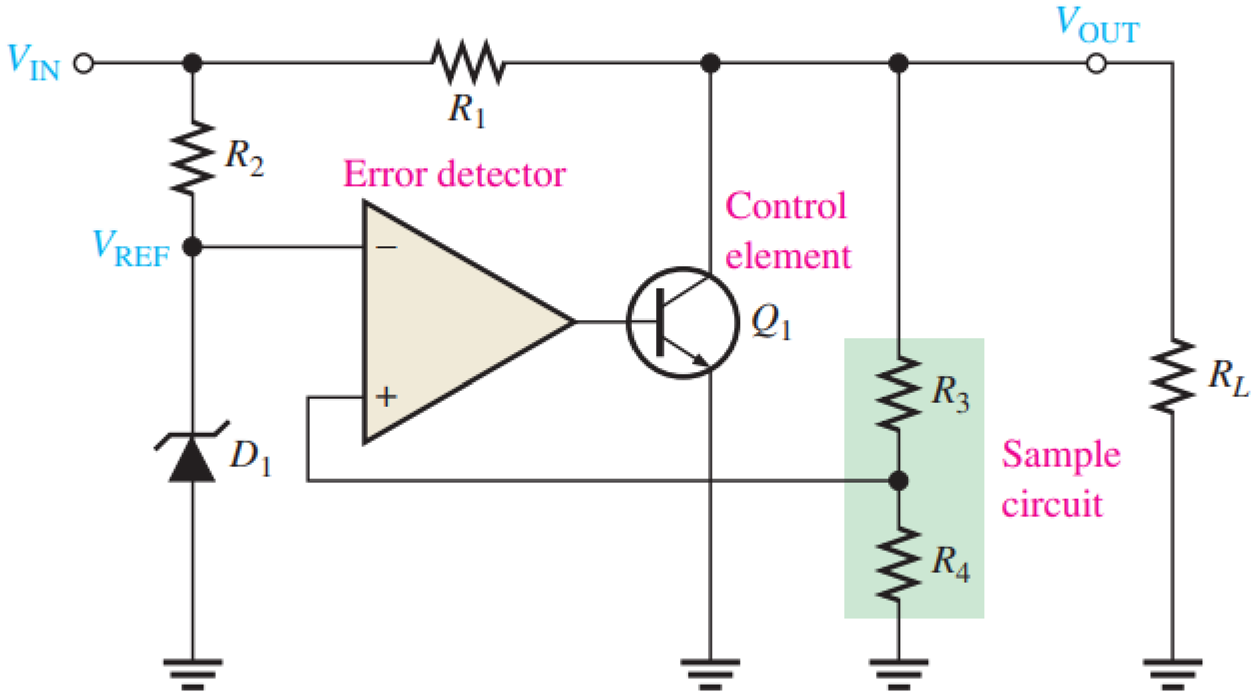
Voltage Regulator

- **Linear Shunt regulator**



Basic op-amp shunt regulator with load resistor.

- In the basic shunt regulator, the control element is a transistor Q1, in parallel with the load, as shown in Figure.
- A resistor, R1 is in series with the load.
- The operation of the circuit is similar to that of the series regulator, except that regulation is achieved by controlling the current through the parallel transistor Q1.

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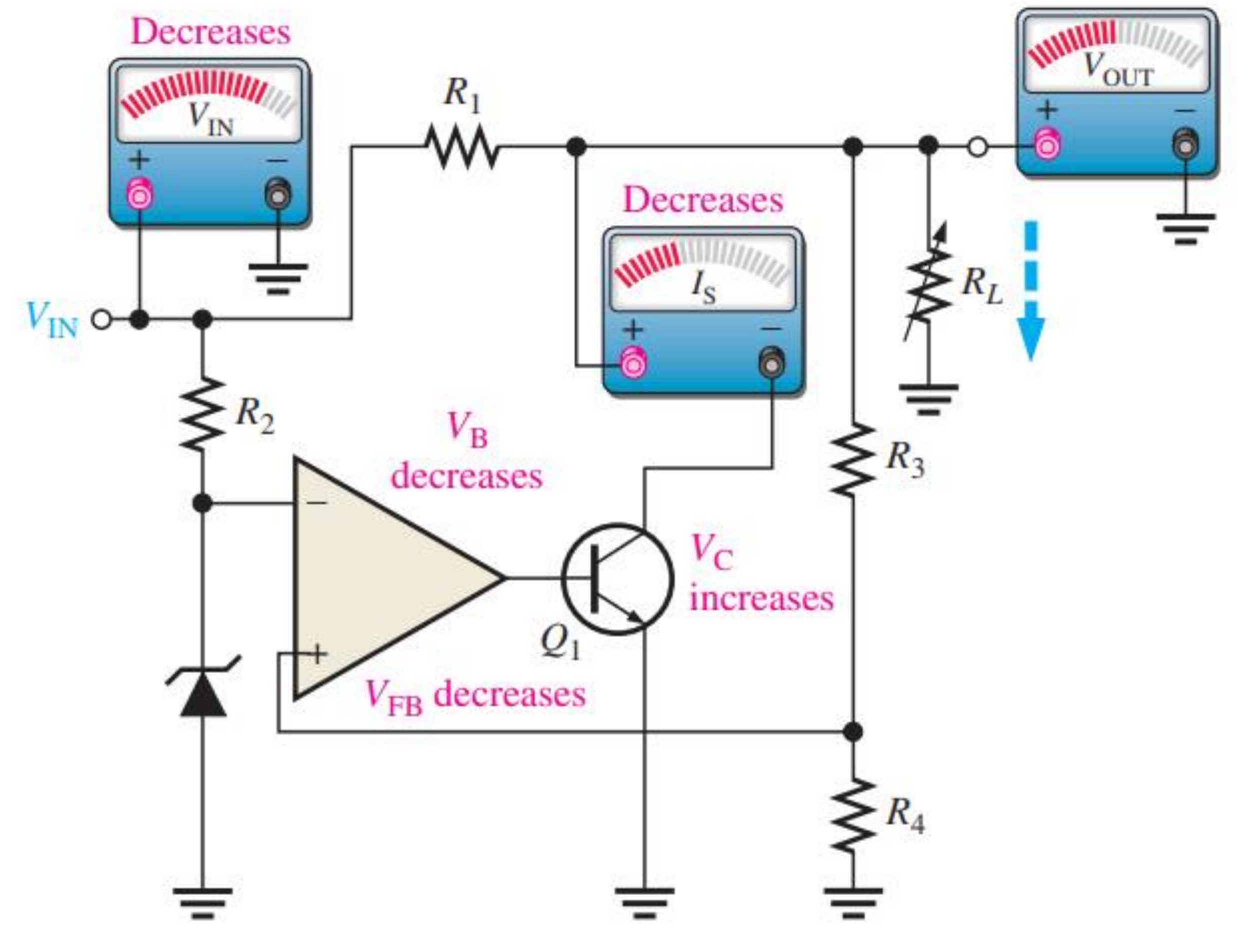
Voltage Regulator

- **Linear Shunt regulator**



(a) Response to a decrease in V_{IN} or R_L

- When the output voltage tries to decrease due to a change in input voltage or load current caused by a change in load resistance, as shown in Figure(a), the attempted decrease is sensed by R3 and R4 and applied to the op-amp's noninverting input.
- The resulting difference voltage reduces the op-amp's output (V_B) driving Q1 less, thus reducing its collector current (shunt current) and increasing the collector voltage.
- Thus, the original decrease in voltage is compensated for by this increase, keeping the output nearly constant.

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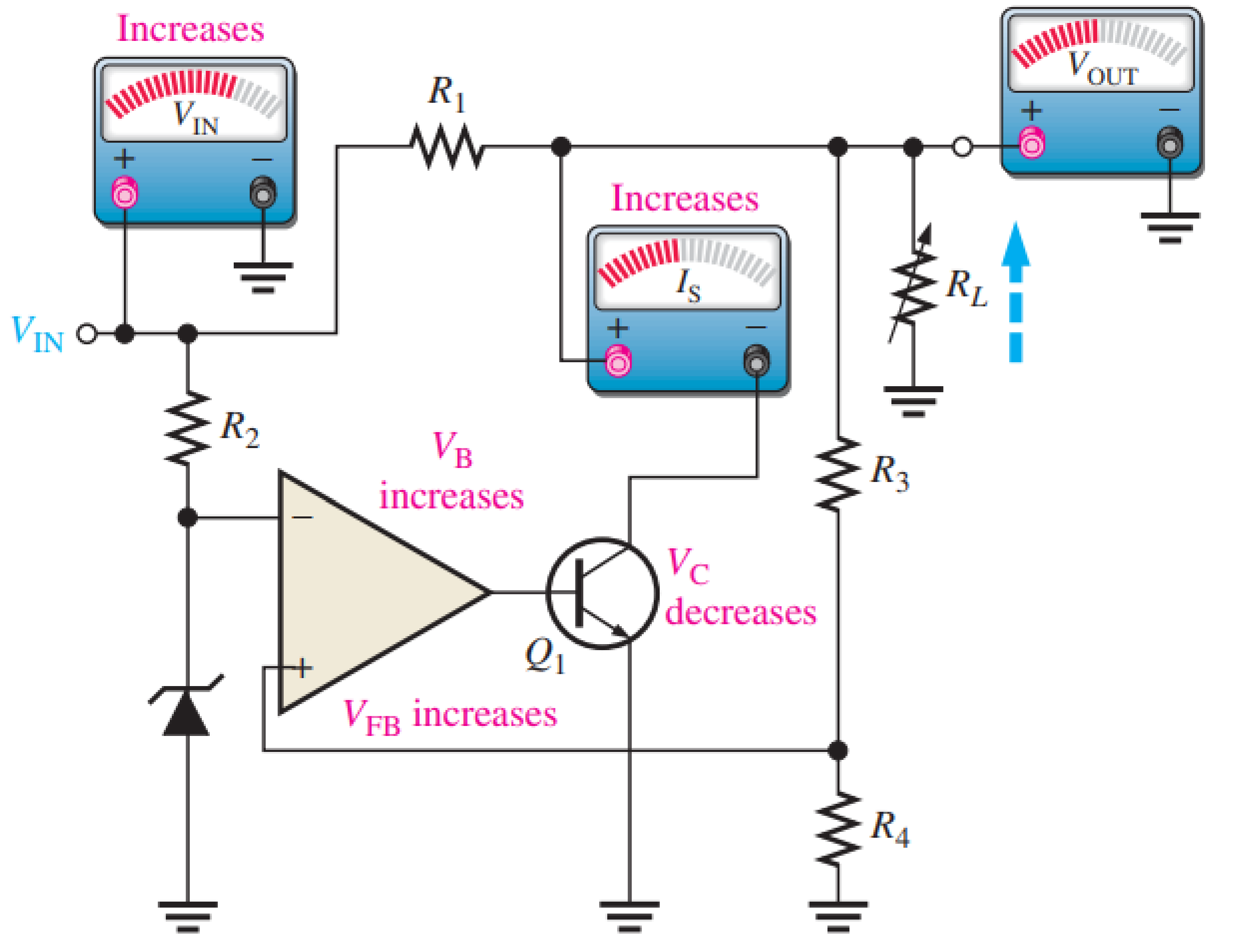
Voltage Regulator

- **Linear Shunt regulator**



(b) Response to an increase in V_{IN} or R_L

- The opposite action occurs when the output tries to increase, as indicated in Figure (b).

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Voltage Regulator IC's

- Many types of integrated circuit (IC) regulators are available.
- The most popular types of linear regulator are the ***three-terminal fixed voltage regulator*** and the ***three-terminal adjustable voltage regulator***

- **Types of Voltage Regulators**
- There are two types of voltage regulators −

1. Fixed voltage regulator
2. Adjustable voltage regulator

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Acknowledgment:-https://www.tutorialspoint.com/

Voltage Regulator

- **Fixed voltage regulator**

- A fixed voltage regulator produces a fixed DC output voltage, which is either positive or negative.
- In other words, some fixed voltage regulators produce positive fixed DC voltage values, while others produce negative fixed DC voltage values.

78xx voltage regulator ICs produce positive fixed DC voltage values, whereas, **79xx** voltage regulator ICs produce negative fixed DC voltage values.

The following points are to be noted while working with **78xx** and **79xx** voltage regulator ICs −

- "xx" corresponds to a two-digit number and represents the amount (magnitude) of voltage that voltage regulator IC produces.
- Both 78xx and 79xx voltage regulator ICs have **3 pins** each and the third pin is used for collecting the output from them.

The purpose of the first and second pins of these two types of ICs is different −

- The first and second pins of **78xx** voltage regulator ICs are used for connecting the input and ground respectively.
- The first and second pins of **79xx** voltage regulator ICs are used for connecting the ground and input respectively.

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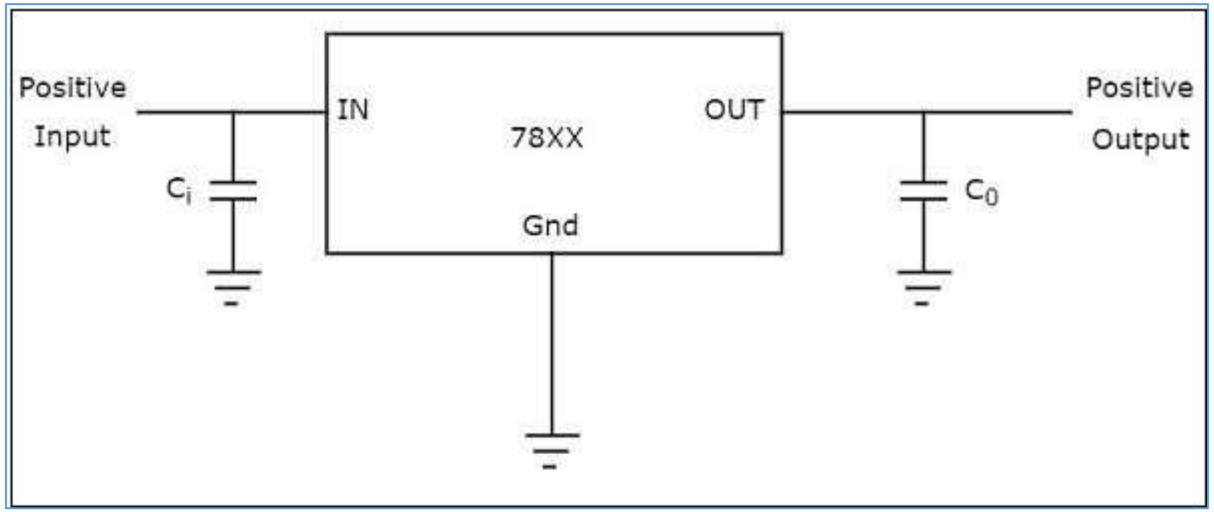
Voltage Regulator

- **Fixed voltage regulator**

- Examples
- 7805 voltage regulator IC produces a DC voltage of +5 volts.
- 7905 voltage regulator IC produces a DC voltage of -5 volts.

The following figure shows how to produce a fixed positive voltage at the output by using a fixed positive voltage regulator with necessary connections.



In the above figure that shows a fixed positive voltage regulator, the input capacitor C_i is used to prevent unwanted oscillations and the output capacitor, C_0 acts as a line filter to improve transient response.

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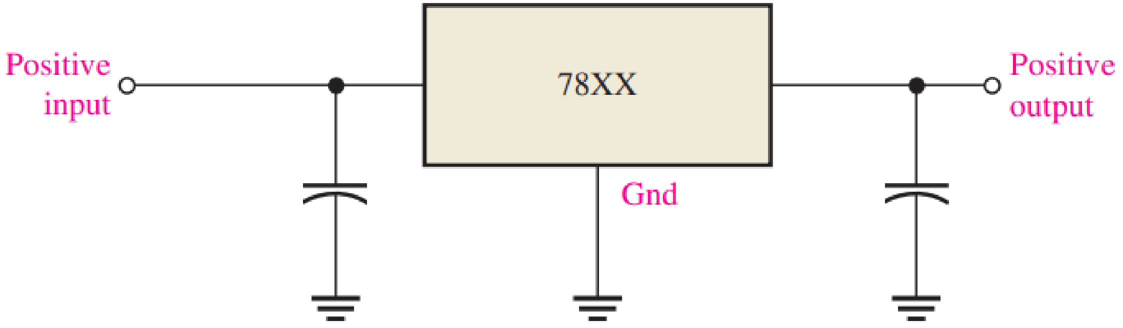
Voltage Regulator

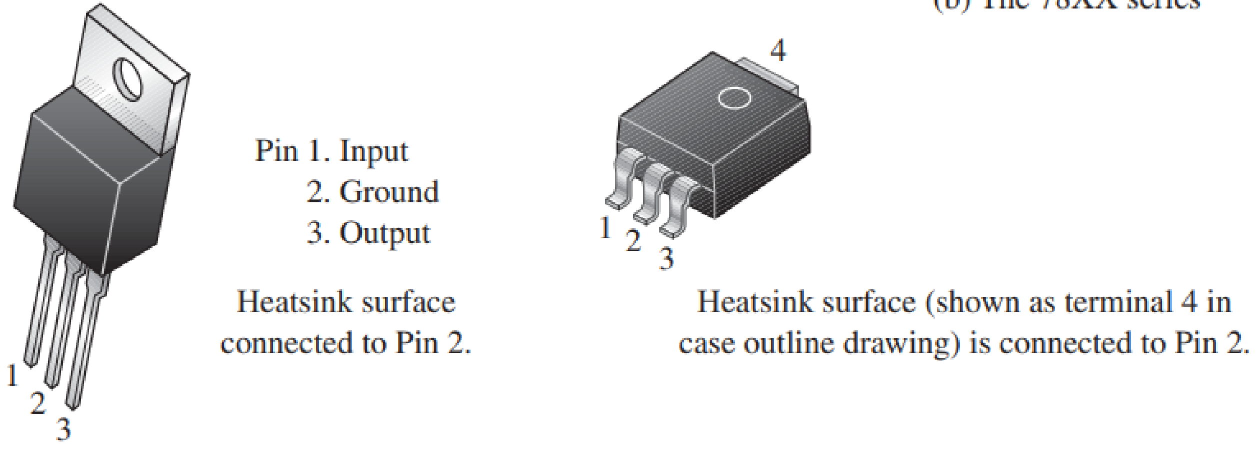
- **Fixed voltage regulator**



(a) Standard configuration

Type number	Output voltage
7805	+5.0 V
7806	+6.0 V
7808	+8.0 V
7809	+9.0 V
7812	+12.0 V
7815	+15.0 V
7818	+18.0 V
7824	+24.0 V

(b) The 78XX series



(c) Typical packages

Positive-Voltage Regulators in the 7800 Series

IC Part	Output Voltage (V)	Minimum V_i (V)
7805	+5	7.3
7806	+6	8.3
7808	+8	10.5
7810	+10	12.5
7812	+12	14.6
7815	+15	17.7
7818	+18	21.0
7824	+24	27.1

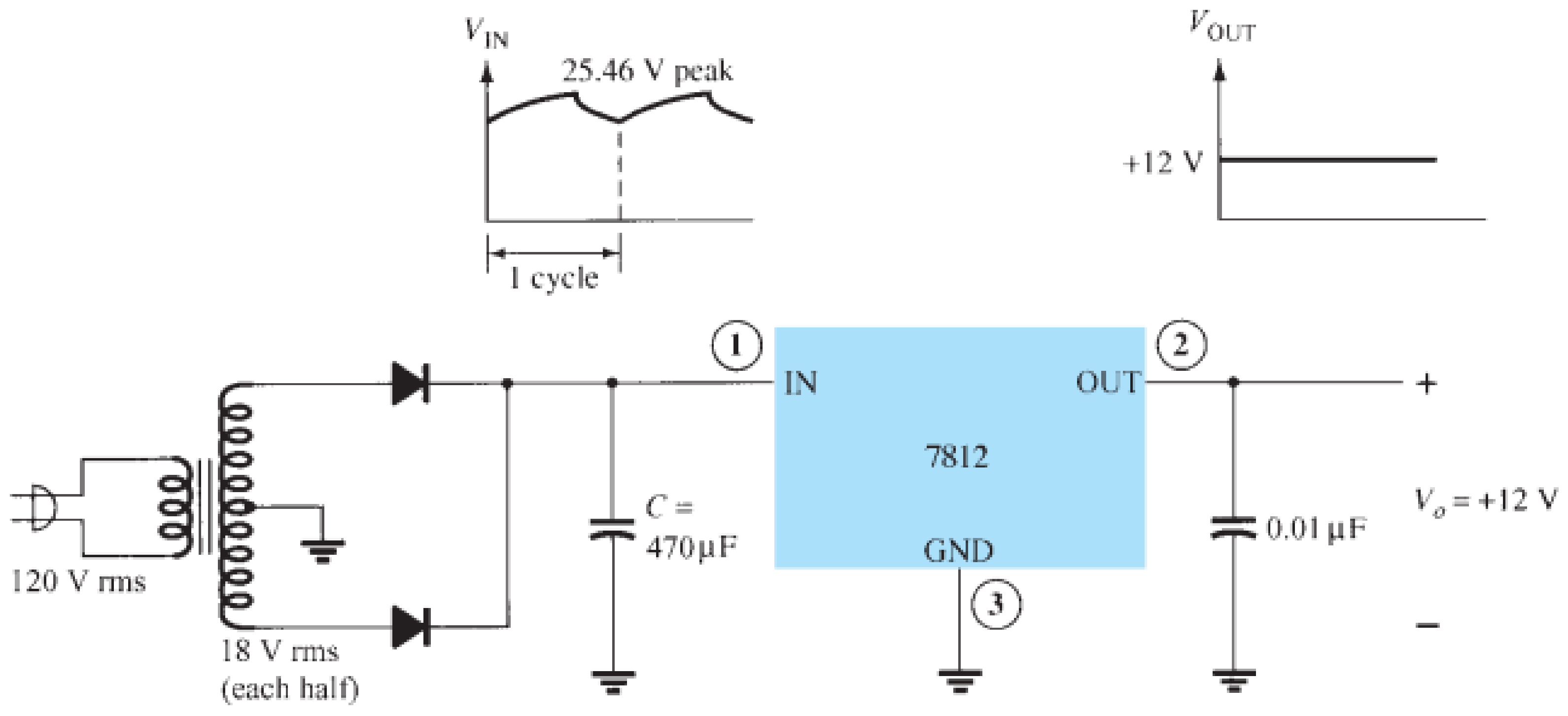
*Acknowledgment:-*Electronic Devices and Circuit Theory, Boylestad and Nashelsky, 11th Edition

*Acknowledgment:-*Thomas L. Floyd *Electronic Devices, Electron Flow Version,* Ninth Edition

Voltage Regulator

- **Fixed voltage regulator**

The connection of a 7812 in a complete voltage supply is shown



A +12 V power supply.

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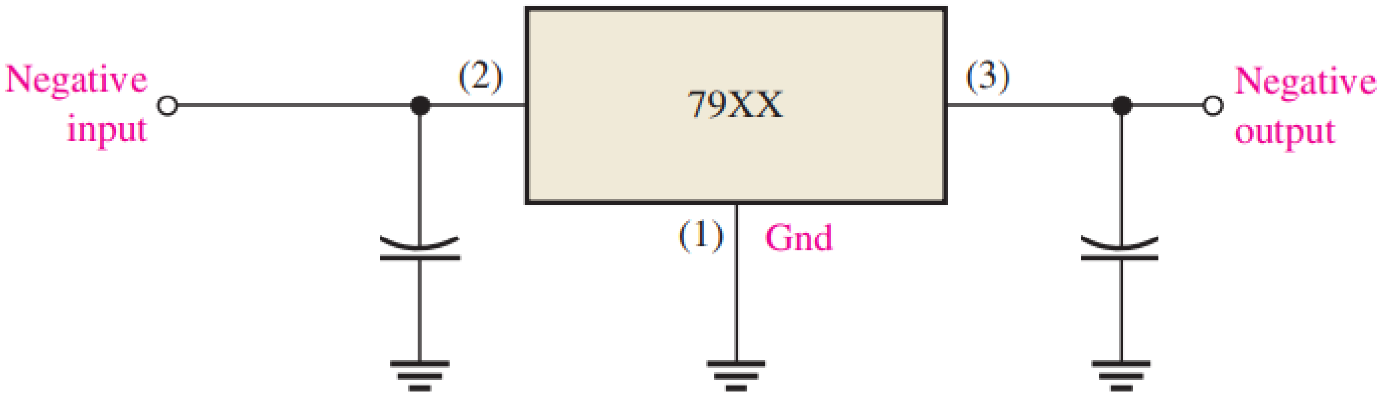
Voltage Regulator

- **Fixed voltage regulator**



(a) Standard configuration

Type number	Output voltage
7905	–5.0 V
7905.2	–5.2 V
7906	–6.0 V
7908	–8.0 V
7912	–12.0 V
7915	–15.0 V
7918	–18.0 V
7924	–24.0 V

The 79XX series three-terminal fixed negative voltage regulators.

Negative-Voltage Regulators in 7900 Series

IC Part	Output Voltage (V)	Minimum V_i (V)
7905	−5	−7.3
7906	−6	−8.4
7908	−8	−10.5
7909	−9	−11.5
7912	−12	−14.6
7915	−15	−17.7
7918	−18	−20.8
7924	−24	−27.1

Acknowledgment:-Electronic Devices and Circuit Theory, Boylestad and Nashelsky, 11th Edition

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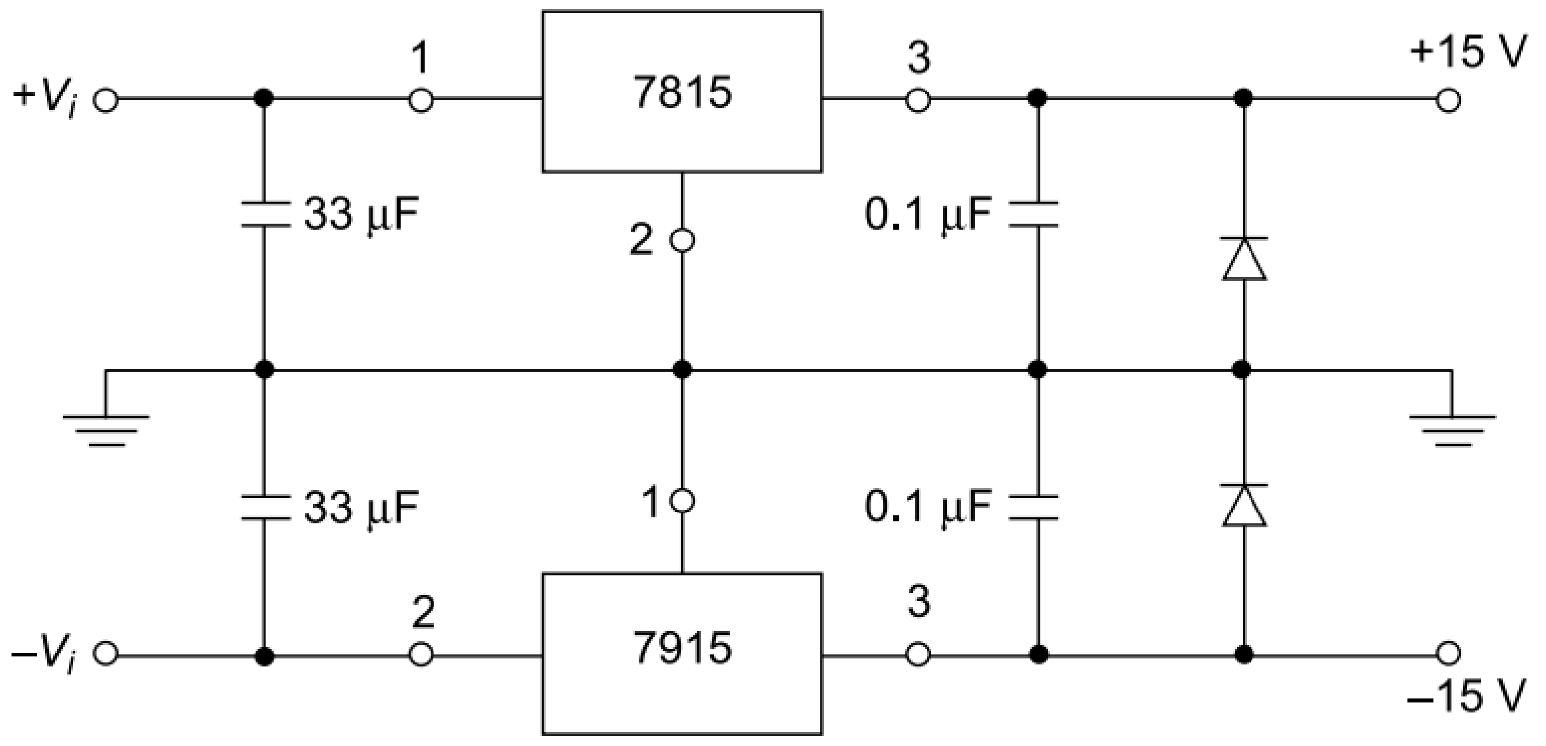
Voltage Regulator

• Dual voltage regulator

- Figure shows a dual voltage regulator.
- The circuit uses fixed positive (IC 7815) and fixed negative (IC 7915) voltage regulators to provide equal +15 V and –15 V respectively.
- The dual-regulated voltage supplies as required for op-amps can be obtained from this circuit.
- The advantage of this method is that it can supply a wide range of voltages at much higher currents with the use of heat sinks and external Metal Can package pass transistor.



Acknowledgment:-Linear Integrated Circuits by S Salivahanan

Voltage Regulator

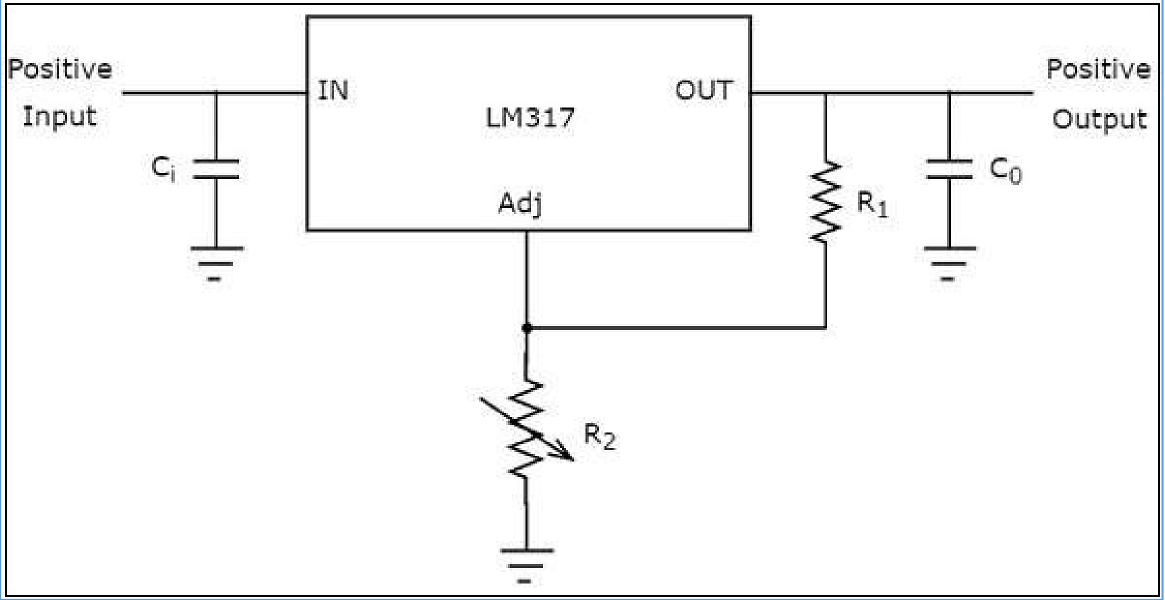
- **Adjustable voltage regulator**

- An adjustable voltage regulator produces a DC output voltage, which can be adjusted to any other value of certain voltage range.
- Hence, adjustable voltage regulator is also called as a **variable voltage regulator**.

The DC output voltage value of an adjustable voltage regulator can be either positive or negative.

LM317 voltage regulator IC

- **LM317** voltage regulator IC can be used for producing a desired positive fixed DC voltage value of the available voltage range.
- LM317 voltage regulator IC has 3 pins.
- The first pin is used for adjusting the output voltage, second pin is used for collecting the output and third pin is used for connecting the input.
- The adjustable pin (terminal) is provided with a variable resistor which lets the output to vary between a wide range.



The above figure shows an unregulated power supply driving a LM 317 voltage regulator IC, which is commonly used. This IC can supply a load current of 1.5A over an adjustable output range of 1.25 V to 37 V.

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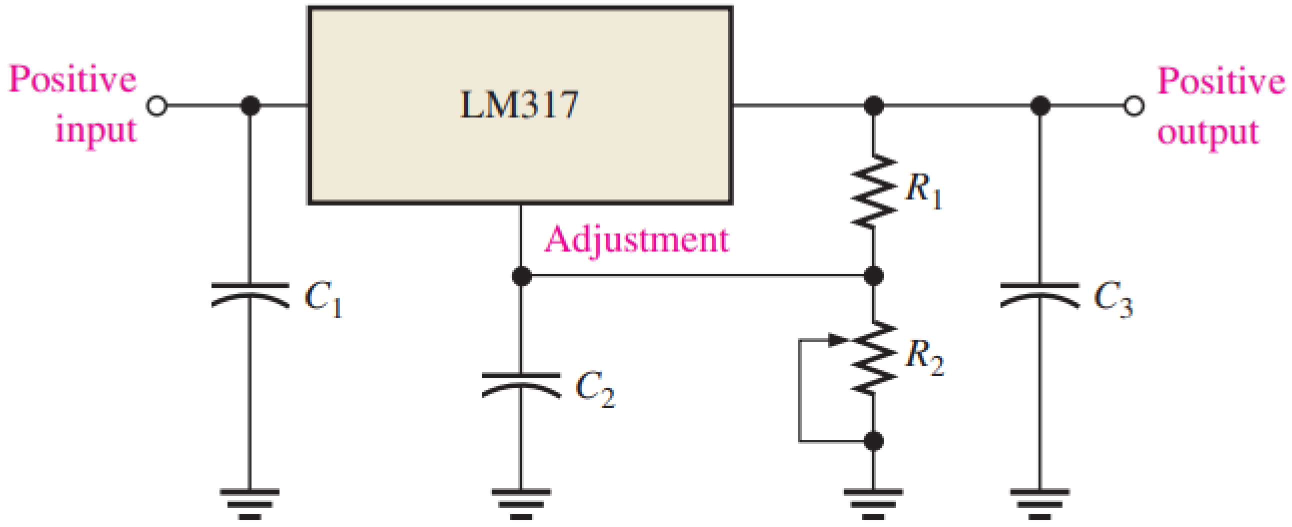
Voltage Regulator

- **Adjustable voltage regulator**
- **Adjustable Positive Linear Voltage Regulators**



The LM317 three-terminal adjustable positive voltage regulator.

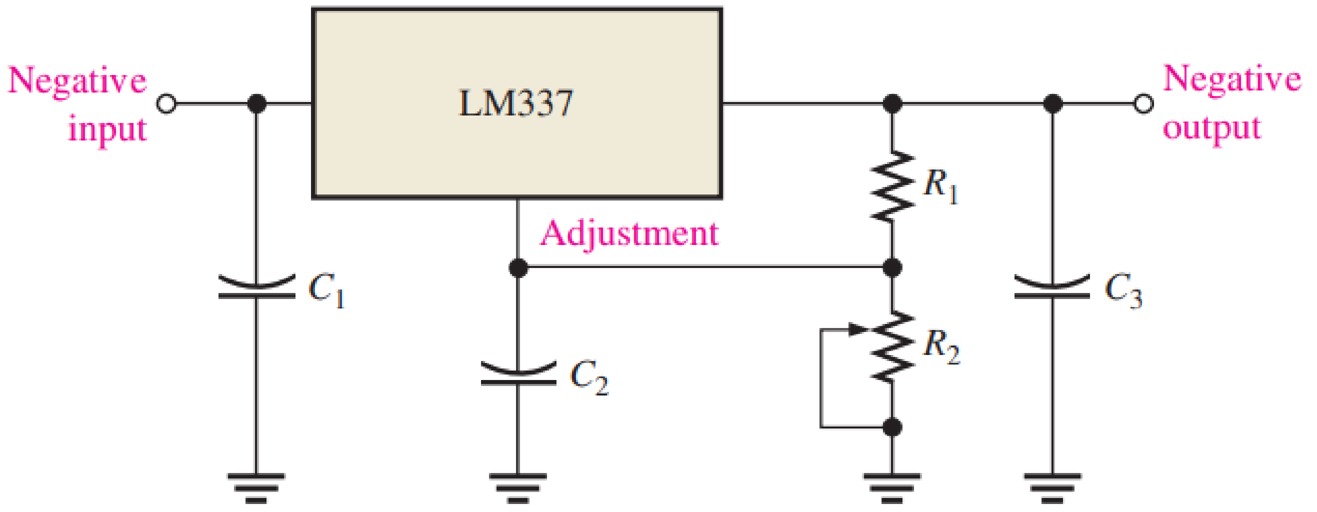
- The LM317 is an example of a three-terminal positive regulator with an adjustable output voltage.
- The standard configuration is shown in Figure.
- The capacitors are for decoupling and do not affect the dc operation.
- Notice that there is an input, an output, and an adjustment terminal.
- The external fixed resistor $\boldsymbol{R_1}$ and the external variable resistor $\boldsymbol{R_2}$ provide the output voltage adjustment.
- ***Vout*** can be varied from 1.2 V to 37 V depending on the resistor values.
- The LM317 can provide over 1.5 A of output current to a load.

***Acknowledgment:*-Thomas L. Floyd** *Electronic Devices, Electron Flow Version,* Ninth Edition

Voltage Regulator

- **Adjustable voltage regulator**

- **Adjustable Negative Linear Voltage Regulators**



The LM337 three-terminal adjustable negative voltage regulator.

- The LM337 is the negative output counterpart of the LM317 and is a good example of this type of IC regulator.
- Like the LM317, the LM337 requires two external resistors for output voltage adjustment as shown in Figure.
- The output voltage can be adjusted from to depending on the external resistor values.
- The capacitors are for decoupling and do not affect the dc operation

Topic Covered

Topics	Unit- IV: Linear Integrated Circuits
1	Introduction to operational amplifiers, √
2	Block diagram of OP-AMP, √
3	Ideal characteristics of OP-AMP, √
4	Positive feedback, √ Negative feedback, √ Inverting √ Non inverting Amplifier, √
5	Comparators, √ Summing amplifier, √Difference amplifier. √
6	Voltage Regulator √– 3 terminal Fixed, √ variable √

On completion of the course UNIT IV, students will be able to:
Illustrate and explain the working of simple Linear Integrated circuits using OP-AMPs

THANK YOU