Operational Amplifiers

Boylestad

Chapter 10

DC-Offset Parameters

Even when the input voltage is zero, an op-amp can have an output **offset**. The following can cause this offset:

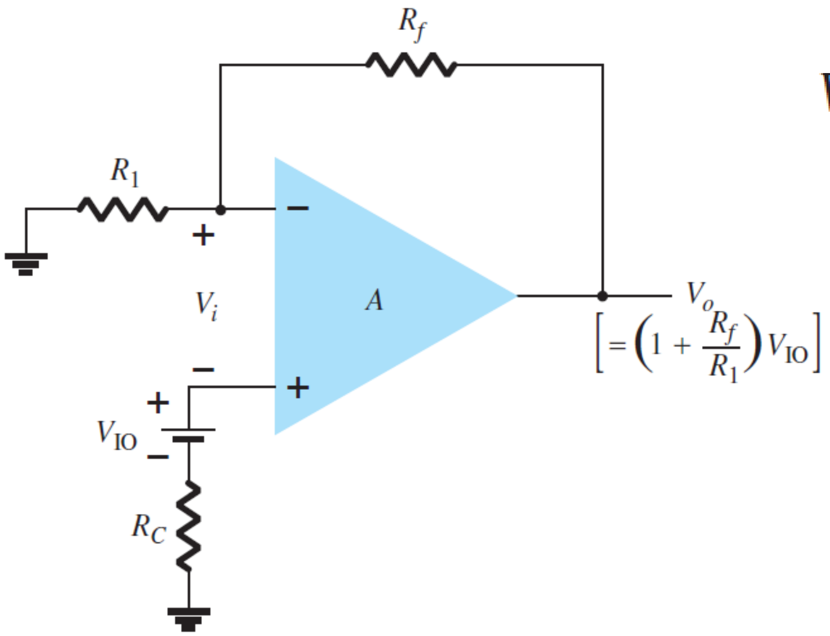
Input offset voltage
Input offset current
Input offset voltage *and* input offset current
Input bias current

Since the user may connect the amplifier circuit for various gain and polarity operations, this output offset voltage is important.

Input Offset Voltage (V_{IO})

The spec. sheet of an op-amp indicates an **input offset voltage** (V_{IO}).

To determine the effect of this input voltage on the output, consider the connection shown below



$$V_o = AV_i = A\left(V_{IO} - V_o \frac{R_1}{R_1 + R_f}\right)$$

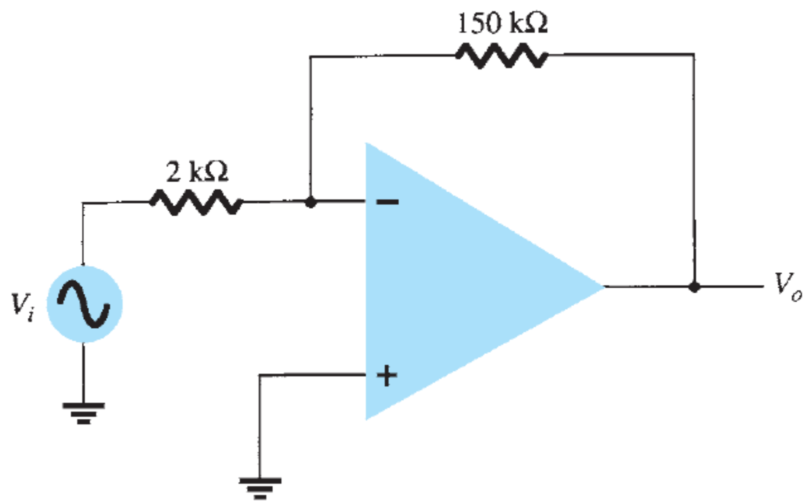
$$V_o = V_{IO} \frac{A}{1 + A\left[R_1/(R_1 + R_f)\right]}$$

$$\approx V_{IO} \frac{A}{A\left[R_1/(R_1 + R_f)\right]}$$

$$V_{o(offset)} = V_{IO} \frac{R_1 + R_f}{R_1}$$

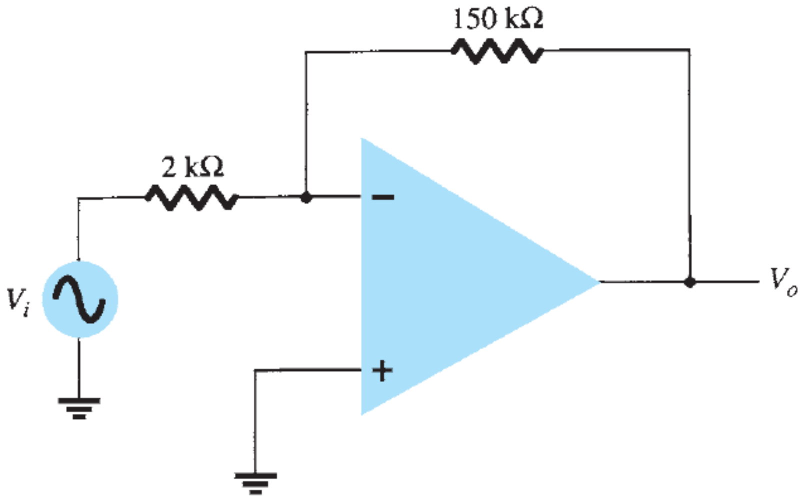
Input Offset Voltage (V_{IO})

EXAMPLE 10.8 Calculate the output offset voltage of the circuit in Fig. 10.43. The op-amp spec lists $V_{IO} = 1.2$ mV.



Input Offset Voltage (V_{IO})

EXAMPLE 10.8 Calculate the output offset voltage of the circuit in Fig. 10.43. The op-amp spec lists $V_{IO} = 1.2$ mV.



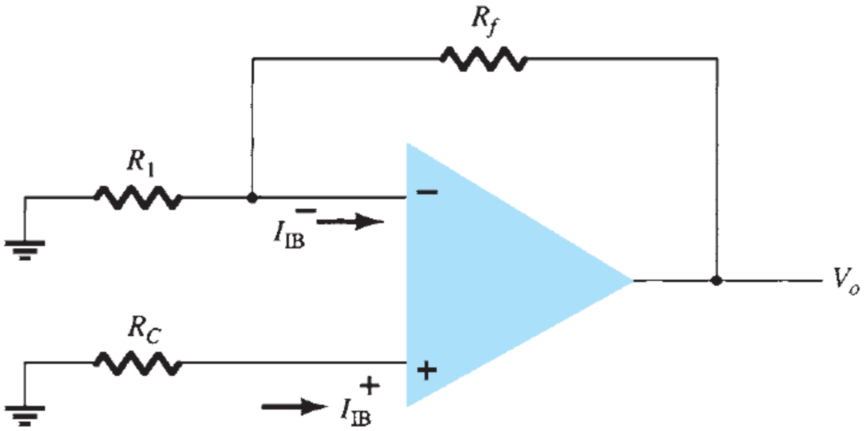
Solution:

$$\text{Eq. (10.16):}\quad V_o(\text{offset}) = V_{IO}\frac{R_1 + R_f}{R_1} = (1.2\text{ mV})\left(\frac{2\text{ k}\Omega + 150\text{ k}\Omega}{2\text{ k}\Omega}\right) = \mathbf{91.2\text{ mV}}$$

Input Offset Current (IIO)

If there is a difference between the dc bias currents generated by the same applied input, this also causes an output offset voltage:

The **input offset current** (I_{IO}) is specified in the specifications for an op-amp



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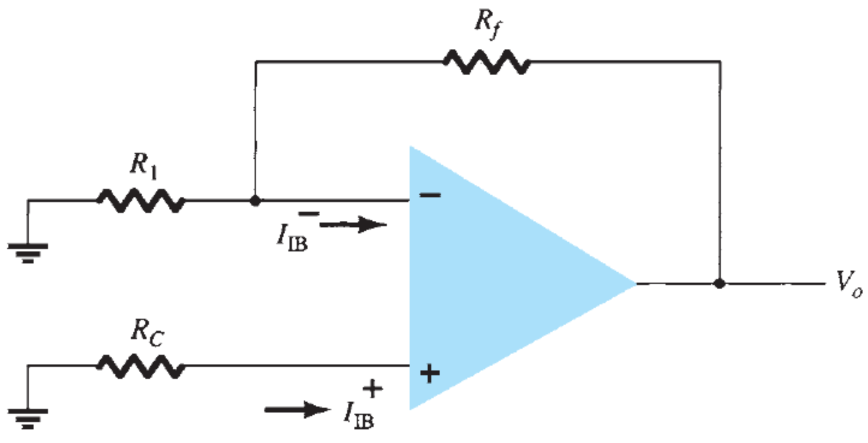
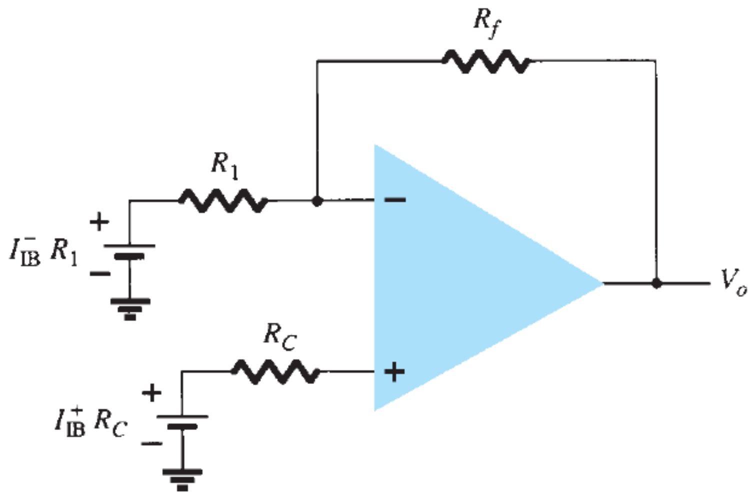
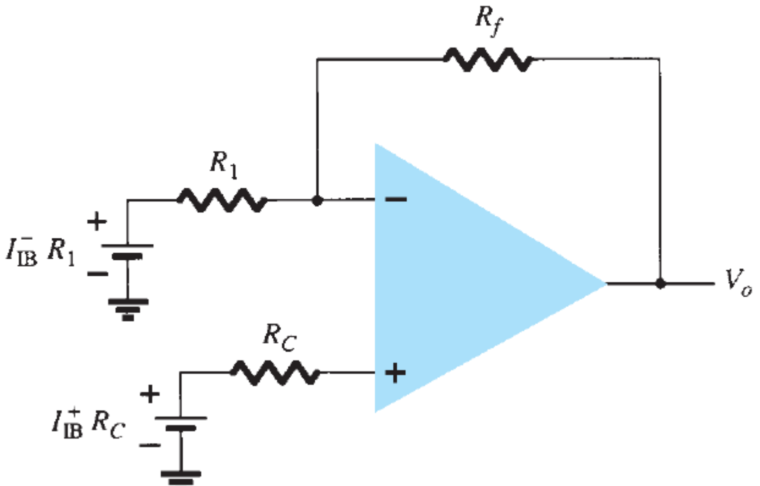




Replace the bias currents through the input resistors by the voltage drop that each develops

Input Offset Current (IIO)

Use superposition



$$V_o^+ = I_{IB}^+ R_C\left(1 + \frac{R_f}{R_1}\right)$$

$$V_o^- = I_{IB}^- R_1\left(-\frac{R_f}{R_1}\right)$$

$$V_o(\text{offset due to } I_{IB}^+ \text{ and } I_{IB}^-) = I_{IB}^+ R_C\left(1 + \frac{R_f}{R_1}\right) - I_{IB}^- R_1\frac{R_f}{R_1}$$

The compensating resistance R_C is usually approximately equal to R_1

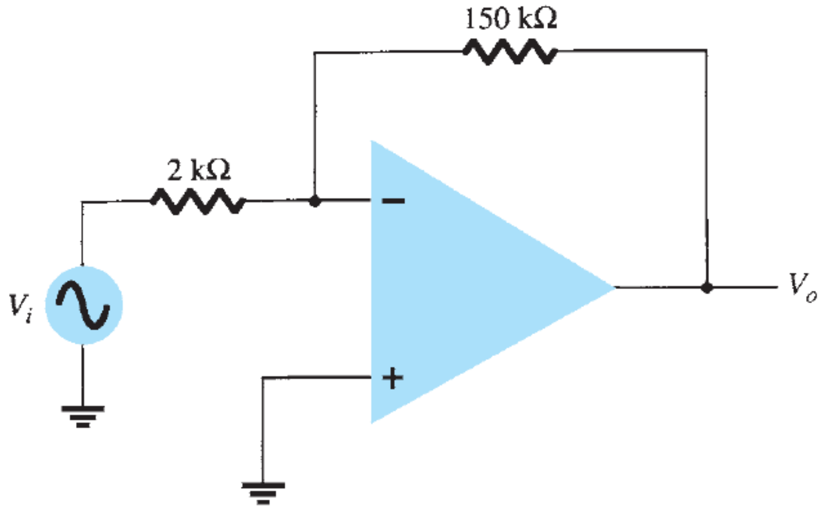
$$\begin{aligned} V_o(\text{offset}) &= I_{IB}^+(R_1 + R_f) - I_{IB}^- R_f \\ &= I_{IB}^+ R_f - I_{IB}^- R_f = R_f(I_{IB}^+ - I_{IB}^-) \end{aligned}$$

$$I_{IO} = I_{IB}^+ - I_{IB}^- \quad \rightarrow \quad \boxed{V_o(\text{offset due to } I_{IO}) = I_{IO} R_f}$$

Input Offset Current (IIO)

Example:

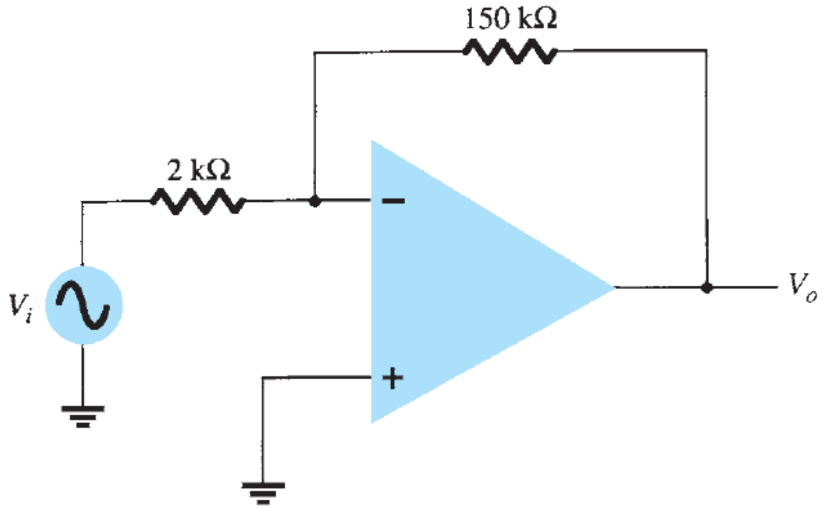
Calculate the offset voltage for the circuit for op-amp specification listing I_{IO} = 100 nA



Input Offset Current (IIO)

Example:

Calculate the offset voltage for the circuit for op-amp specification listing I_{IO} = 100 nA



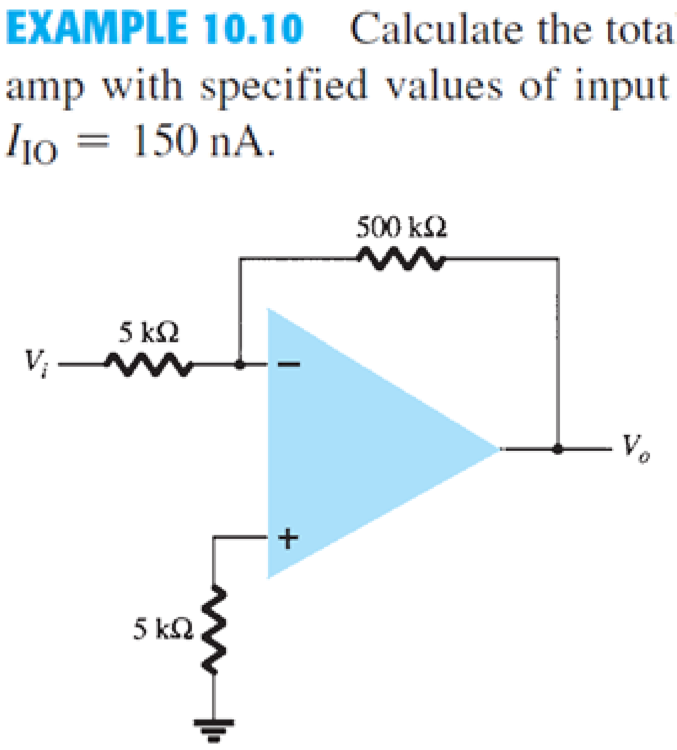
Solution: $V_o = I_{\mathrm{IO}} R_f = (100\ \mathrm{nA})(150\ \mathrm{k\Omega}) = \mathbf{15\ mV}$

Total Offset Due to V_{IO} and I_{IO}

Op-amps may have an output offset voltage due to V_{IO} and I_{IO}. The total output offset voltage equals the sum of the effects of both:

$$V_o(offset) = V_o(offset\ due\ to\ V_{IO}) + V_o(offset\ due\ to\ I_{IO})$$

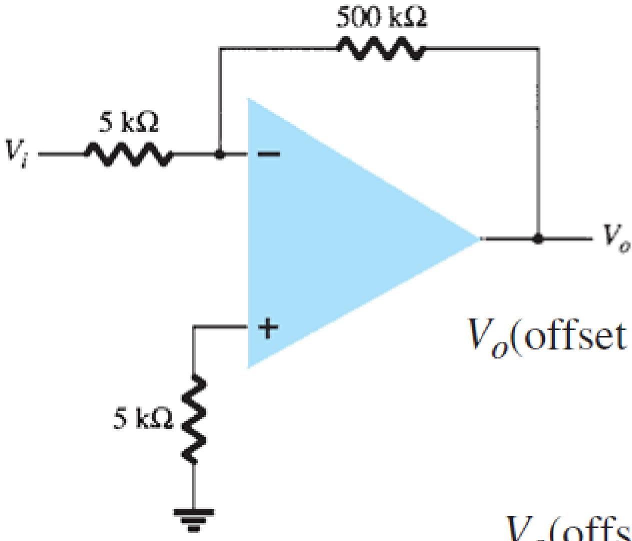
Total Offset Due to V_{IO} and I_{IO}



EXAMPLE 10.10 Calculate the total offset voltage for the circuit of Fig. 10.46 for an op-amp with specified values of input offset voltage $V_{IO} = 4$ mV and input offset current $I_{IO} = 150$ nA.

Total Offset Due to V_{IO} and I_{IO}

EXAMPLE 10.10 Calculate the total offset voltage for the circuit of Fig. 10.46 for an op-amp with specified values of input offset voltage $V_{IO} = 4\text{ mV}$ and input offset current $I_{IO} = 150\text{ nA}$.



$$V_o(\text{offset due to } V_{IO}) = V_{IO}\frac{R_1 + R_f}{R_1} = (4\text{ mV})\left(\frac{5\text{ k}\Omega + 500\text{ k}\Omega}{5\text{ k}\Omega}\right)$$
$$= 404\text{ mV}$$

$$V_o(\text{offset due to } I_{IO}) = I_{IO}R_f = (150\text{ nA})(500\text{ k}\Omega) = 75\text{ mV}$$

$$V_o(\text{total offset}) = V_o(\text{offset due to } V_{IO}) + V_o(\text{offset due to } I_{IO})$$
$$= 404\text{ mV} + 75\text{ mV} = \mathbf{479\text{ mV}}$$

Input Bias Current (I_{IB})

A parameter that is related to input offset current (I_{IO}) is called **input bias current** (I_{IB})

The input bias currents are calculated using:

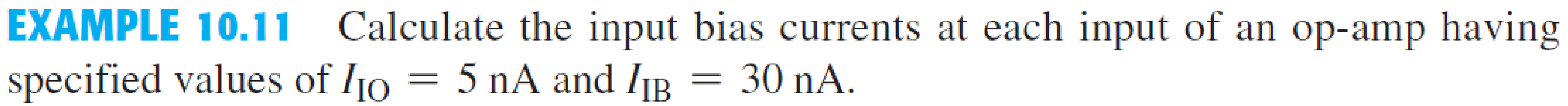
$$I_{IB}^{-} = I_{IB} - \frac{I_{IO}}{2}$$

$$I_{IB}^{+} = I_{IB} + \frac{I_{IO}}{2}$$

The total input bias current is the average of the two:

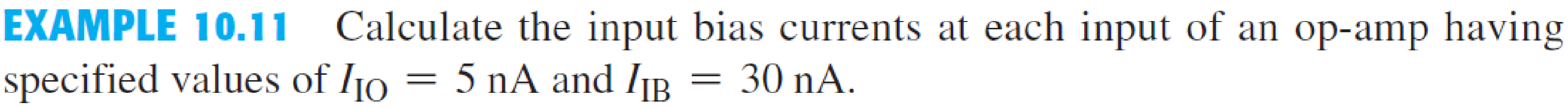
$$I_{IB} = \frac{I_{IB}^{-} + I_{IB}^{+}}{2}$$

Input Bias Current (I_{IB})

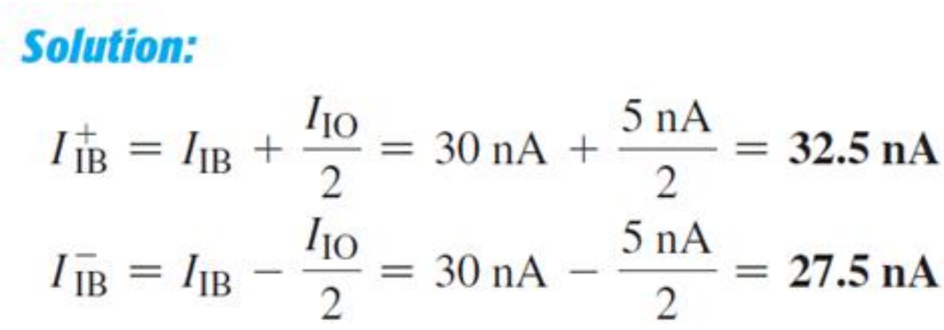


EXAMPLE 10.11 Calculate the input bias currents at each input of an op-amp having specified values of $I_{IO} = 5$ nA and $I_{IB} = 30$ nA.

Input Bias Current (I_{IB})



EXAMPLE 10.11 Calculate the input bias currents at each input of an op-amp having specified values of $I_{IO} = 5\text{ nA}$ and $I_{IB} = 30\text{ nA}$.



Solution:

$$I_{IB}^{+} = I_{IB} + \frac{I_{IO}}{2} = 30\text{ nA} + \frac{5\text{ nA}}{2} = \mathbf{32.5\ nA}$$

$$I_{IB}^{-} = I_{IB} - \frac{I_{IO}}{2} = 30\text{ nA} - \frac{5\text{ nA}}{2} = \mathbf{27.5\ nA}$$

Frequency Parameters

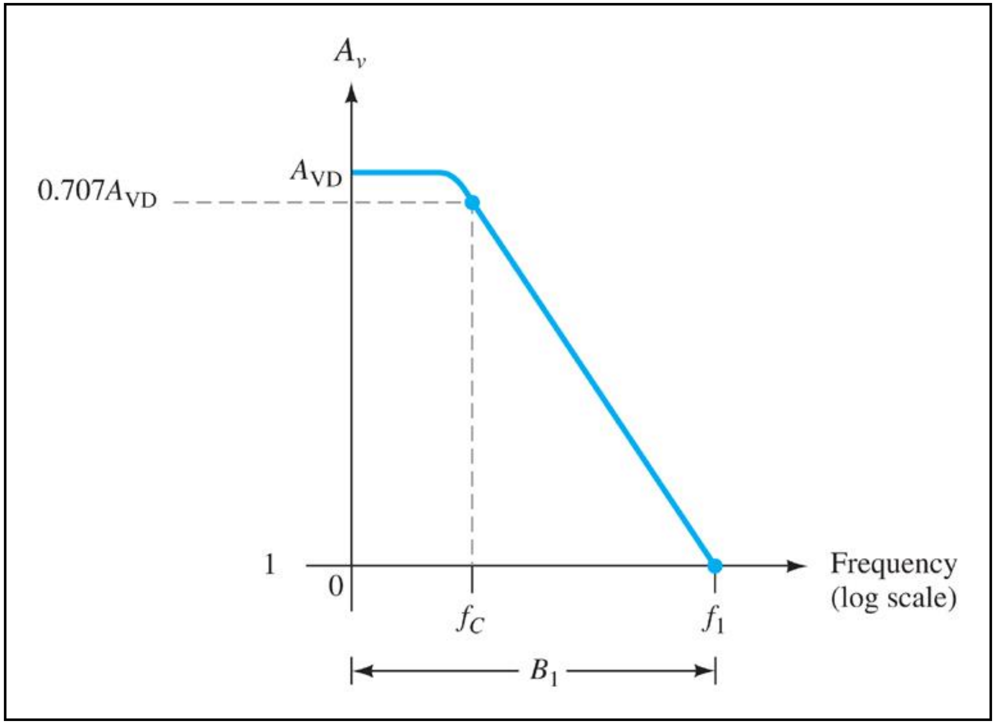
An op-amp is a wide-bandwidth amplifier. The following factors affect the bandwidth of the op-amp:

Gain

Slew rate

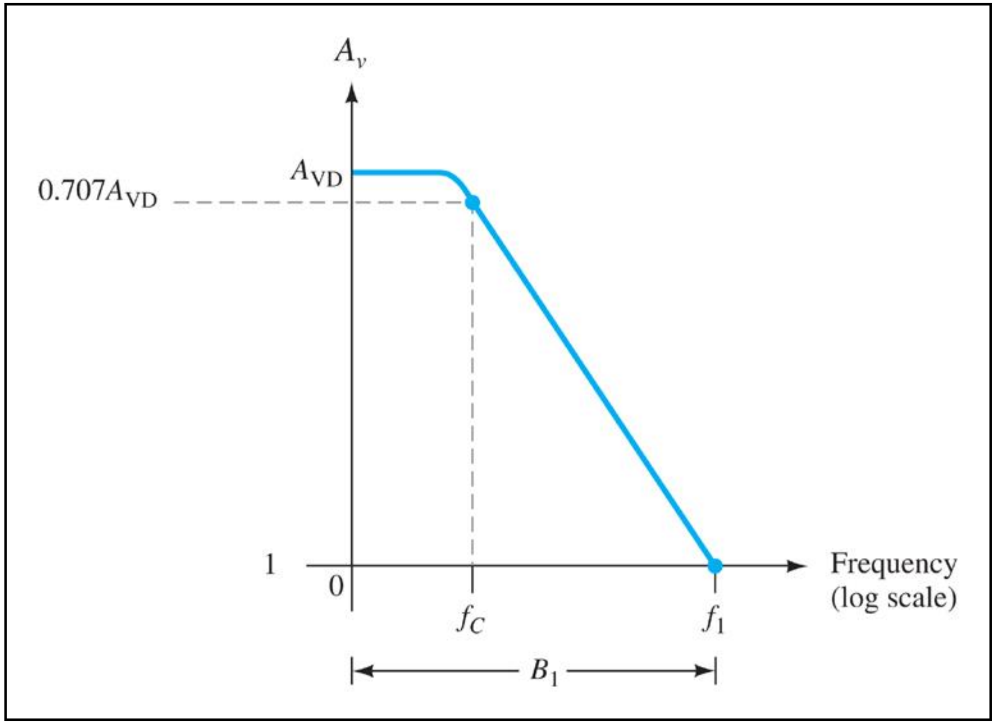
Gain and Bandwidth

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



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

Gain and Bandwidth



- Low frequency open loop gain listed by the manufacturer's specification *as* A_{VD} (voltage differential gain)
- As the frequency increases, gain drops off until it finally reaches the value of 1 (unity).
- The frequency at this gain value is specified by the manufacturer as the **unity-gain bandwidth**, B_1

- Another frequency of interest is that at which the gain drops by 3 dB (or to 0.707 the dc gain, A_{VD})
- This is the **cutoff frequency** of the op-amp, f_C.
- The unity-gain frequency and cutoff frequency are related by

$$\boxed{f_1 = A_{VD} f_C}$$

→ unity-gain frequency may also be called the **gain–bandwidth product**

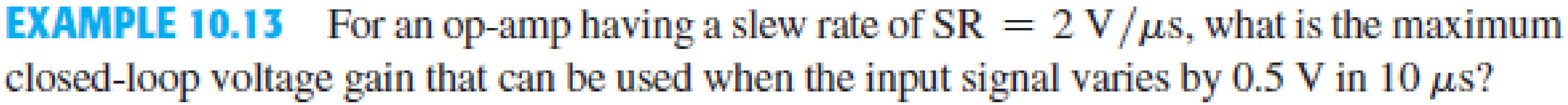
Slew Rate (SR)

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

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

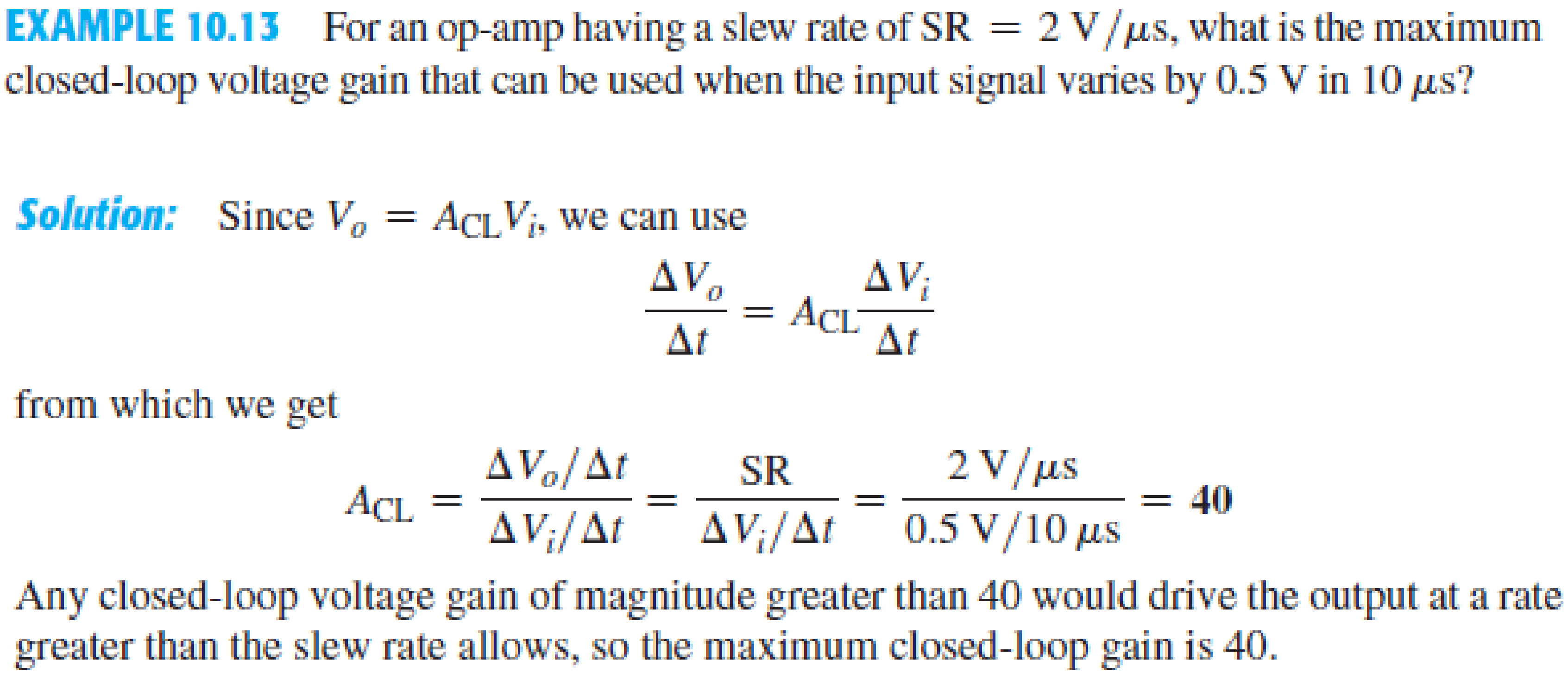
The SR rating is listed in the specification sheets as the V/μs rating.

Slew Rate (SR)



EXAMPLE 10.13 For an op-amp having a slew rate of $\text{SR} = 2\ \text{V}/\mu\text{s}$, what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.5 V in 10 μs?

Slew Rate (SR)



EXAMPLE 10.13 For an op-amp having a slew rate of SR $= 2\ \text{V}/\mu\text{s}$, what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.5 V in 10 μs?

Solution: Since $V_o = A_{\text{CL}}V_i$, we can use

$$\frac{\Delta V_o}{\Delta t} = A_{\text{CL}}\frac{\Delta V_i}{\Delta t}$$

from which we get

$$A_{\text{CL}} = \frac{\Delta V_o/\Delta t}{\Delta V_i/\Delta t} = \frac{\text{SR}}{\Delta V_i/\Delta t} = \frac{2\ \text{V}/\mu\text{s}}{0.5\ \text{V}/10\ \mu\text{s}} = \mathbf{40}$$

Any closed-loop voltage gain of magnitude greater than 40 would drive the output at a rate greater than the slew rate allows, so the maximum closed-loop gain is 40.

Maximum Signal Frequency

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

For a sinusoidal signal of general form $v_o = K\sin(2\pi ft)$

$$\text{signal maximum rate of change} = 2\pi fK \text{ V/s}$$

To prevent distortion at the output, the rate of change must be less than slew rate

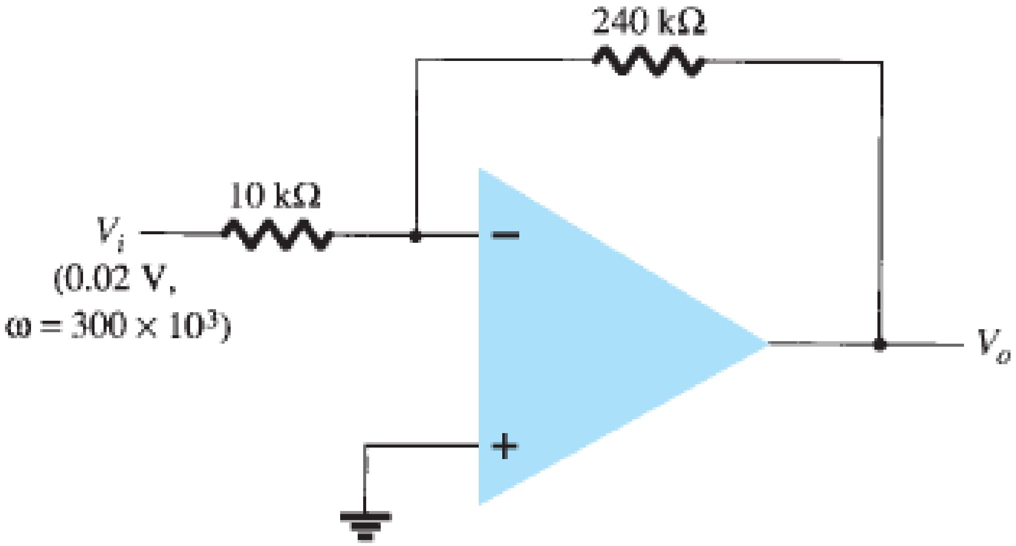
$$2\pi fK \leq \mathrm{SR}$$

$$\omega K \leq \mathrm{SR}$$

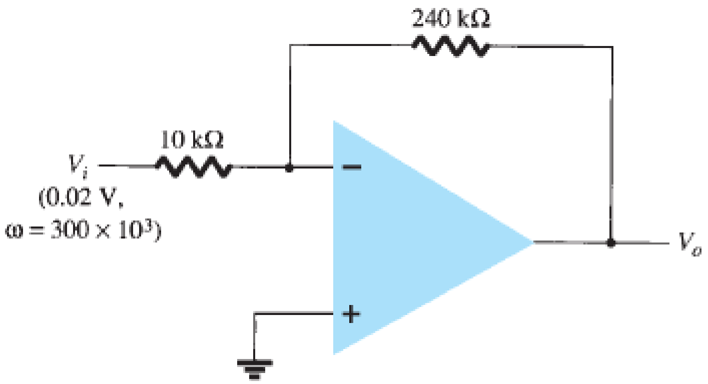
$$\boxed{f \leq \frac{SR}{2\pi K}}$$

Maximum Signal Frequency

EXAMPLE 10.14 For the signal and circuit of Fig. 10.48, determine the maximum frequency that may be used. Op-amp slew rate is $SR = 0.5\ V/\mu s$.



Maximum Signal Frequency



Solution: For a gain of magnitude

$$A_{CL} = \left|\frac{R_f}{R_1}\right| = \frac{240\ \text{k}\Omega}{10\ \text{k}\Omega} = 24$$

the output voltage provides

$$K = A_{CL}V_i = 24(0.02\ \text{V}) = 0.48\ \text{V}$$

$$\omega \leq \frac{\text{SR}}{K} = \frac{0.5\ \text{V}/\mu\text{s}}{0.48\ \text{V}} = \mathbf{1.1 \times 10^6\ rad/s}$$

Since the signal frequency $\omega = 300 \times 10^3$ rad/s is less than the maximum value determined above, no output distortion will result.

General Op-Amp Specifications

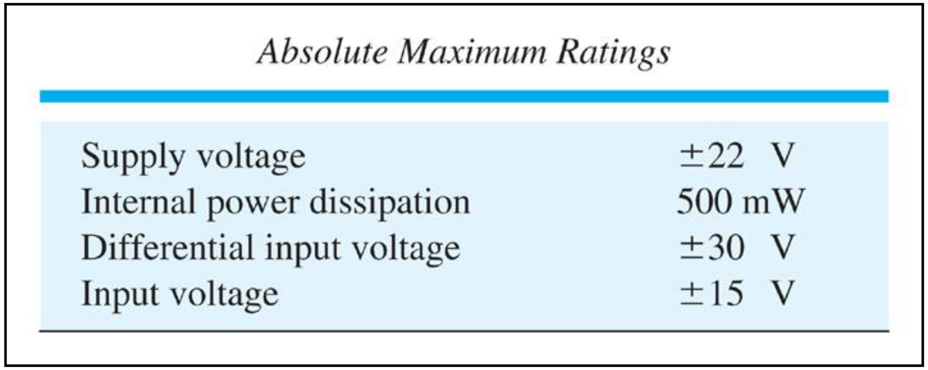
Other op-amp ratings found on specification sheets are:

Absolute Ratings

Electrical Characteristics

Absolute Ratings

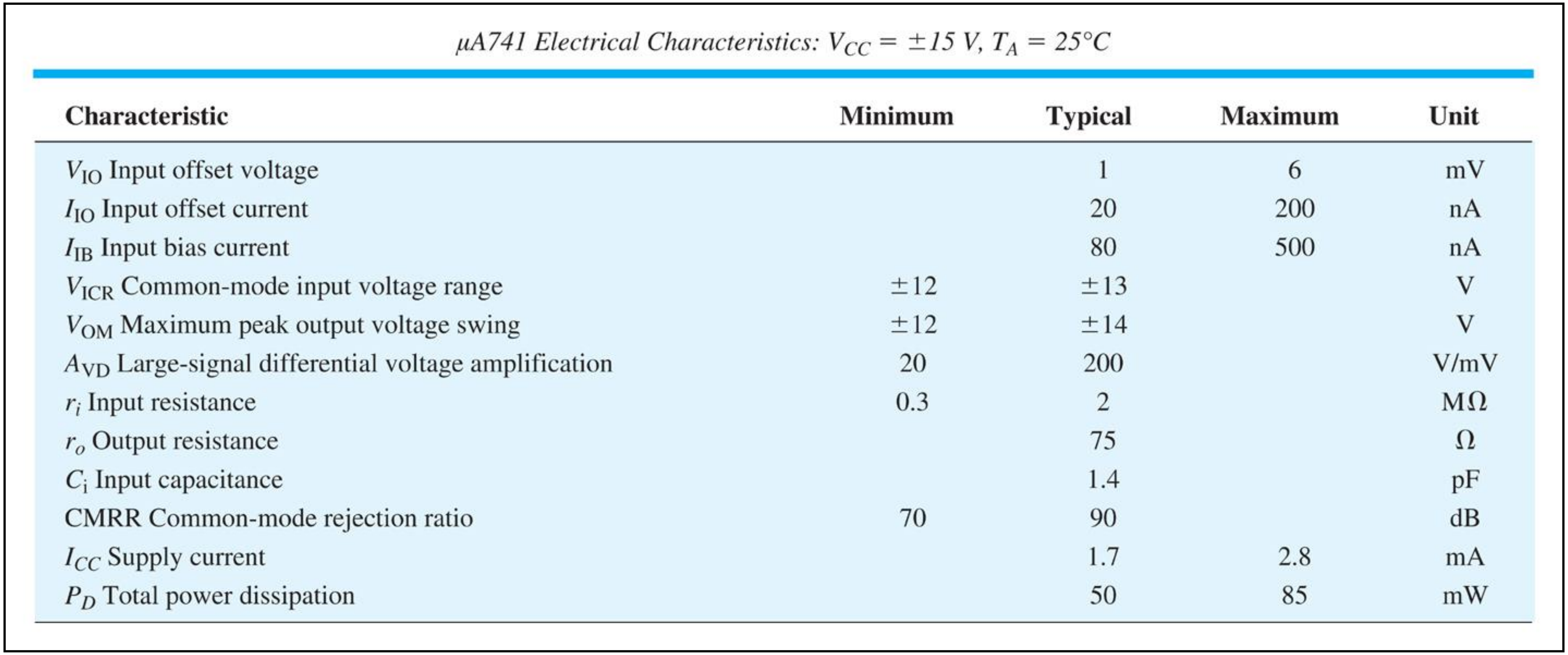
These are common maximum ratings for the op-amp.



Absolute Maximum Ratings

Supply voltage	±22 V
Internal power dissipation	500 mW
Differential input voltage	±30 V
Input voltage	±15 V

Electrical Characteristics



$\mu A741$ *Electrical Characteristics:* $V_{CC} = \pm 15$ V, $T_A = 25°C$

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

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

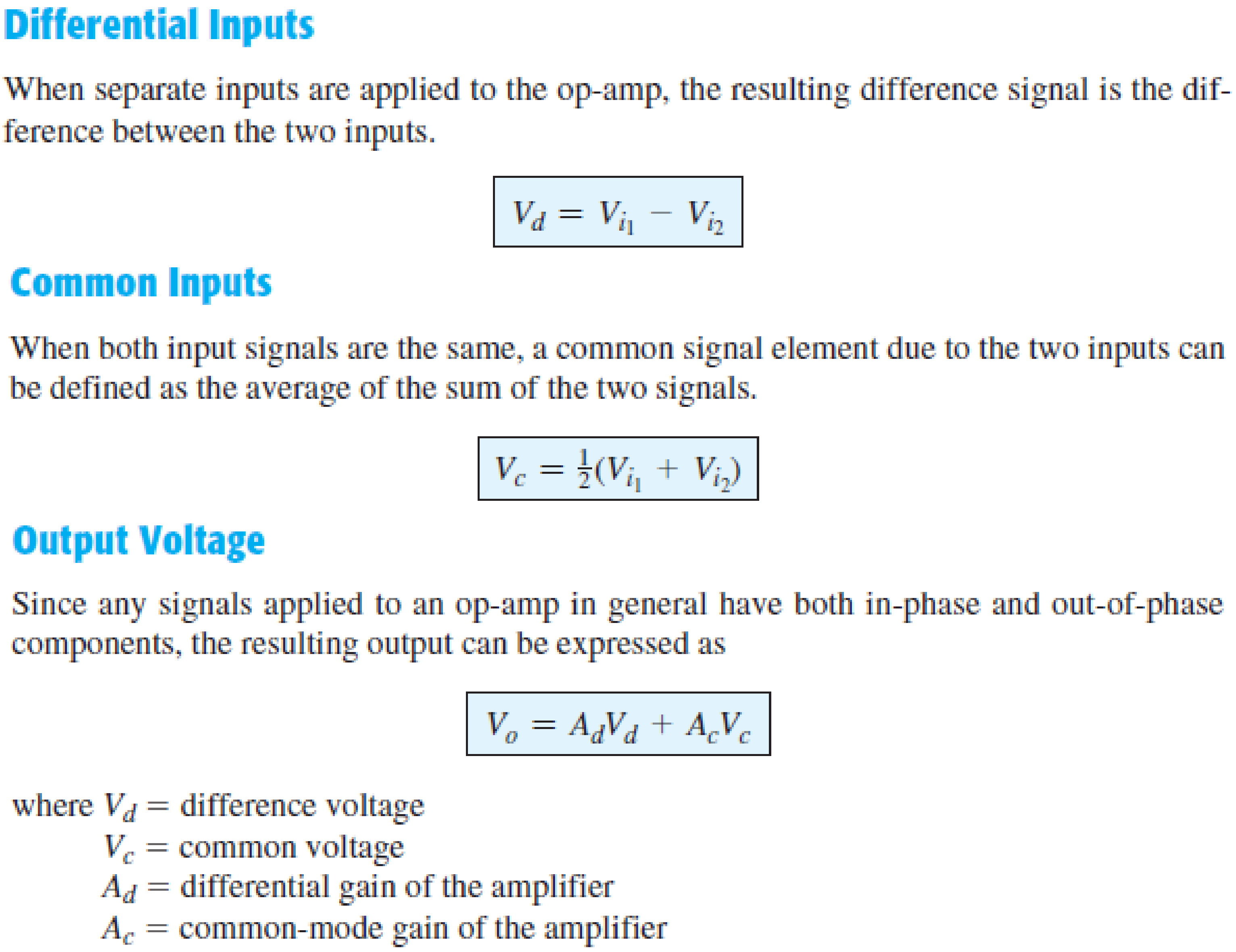
Common Mode Rejection Ratio (CMMR)

One rating that is unique to op-amps is **CMRR** or **common-mode rejection ratio**.

Because the op-amp has two inputs that are opposite in phase (inverting input and the non-inverting input) any signal that is common to both inputs will be cancelled.

Op-amp CMRR is a measure of the ability to cancel out common-mode signals.

Common Mode Rejection Ratio (CMMR)



Differential Inputs

When separate inputs are applied to the op-amp, the resulting difference signal is the difference between the two inputs.

$$\boxed{V_d = V_{i_1} - V_{i_2}}$$

Common Inputs

When both input signals are the same, a common signal element due to the two inputs can be defined as the average of the sum of the two signals.

$$\boxed{V_c = \tfrac{1}{2}(V_{i_1} + V_{i_2})}$$

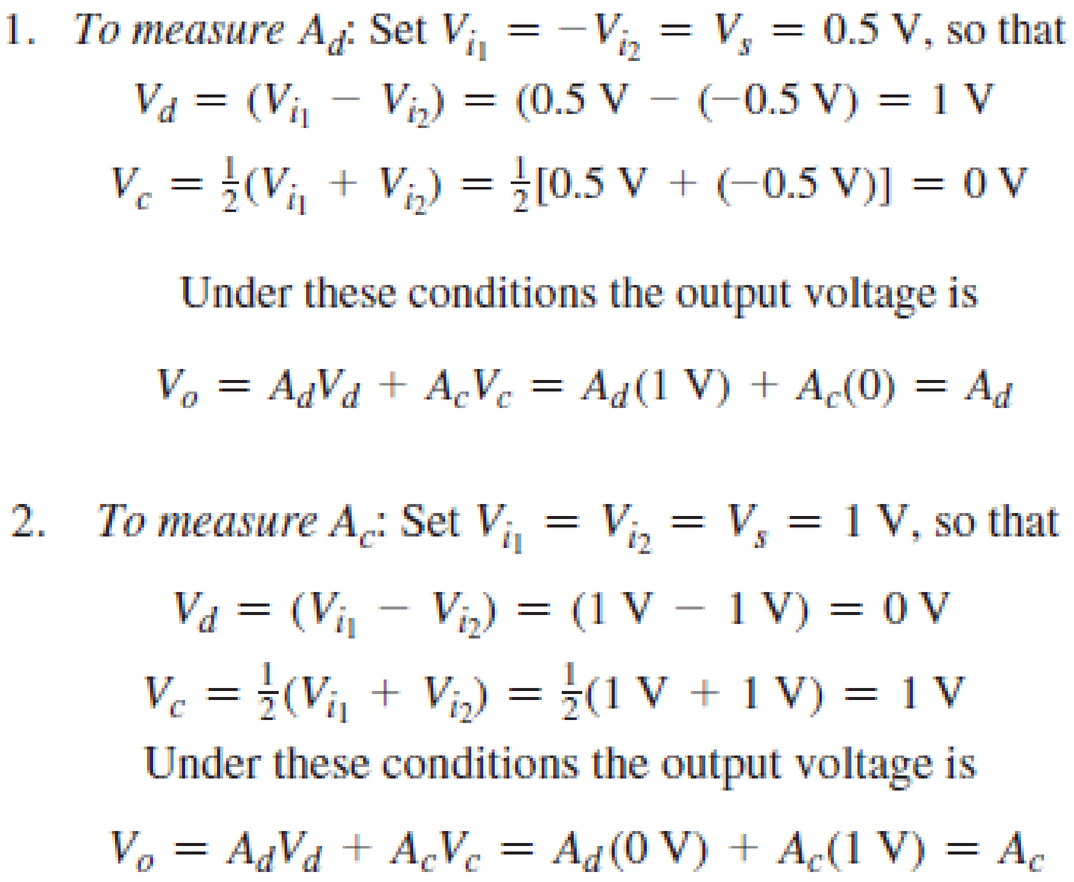
Output Voltage

Since any signals applied to an op-amp in general have both in-phase and out-of-phase components, the resulting output can be expressed as

$$\boxed{V_o = A_d V_d + A_c V_c}$$

where V_d = difference voltage
V_c = common voltage
A_d = differential gain of the amplifier
A_c = common-mode gain of the amplifier

Common Mode Rejection Ratio (CMMR)



1. *To measure A_d*: Set $V_{i_1} = -V_{i_2} = V_s = 0.5\text{ V}$, so that

$$V_d = (V_{i_1} - V_{i_2}) = (0.5\text{ V} - (-0.5\text{ V}) = 1\text{ V}$$

$$V_c = \tfrac{1}{2}(V_{i_1} + V_{i_2}) = \tfrac{1}{2}[0.5\text{ V} + (-0.5\text{ V})] = 0\text{ V}$$

Under these conditions the output voltage is

$$V_o = A_d V_d + A_c V_c = A_d(1\text{ V}) + A_c(0) = A_d$$

2. *To measure A_c*: Set $V_{i_1} = V_{i_2} = V_s = 1\text{ V}$, so that

$$V_d = (V_{i_1} - V_{i_2}) = (1\text{ V} - 1\text{ V}) = 0\text{ V}$$

$$V_c = \tfrac{1}{2}(V_{i_1} + V_{i_2}) = \tfrac{1}{2}(1\text{ V} + 1\text{ V}) = 1\text{ V}$$

Under these conditions the output voltage is

$$V_o = A_d V_d + A_c V_c = A_d(0\text{ V}) + A_c(1\text{ V}) = A_c$$

Common Mode Rejection Ratio (CMMR)

$$\boxed{V_o = A_d V_d + A_c V_c}$$

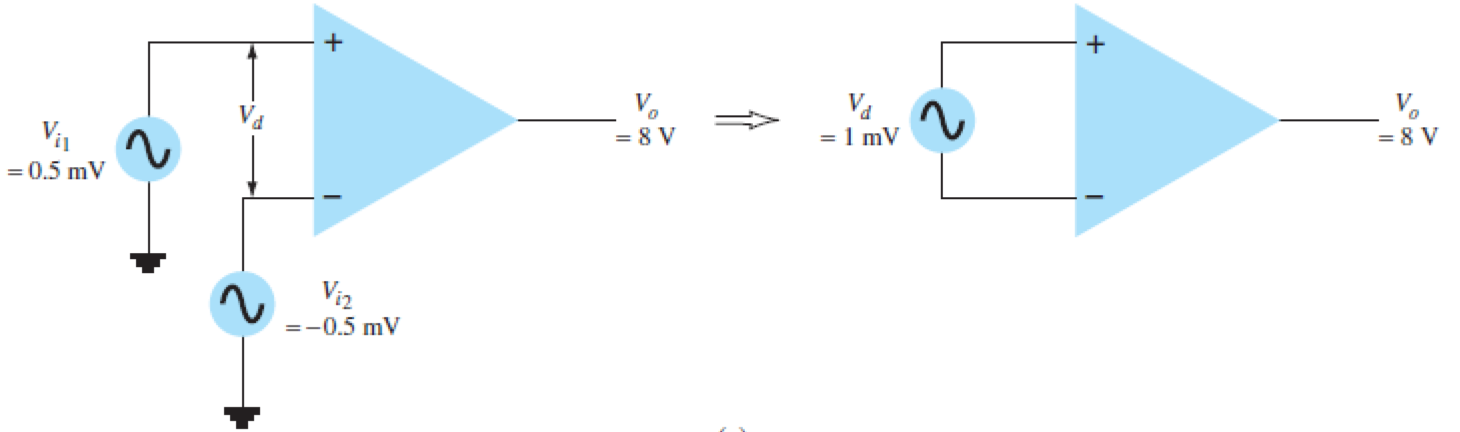
$$\boxed{\text{CMRR} = \frac{A_d}{A_c}}$$

The value of CMRR can also be expressed in logarithmic terms as

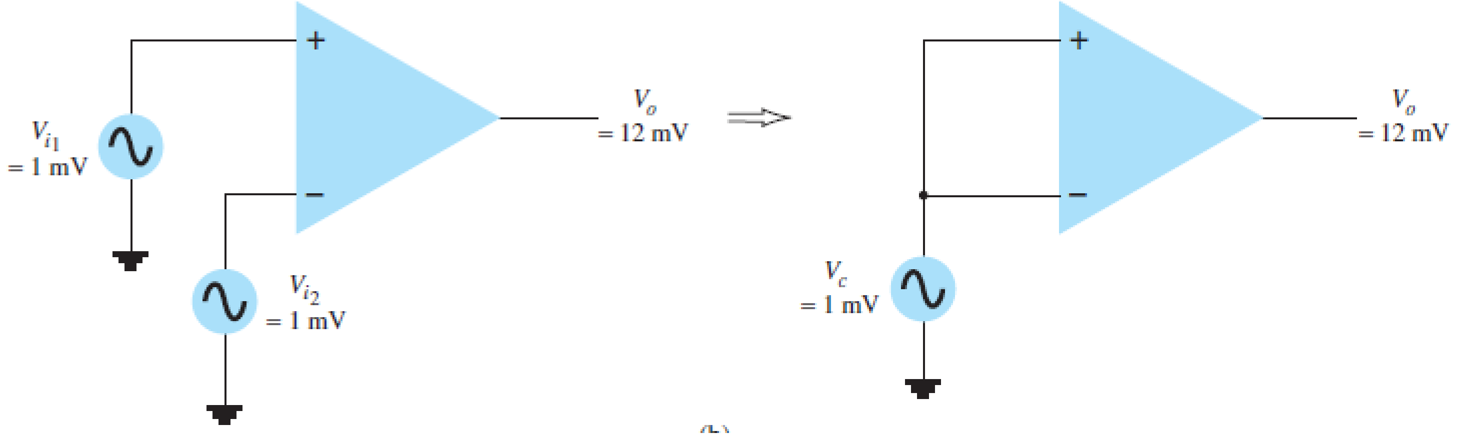
$$\boxed{\text{CMRR (log)} = 20 \log_{10} \frac{A_d}{A_c}} \quad \text{(dB)}$$

Common Mode Rejection Ratio (CMMR)

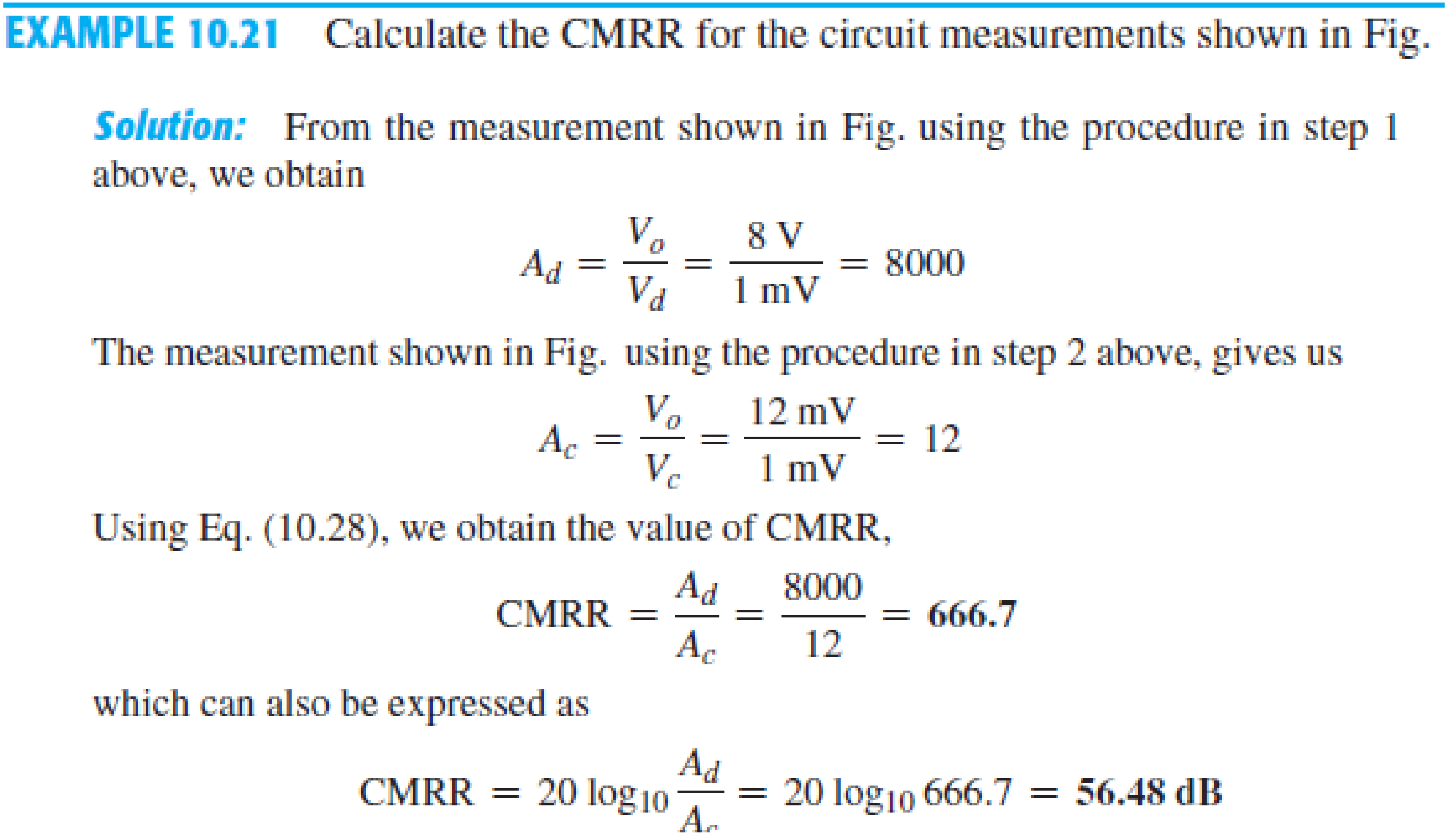
EXAMPLE 10.21 Calculate the CMRR for the circuit measurements shown in Fig.



(a)



Common Mode Rejection Ratio (CMMR)



EXAMPLE 10.21 Calculate the CMRR for the circuit measurements shown in Fig.

Solution: From the measurement shown in Fig. using the procedure in step 1 above, we obtain

$$A_d = \frac{V_o}{V_d} = \frac{8\ \text{V}}{1\ \text{mV}} = 8000$$

The measurement shown in Fig. using the procedure in step 2 above, gives us

$$A_c = \frac{V_o}{V_c} = \frac{12\ \text{mV}}{1\ \text{mV}} = 12$$

Using Eq. (10.28), we obtain the value of CMRR,

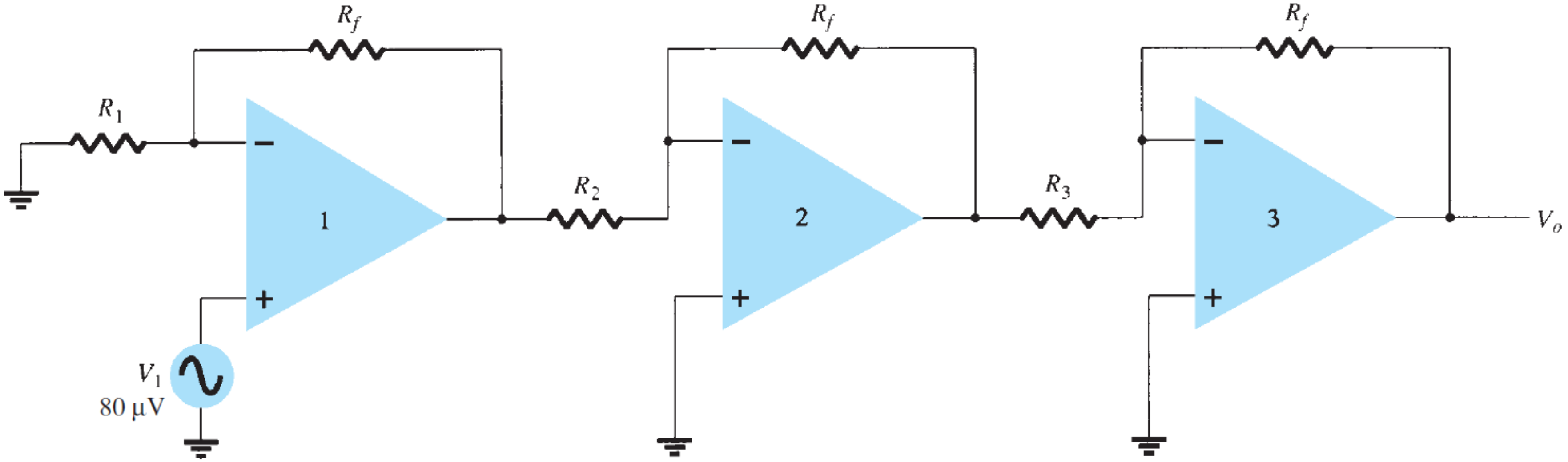
$$\text{CMRR} = \frac{A_d}{A_c} = \frac{8000}{12} = \mathbf{666.7}$$

which can also be expressed as

$$\text{CMRR} = 20 \log_{10} \frac{A_d}{A_c} = 20 \log_{10} 666.7 = \mathbf{56.48\ dB}$$

Op-Amp Applications - Multiple Stage Gains

When a number of stages are connected in series, the overall gain is the product of the individual stage gains



$$A = A_1 A_2 A_3$$

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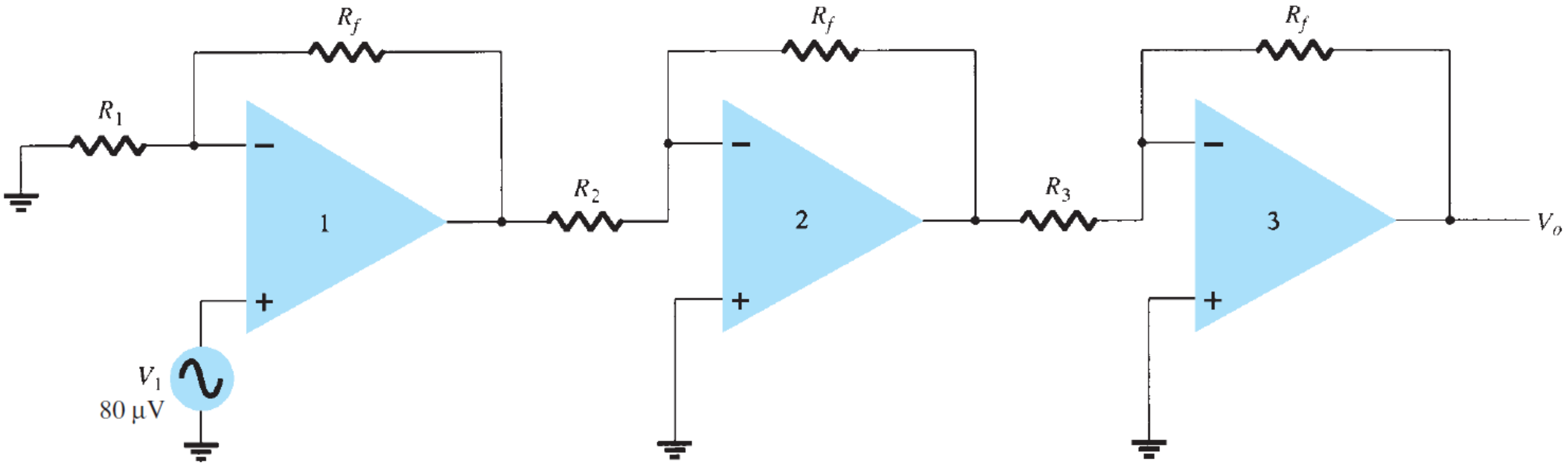

$$A = A_1 A_2 A_3$$

$$A_1 = 1 + R_f/R_1, A_2 = -R_f/R_2, \text{ and } A_3 = -R_f/R_3.$$

Op-Amp Applications - Multiple Stage Gains

A number of op-amp stages could also be used to provide separate gains

Example: Design a circuit usng op-amps to provide outputs that are 10, 20, and 50 times larger than the input. Use a feedback resistor of Rf = 500 kΩ in all stages.

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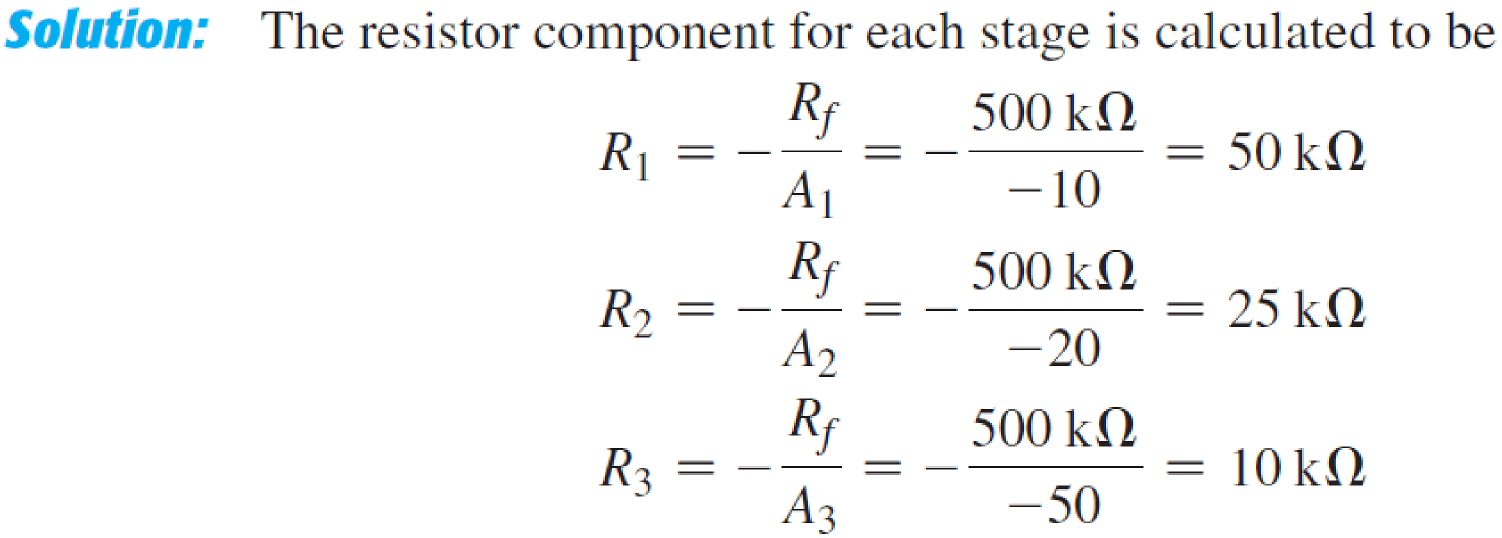


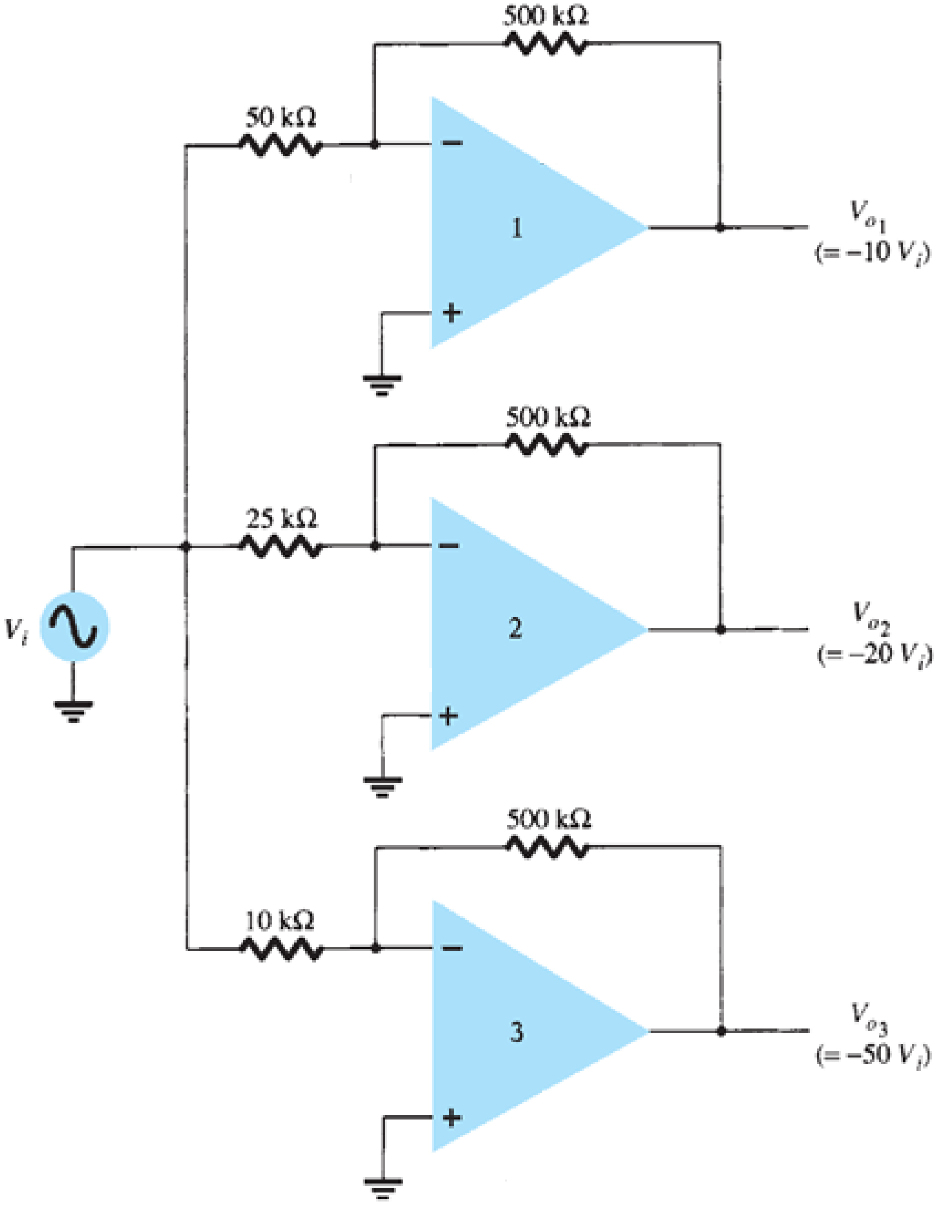
Solution: The resistor component for each stage is calculated to be

$$R_1 = -\frac{R_f}{A_1} = -\frac{500\text{ k}\Omega}{-10} = 50\text{ k}\Omega$$

$$R_2 = -\frac{R_f}{A_2} = -\frac{500\text{ k}\Omega}{-20} = 25\text{ k}\Omega$$

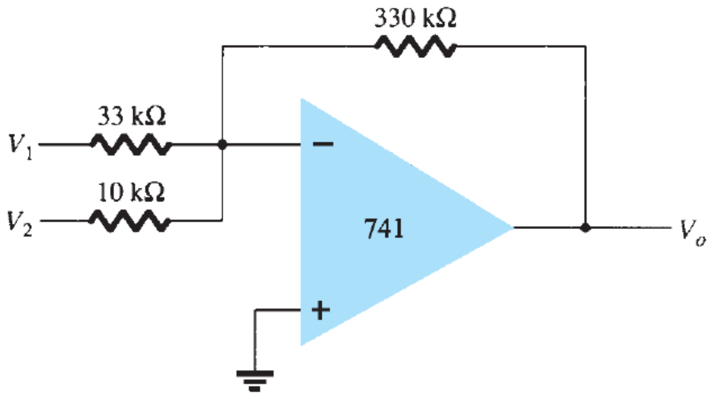
$$R_3 = -\frac{R_f}{A_3} = -\frac{500\text{ k}\Omega}{-50} = 10\text{ k}\Omega$$

Op-Amp Applications - Multiple Stage Gains



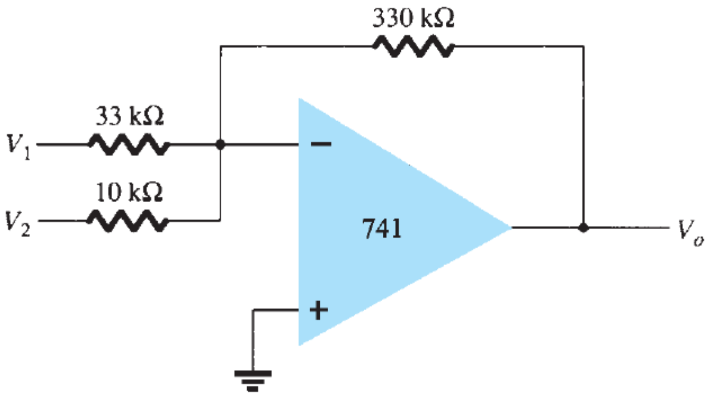
Op-Amp Applications

Calculate the output voltage for the circuit below. The inputs are V_1 = 50 sin(1000 t) mV and V_2 =10 sin(3000 t) mV.



Op-Amp Applications - Voltage Summing

Calculate the output voltage for the circuit below. The inputs are V_1 = 50 sin(1000 t) mV and V_2 =10 sin(3000 t) mV.



Solution: The output voltage is

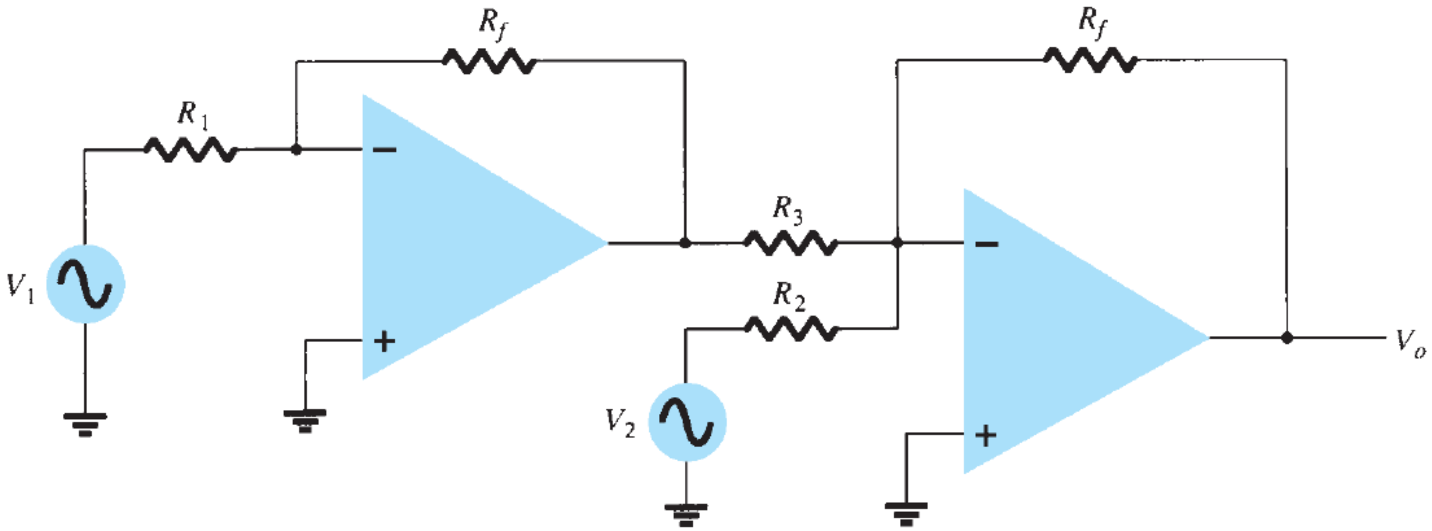
$$V_o = -\left(\frac{330\ \text{k}\Omega}{33\ \text{k}\Omega} V_1 + \frac{330\ \text{k}\Omega}{10\ \text{k}\Omega} V_2\right) = -(10\ V_1 + 33\ V_2)$$

$$= -[10(50\ \text{mV})\sin(1000t) + 33(10\ \text{mV})\sin(3000t)]$$

$$= \mathbf{-[0.5\ sin\ (1000\mathit{t})\ +\ 0.33\ sin\ (3000\mathit{t})]}$$

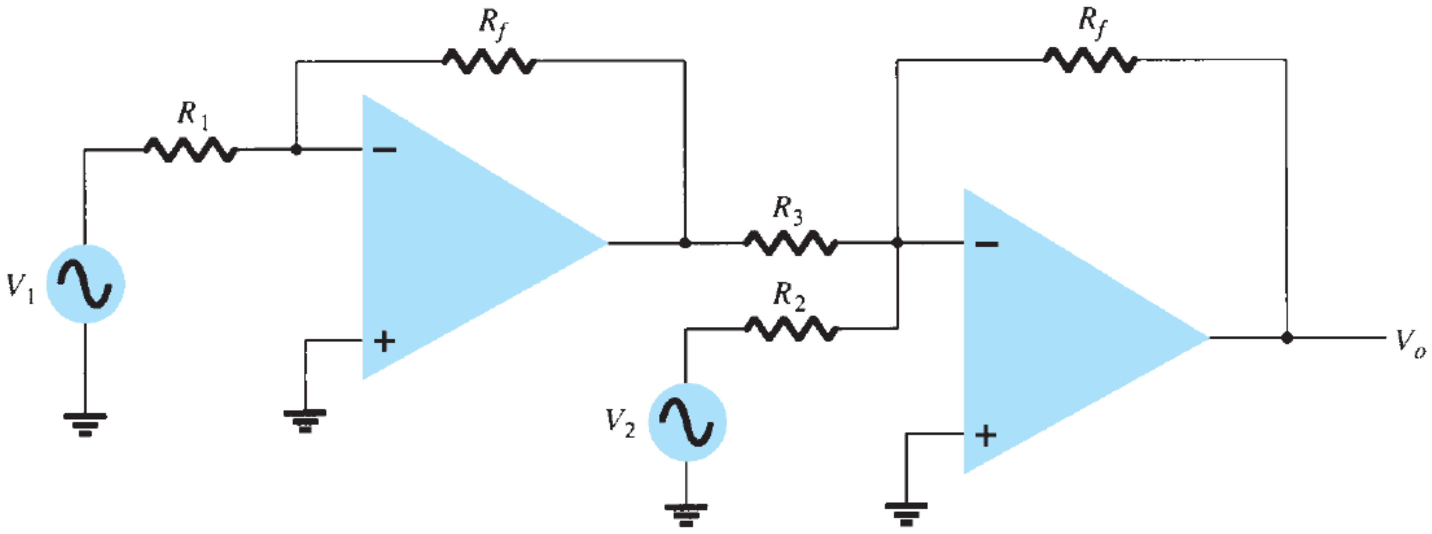
Op-Amp Applications

Determine the output for the circuit of figure below with components R_f = 1 MΩ, R_1 = 100 kΩ, R_2 = 50 kΩ, and R_3 = 500 kΩ.



Op-Amp Applications - Voltage Subtraction

Determine the output for the circuit of figure below with components R_f = 1 MΩ, R_1 = 100 kΩ, R_2 = 50 kΩ, and R_3 = 500 kΩ.



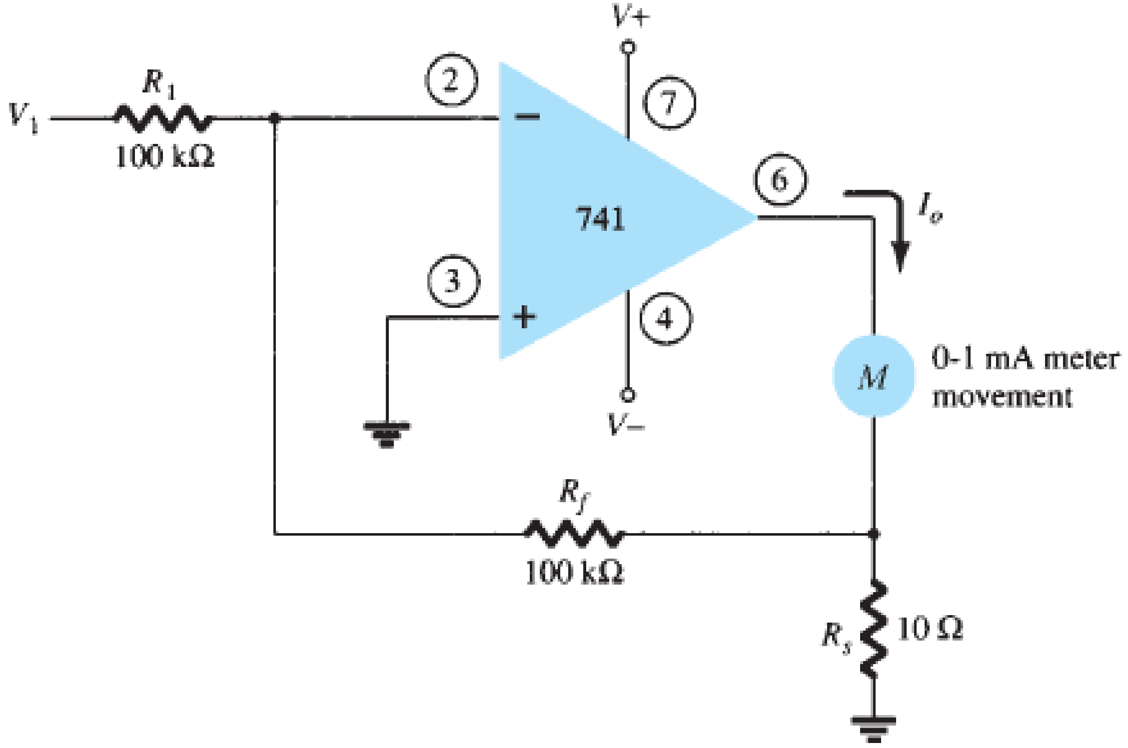
Solution: The output voltage is calculated to be

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

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

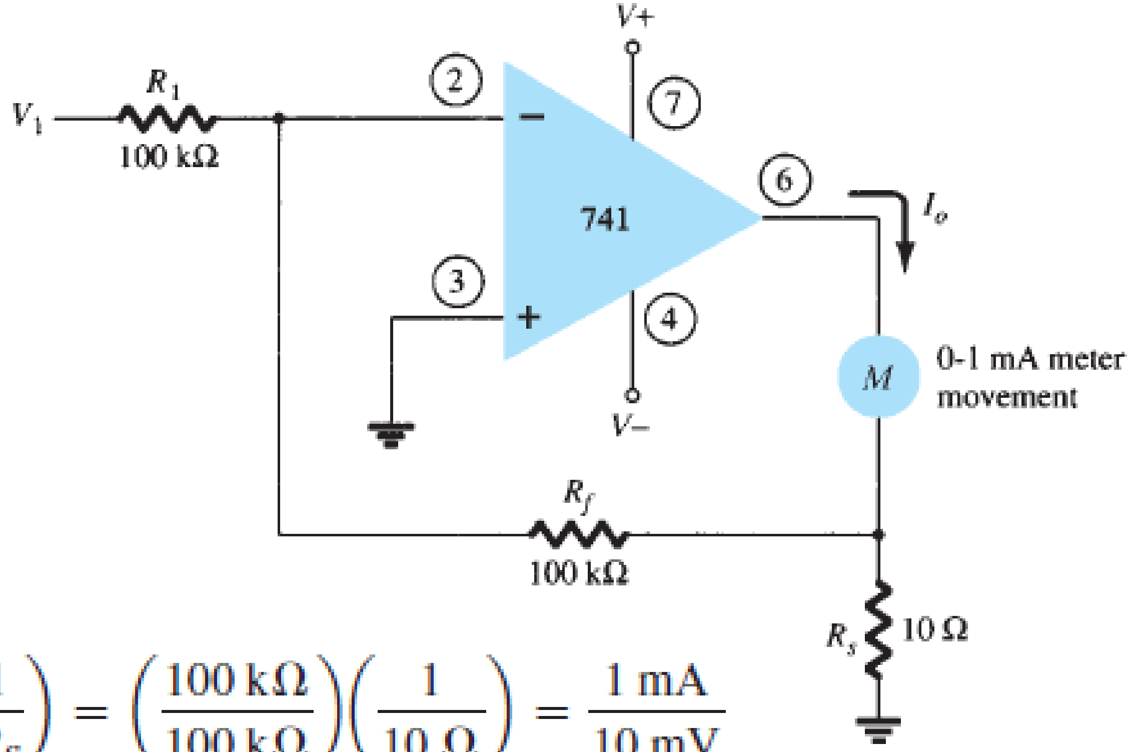
Op-Amp Applications - Voltmeter

Figure below shows a 741 op-amp used as the basic amplifier in a dc millivoltmeter
The amplifier provides a meter with high input impedance



Op-Amp Applications - Voltmeter

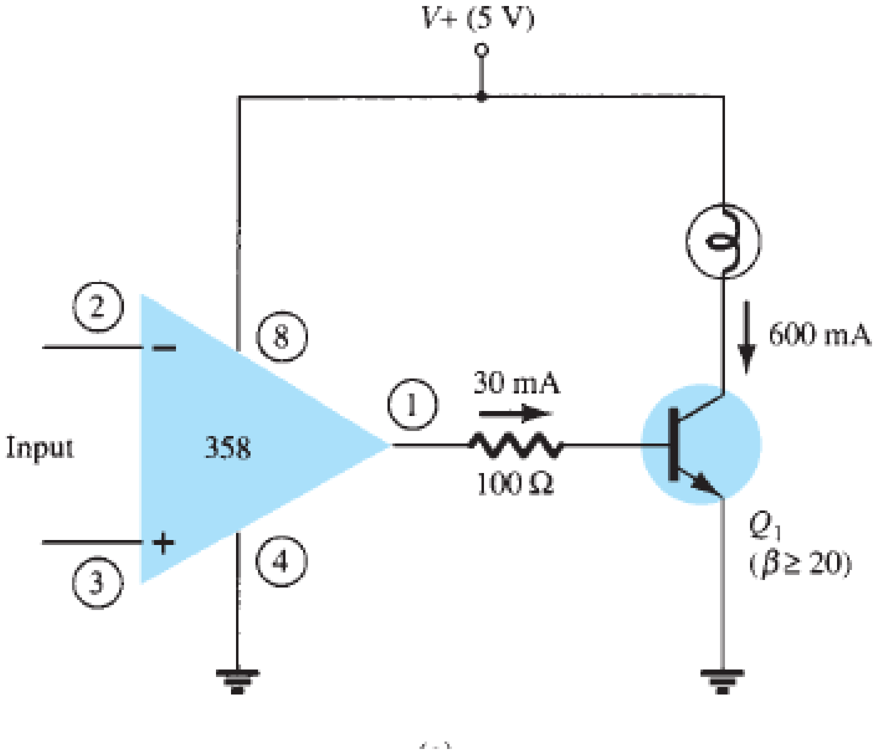
Figure below shows a 741 op-amp used as the basic amplifier in a dc millivoltmeter
The amplifier provides a meter with high input impedance



$$\left|\frac{I_o}{V_1}\right| = \frac{R_f}{R_1}\left(\frac{1}{R_S}\right) = \left(\frac{100\text{ k}\Omega}{100\text{ k}\Omega}\right)\left(\frac{1}{10\ \Omega}\right) = \frac{1\text{ mA}}{10\text{ mV}}$$

Multiple Stage Gains – Lamp Driver

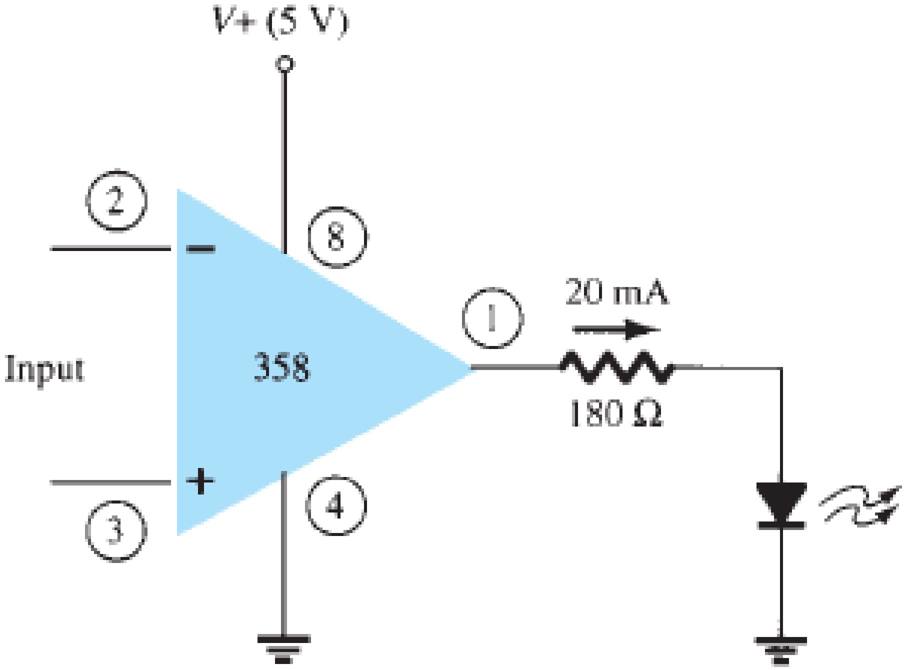
- Figure shows an op-amp circuit that drives a lamp display
- When the noninverting input goes above the inverting input, the output at terminal 1 goes to the positive saturation level (near 5 V in this example)
- Then lamp is driven “on” when transistor Q_1 conducts



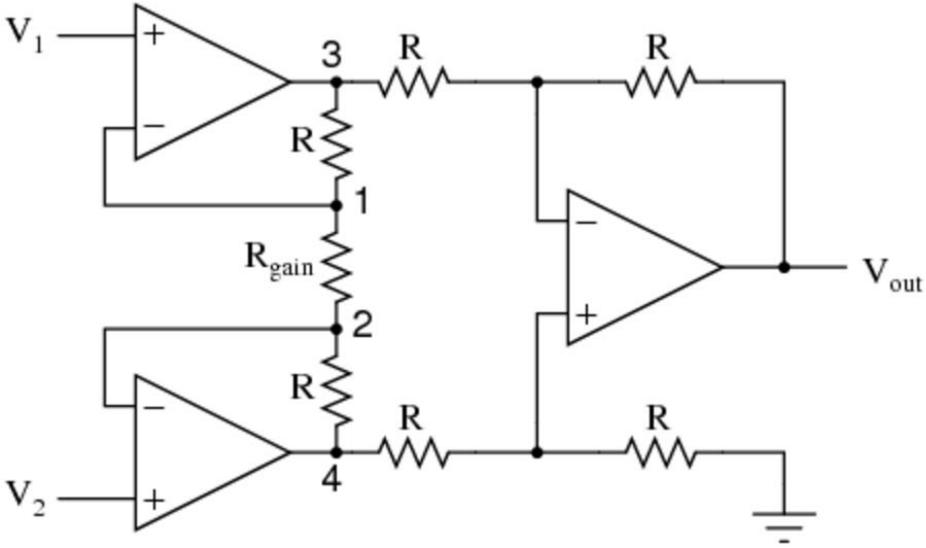
- Output of the op-amp provides 30 mA current to transistor Q_1
- Q_1 drives 600 mA through a suitably selected transistor (with $\beta \geq 20$)

Multiple Stage Gains – LED Driver

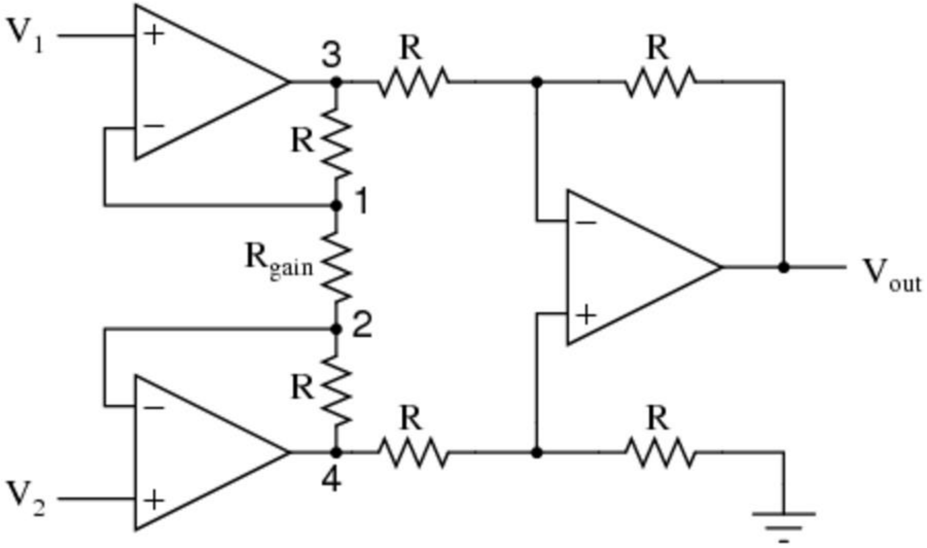
- Figure shows an op-amp circuit that drives LED display
- Op-amp circuit supplies 20 mA to drive an LED display when the noninverting input goes positive compared to the inverting input.



Instrumentation Amplifier



Instrumentation Amplifier



Negative feedback of the upper-left op-amp causes voltage at point 1 to be V_1

Likewise, the voltage at point 2 (bottom of R_{gain}) is held to a value equal to V_2

Hence, a voltage drop across R_{gain} equal to the difference between V_1 and V_2.

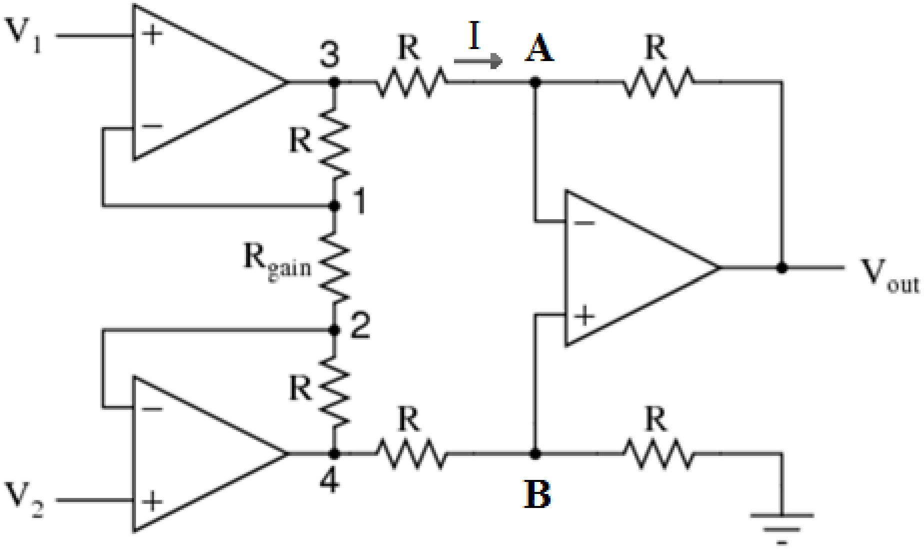
This causes a current through R_{gain},

Same amount of current must be going through the two “R” resistors

This produces a voltage drop between points 3 and 4 equal to:

$$V_{3\text{-}4} = (V_2 - V_1)(1 + \frac{2R}{R_{gain}})$$

Instrumentation Amplifier



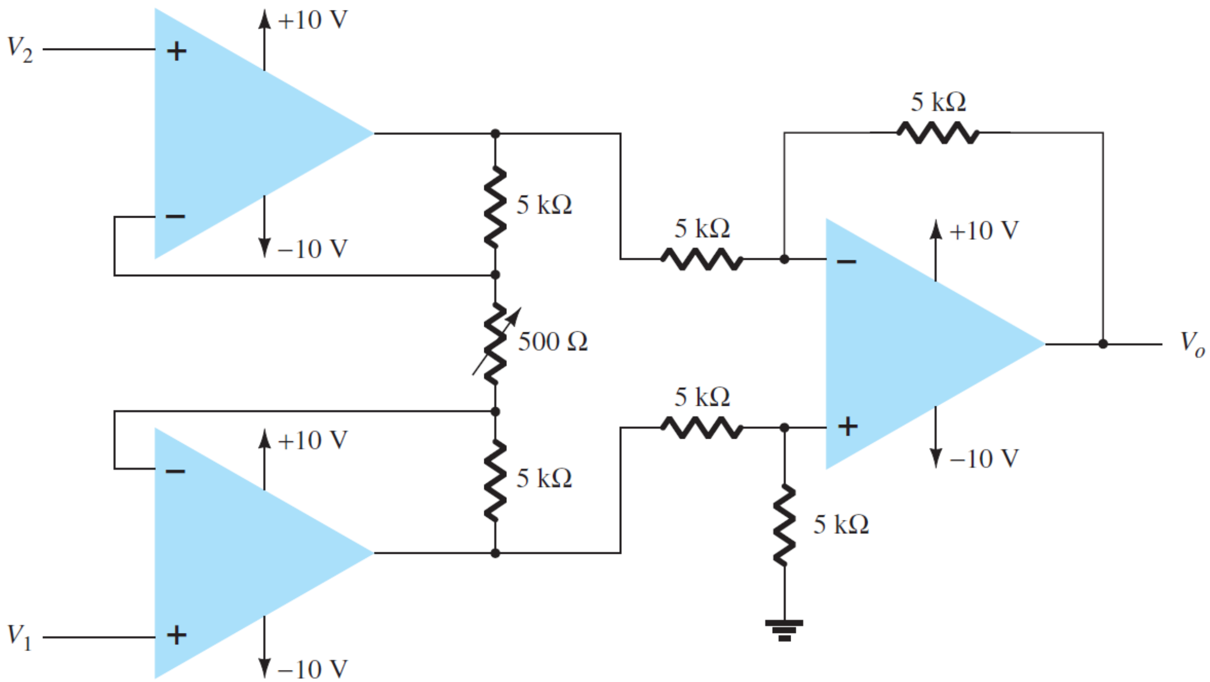
$$V_B = \frac{V_4}{2} \approx V_A$$

$$I = \frac{V_3 - \frac{V_4}{2}}{R} = \frac{\frac{V_4}{2} - V_o}{R} \Rightarrow \; V_3 - \frac{V_4}{2} = \frac{V_4}{2} - V_o$$

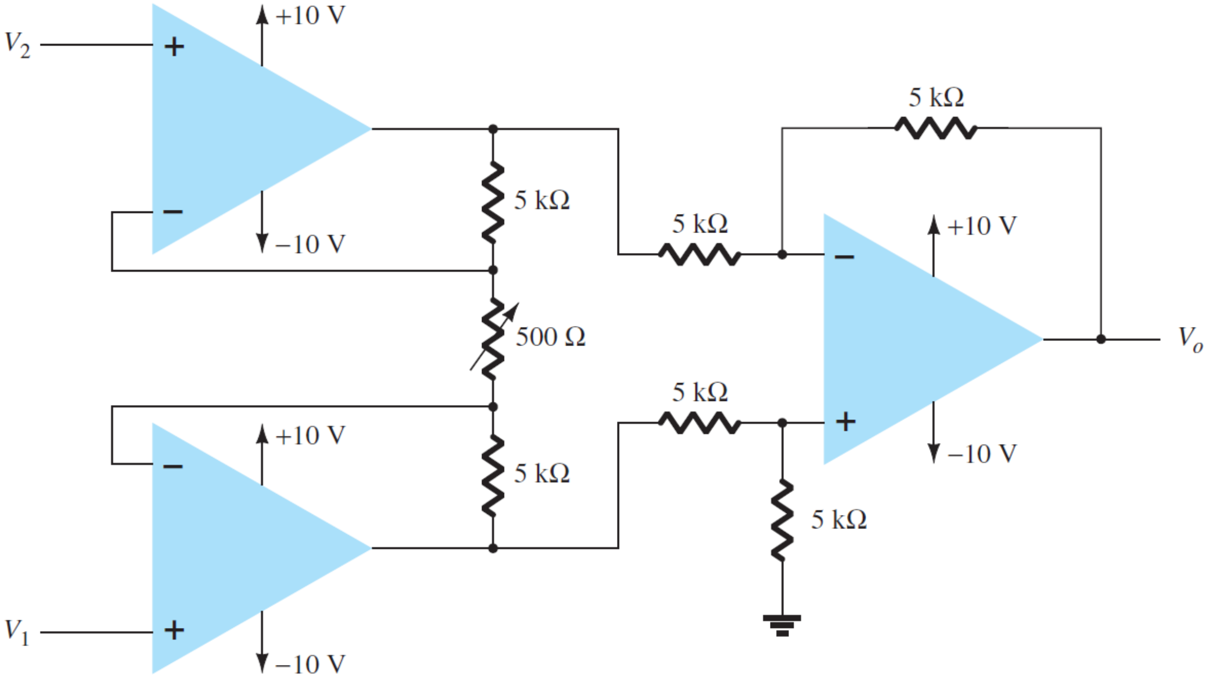
$$V_3 - V_4 = V_o = (V_2 - V_1)\left(1 + \frac{2R}{R_{gain}}\right)$$

$$\frac{V_o}{V_2 - V_1} = A_v = \left(1 + \frac{2R}{R_{gain}}\right)$$

Instrumentation Amplifier



Instrumentation Amplifier



$$V_o = \left(1 + \frac{2R}{R_P}\right)(V_1 - V_2) = \left[1 + \frac{2(5000)}{500}\right](V_1 - V_2)$$

$$= \mathbf{21(V_1 - V_2)}$$