Operational Amplifier
(Op-Amp)

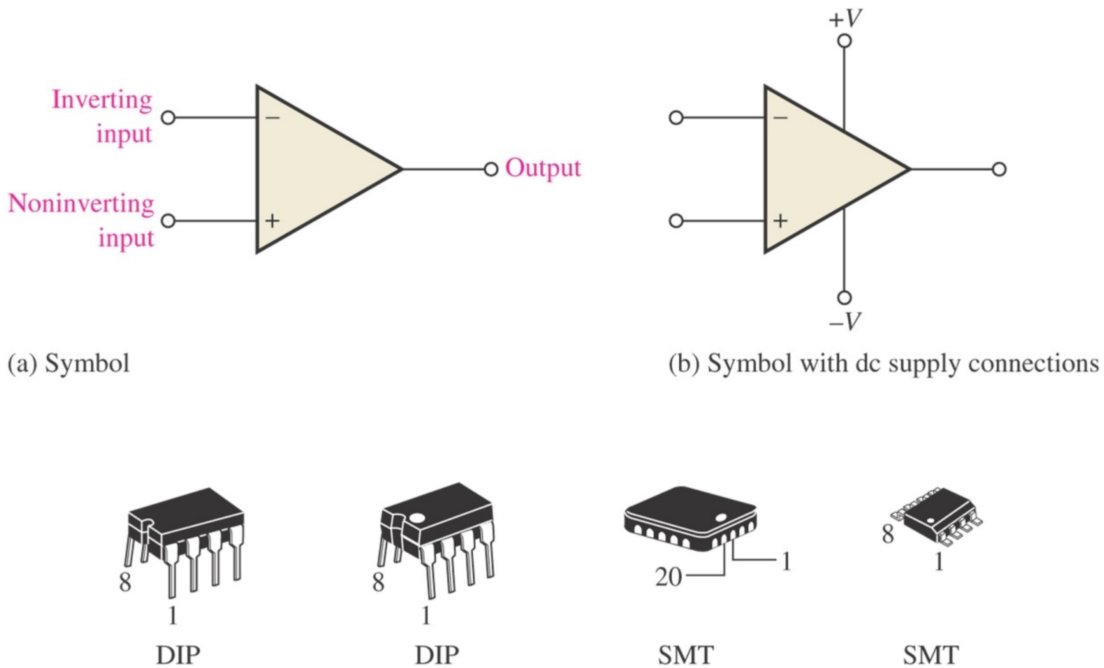
Contents

- Op-Amp Characteristics
- Op-Amp Circuits

  - Noninverting Amplifier
  - Inverting Amplifier
  - Comparator
  - Differential
  - Summing
  - Integrator
  - Differentiator

Introduction

- Op-amps are very high gain amplifier with differential inputs.
- Most op-amps operate with two dc supply voltages.

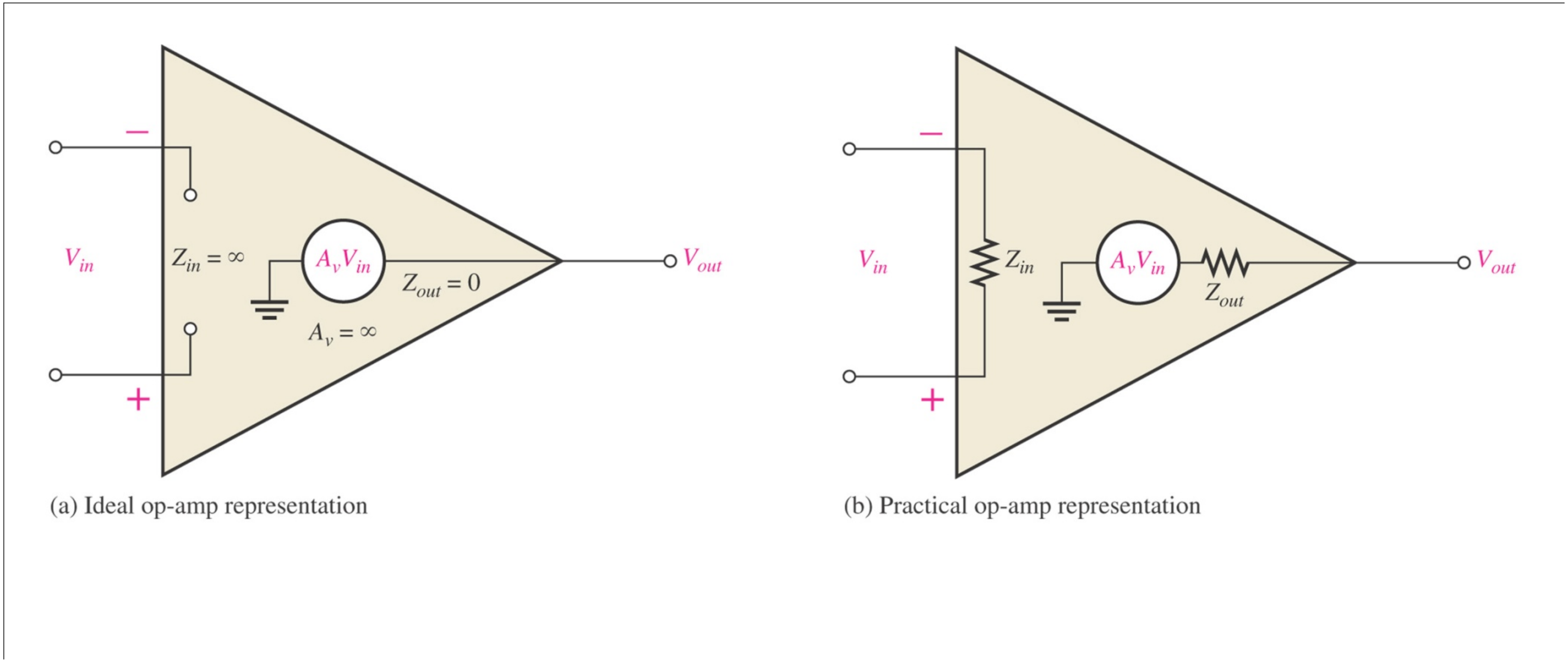


(c) Typical packages. Pin 1 is indicated by a notch or dot on dual in-line (DIP) and surface-mount technology (SMT) packages, as shown.

Ideal Op-amp

- Infinite Voltage gain
- Infinite Bandwidth

- Infinite Input impedance
- Zero output impedance



Voltage and Current Parameters

$V_{O(p-p)}$: 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

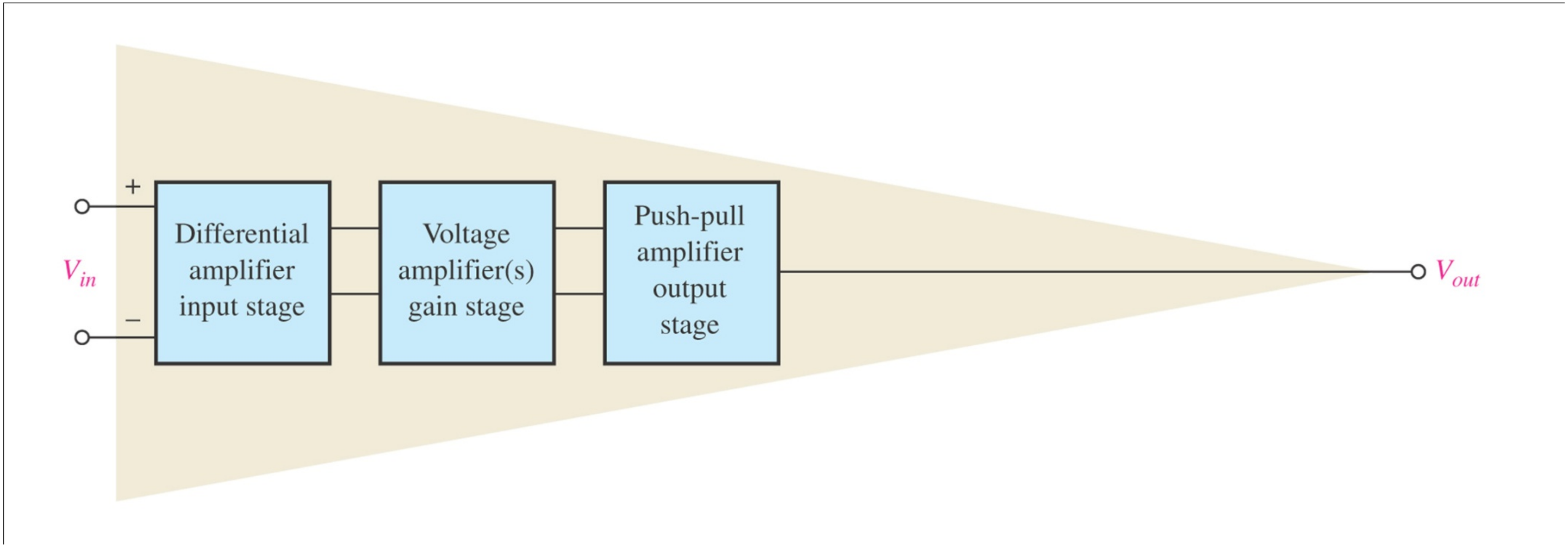
I_{BIAS}: The **input bias current** is the average of the two dc currents required to bias the differential amplifier

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

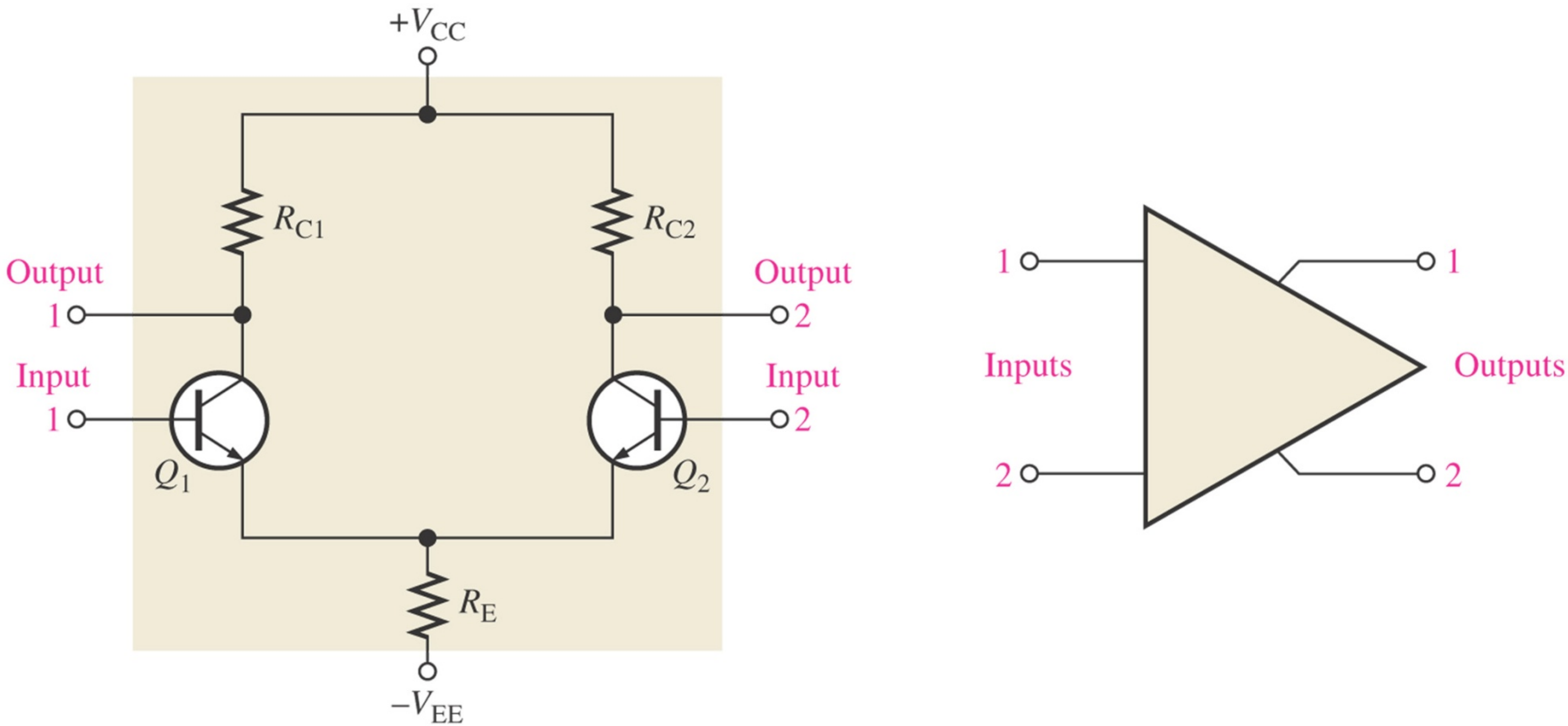
I_{OS}: The **input offset current** is the difference between the two dc bias currents

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

Internal Block Diagram

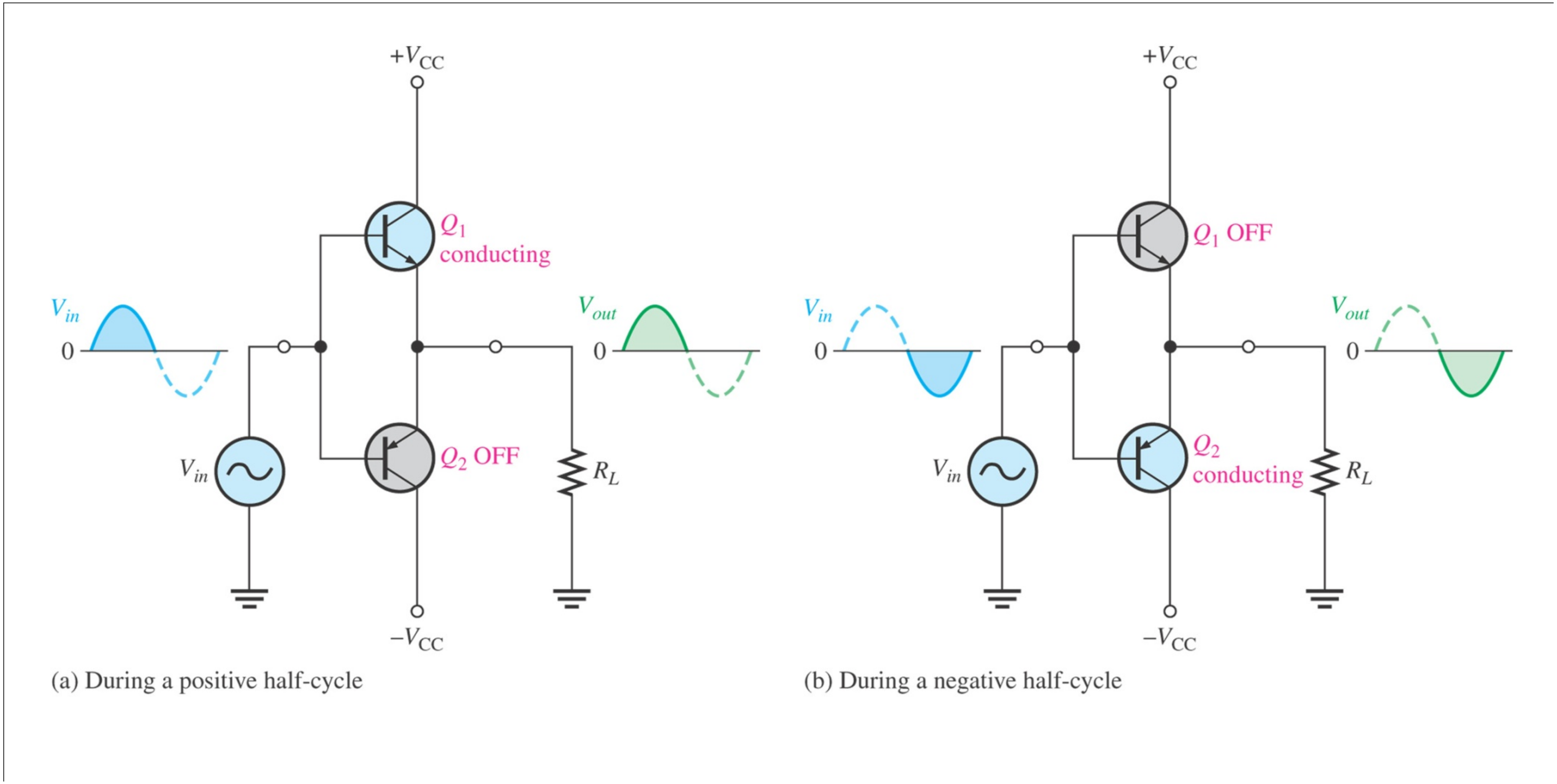


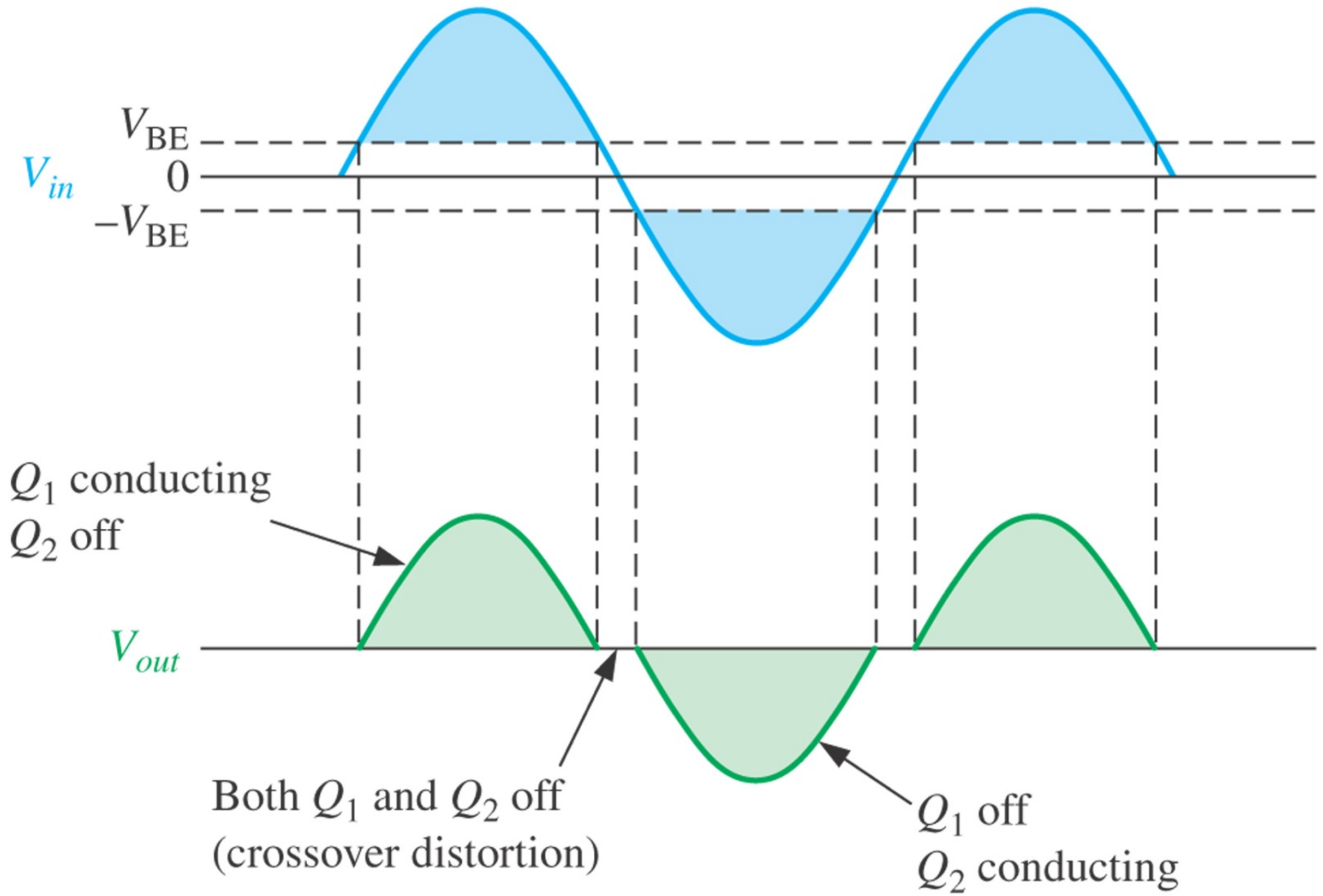
Basic Differential Amp



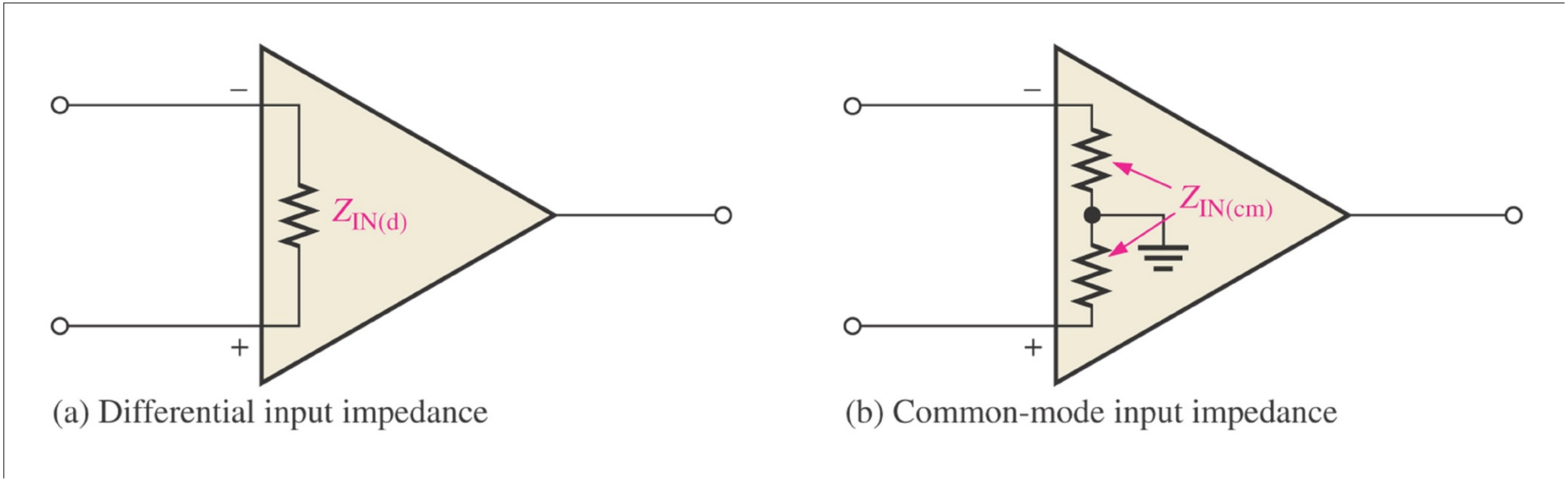
(a) Circuit (b) Symbol

Push-pull amplifier




V_{BE}
V_{in}
0
$-V_{BE}$
Q_1 conducting
Q_2 off
V_{out}
Both Q_1 and Q_2 off
(crossover distortion)
Q_1 off
Q_2 conducting

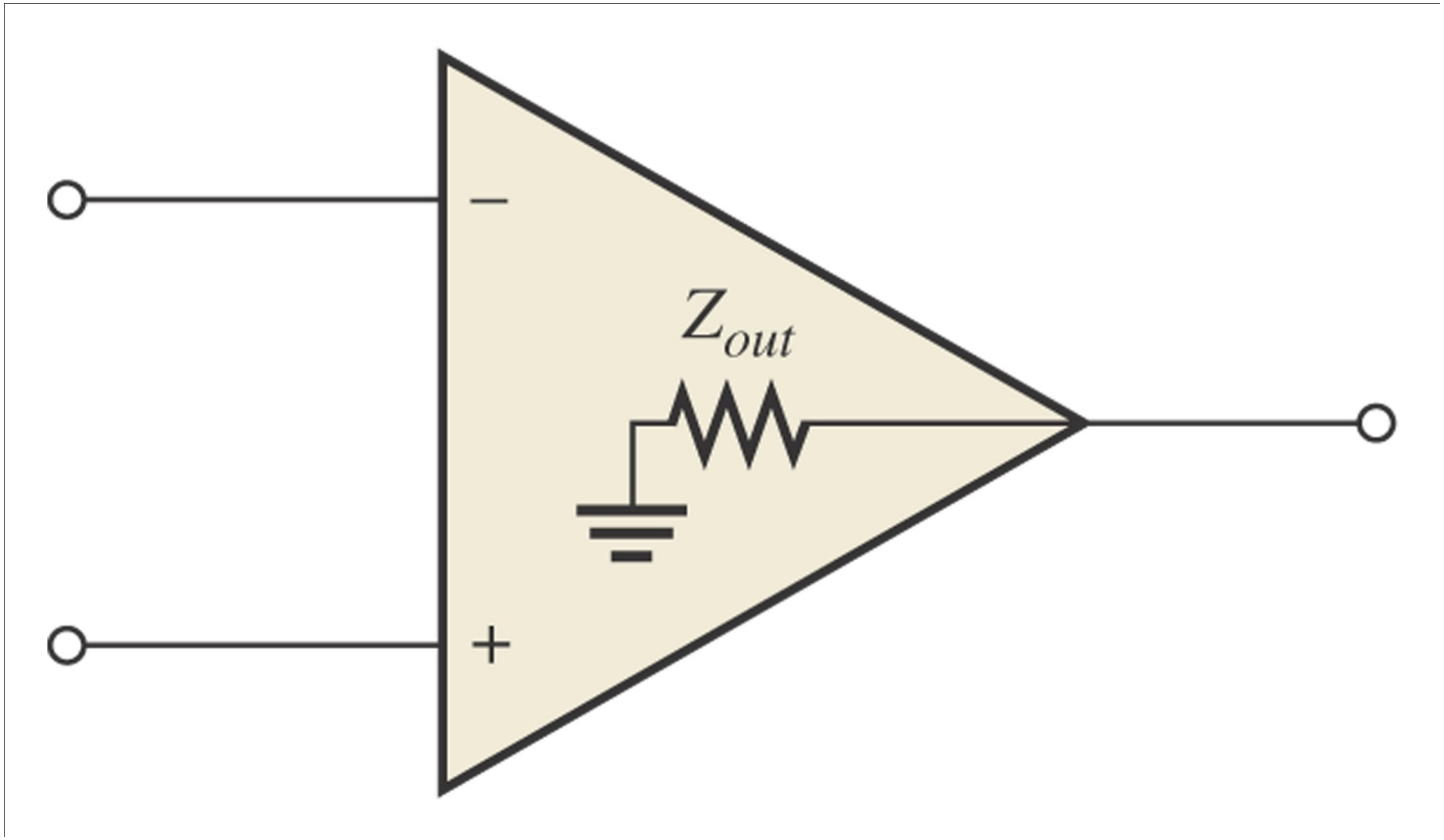
Input Impedance



$Z_{IN(d)}$: 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

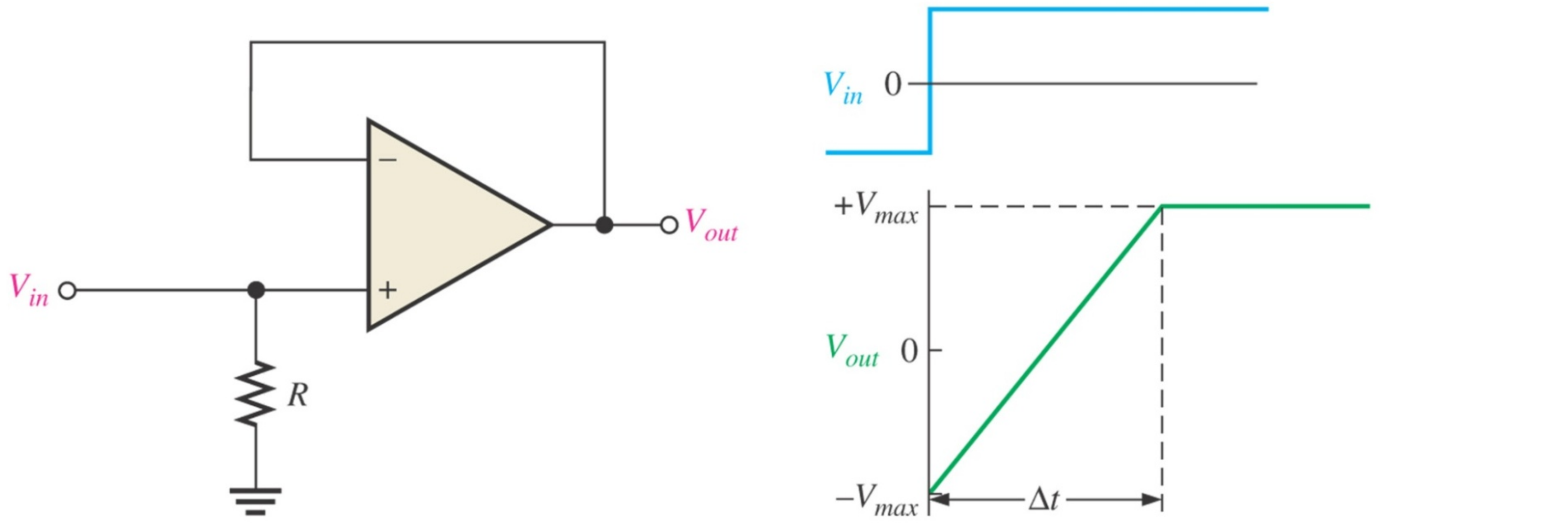
Output Impedance



Slew rate

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

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

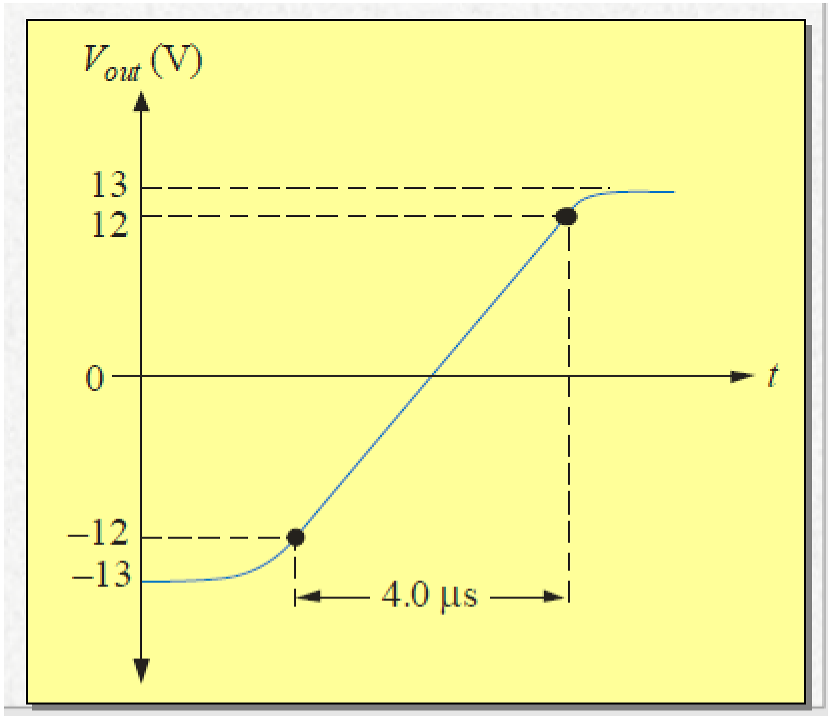


(a) Test circuit

(b) Step input voltage and the resulting output voltage

Example

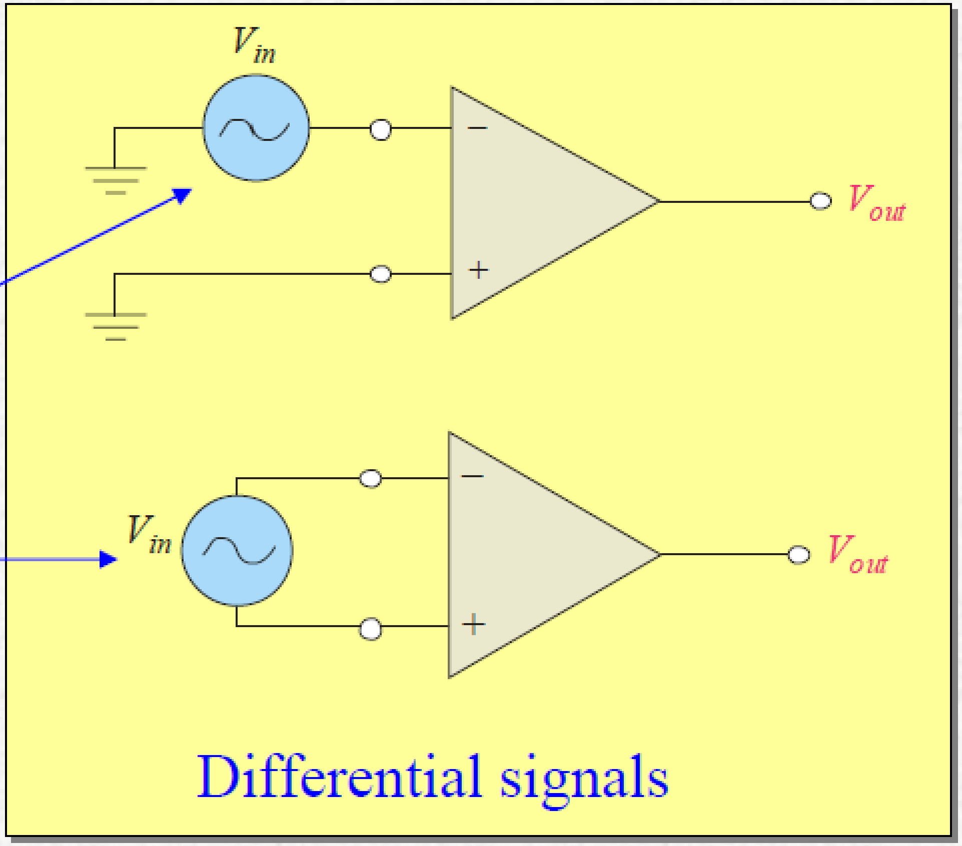
- Determine the slew rate for the output response to a step input given in the figure.



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).



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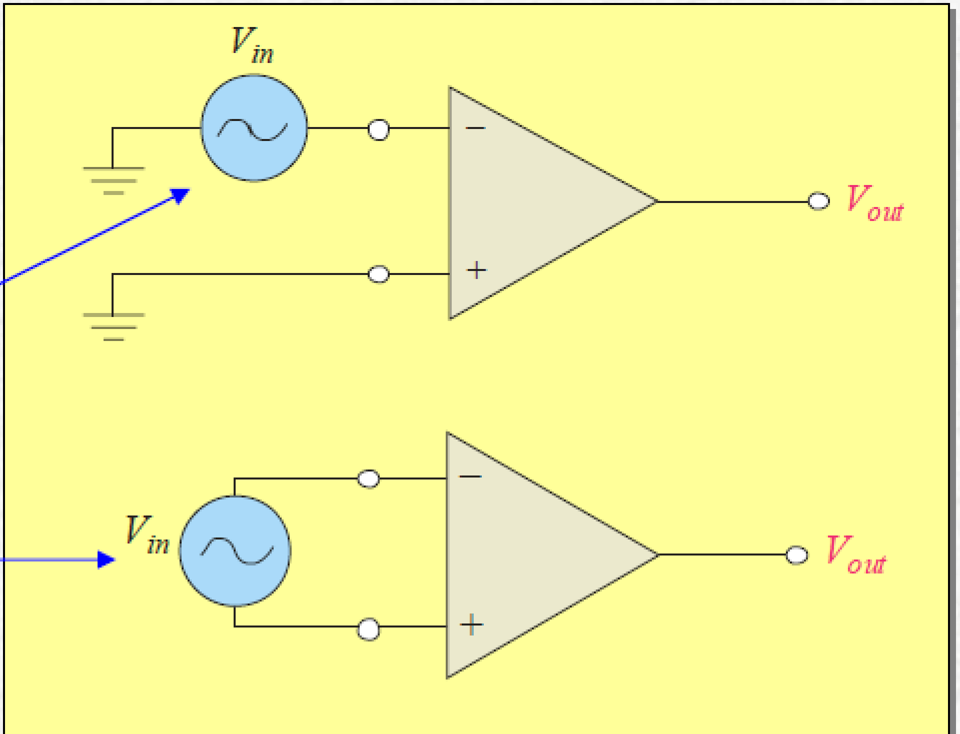
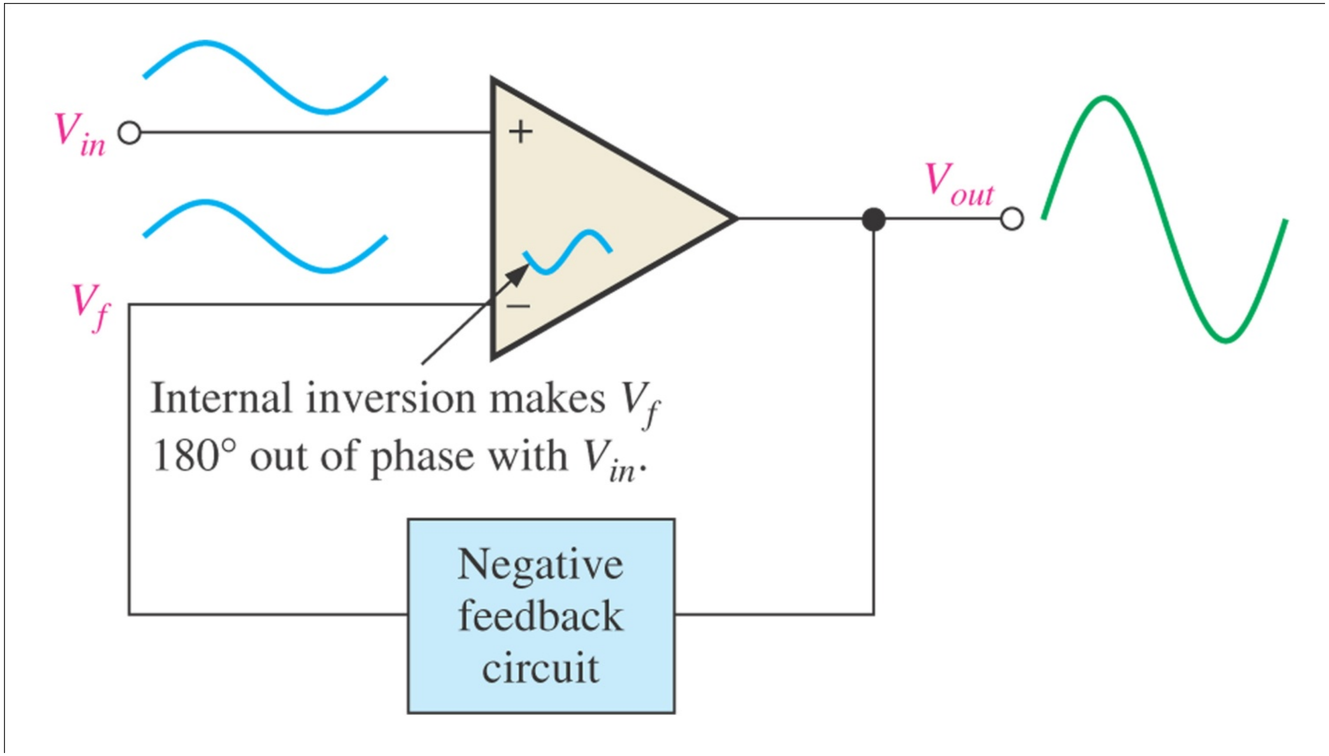


Differential signals

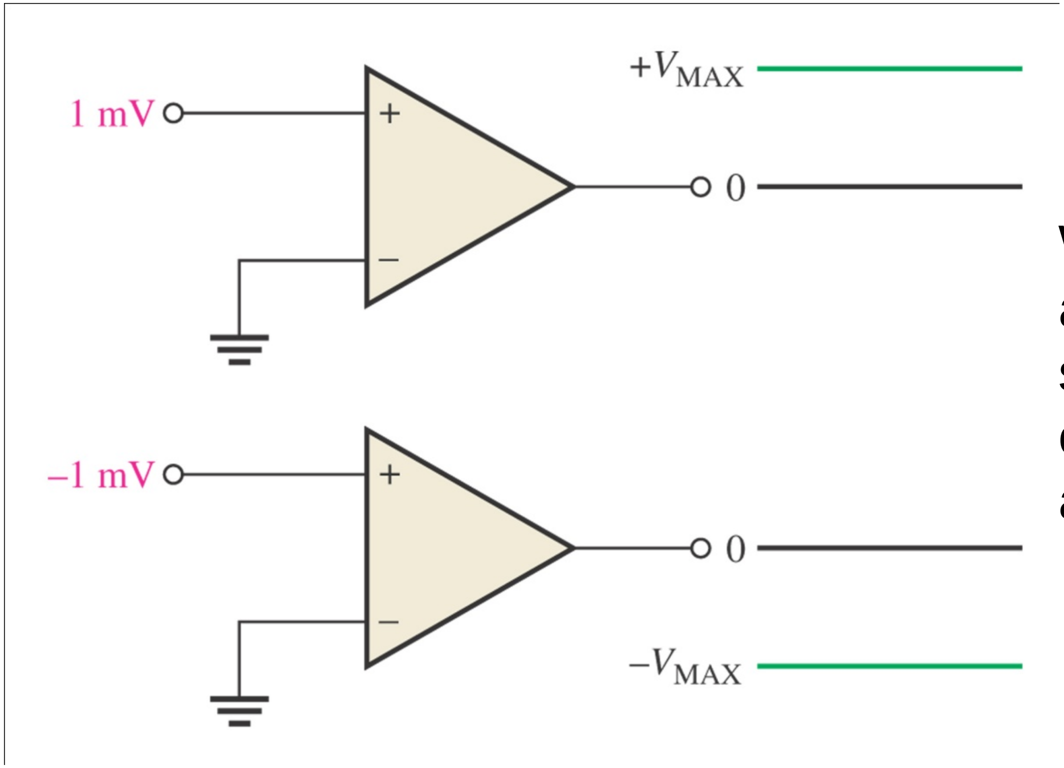
Negative Feedback

- 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.



Advantage of Negative feedback

- The precise values of amplifier gain can be set. In addition, bandwidth and input and output impedance can be controlled

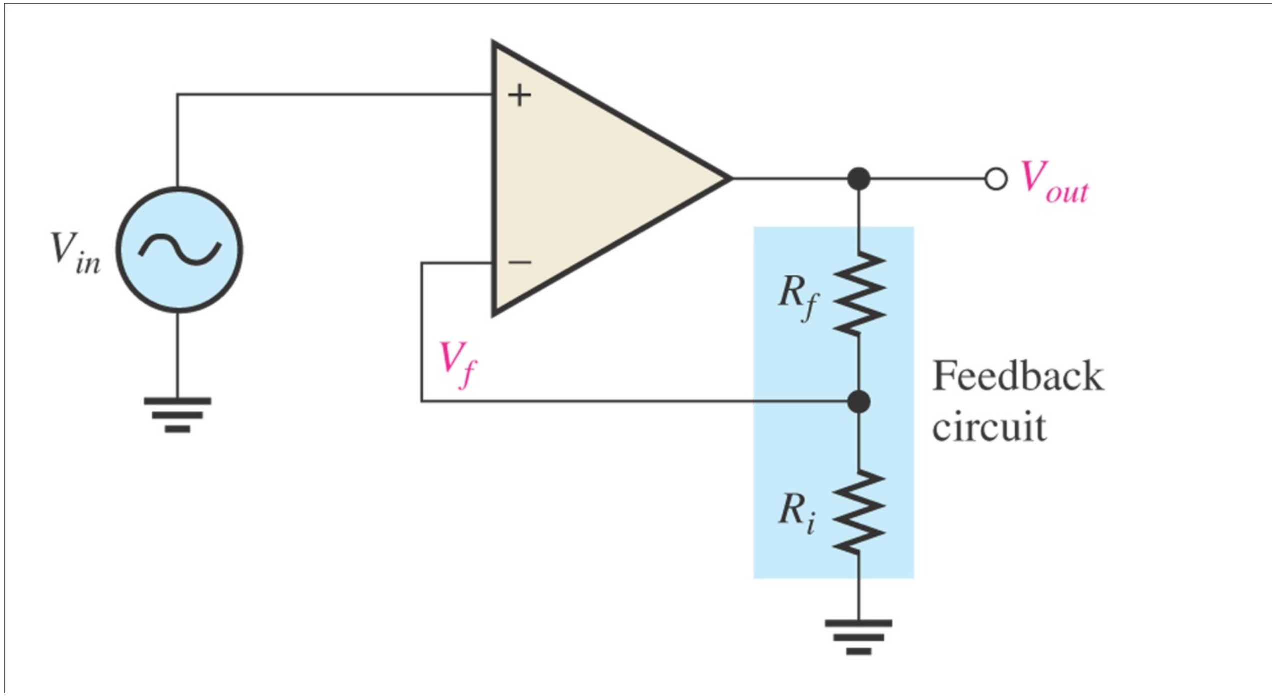


Without negative feedback and due to infinite gain, a small input voltage drives the op-amp to its output limits and it becomes nonlinear.

Question. Which parameter usually determines the op-amp output limit?

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 force V_f to be equal to V_{in}, hence Vin is across R_i.

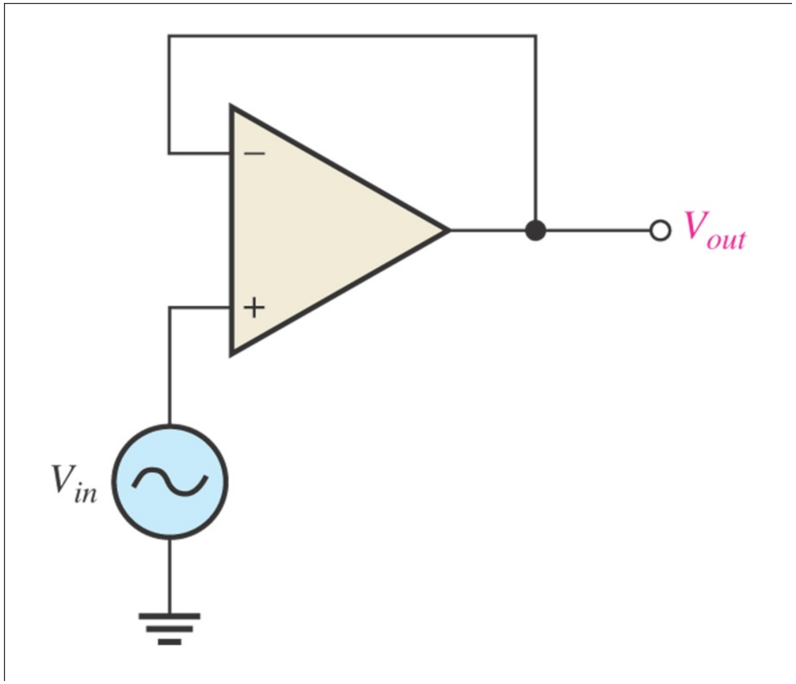


- The closed-loop gain of the noninverting(NI) amplifier can be found from the feedback circuit(voltage divider).

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

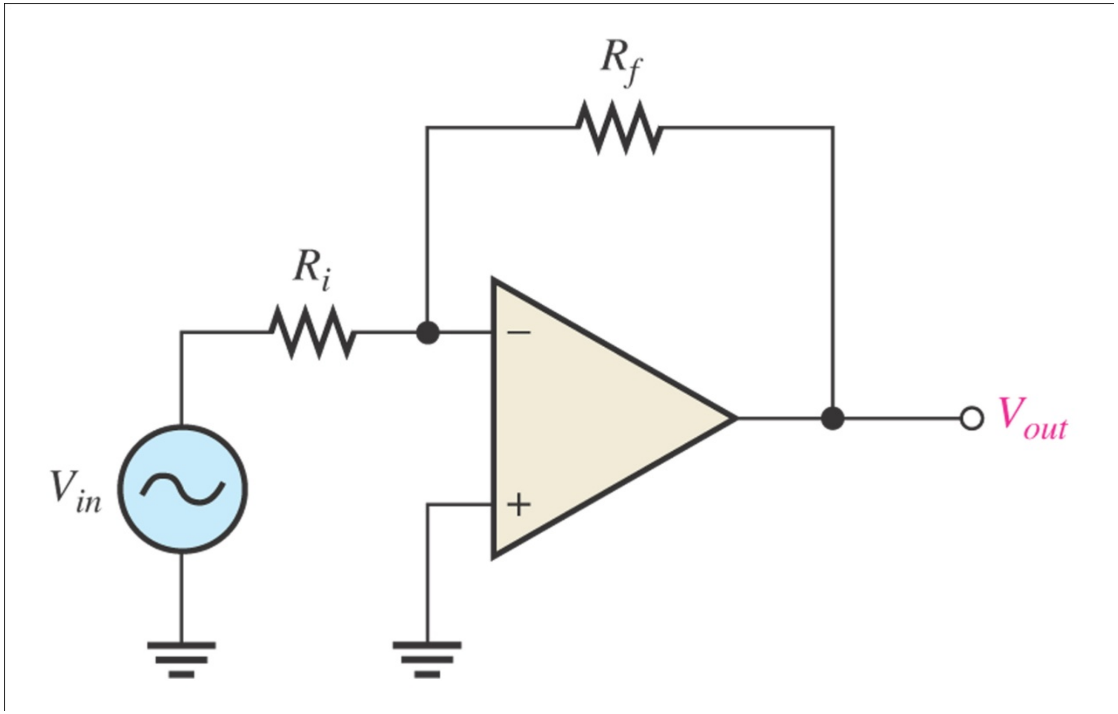
Voltage Follower

- A special case of the noninverting amplifier is when R_f=0 and R_i=infinity.
- This form a unity gain buffer.(gain=1)
- Input impedance is very high(avoid loading effects).
- Excellent for circuit interfacing.



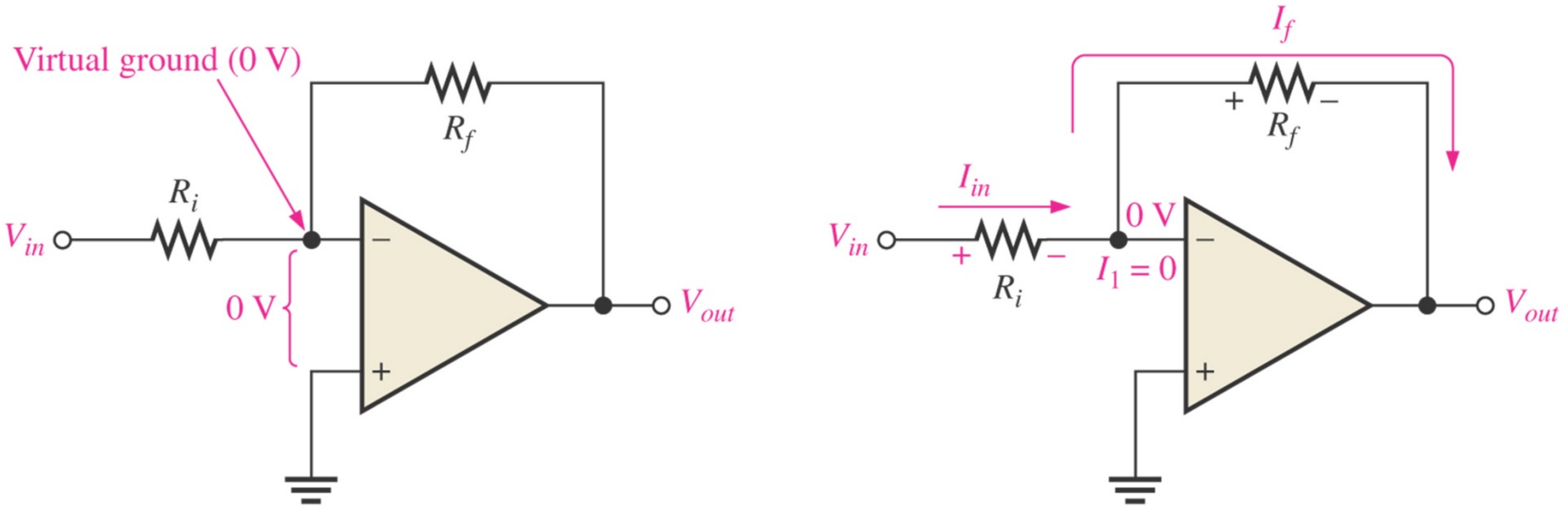
Inverting Amplifier

- The input is connected to the inverting pin(-).
- Negative feedback controls the amount of voltage gain.



Virtual Ground Concept

- Feedback forces the inputs to be nearly identical hence the inverting input is very close to 0V.
- The zero voltage at the inverting input is referred to as **virtual ground**.



(a) Virtual ground

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

- The closed-loop gain of inverting(I) amplifier can be expressed as:

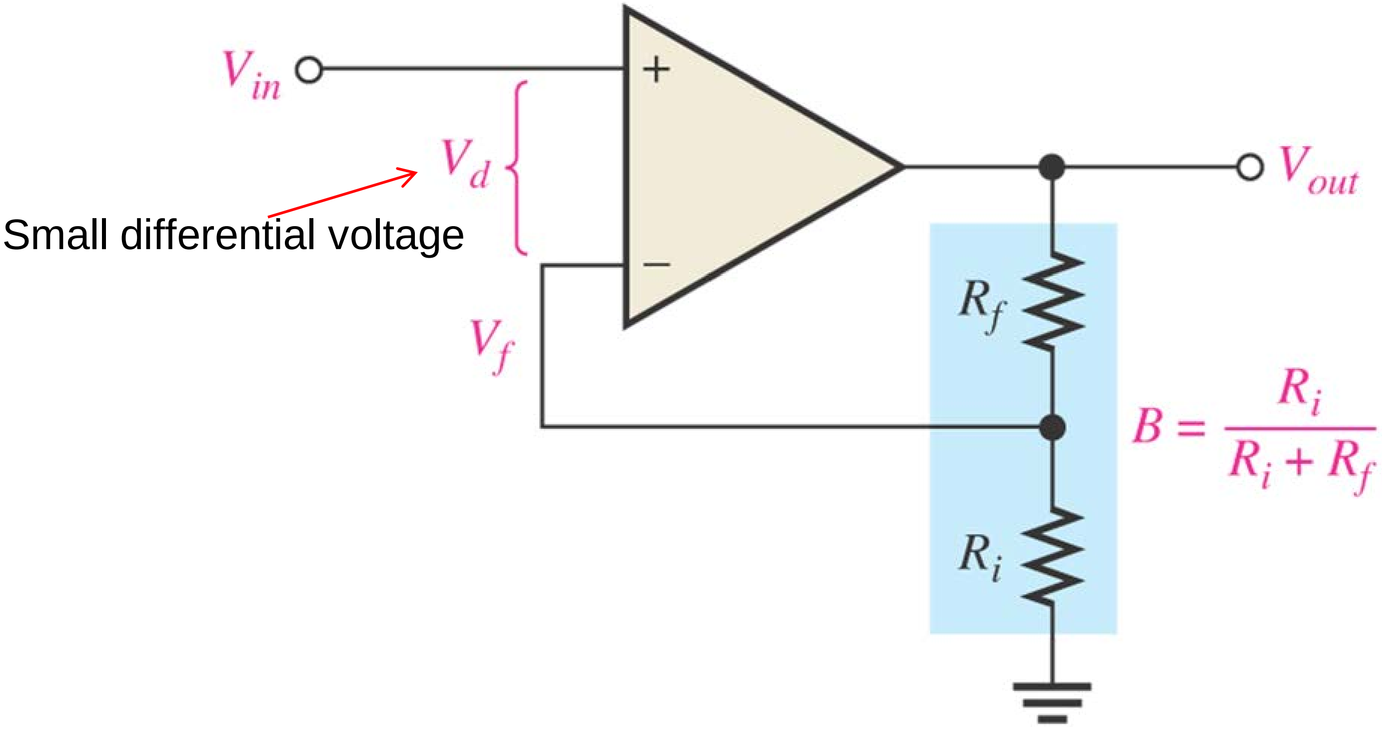
$$A_{cl(\mathrm{I})} = -\frac{R_f}{R_i}$$

Impedance of a noninverting amplifier

- Input Impedance

$$Z_{in(NI)} = (1 + A_{ol}B)Z_{in}$$

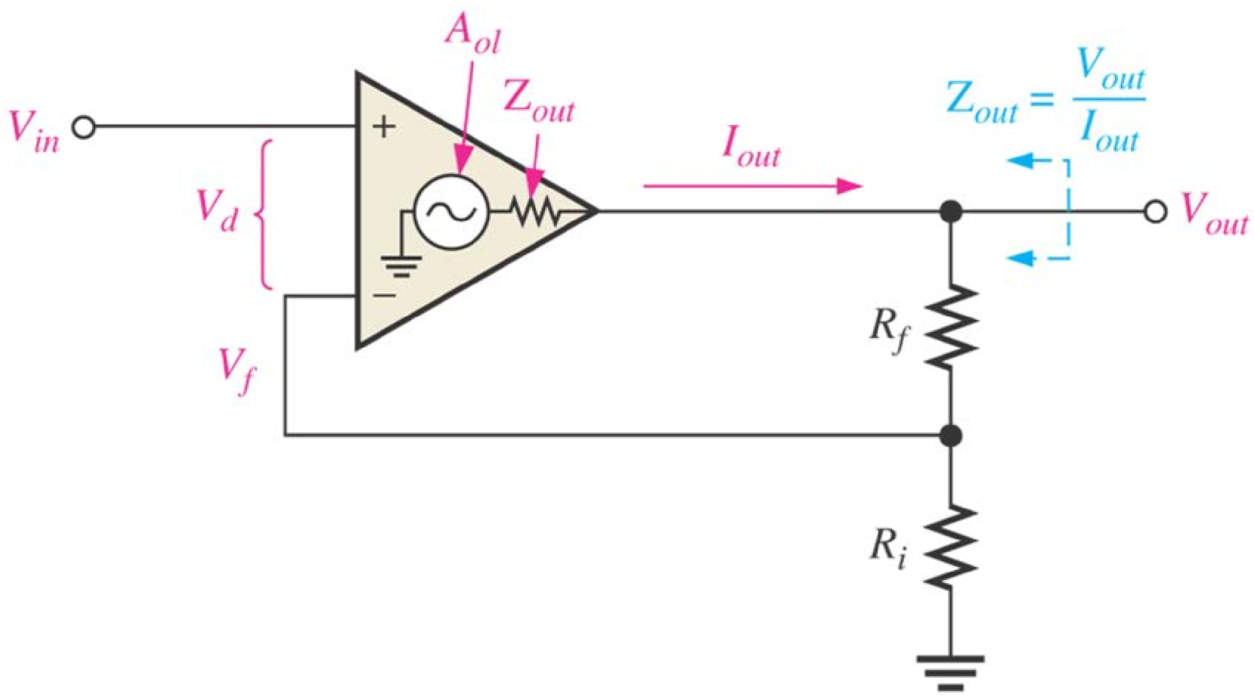
or assumed to be infinity.



- Output Impedance

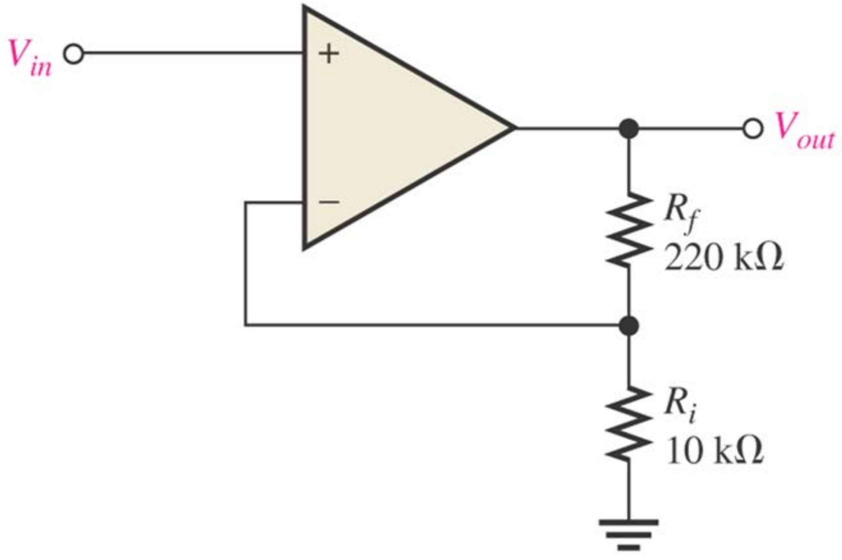
$$Z_{out(NI)} = \frac{Z_{out}}{(1 + A_{ol}B)}$$

or assumed to be zero



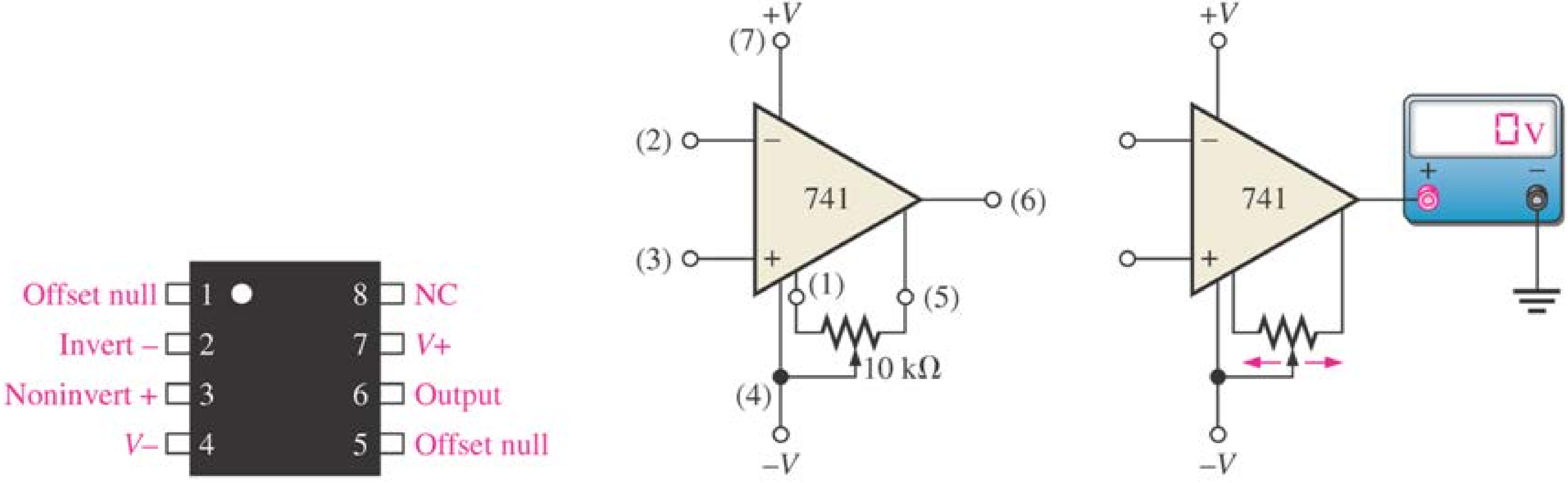
Example

- Find the closed-loop voltage gain.
- Determine the input and output impedance. The datasheet gives Z_{in}=2MΩ , Z_{out}= 75Ω , and A_{ol}=200,000.



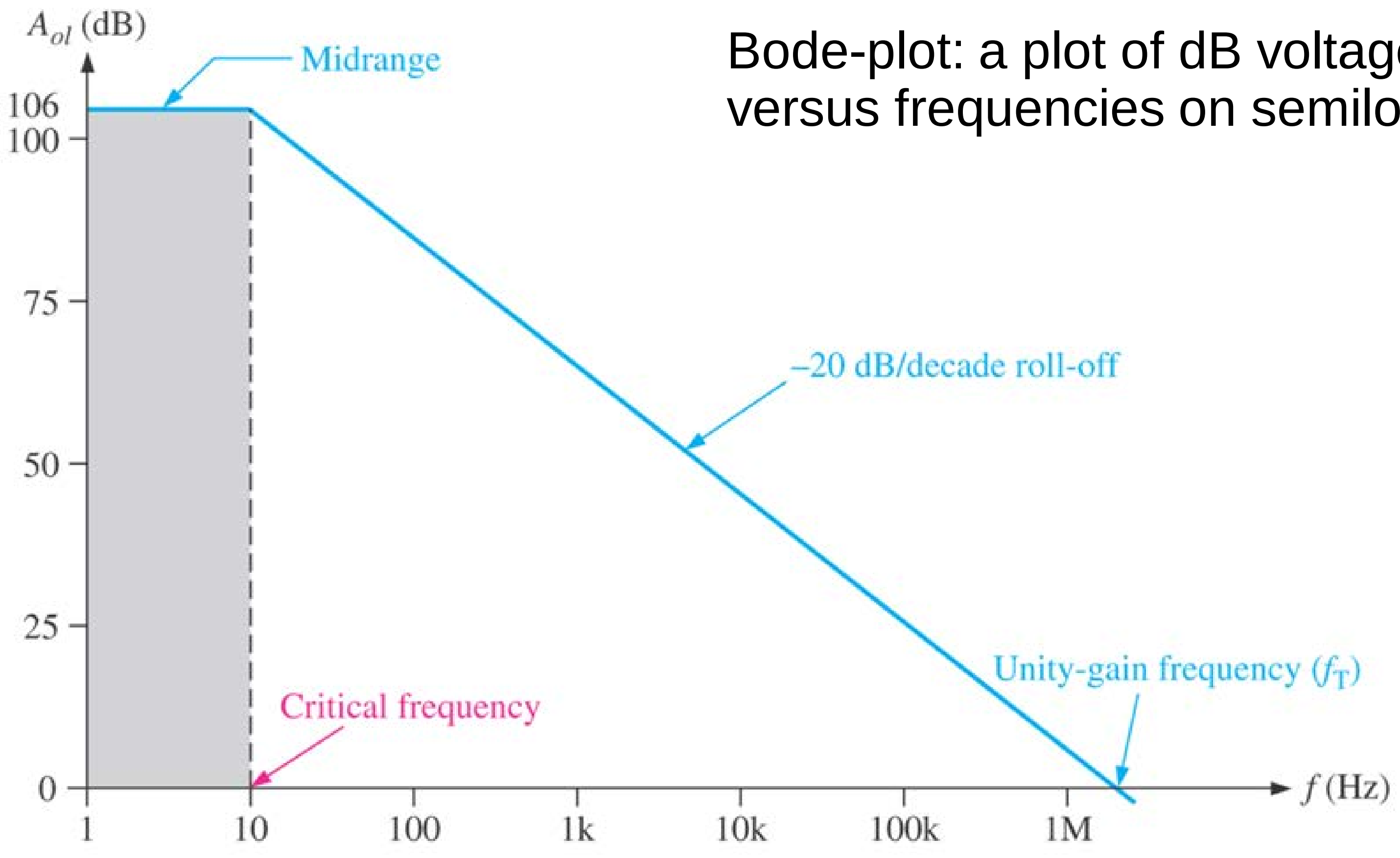
Input Offset Compensation

The output voltage of an op-amp should be zero when differential input is zero. If not, the compensation for offset voltage should be done by connecting external potentiometer between "offset null" pins.



(a) 8-pin DIP or SMT package (b) External potentiometer (c) Adjust for zero output

Open-loop response

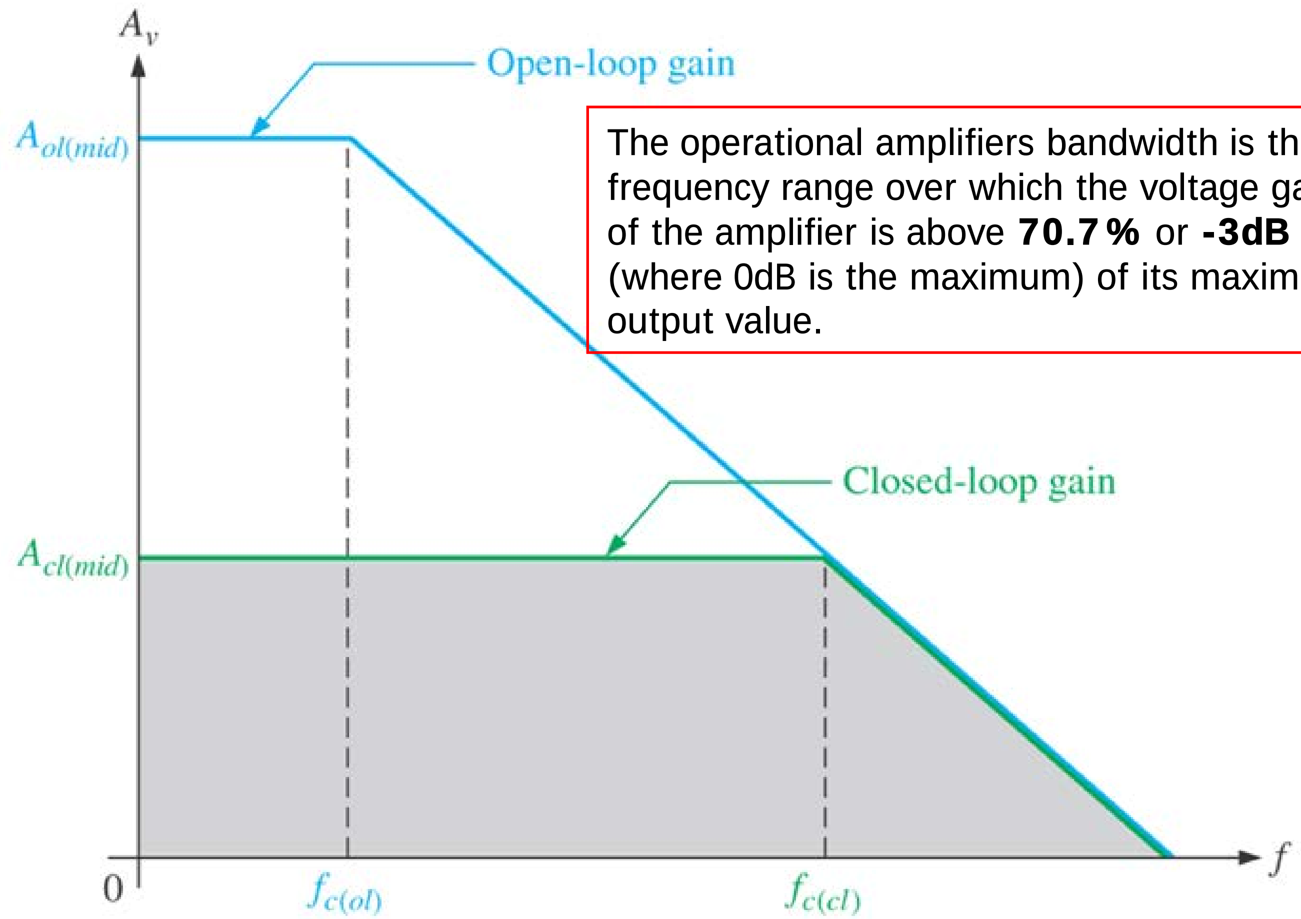


Bode-plot: a plot of dB voltage gain versus frequencies on semilog graph.

Ideal plot of open-loop voltage gain versus frequency for a typical op-amp. The frequency scale is logarithmic.

Closed-loop Frequency Response

- A closed-loop configuration with negative feedback to achieve precise control of the gain and bandwidth.
- For closed-loop response, the gain is reduced while the bandwidth*(BW) is increased.

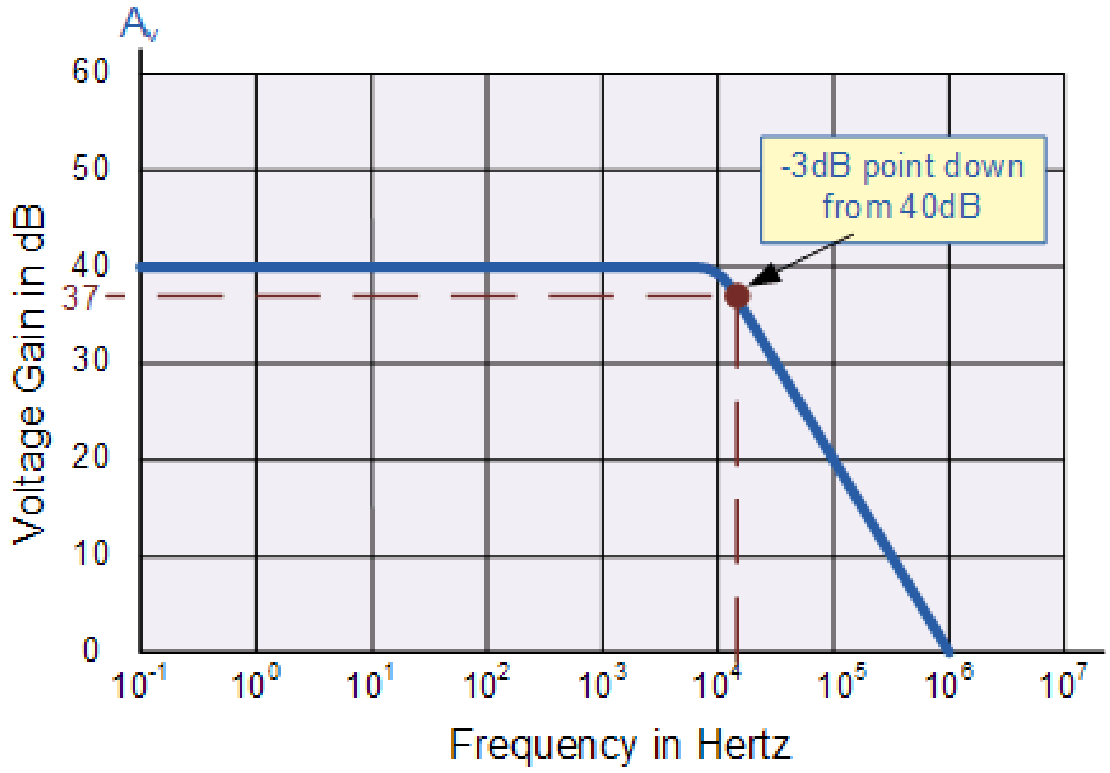


The operational amplifiers bandwidth is the frequency range over which the voltage gain of the amplifier is above **70.7%** or **-3dB** (where 0dB is the maximum) of its maximum output value.

*** *Bandwidth*** is the characteristic of certain types of electronic circuits that specifies the usable range of frequencies that pass from input to output.

Example

- From a given bode plot, find the bandwidth of this op-amp.



Comparator

- A comparator is a specialized nonlinear op-amp circuit that compares two input voltages and produces an output state that indicates which one is greater.
- Comparators are designed to be fast and frequently have other capabilities to optimize the comparison function.

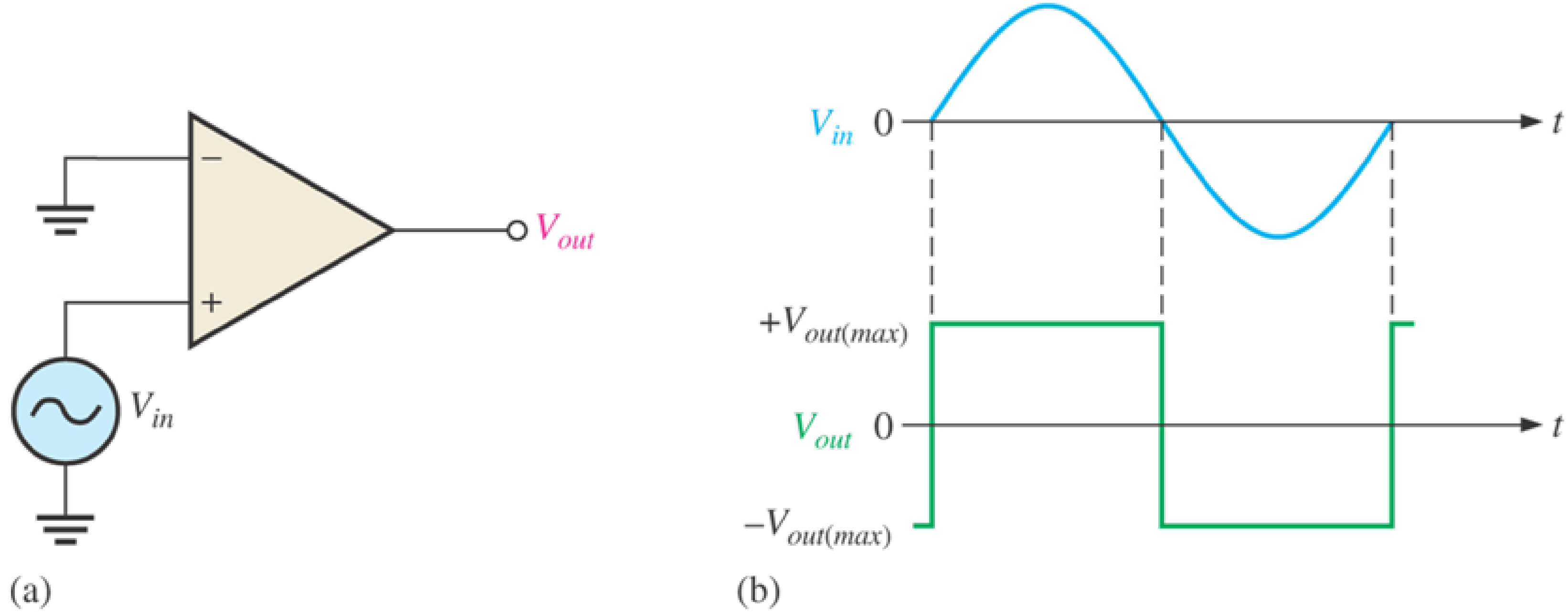
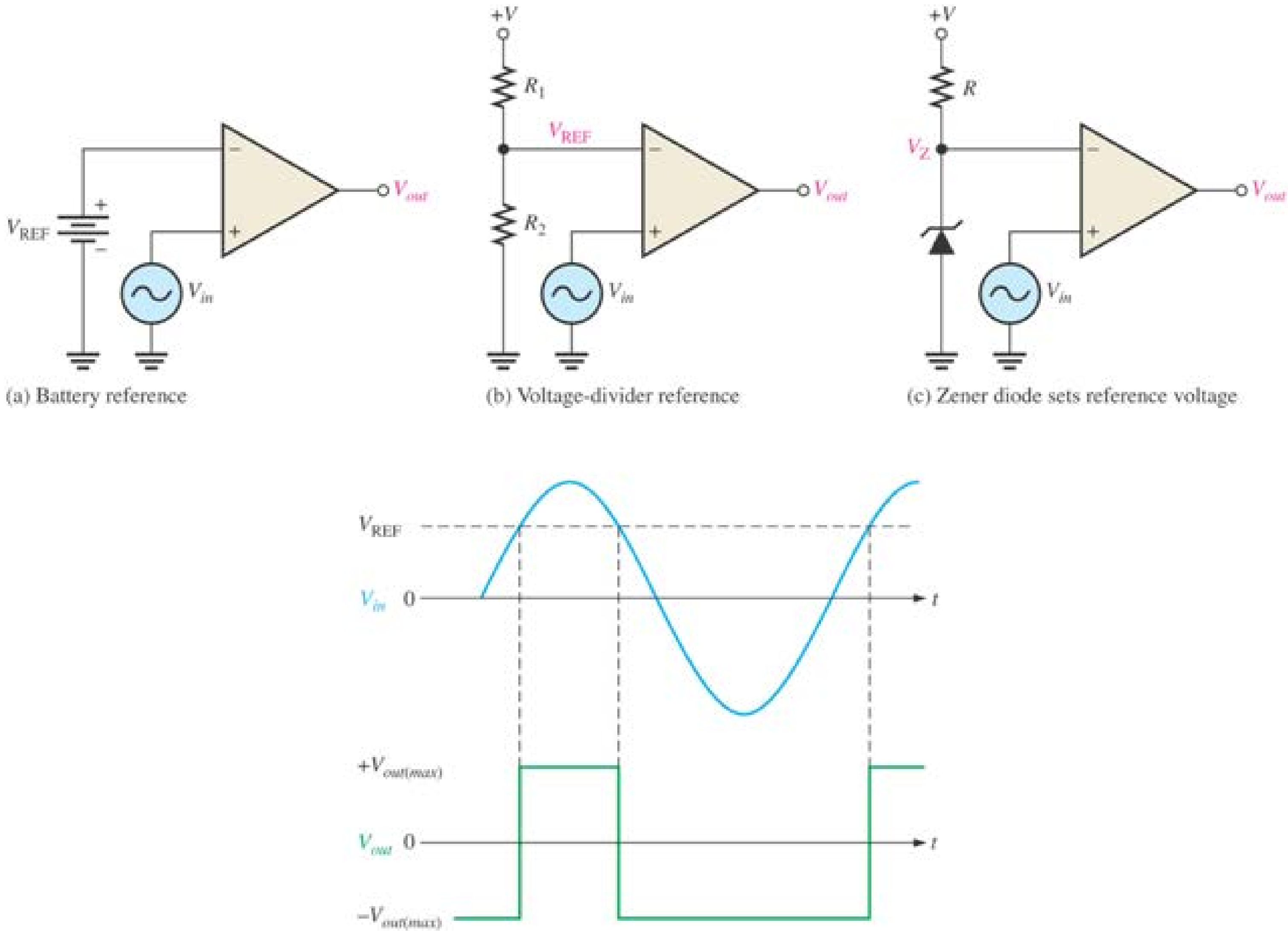


Fig. The op-amp as a zero-level detector.

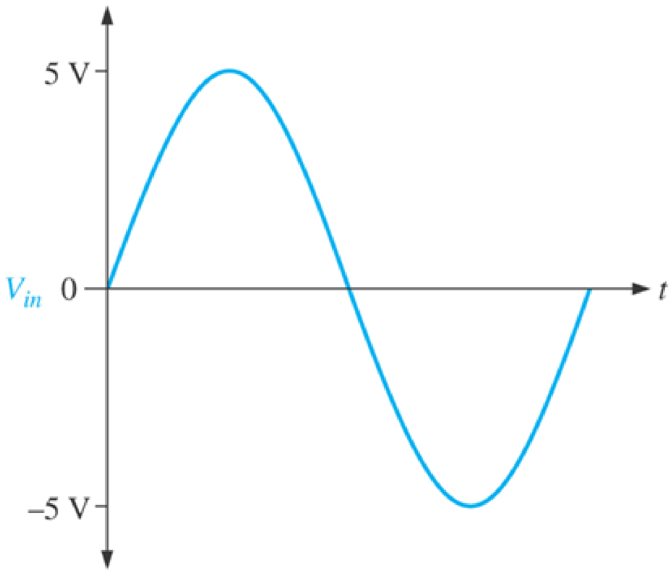
Nonzero level detection



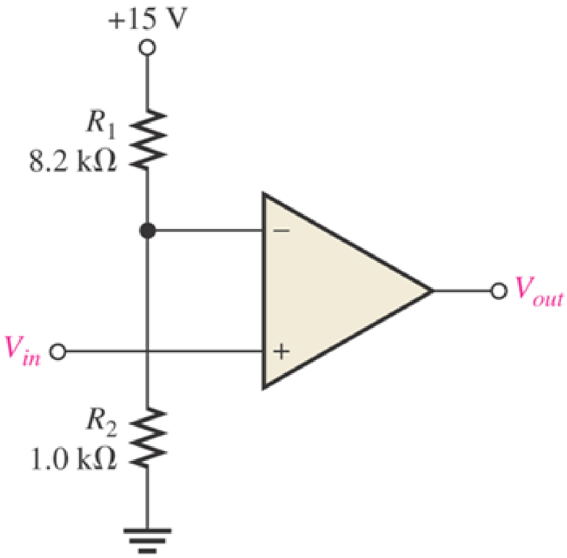
(d) Waveforms

Example

- Draw the output waveform showing its proper relationship to the input signal. Assume the maximum output levels of the comparator is ± 14V.

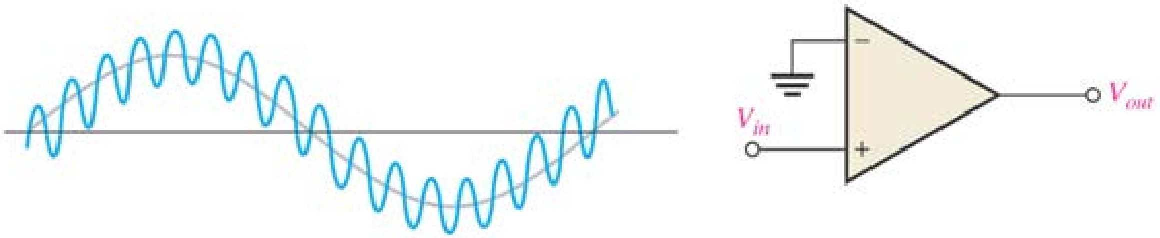


(a)

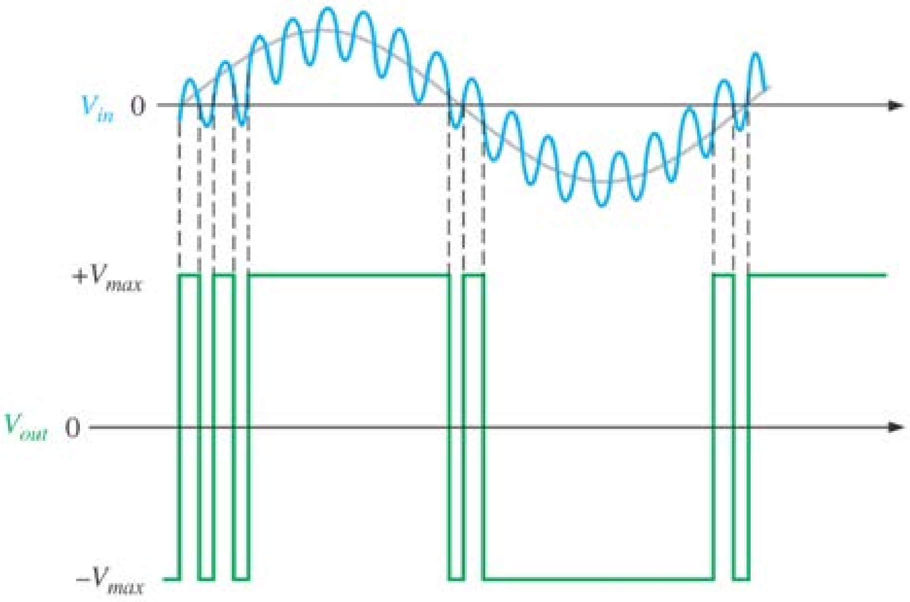


(b)

Effect of Noise in Comparator



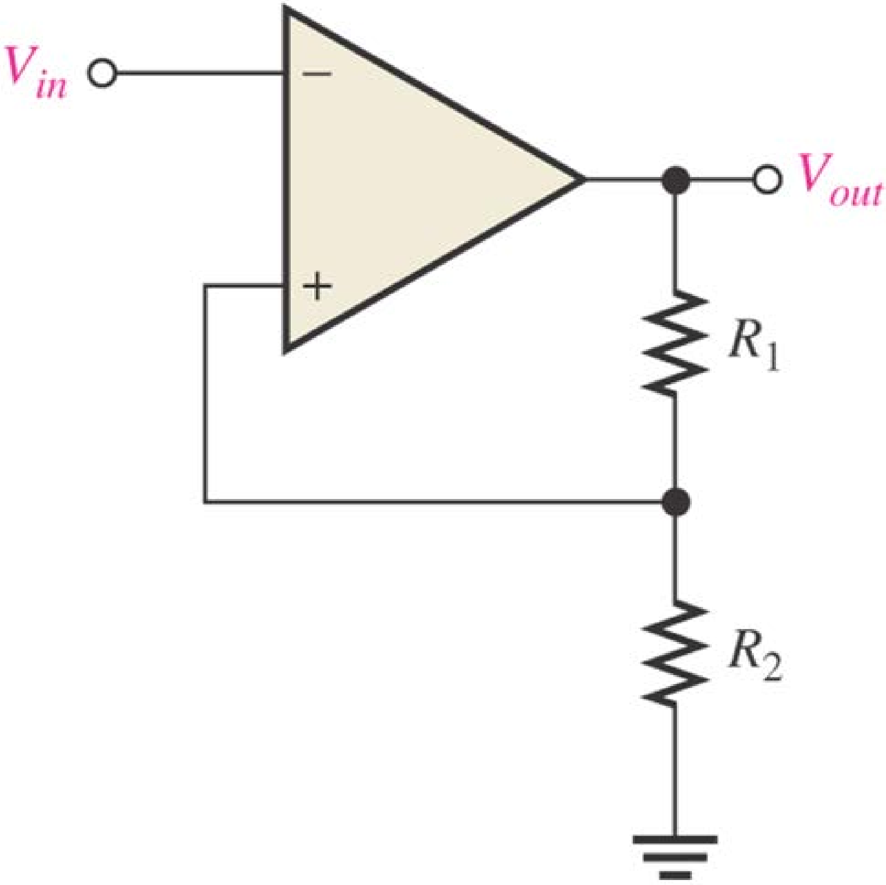
(a)

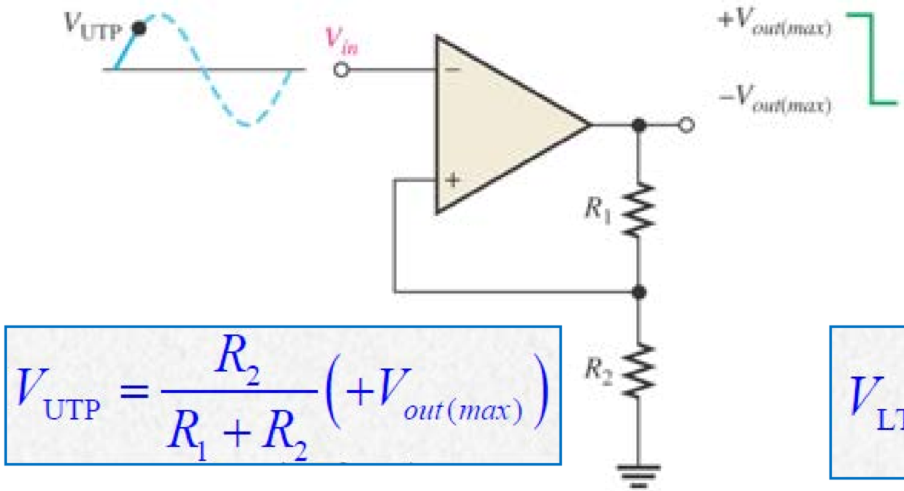


(b)

Comparator with Hysteresis

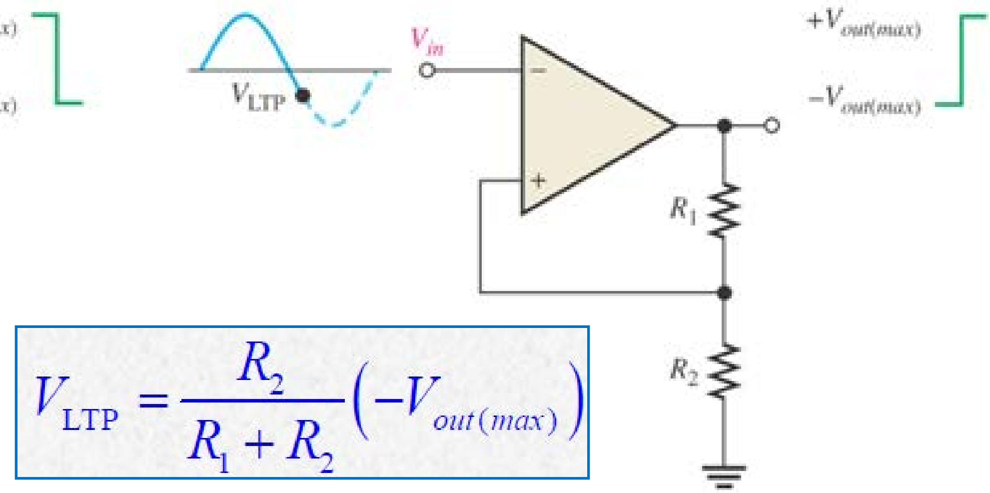
- It is positive feedback.





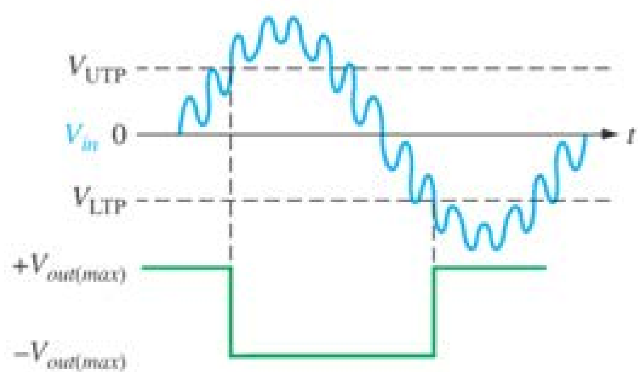
$$V_{UTP} = \frac{R_2}{R_1 + R_2}\left(+V_{out(max)}\right)$$

(a) When the output is at the maximum positive voltage and the input exceeds UTP, the output switches to the maximum negative voltage.



$$V_{LTP} = \frac{R_2}{R_1 + R_2}\left(-V_{out(max)}\right)$$

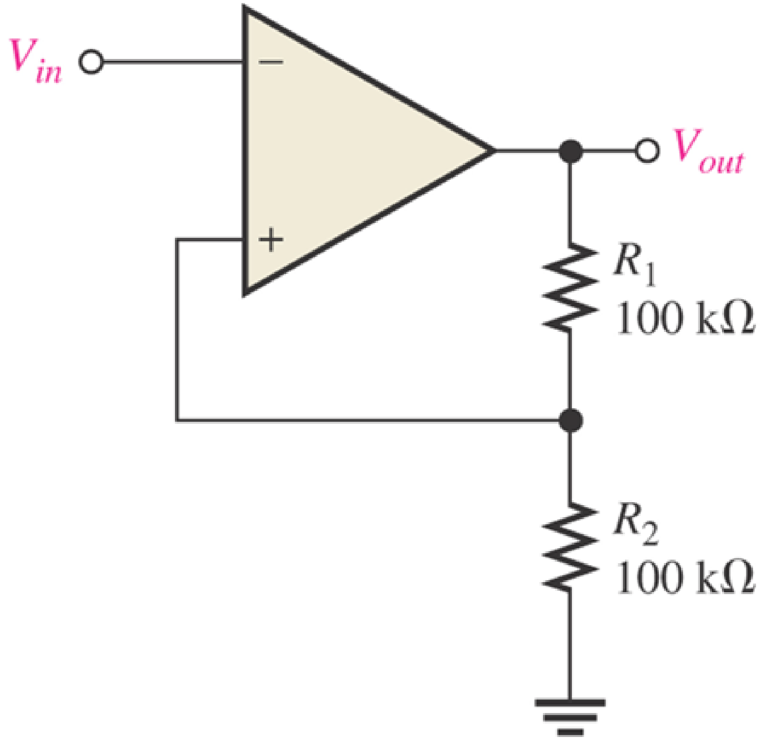
(b) When the output is at the maximum negative voltage and the input goes below LTP, the output switches back to the maximum positive voltage.



(c) Device triggers only once when UTP or LTP is reached; thus, there is immunity to noise that is riding on the input signal.

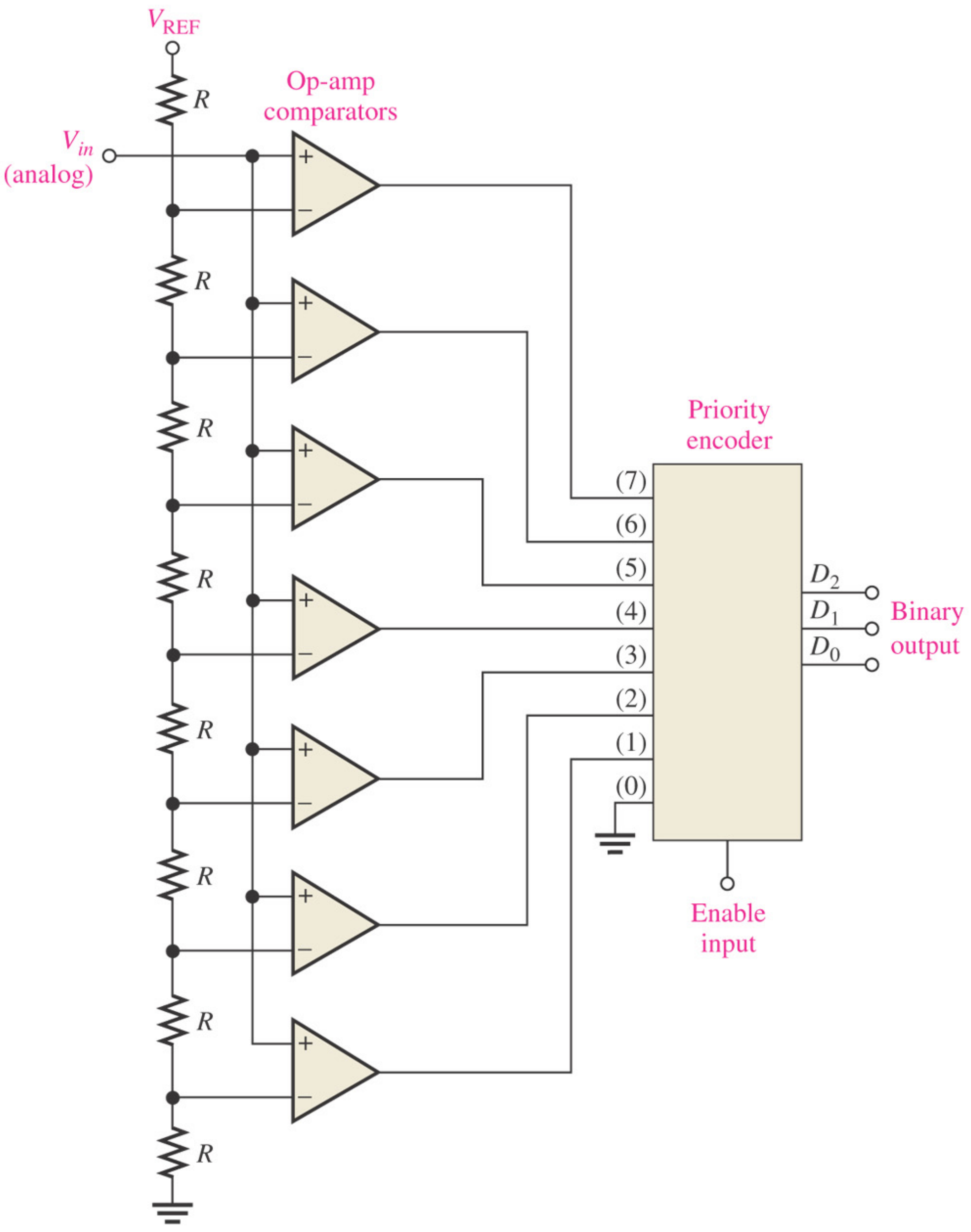
Example

- Determine the upper and lower trigger points for the comparator circuit. Assume that +Vout(max)= 5V and -Vout(max)= -5V



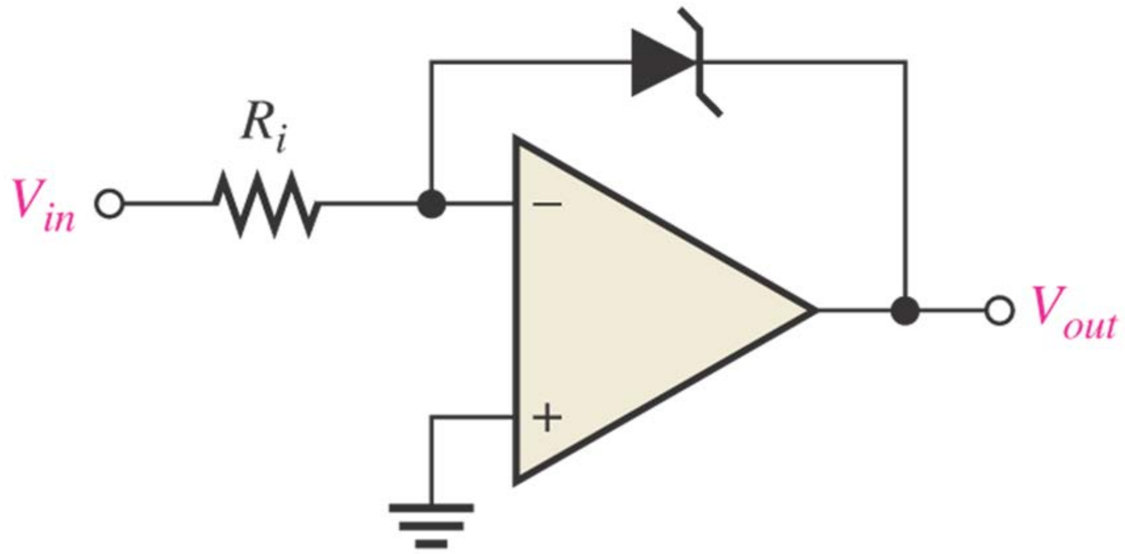
Application

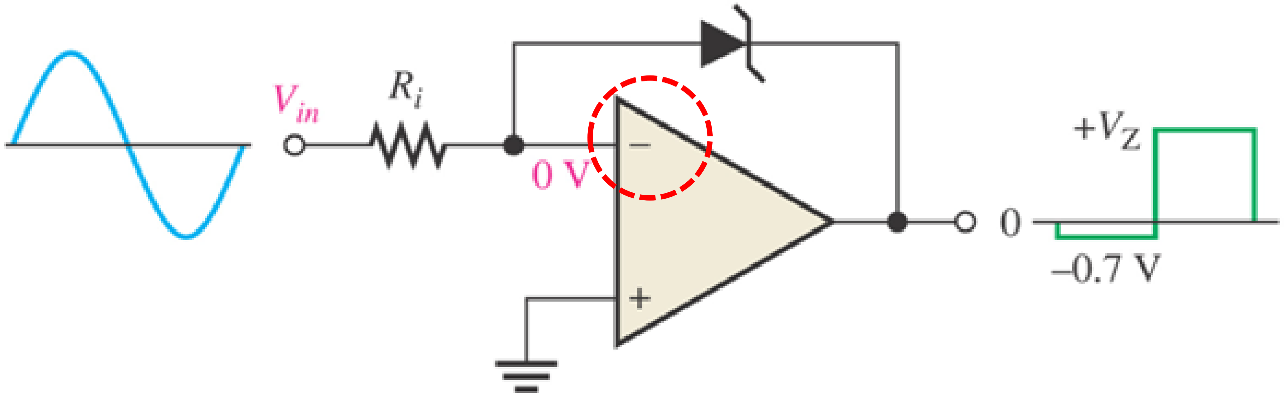
- Analog-to-digital converter (ADC) using op-amps as comparators



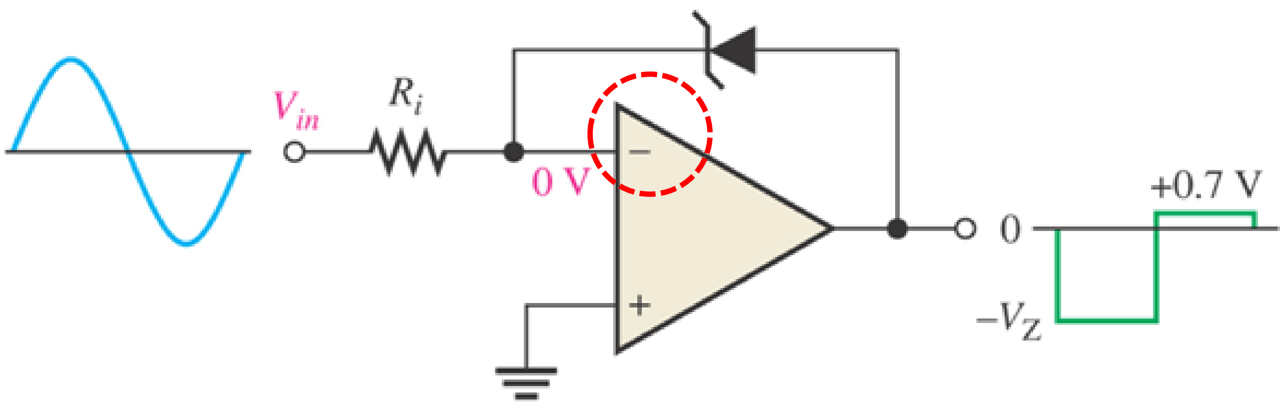
Comparator with output bounding

- To limit the output voltage level of a comparator to a value less than the saturated level.
- The process of limiting the output range is called **bounding**.



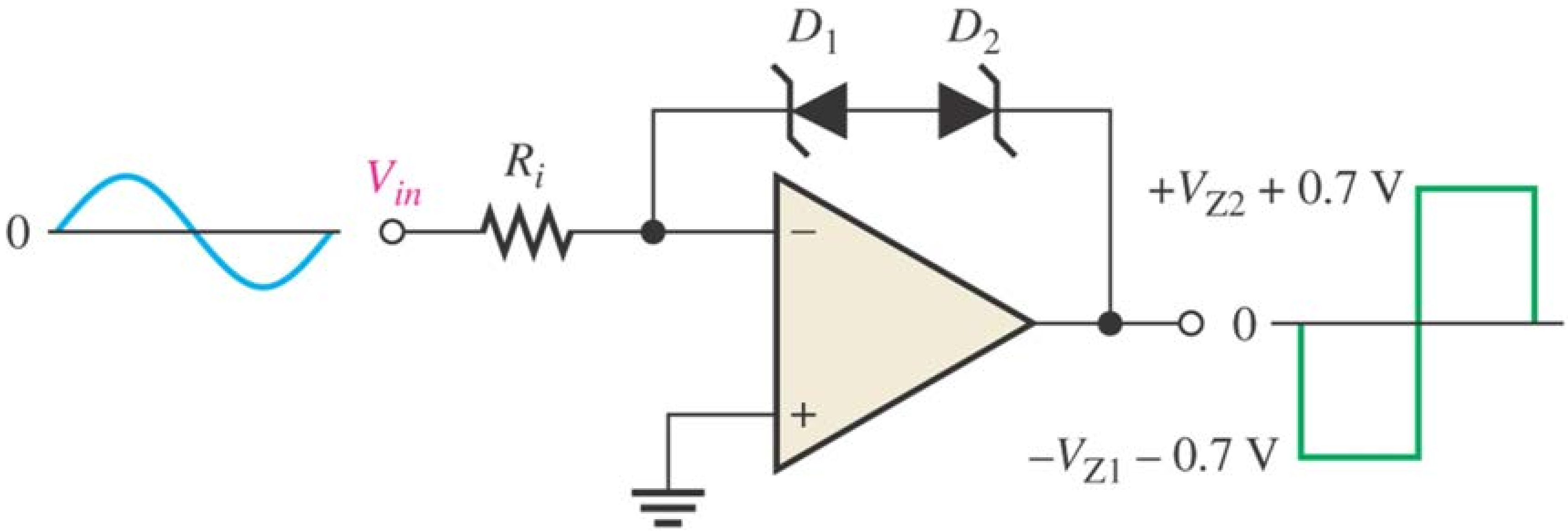


(a) Bounded at a positive value



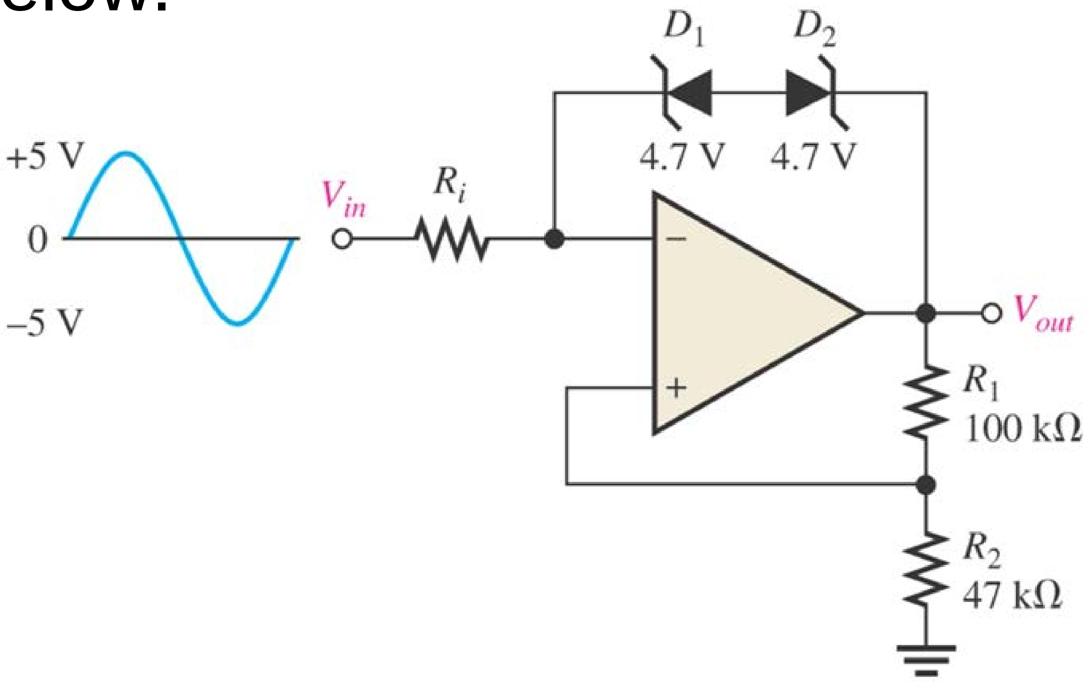
(b) Bounded at a negative value

Double-bounded comparator

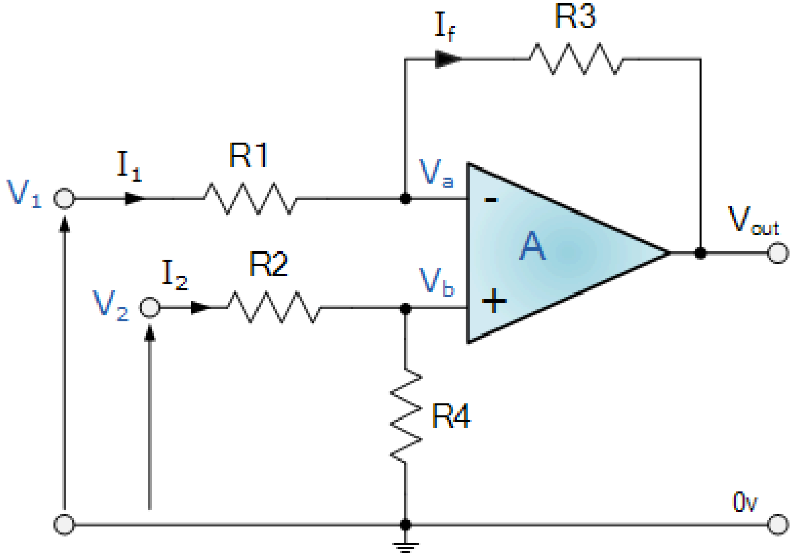


Example

- Draw the output waveform of a Double-bounded comparator given below.



Differential Op-amp



$$I_1 = \frac{V_1 - V_a}{R_1}, \quad I_2 = \frac{V_2 - V_b}{R_2}, \quad I_f = \frac{V_a - (-V_{out})}{R_3}$$

Summing point $V_a = V_b$

If $V_b = 0$, then: $V_{out(a)} = -V_1\left(\frac{R_3}{R_3+R_1}\right) = -V_1\left(\frac{R_3}{R_1}\right)$

If $V_a = 0$, then: $V_{out(b)} = V_2\left(\frac{R_4}{R_2+R_4}\right)\left(1+\frac{R_3}{R_1}\right)$

$$V_{out} = V_{out(a)} + V_{out(b)}$$

$$\therefore \; V_{out} = -V_1\left(\frac{R_3}{R_1}\right) + V_2\left(\frac{R_4}{R_2+R_4}\right)\left(1+\frac{R_3}{R_1}\right)$$

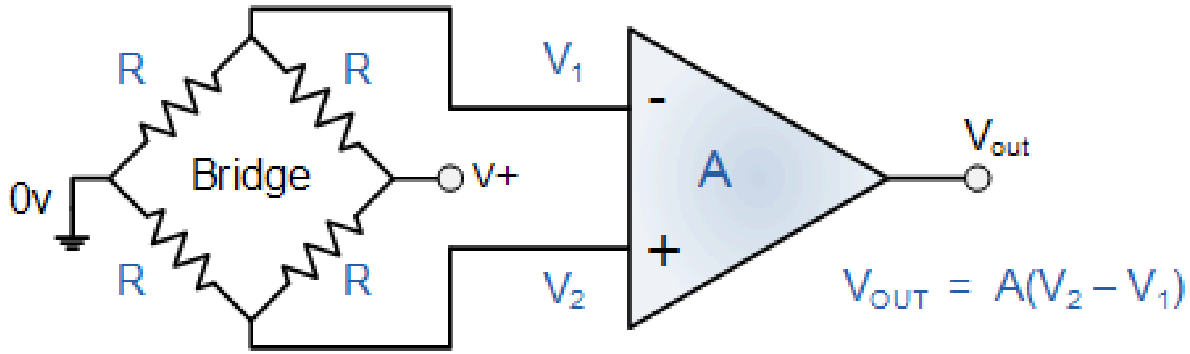
When resistors, $R_1 = R_2$ and $R_3 = R_4$

$$V_{OUT} = \frac{R_3}{R_1}\left(V_2 - V_1\right)$$

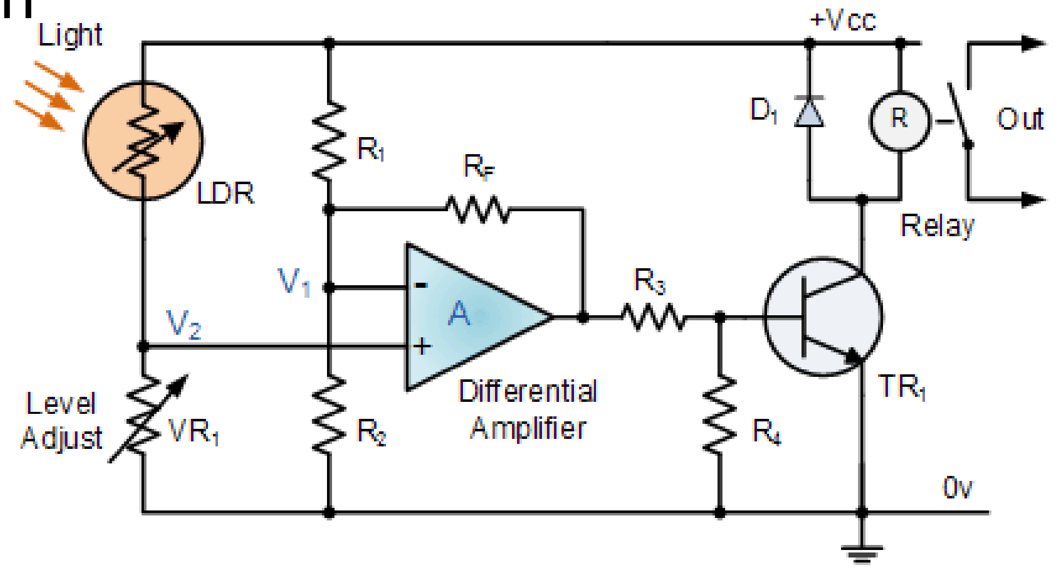
If R1 = R2 = R3 = R4 then the circuit will become a **Unity Gain Differential Amplifier** and the voltage gain of the amplifier will be exactly one or unity.
Then the output expression would simply be $V_{out} = V_2 - V_1$.

Applications

- Bridge Amplifier



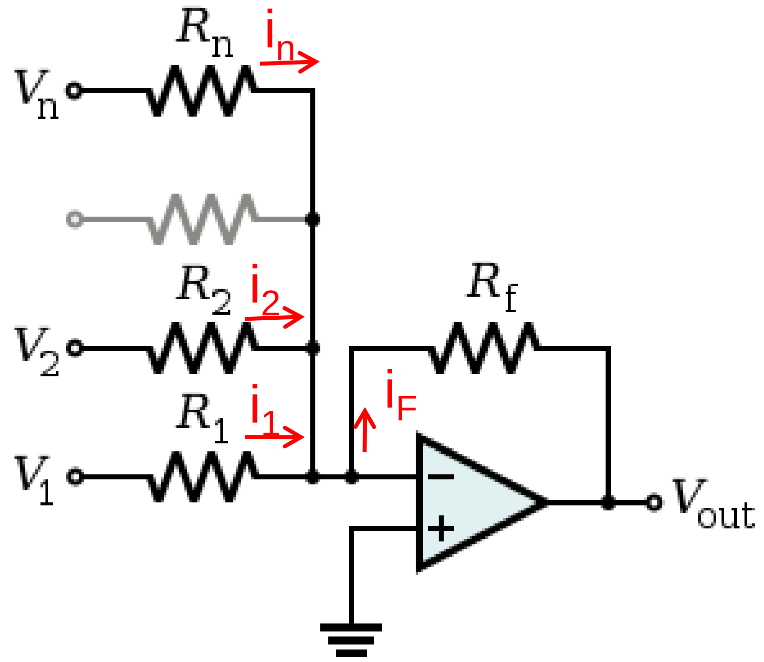
- Light activated switch



Summing Amplifier

- A summing amplifier sums several (weighted) voltages:

$$V_{\text{out}} = -R_{\text{f}}\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n}\right)$$



- When $R_1 = R_2 = \cdots = R_n$

$$V_{\text{out}} = -\frac{R_{\text{f}}}{R_1}(V_1 + V_2 + \cdots + V_n)$$

- When $R_1 = R_2 = \cdots = R_n = R_{\text{f}}$

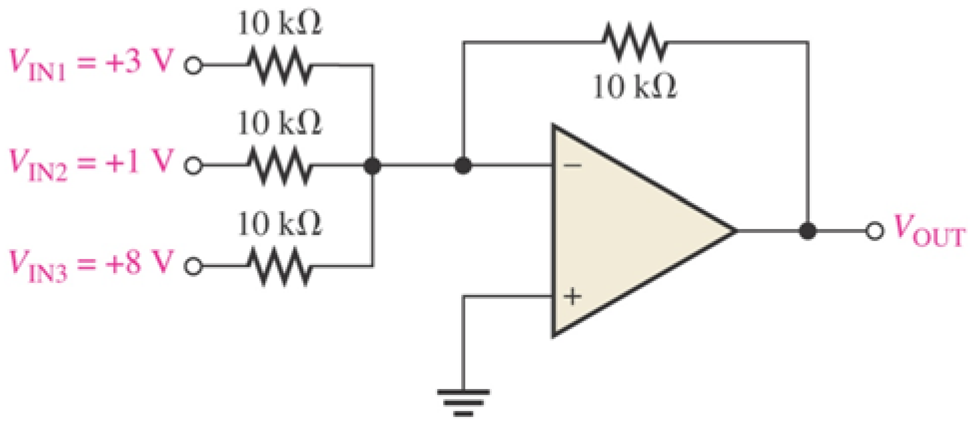
$$V_{\text{out}} = -(V_1 + V_2 + \cdots + V_n)$$

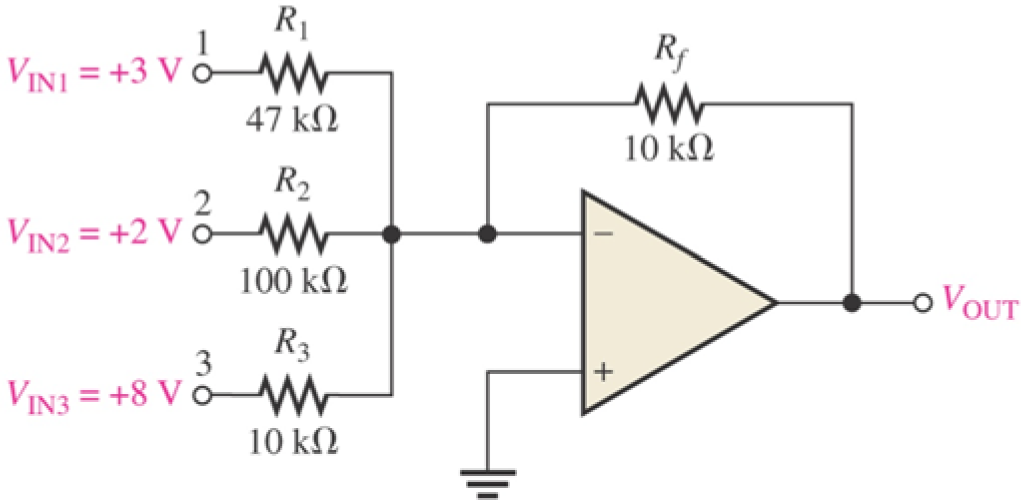
The equation of output voltage can be proof by KCL at Op-amp negative input.

Applictions

- Offset adjustment
- Voltage level shifter
- Zero-span circuit
- Digital to analog converter(DAC or D/A)

Example

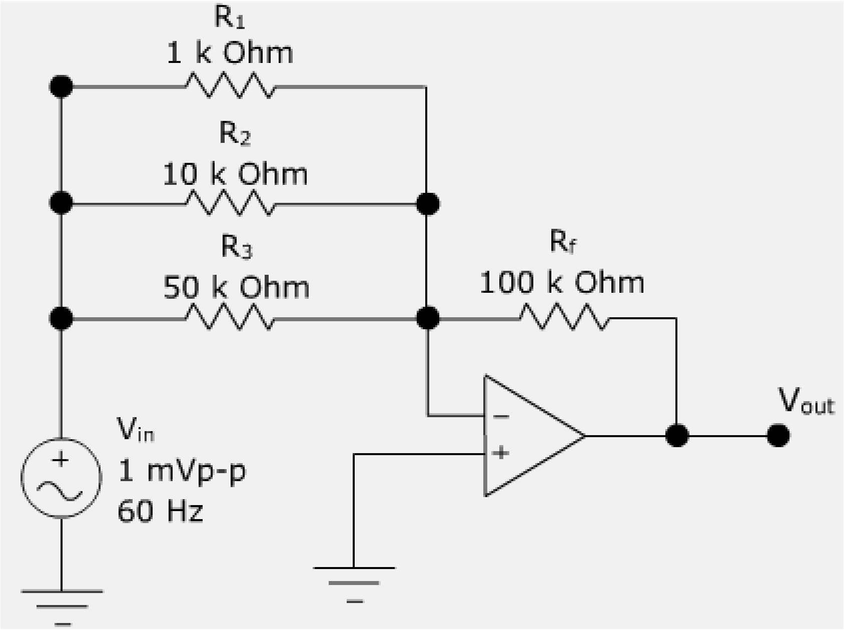




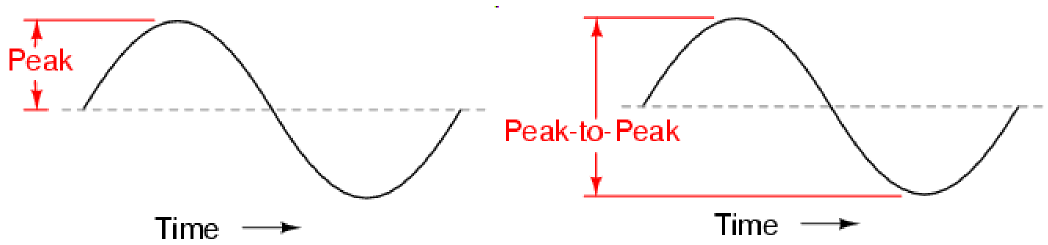
Calculate V_{out}

Example

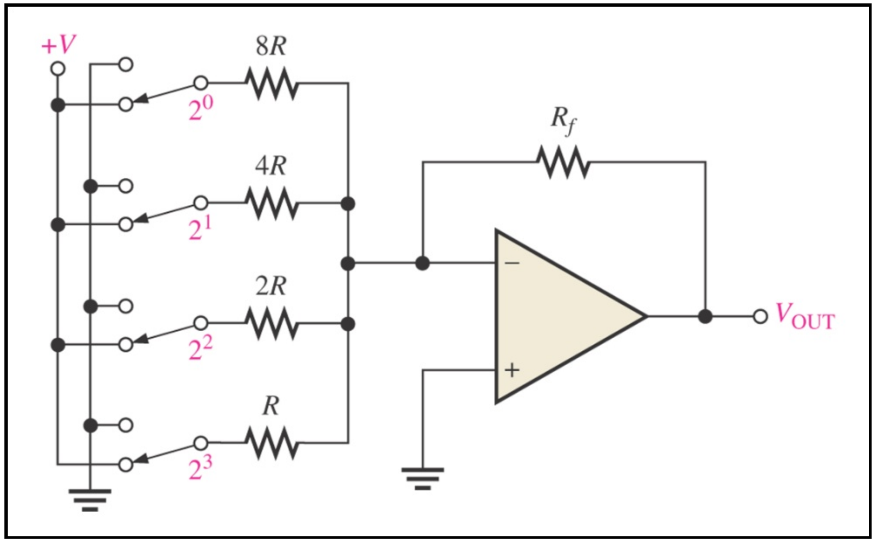
- Draw output voltage waveform.

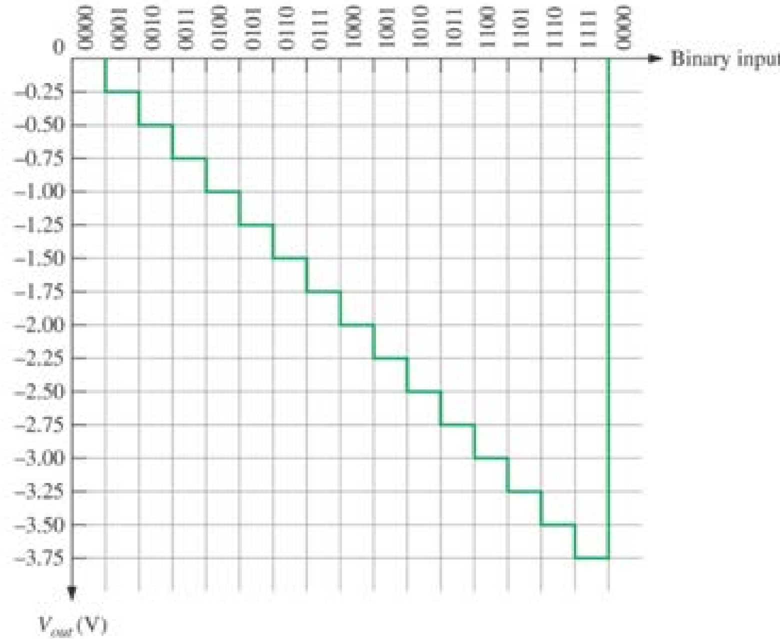


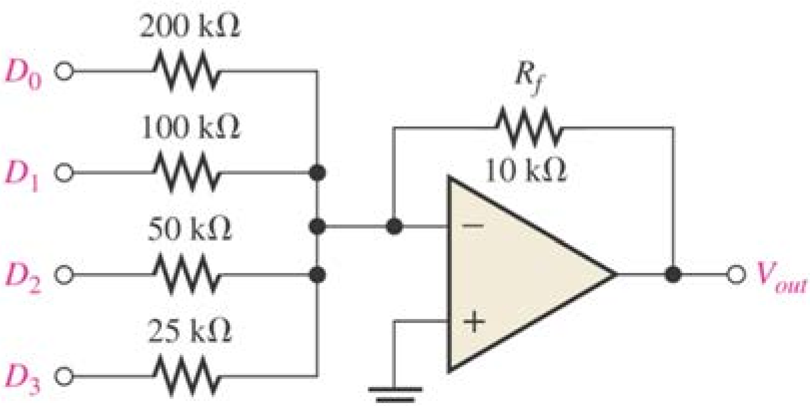
Reminder



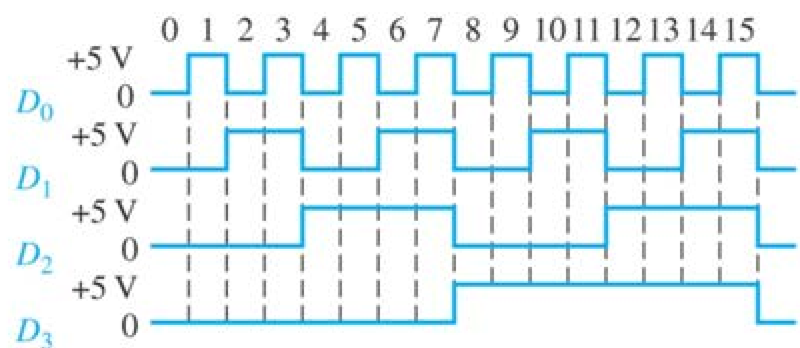
Digital to Analog Converter(DAC)







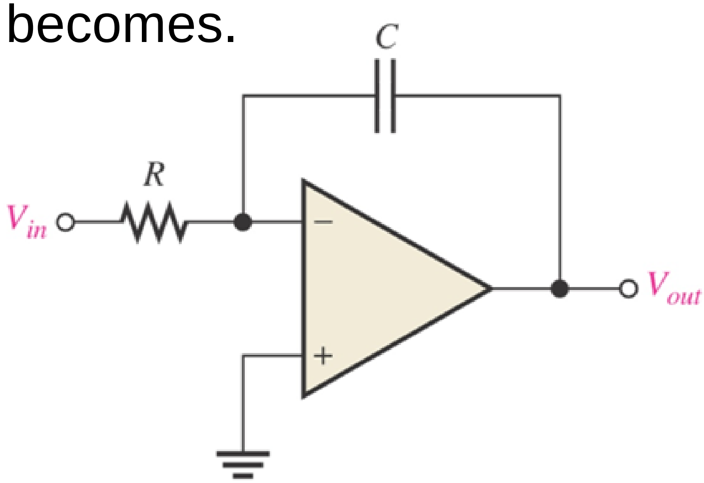
(a)

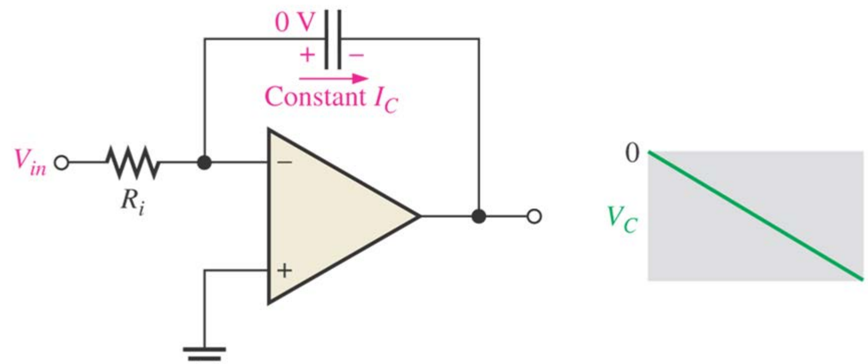


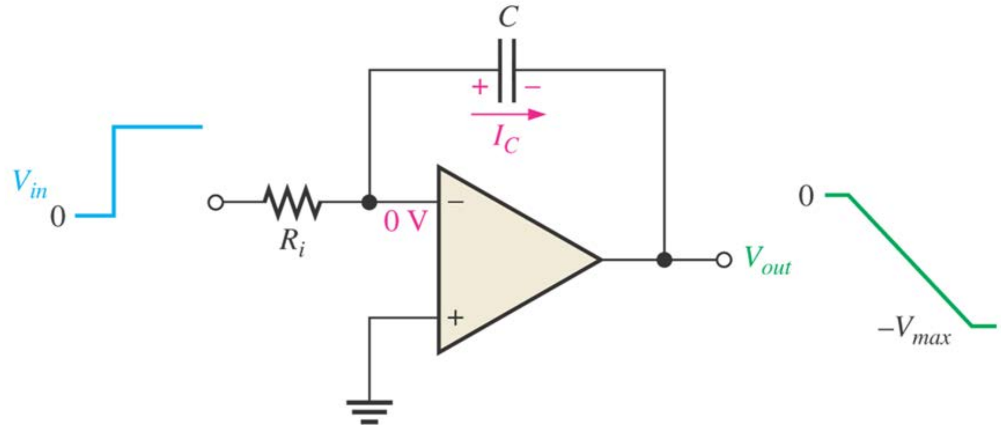
(b)

An op-amp integrator

- The magnitude of output is determined by the length of time a voltage is present at its input. The longer the input is present, the greater the output becomes.







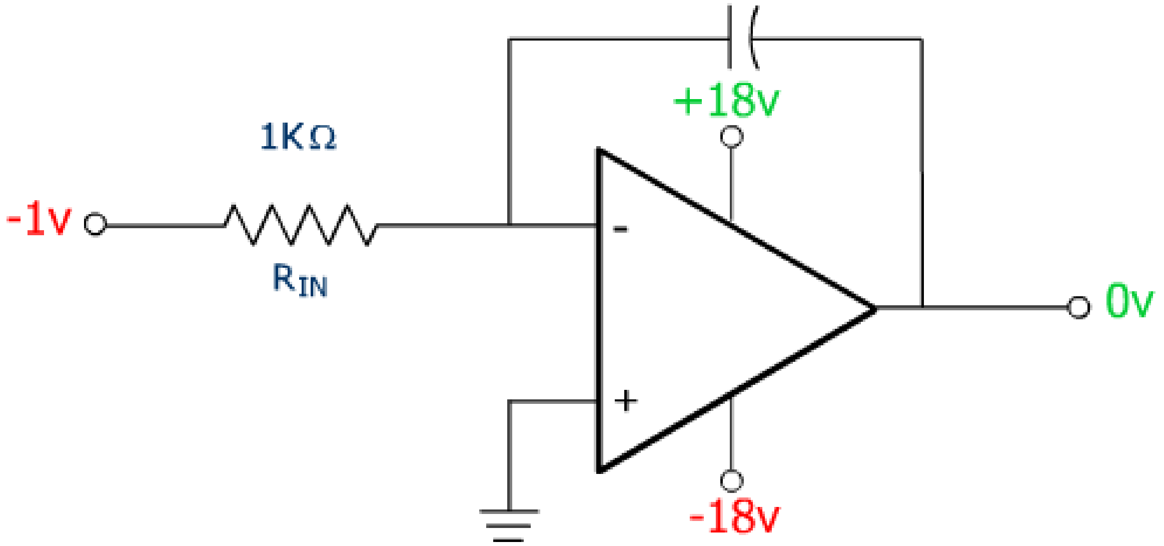
$$V_{\text{out}} = -\int_0^t \frac{V_{\text{in}}}{RC}\,\mathrm{d}t + V_{\text{initial}}$$

(where V_{in} and V_{out} are functions of time, $V_{initial}$ is the output voltage of the integrator at time $t = 0$.)

How the integrator op-amp works

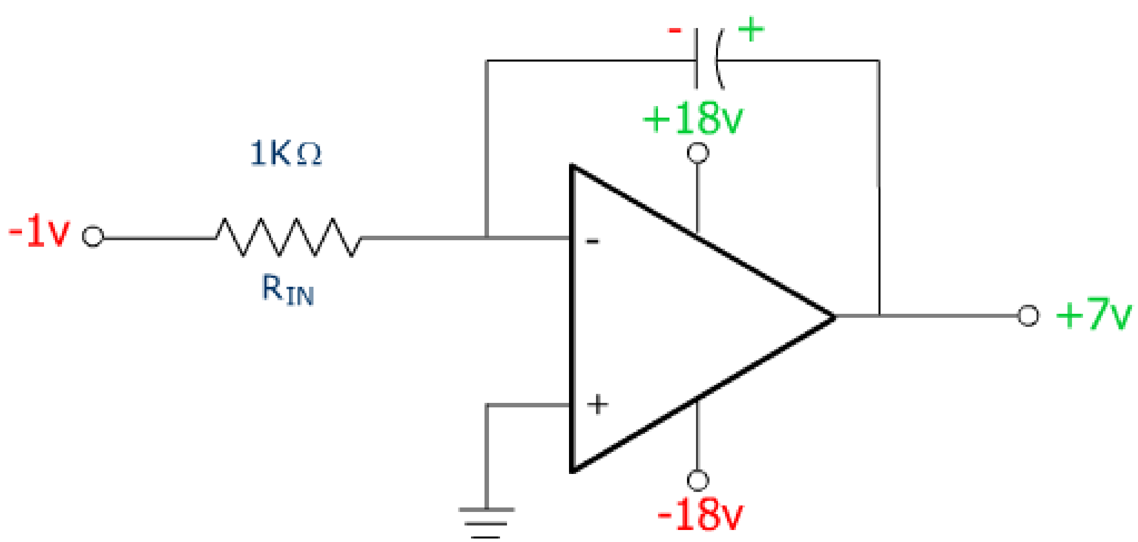
When the voltage is first applied to an integrator op amp:

- The uncharged capacitor acts like a short and has very little resistance.
- The resistance ratio of the capacitor/input resistor R_{IN} is very low.
- The gain of the op amp is less than 1.
- The output voltage is 0 volts.



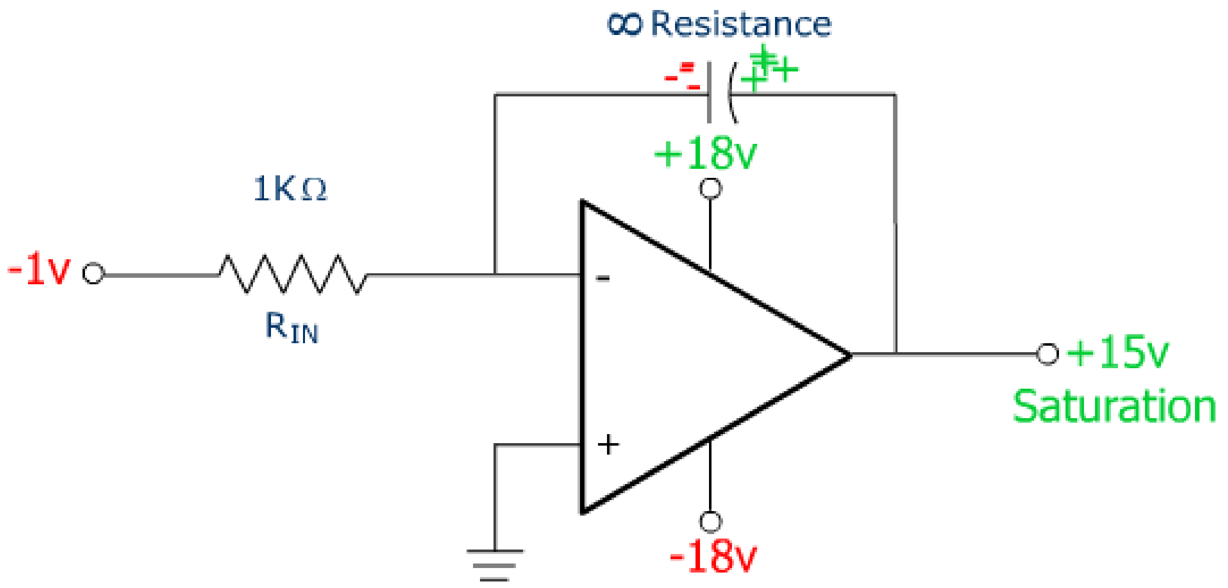
As the capacitor is charging:

- The effective resistance of the capacitor is increasing.
- The resistance ratio of the capacitor / R_{IN} resistor is increasing.
- The voltage at the output is increasing.

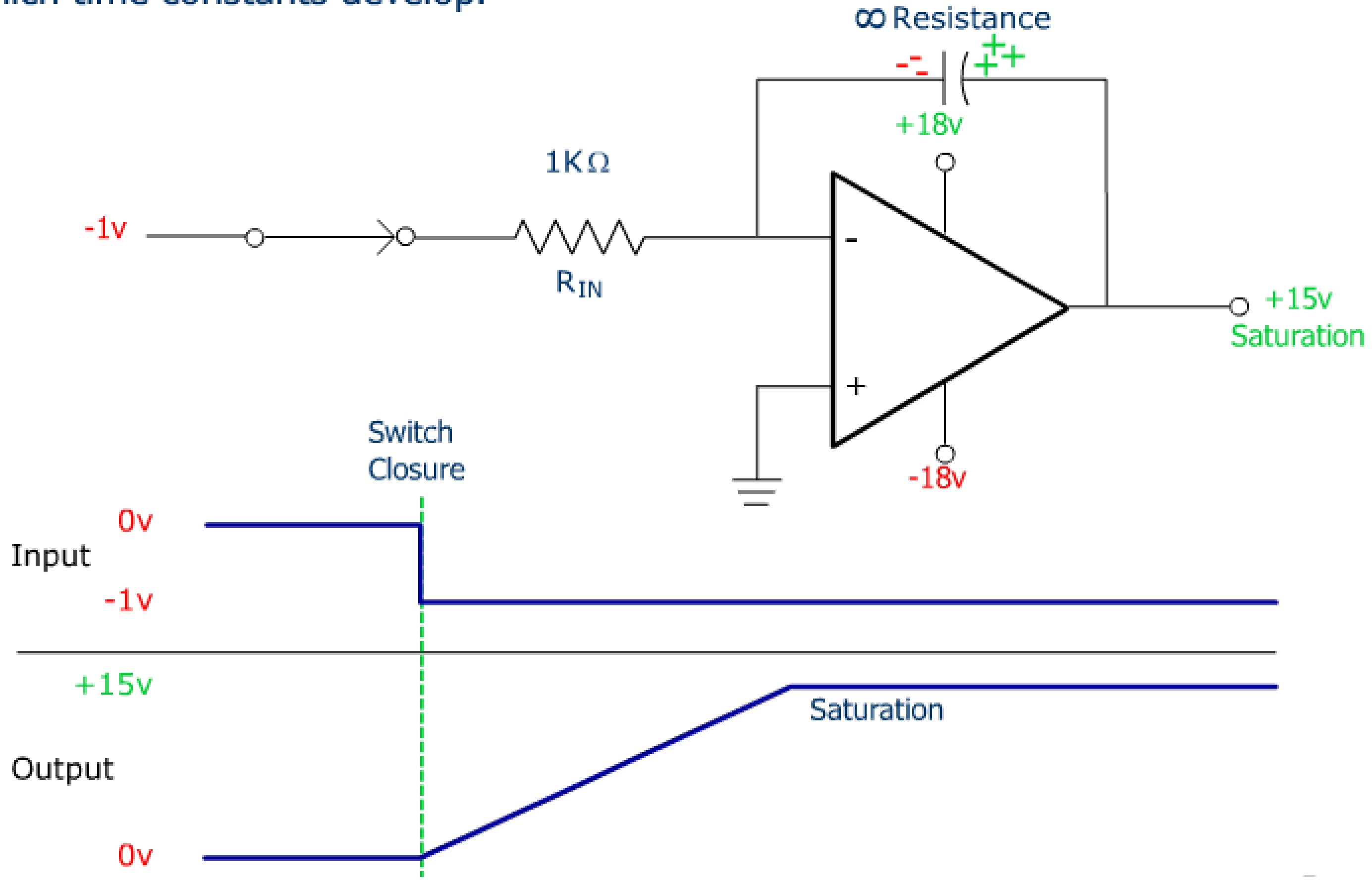


When the capacitor is fully charged:

- The capacitor acts like an open with resistance.
- The resistance ratio of the capacitor/R_{IN} resistor is infinite.
- The gain is infinite, causing the op amp to go into positive saturation.

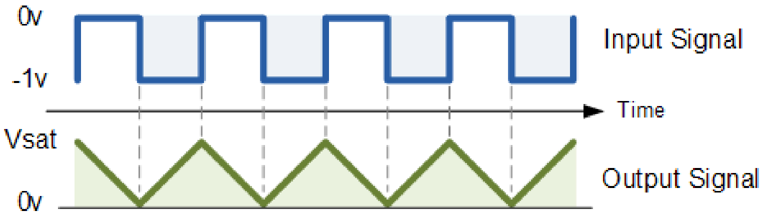


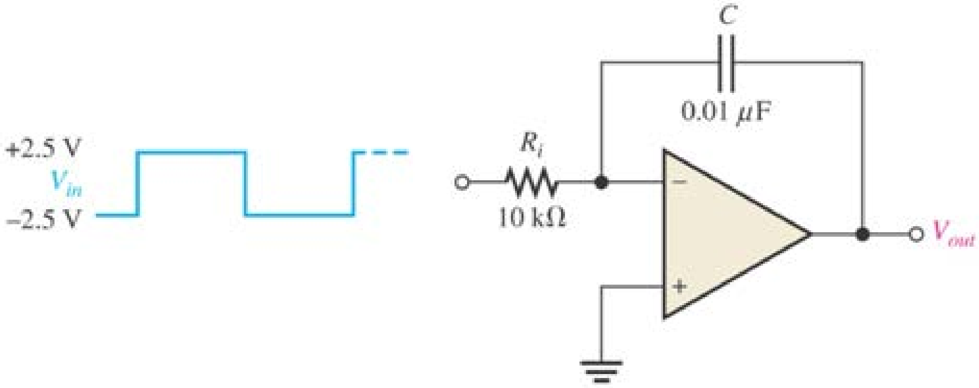
The rate at which the output voltage of the integrator op amp increases is determined by the values of the resistor and the capacitor, an RC network in which time constants develop.



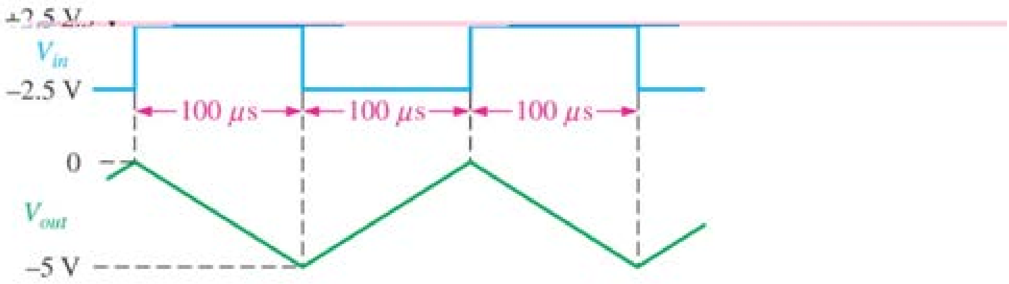
Applications

- Ramp generator



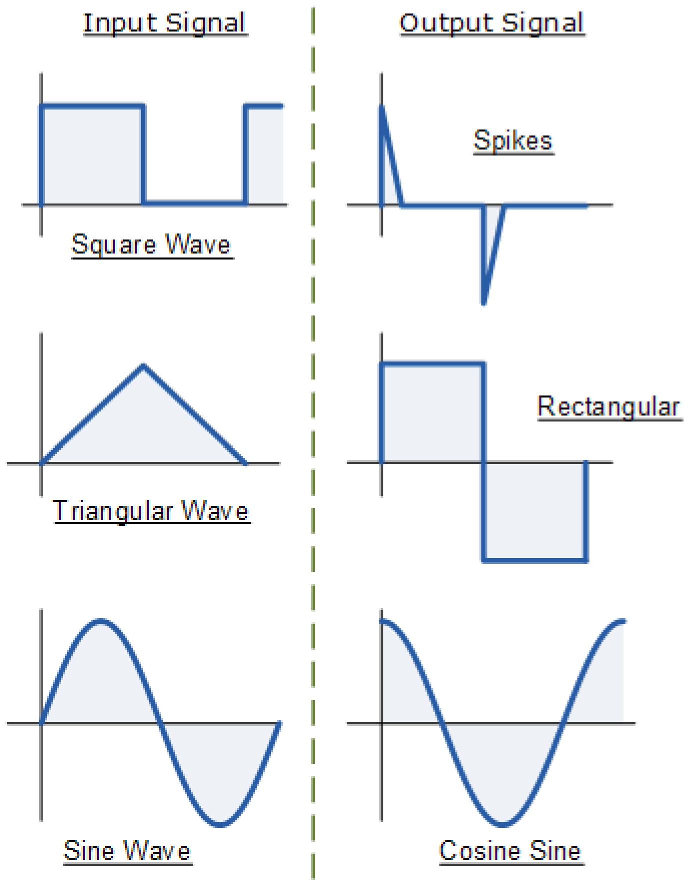


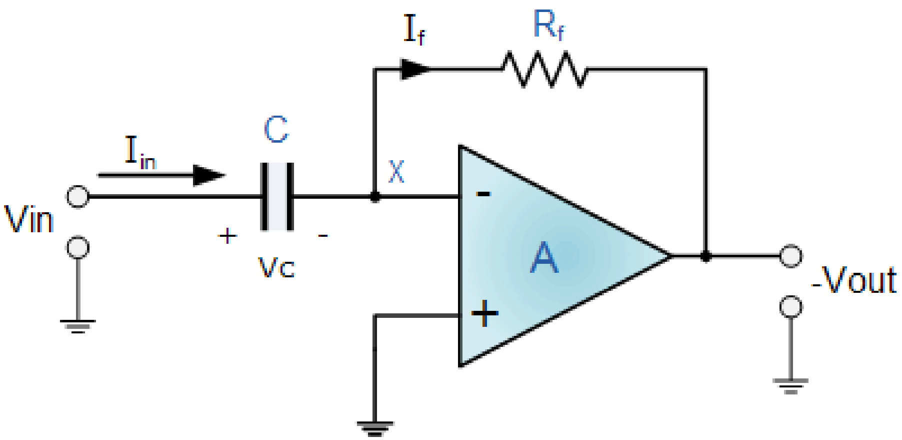
(a)



(b)

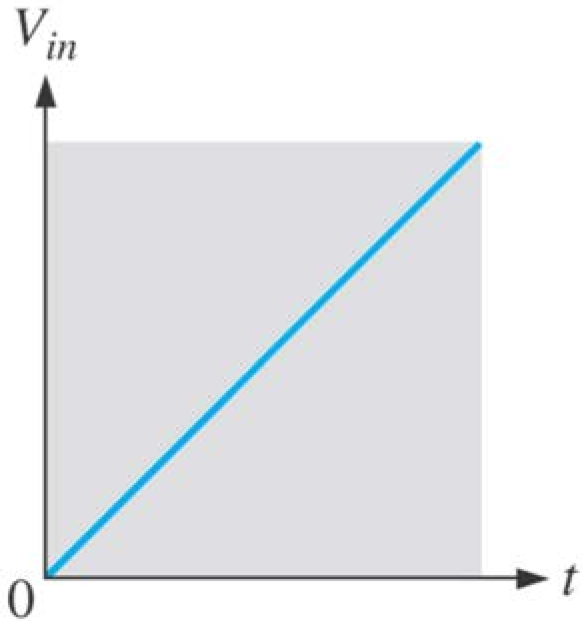
Differentiator Op-amp

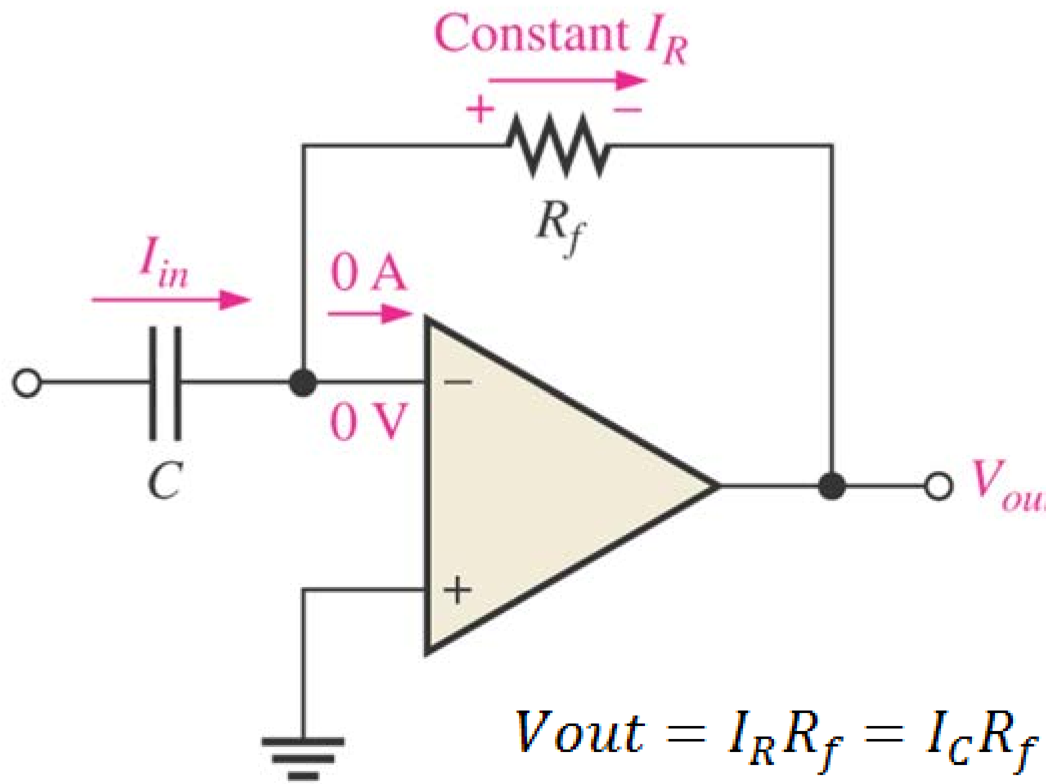




$$V_{OUT} = -R_F C \frac{dV_{IN}}{dt}$$

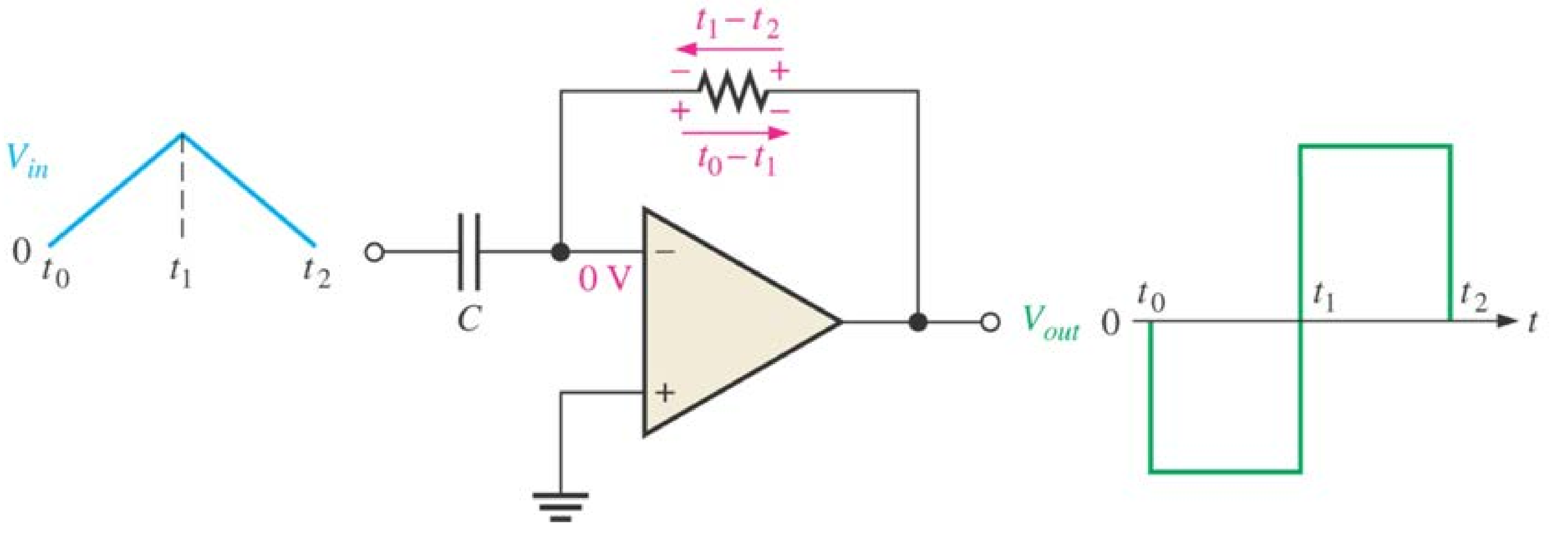
Differentiator with Ramp input





$$Vout = I_R R_f = I_C R_f$$

$$Vout = -\left(\frac{V_C}{t}\right) C R_f$$



V_{in}
0
t_0
t_1
t_2
$t_1 - t_2$
$t_0 - t_1$
C
0 V
V_{out}
0
t_0
t_1
t_2
t

Example

Determine the output voltage of the ideal differentiator in figure below.