Electronic Devices & Circuits

Dr. Hina Gohar Ali

Hina.gohar@seecs.edu.pk

Office : KBS Lab 1st floor SEECS Building

Office Hours: Open door policy/Appointment through emails

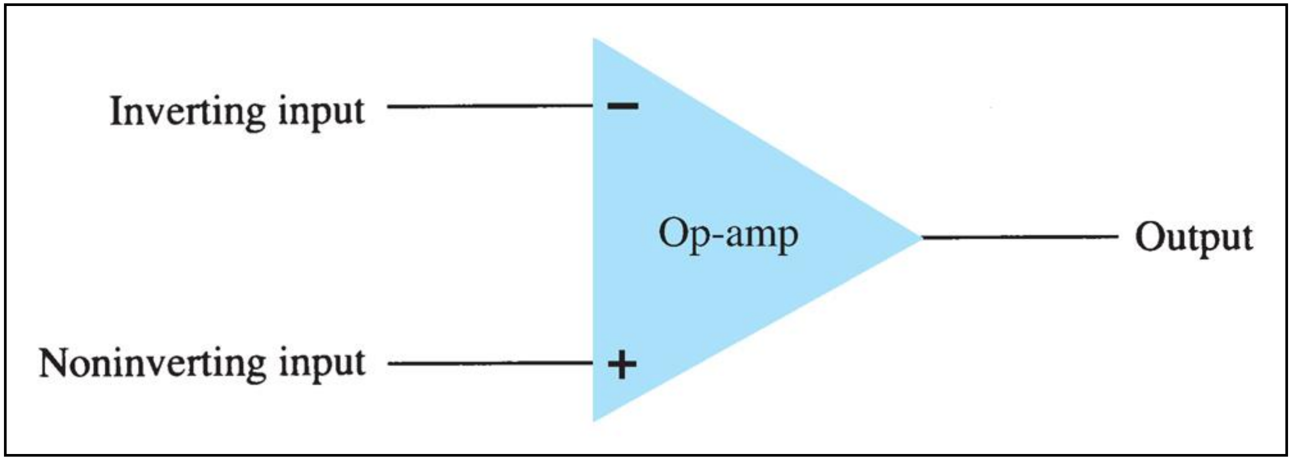
Research Interest: Photovoltaic systems, Power Electronics and Control, Renewable energy, Sliding mode control (SMC), Artificial Intelligence for PV systems

Electronic Devices & Circuits

Chapter 2

Operational Amplifiers

The Basic Op-Amp



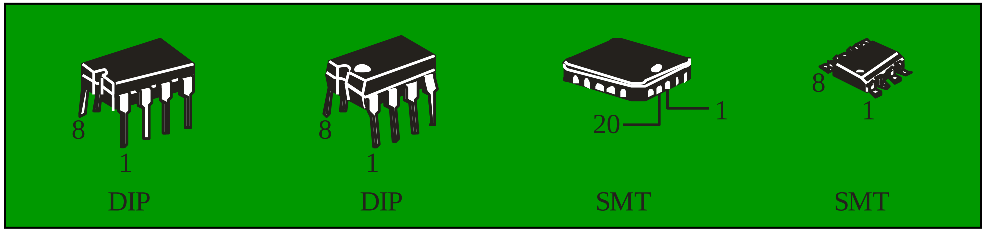
Operational amplifier (Op-amp): A high gain differential amplifier with a high input impedance (typically in MΩ) and low output impedance (less than 100Ω).

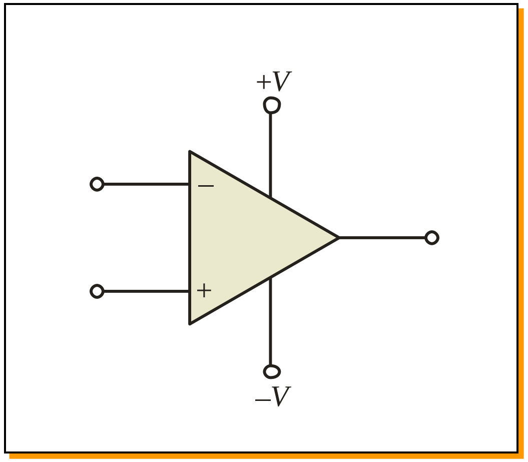
Note the op-amp has two inputs and one output.

The Basic Op-Amp

Operational amplifiers (op-amps) are very high gain dc coupled amplifiers with differential inputs. One of the inputs is called the inverting input (–); the other is called the noninverting input. Usually there is a single output.

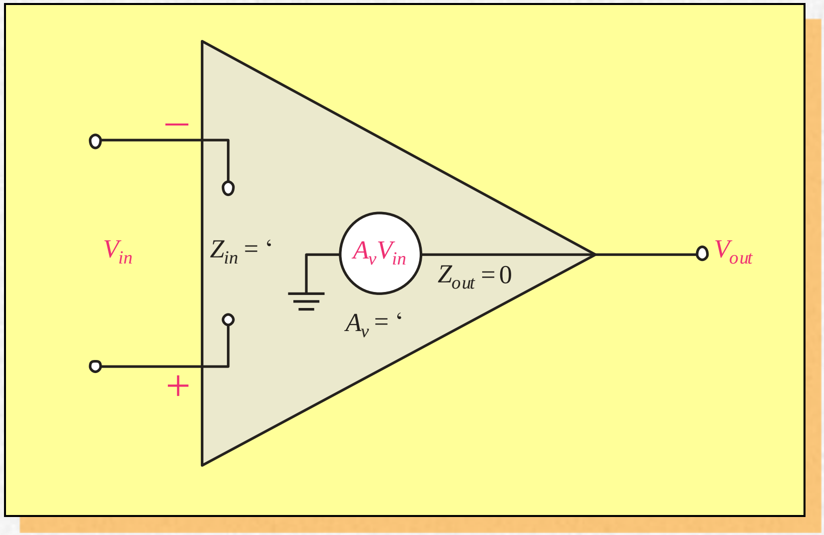
Most op-amps operate from plus and minus supply voltages, which may or may not be shown on the schematic symbol.





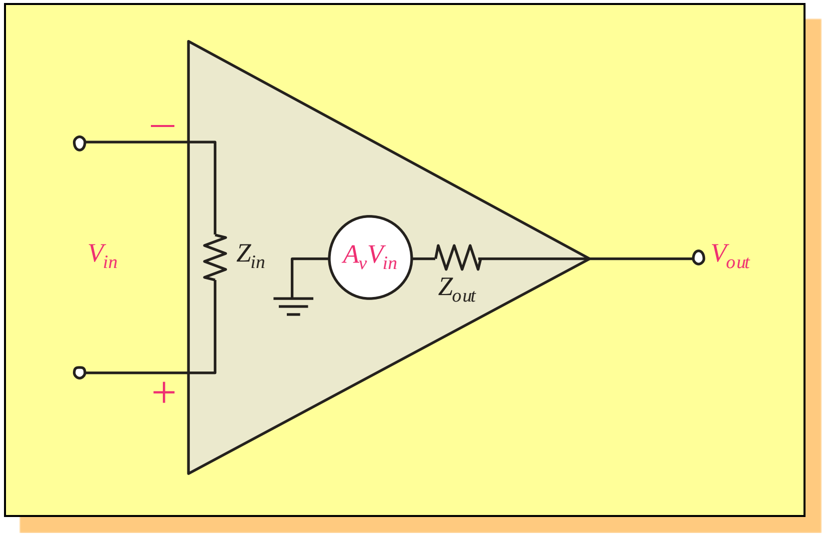
The Ideal Op-Amp

The ideal op-amp has characteristics that simplify analysis of op-amp circuits. Ideally, op-amps have *infinite voltage gain*, *infinite bandwidth*, and *infinite input impedance*. In addition, the ideal op-amp has *zero output impedance*.



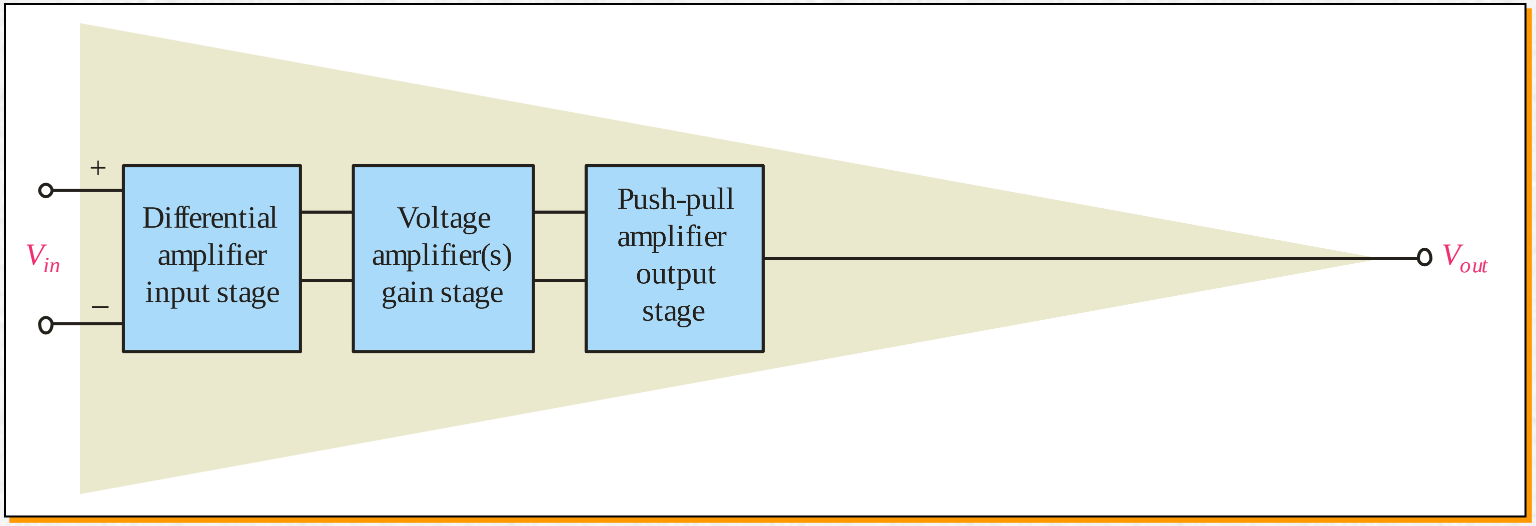
The Practical Op-Amp

Practical op-amps have characteristics that often can be treated as ideal for certain situations, but can never actually attain ideal characteristics. In addition to finite gain, bandwidth, and input impedance, they have other limitations.



Block Diagram

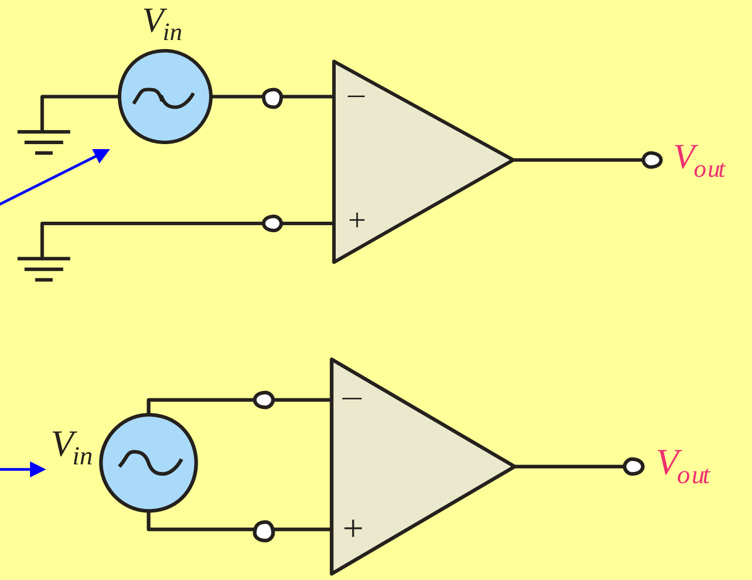
Internally, the typical op-amp has a differential input, a voltage amplifier, and a push-pull output. Recall from the discussion in Section 6-7 of the text that the differential amplifier amplifies the *difference* in the two inputs.



Signal modes

The input signal can be applied to an op-amp in differential-mode or in common-mode.

Differential-mode signals are applied either as single-ended (one side on ground) or double-ended (opposite phases on the inputs).



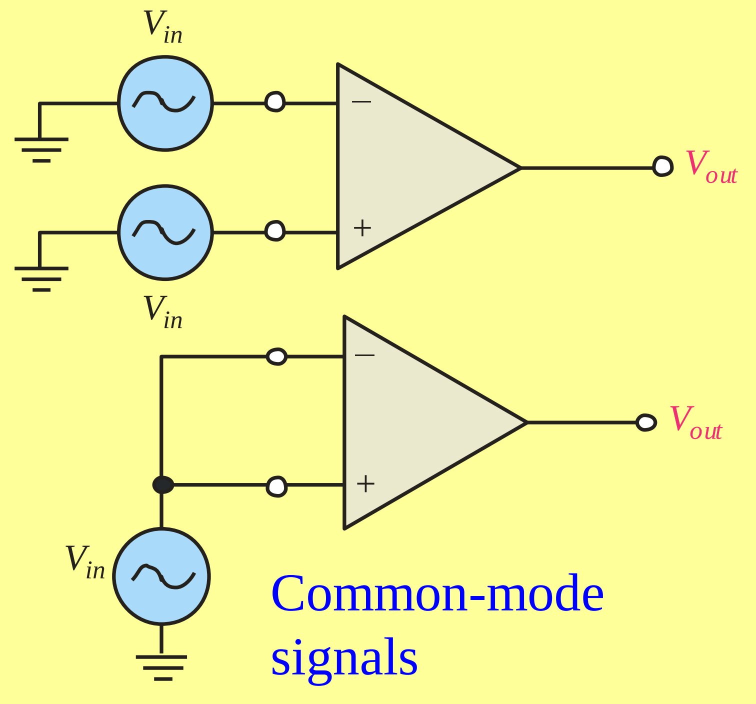
Differential signals

Signal modes

The input signal can be applied to an op-amp in differential-mode or in common-mode.

Common-mode signals are applied to both sides with the same phase on both.

Usually, common-mode signals are from unwanted sources, and affect both inputs in the same way. The result is that they are essentially cancelled at the output.



Common-mode signals

Op-Amp Gain

Op-Amps can be connected in *open-loop* or *closed-loop* configurations.

Open-loop: A configuration with no feedback from the op-amp output back to its input. Op-amp open-loop gain typically exceeds 10,000.

Closed-loop: A configuration that has a negative feedback path from the op-amp output back to its input. **Negative feedback** reduces the gain and improves many characteristics of the op-amp.

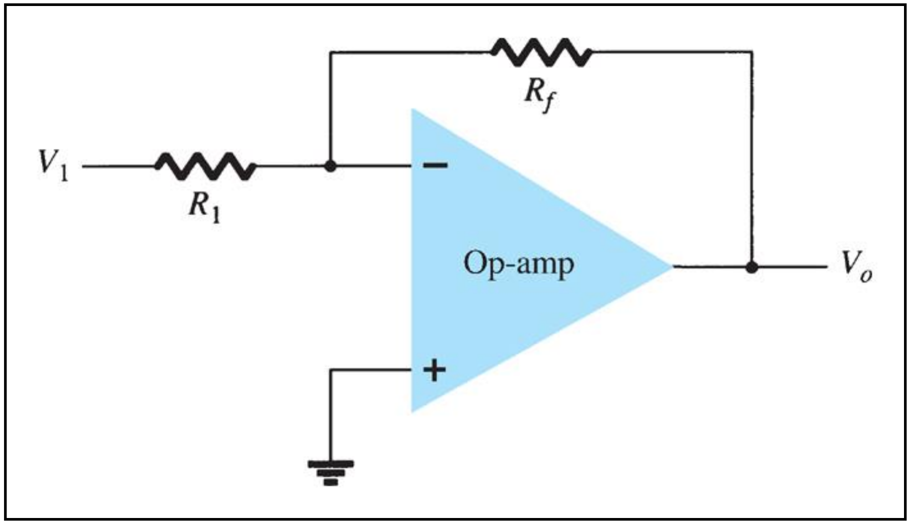
- Closed-loop gain is always lower than open-loop gain.

Inverting Op-Amp

The input signal is applied to the **inverting (–) input**

The **non-inverting input (+)** is grounded

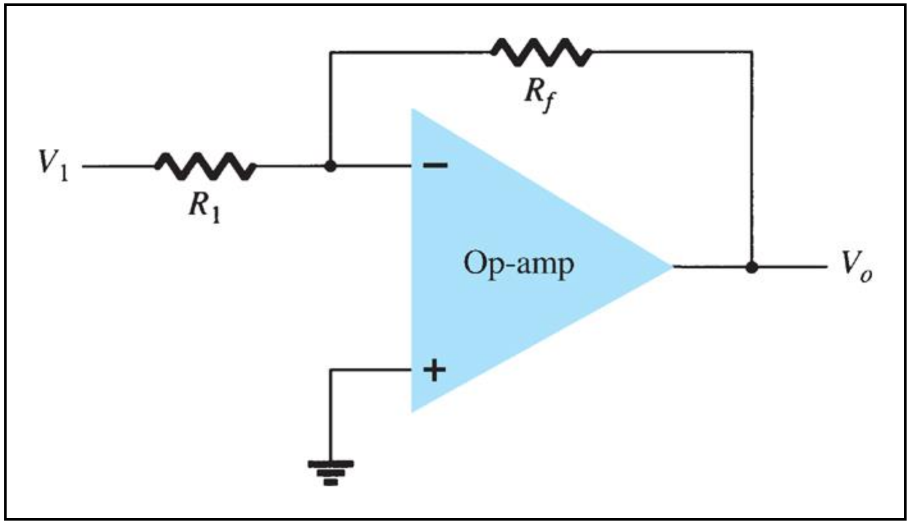
The **feedback resistor** (R_f) is connected from the output to the negative (inverting) input; providing *negative feedback*.



Inverting Op-Amp Gain

Gain is set using external resistors: *R_f* and *R_1*

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



Gain can be set to any value by manipulating the values of R_f and R_1.

Unity gain ($A_v = 1$):

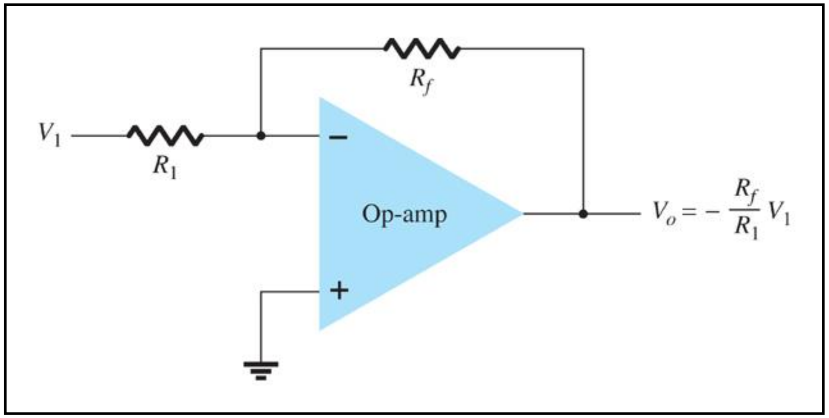
$$R_f = R_1$$

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

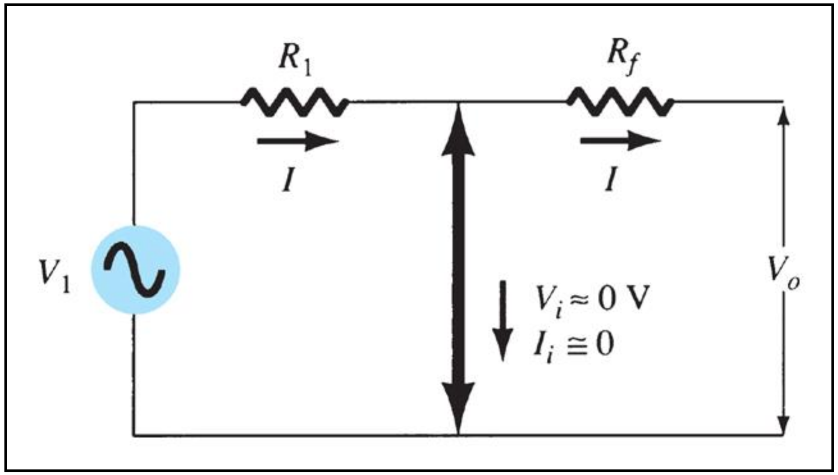
The negative sign denotes a 180° phase shift between input and output.

Virtual Ground

Virtual ground: A term used to describe the condition where $V_i \cong 0$ V (at the inverting input) when the noninverting input is grounded.



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



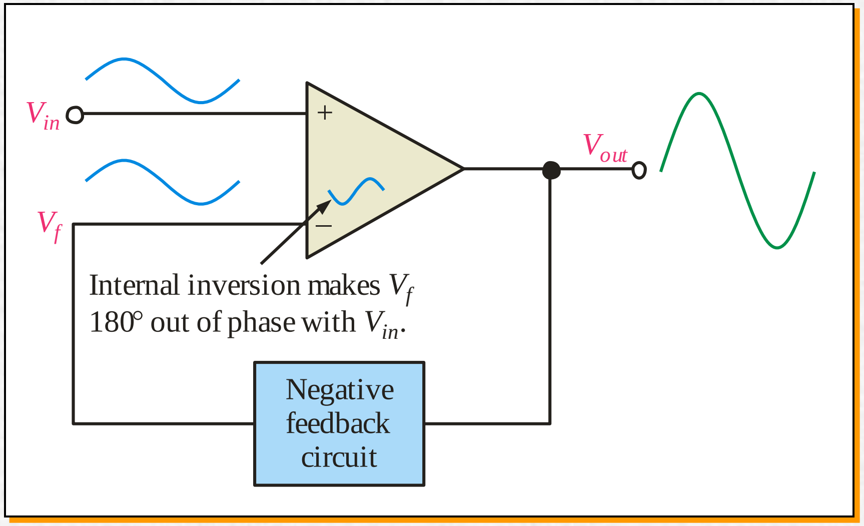
Common Op-Amp Circuits

- Inverting amplifier
- Noninverting amplifier
- Unity follower
- Summing amplifier
- Integrator
- Differentiator

Negative Feedback

Negative feedback is the process of returning a portion of the output signal to the input with a phase angle that opposes the input signal.

The advantage of negative feedback is that precise values of amplifier gain can be set. In addition, bandwidth and input and output impedances can be controlled.

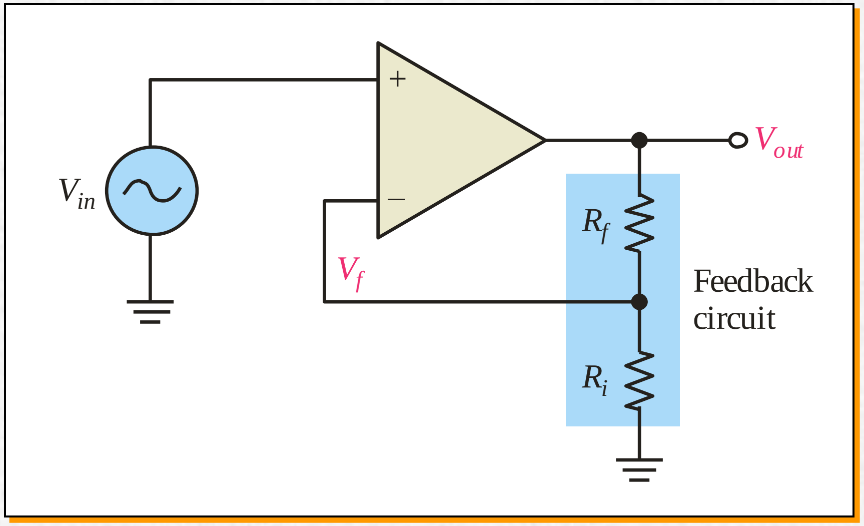


Noninverting Amplifier

A **noninverting amplifier** is a configuration in which the signal is on the noninverting input and a portion of the output is returned to the inverting input.

Feedback forces V_f to be equal to V_{in}, hence V_{in} is across R_i. With basic algebra, you can show that the closed-loop gain of the noninverting amplifier is

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



Noninverting Amplifier

Example:

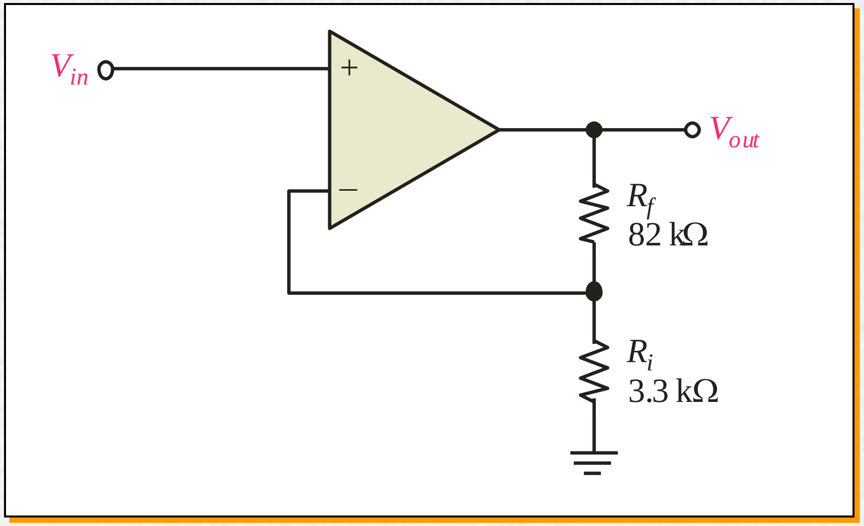
Determine the gain of the noninverting amplifier shown.

Solution:

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

$$= 1 + \frac{82\ \mathrm{k\Omega}}{3.3\ \mathrm{k\Omega}}$$

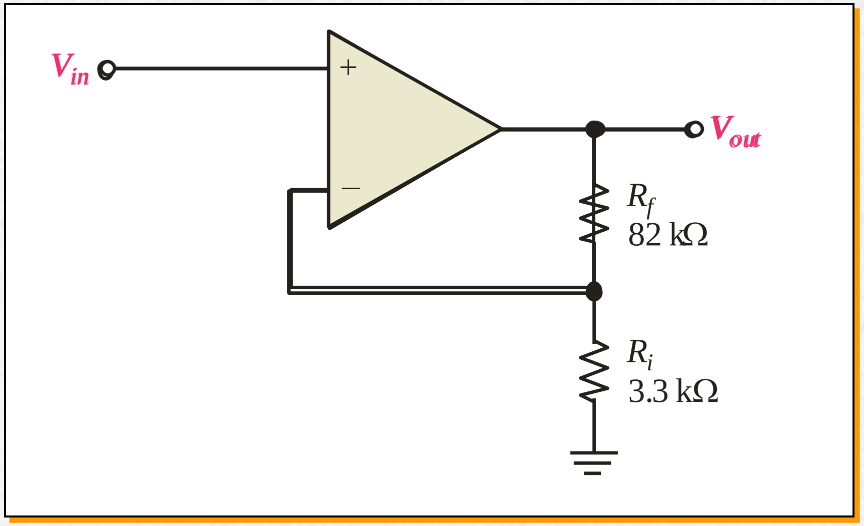
$$= 25.8$$



Noninverting Amplifier

A special case of the inverting amplifier is when R_f =0 and $R_i = \infty$. This forms a voltage follower or unity gain buffer with a gain of 1.

The input impedance of the voltage follower is very high, producing an excellent circuit for isolating one circuit from another, which avoids "loading" effects.

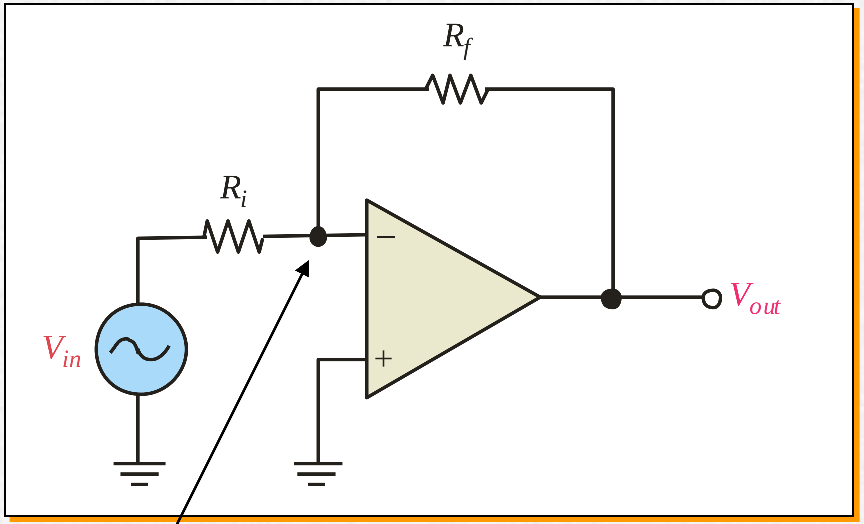


Inverting Amplifier

An **inverting amplifier** is a configuration in which the noninverting input is grounded and the signal is applied through a resistor to the inverting input.

Feedback forces the inputs to be nearly identical; hence the inverting input is very close to 0 V. The closed-loop gain of the inverting amplifier is

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



0 V (virtual ground)

Inverting Amplifier

Example:

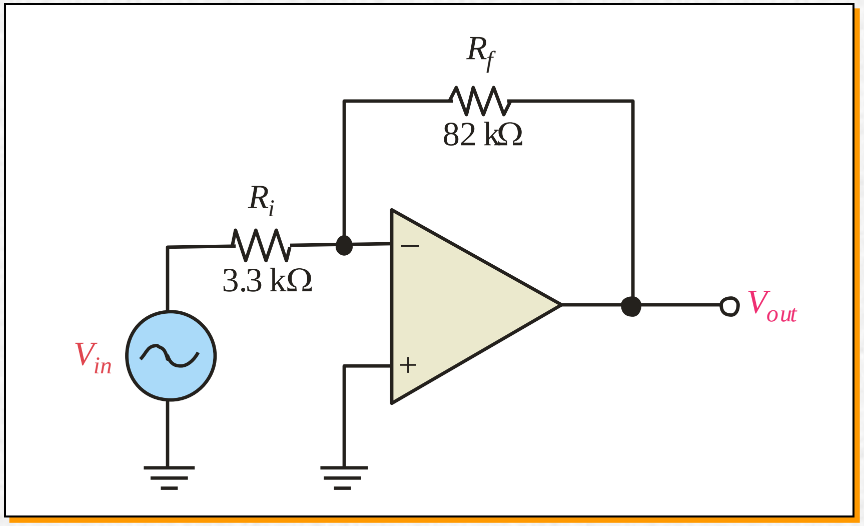
Determine the gain of the inverting amplifier shown.

Solution:

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

$$= -\frac{82\ \mathrm{k\Omega}}{3.3\ \mathrm{k\Omega}}$$

$$= -24.8$$



The minus sign indicates inversion.

Impedances

Noninverting amplifier:

$$Z_{in(\mathrm{NI})} = \left(1 + A_{ol}B\right) Z_{in}$$

Generally, assumed to be ∞

$$Z_{out(\mathrm{NI})} = \frac{Z_{out}}{\left(1 + A_{ol}B\right)}$$

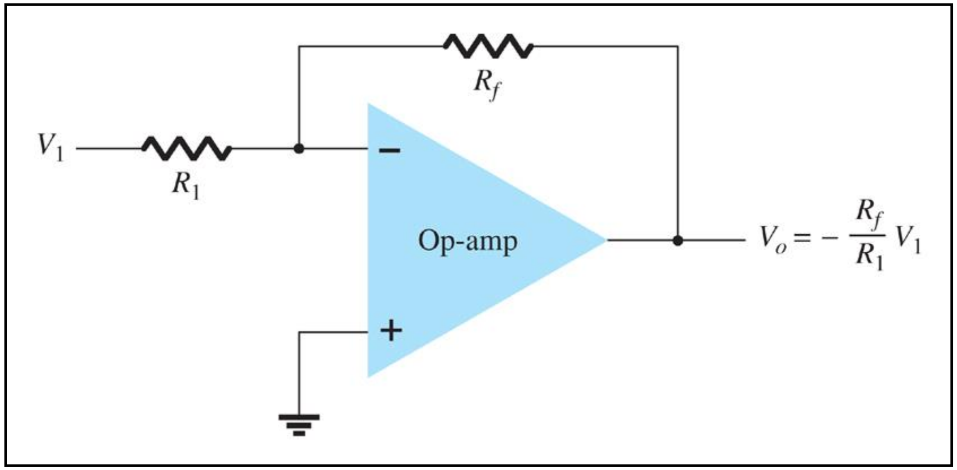
Generally, assumed to be 0

Note that the output impedance has the same form for both amplifiers.

Inverting/Noninverting Amplifiers

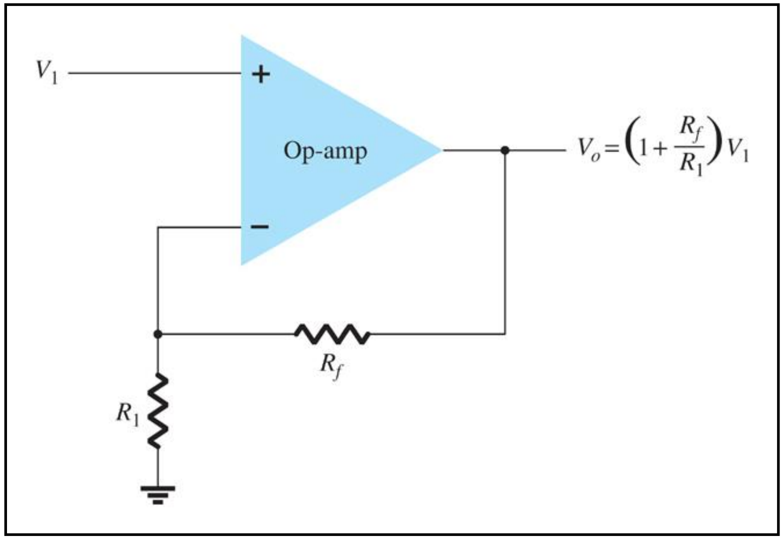
Inverting Amplifier

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



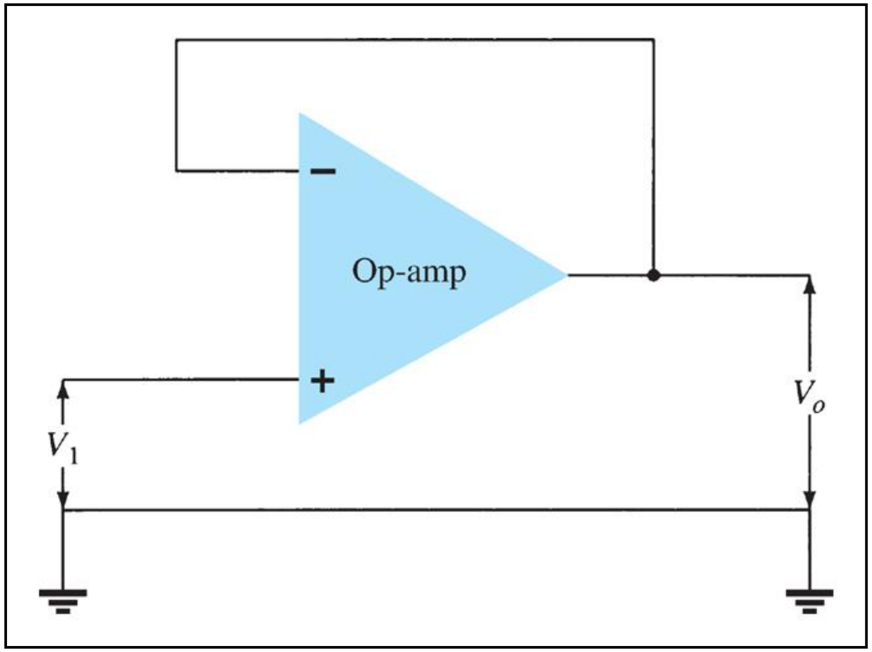
Noninverting Amplifier

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



Unity Follower

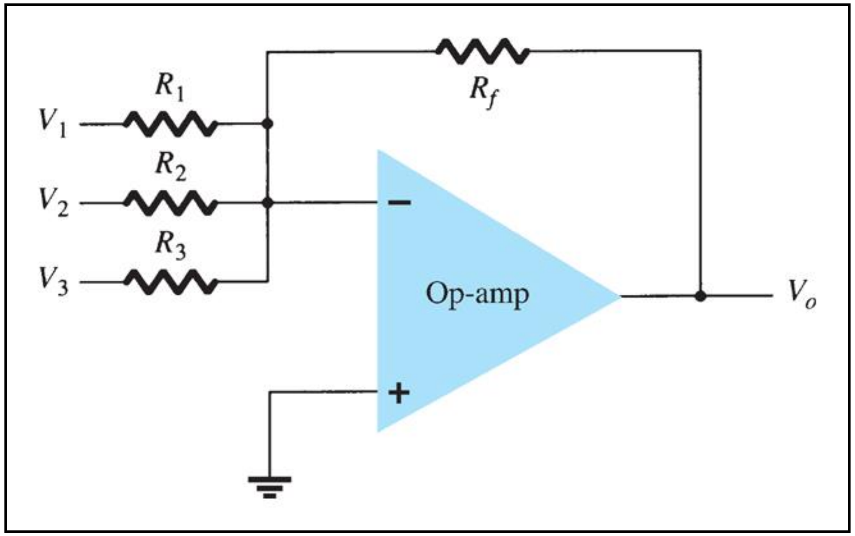
$$V_o = V_1$$



Summing Amplifier

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

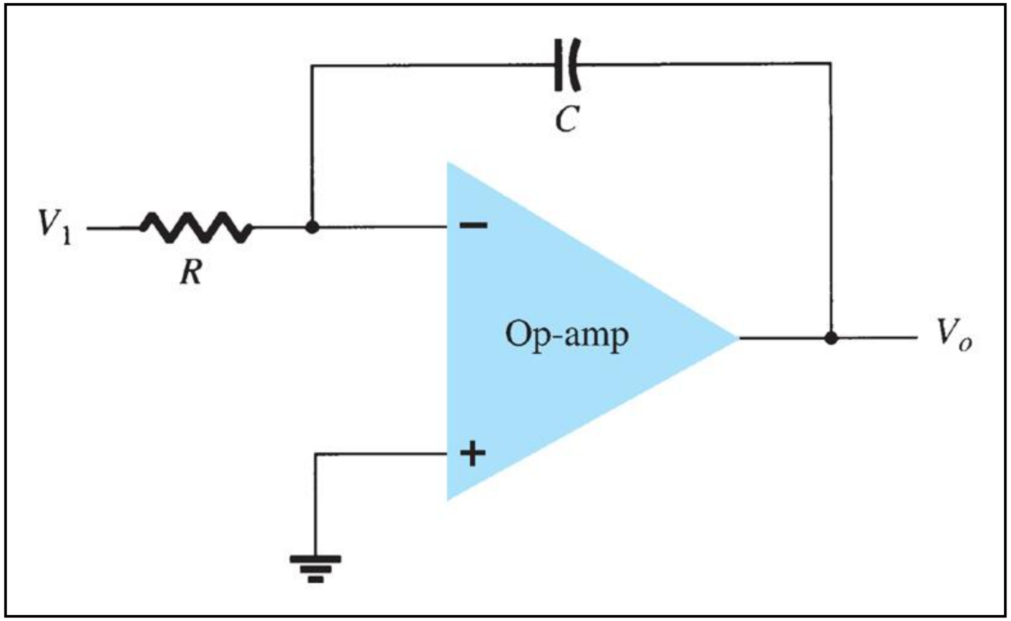
$$V_o = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 \right)$$



Integrator

The output is the integral of the input; i.e., proportional to the area under the input waveform. This circuit is useful in low-pass filter circuits and sensor conditioning circuits.

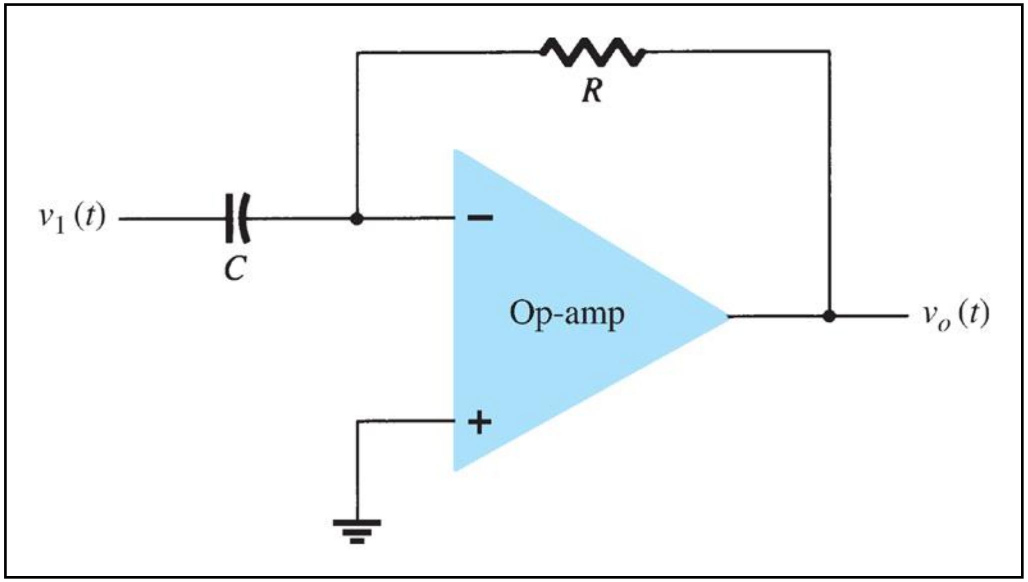
$$v_o(t) = -\frac{1}{RC}\int v_1(t)dt$$



Differentiator

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

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



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

Input Offset Voltage (V_{IO})

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

The effect of this input offset voltage on the output can be calculated with

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

Input Offset Current (I_{IO})

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.

The effect of I_{IO} on the output offset voltage can be calculated using:

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

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

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:

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

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:

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

Frequency Parameters

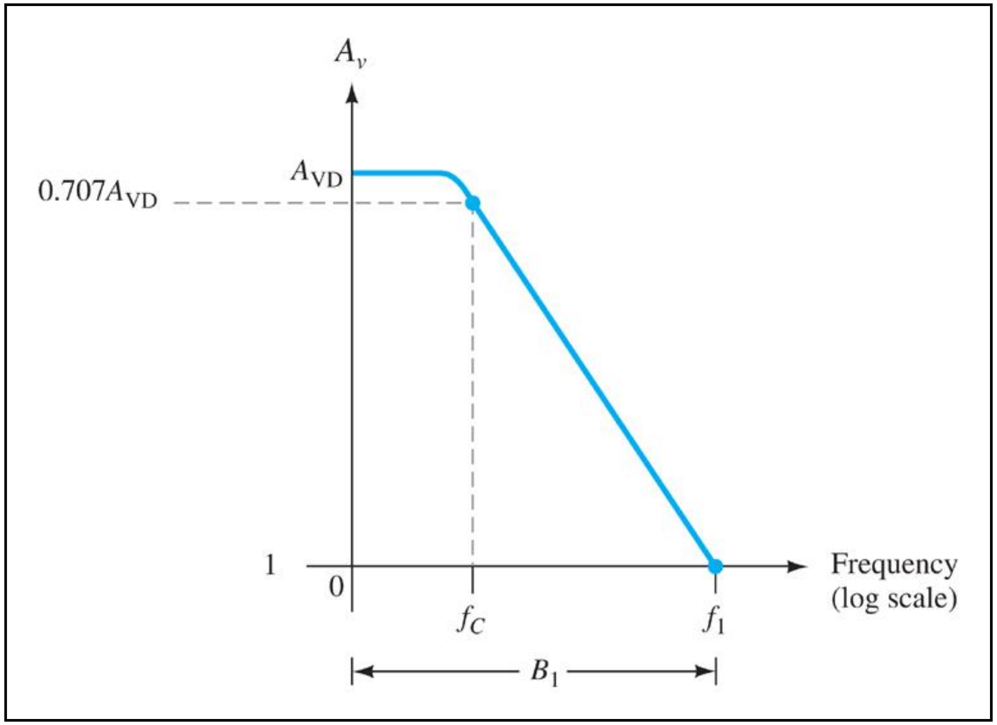
An op-amp is a wide-bandwidth amplifier. The following factors affect the bandwidth of the op-amp:

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.

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.

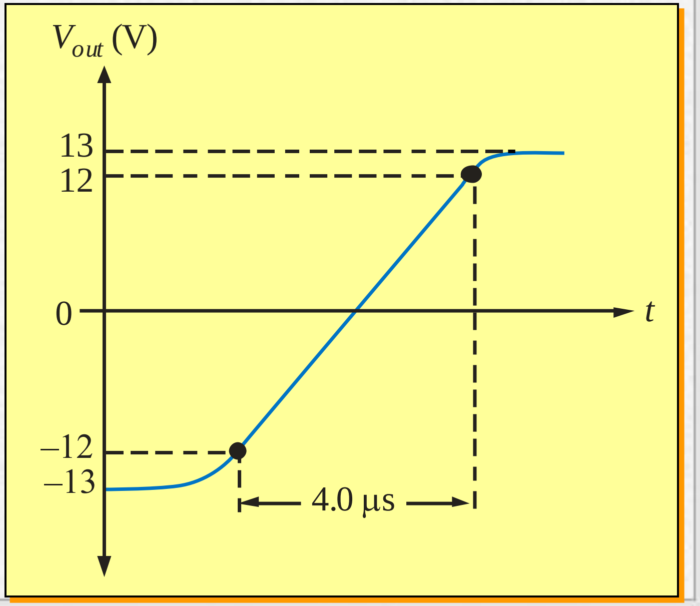
Other Parameters

Slew rate: The **slew rate** is the maximum rate of change of the output voltage in response to a step input voltage

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

Example:

Determine the slew rate for the output response to a step input.



Solution:

$$\text{Slew Rate} = \frac{\Delta V_{out}}{\Delta t} = \frac{(+12\text{ V}) - (-12\text{ V})}{4.0\ \mu\text{s}}$$

$$= 6\ \text{V}/\mu\text{s}$$

Maximum Signal Frequency

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

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

where V_P is the peak voltage

General Op-Amp Specifications

Other op-amp ratings found on specification sheets are:

Absolute Ratings

Electrical Characteristics

Performance

Absolute Ratings

These are common maximum ratings for the op-amp.

Absolute Maximum Ratings

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

Electrical Characteristics

μA741 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.

CMRR

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

The ability of an amplifier to amplify differential signals and reject common-mode signals is called the **common-mode rejection ratio (CMRR)**.

CMRR is defined as $\mathbf{CMRR} = \dfrac{A_{ol}}{A_{cm}}$

where A_{ol} is the open-loop differential-gain and A_{cm} is the common-mode gain.

CMRR can also be expressed in decibels as $\mathbf{CMRR} = 20\log\left(\dfrac{A_{ol}}{A_{cm}}\right)$

Common-Mode Rejection Ratio

Example:

What is CMRR in decibels for a typical 741C op-amp?

The typical open-loop differential gain for the 741C is 200,000 and the typical common-mode gain is 6.3.

Solution:

$$\mathbf{CMRR} = 20\log\left(\frac{A_{ol}}{A_{cm}}\right)$$

$$= 20\log\frac{200,000}{6.3} = 90\text{ dB}$$

(The minimum specified CMRR is 70 dB.)

Voltage and Current Parameters

$V_{O(p\text{-}p)}$: The **maximum output voltage swing** is determined by the op-amp and the power supply voltages

V_{OS}: The **input offset voltage** is the differential dc voltage required between the inputs to force the output to zero volts

I_{BIAS}: The **input bias current** is the average of the two dc currents required to bias the differential amplifier

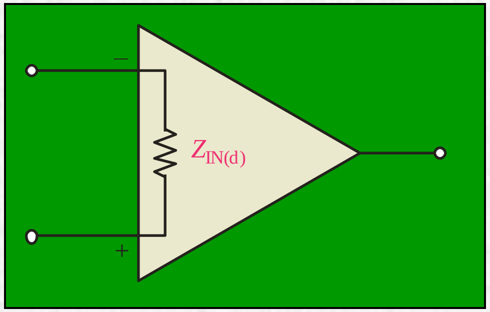
$$I_{BIAS} = \frac{I_1 + I_2}{2}$$

I_{OS}: The **input offset current** is the difference between the two dc bias currents

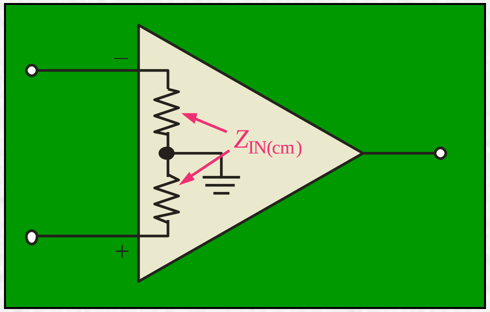
$$I_{OS} = |I_1 - I_2|$$

Impedance Parameters

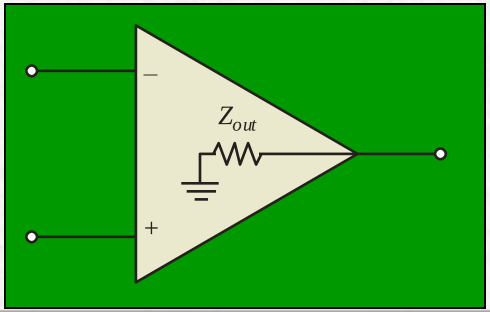
$Z_{IN(d)}$: The **differential input impedance** is the total resistance between the inputs



$Z_{IN(cm)}$: The **common-mode input impedance** is the resistance between each input and ground

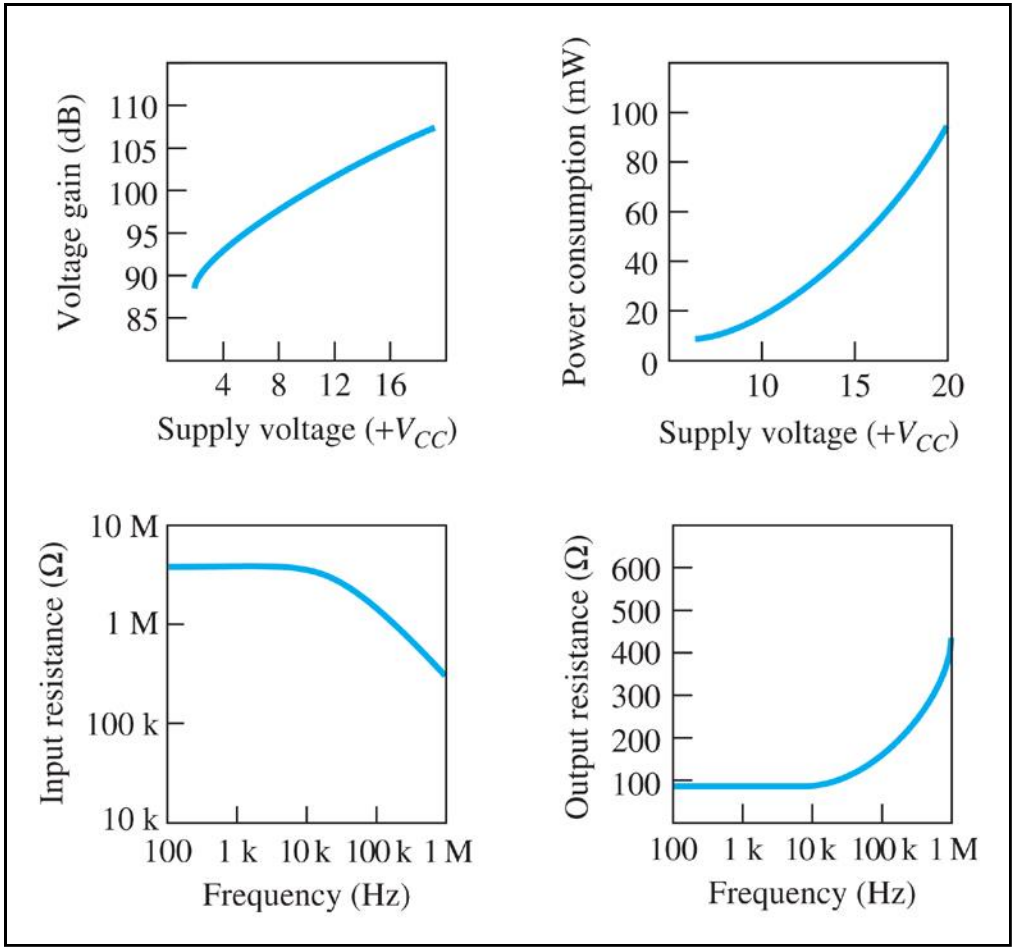


Z_{out}: The **output impedance** is the resistance viewed from the output of the circuit.



Op-Amp Performance

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



Summary

That's all for Today !