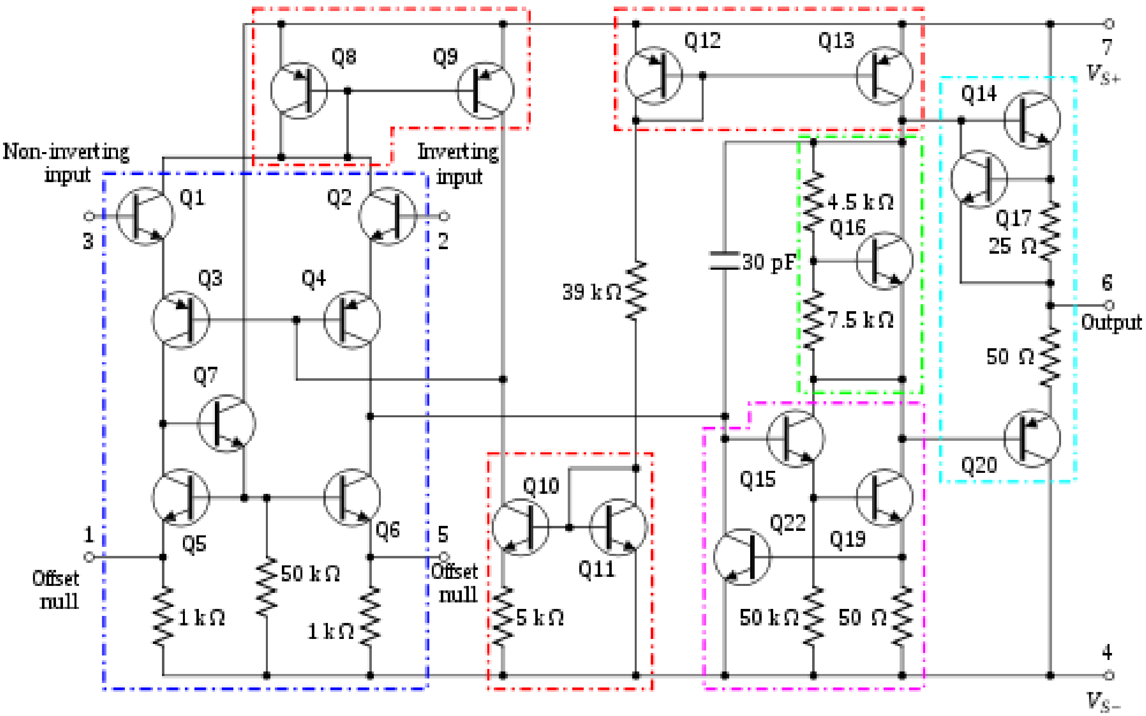
CHAPTER 2

Operational Amplifiers

Op-Amp designed by BJT

Design structure

Physical design

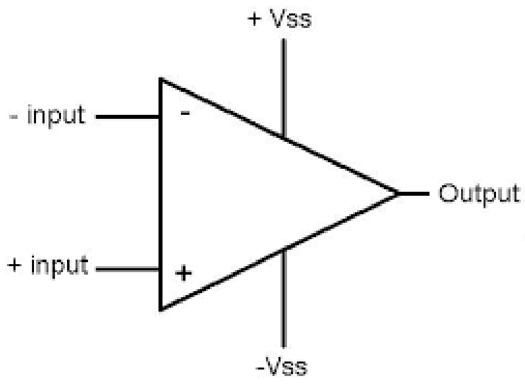


A component-level diagram of the common 741 Op-Amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (purple); voltage level shifter (green); output stage (light blue).

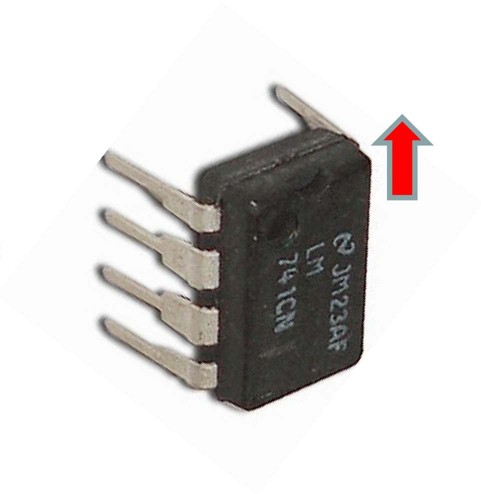
The components will be learned and used in the lab

- Different views of Op-Amp

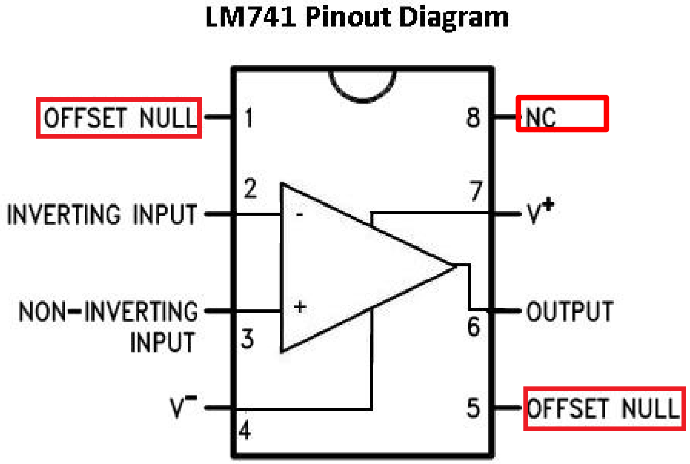
Symbol



Physical



Pin-out



Outline

- 2.1 The ideal OpAmp
- 2.2 The inverting configuration
- 2.3 The non-inverting configuration
- 2.4 Difference amplifiers
- 2.5 Integrators and Differentiators
- 2.8 Large-signal operation of OpAmps

2.1 The ideal OpAmp

- $v_3 = A(v_2 - v_1)$
  - Infinite input impedance
  - Zero output impedance
  - Infinite open-loop gain A: $v_3 = A(v_2 - v_1)$, so $v_2 \approx v_1$
  - Zero common-mode gain or, equivalently, infinite common-mode rejection
  - Infinite bandwidth

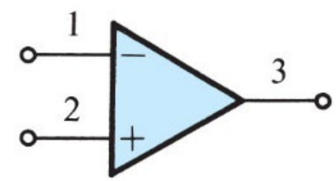


Figure 2.1 Circuit symbol for the op amp.

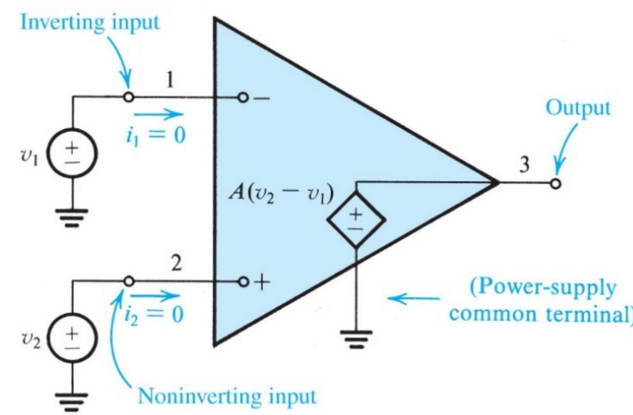


Figure 2.3 Equivalent circuit of the ideal op amp.

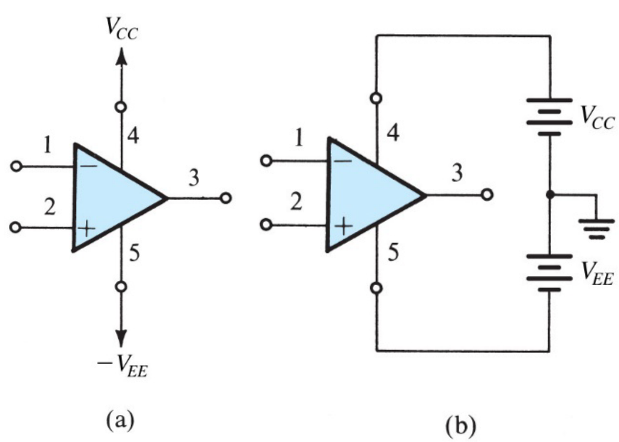


Figure 2.2 The op amp shown connected to dc power supplies.

2.2 The inverting configuration

- The inverting configuration
  - Negative feedback: R_2
  - Non-inverting input (terminal 2): ground
  - Inverting input (terminal 1)

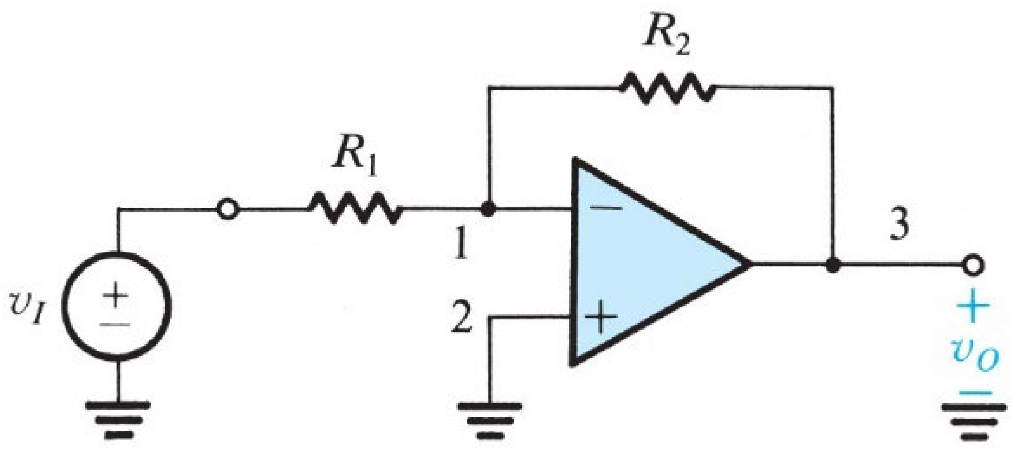


Figure 2.5 The inverting closed-loop configuration.

- 2.2.1 Close-loop gain ($G = \frac{v_O}{v_I}$)
  - **Virtual** short circuit/ground: $v_1 = v_2 \approx 0$ (not physically connected to ground, $A = \frac{v_O}{v_2 - v_1}$)
  - Ohm's law: $i_1 = \frac{v_I}{R_1}$ (Where will this current go?)
  - Ohm's law: $i_2 = \frac{0 - v_O}{R_2} = -\frac{v_O}{R_2}$
  - Thus, $G = \frac{v_O}{v_I} = -\frac{R_2}{R_1}$

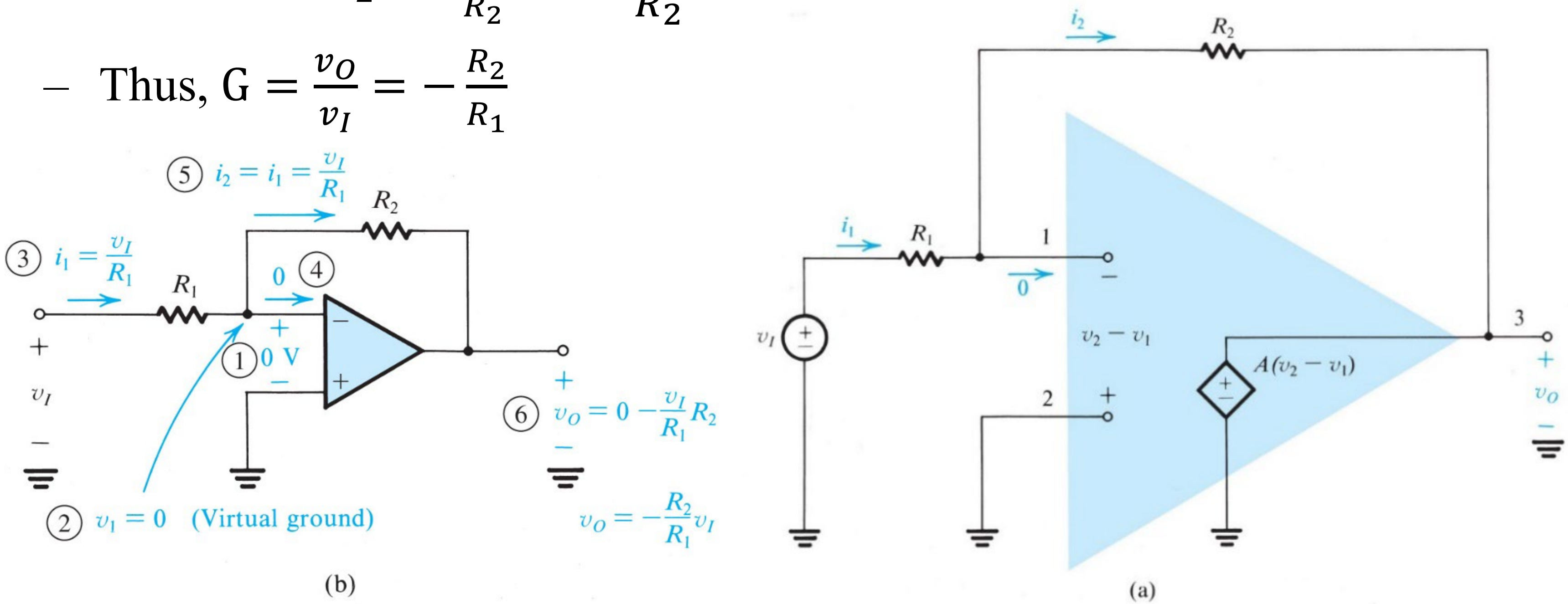


Figure 2.6 Analysis of the inverting configuration. The circled numbers indicate the order of the analysis steps.

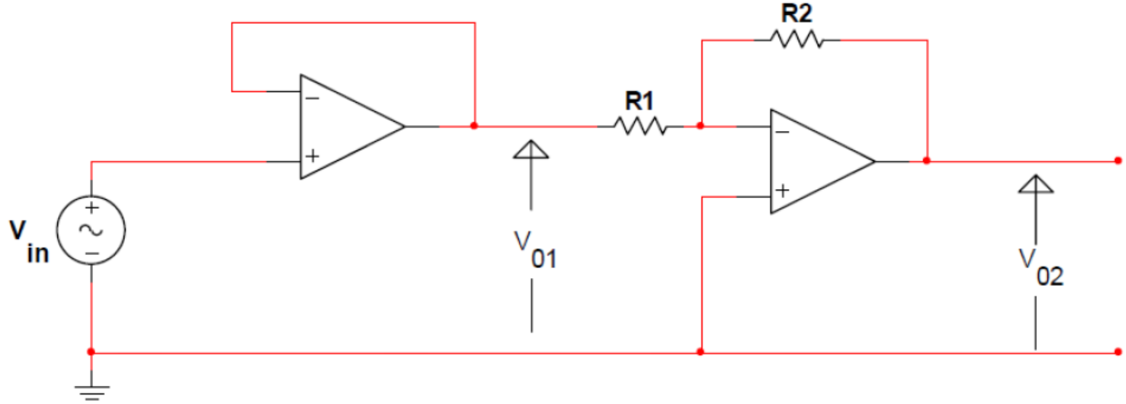
- Experiment 3.1

$v_{in}(t) = V_p \sin(\omega t)\ \ volts.\ V_p \geq 100mV, f = 1KHz.$

$R_1 = 1k\Omega,\ R_2 = 2k\Omega$

Measure and tabulate $V_{01}(t)$ and $V_{02}(t)$

Briefly comment your results.

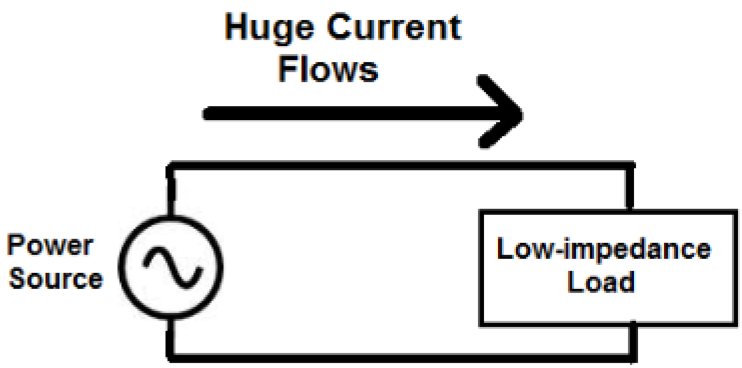


$V_{in(P-P)}$	$V_{o1(P-P)}$	$V_{o2(P-P)}$
$200mV$		

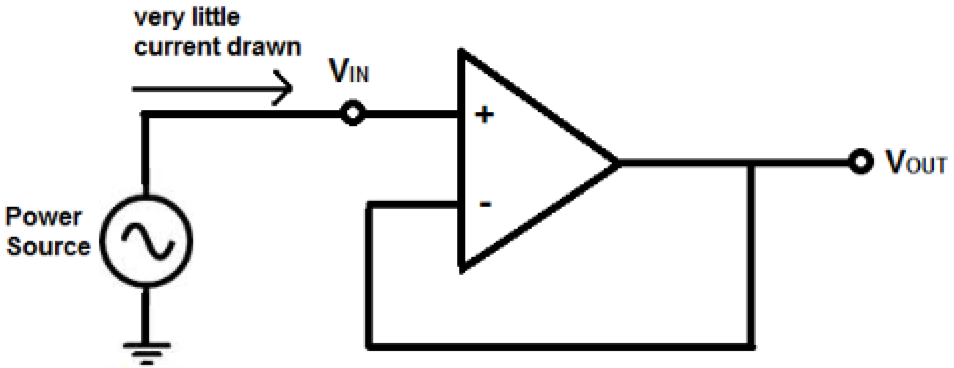
- What is the purpose of a buffer?

Ref: http://www.learningaboutelectronics.com/Articles/Unity-gain-buffer

This is the reason unity gain buffers are used. They **draw very little current**, not disturbing the original circuit, and **give the same voltage signal as output**. They act as isolation buffers, isolating a circuit so that the power of a circuit is disturbed very little.



The load demands and draws a huge amount of current, because the load is low impedance. This causes huge amounts of power to be drawn by the power source and, because of this, causes high disturbances and use of the power source powering the load.

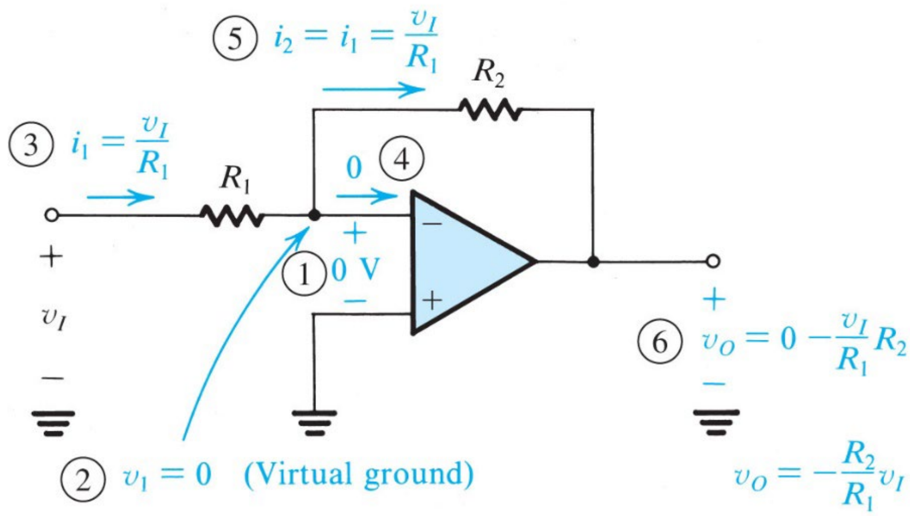


This circuit above now draws very little current from the power source above. Because the op amp has such high impedance, it draw very little current. And because an op amp that has no feedback resistors gives the same output, the circuit outputs the same signal that is fed in.

- 2.2.3 Input and output resistance
  - The input resistance of the closed loop inverting amplifier

$$R_i = \frac{v_I}{i_I} = \frac{v_I}{v_I/R_1} = R_1$$

    - To make R_i high impedance for inverting configuration, we should select a high value for R_1, which is a conflict with $G = \frac{v_O}{v_I} = -\frac{R_2}{R_1}$.
  - Output resistance: 0 with the ideal voltage source $A(v_2 - v_1)$



- 2.2.4 An important application – the weighted summing
  - All the summing coefficients are the same sign

$$i_1 = \frac{v_1}{R_1}, i_2 = \frac{v_2}{R_2}, i_3 = \frac{v_3}{R_3}, \cdots i_n = \frac{v_n}{R_n} \quad \text{(Ohm's law)}$$

$$i = i_1 + i_2 + i_3 \cdots i_n \quad \text{(KCL)}$$

$$v_o = 0 - iR_f = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \cdots + \frac{R_f}{R_n}v_n\right) \quad \text{(KVL)}$$

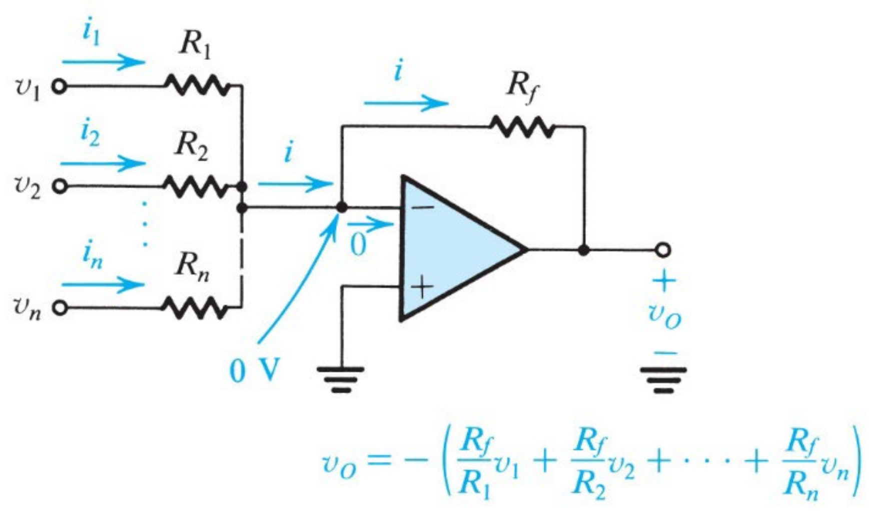


Figure 2.10 A weighted summer.

- # Exercise D2.7

Design a weighted sum $v_o = -(v_1 + 5v_2)$.

Choose values for R_1, R_2, R_f so that for a maximum output voltage of 10V and the current in the feedback resistor will not exceed 1mA.

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2\right) = -(v_1 + 5v_2)$$

$$\frac{R_f}{R_1} = 1 \text{ and } \frac{R_f}{R_2} = 5$$

$$\frac{10V}{R_f} \leq 1mA \Rightarrow R_f \geq 10\ k\Omega$$

Let us choose R_f to be 10 kΩ, then

$$R_1 = R_f = 10\ k\Omega$$

$$R_2 = \frac{R_f}{5} = 2\ k\Omega$$

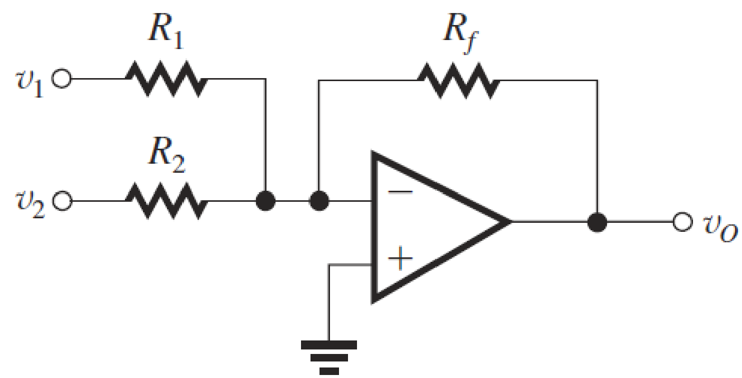


Figure A weighted summer.

- The weighted summing (opposite sign)
  - The summing coefficients can have opposite signs

$$v_{o1} = -(\frac{R_a}{R_1}v_1 + \frac{R_a}{R_2}v_2)$$

$$v_o = -\left(\frac{R_c}{R_b}v_{o1} + \frac{R_c}{R_3}v_3 + \frac{R_c}{R_4}v_4\right)$$

$$= \left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right)v_1 + \left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right)v_2 - (\frac{R_c}{R_3}v_3 + \frac{R_c}{R_4}v_4)$$

One application: mixing signals from different musical instruments

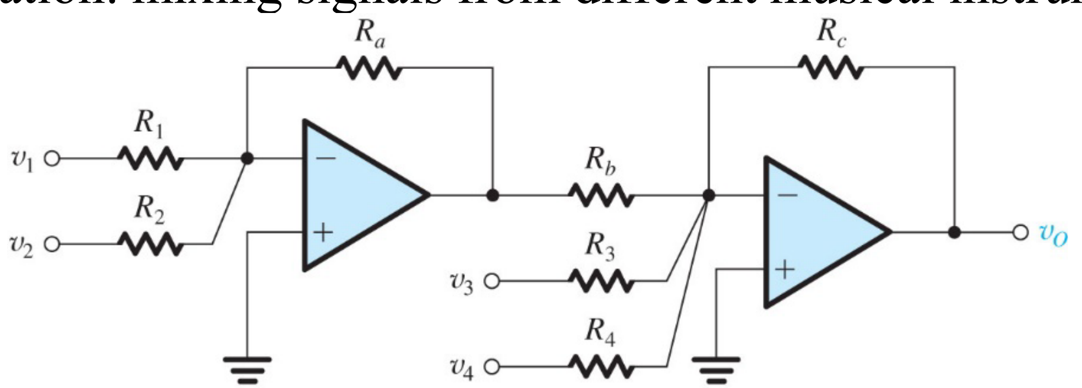


Figure 2.11 A weighted summer capable of implementing summing coefficients of both signs.

Exercise D2.8

- Design a weighted sum $v_o = 2v_1 + v_2 - 4v_3$. Choose values for $R_1, R_2, R_3, R_a, R_b, R_c$ so that for a maximum output voltage of 10V and the current in the feedback resistor will not exceed 1mA.

$$v_o = \left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right)v_1 + \left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right)v_2 - \left(\frac{R_c}{R_3}v_3\right)$$

$$\left(\frac{R_a}{R_1}\right)\left(\frac{R_c}{R_b}\right) = 2$$

$$\left(\frac{R_a}{R_2}\right)\left(\frac{R_c}{R_b}\right) = 1$$

$$\frac{R_c}{R_3} = 4$$

Let us choose $R_a = R_b = R_c = 10k\Omega$

$$R_3 = \frac{10\ k\Omega}{4} = 2.5\ k\Omega$$

$$R_2 = 10k\Omega$$

$$R_1 = 5k\Omega$$

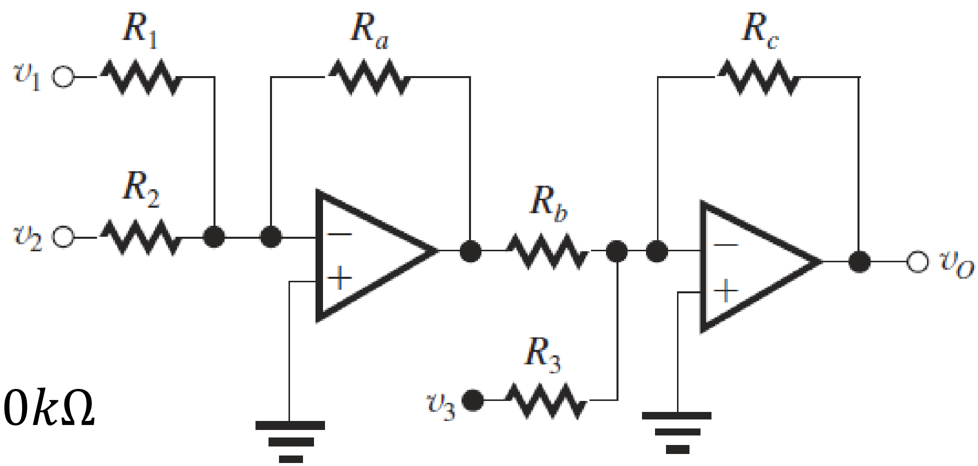


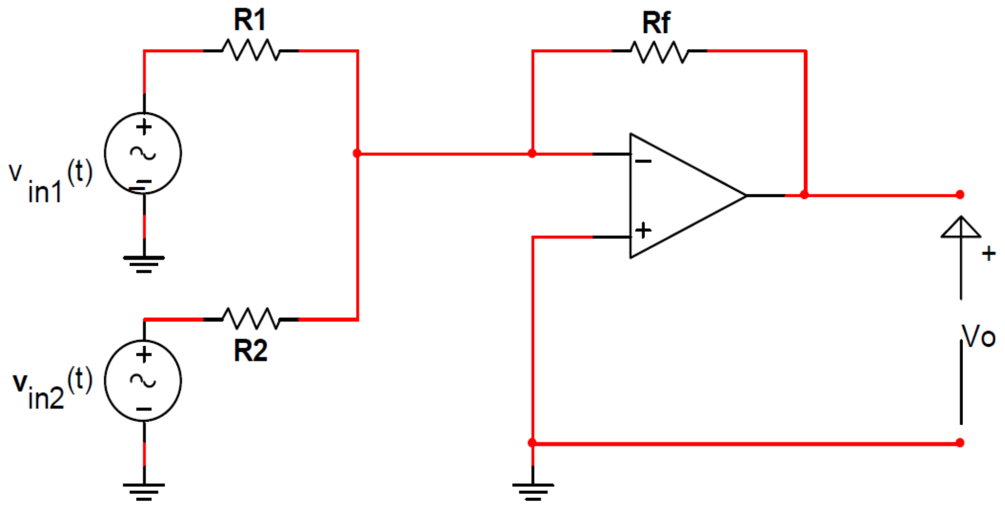
Figure A weighted summer.

- Experiment 3.2

$R_1 = R_2 = 1k\Omega,$

$v_{in1}(t) = v_{in2}(t) = V_p \sin(\omega t)\ \ volts\,, V_p = 1V, f = 1KHz$

Measure and **graph** $v_o(t)$. Briefly explain and comment your results.



Test	R_f	v_o
Test #1	$1k\Omega$	$v_{o(p-p)} =$
Test #2	$2k\Omega$	$v_{o(p-p)} =$

2.3 The non-inverting configuration

- The non-inverting configuration
  - Negative feedback: R_2
  - Non-Inverting input: Input signal v_I
  - Inverting input: R_1 and ground

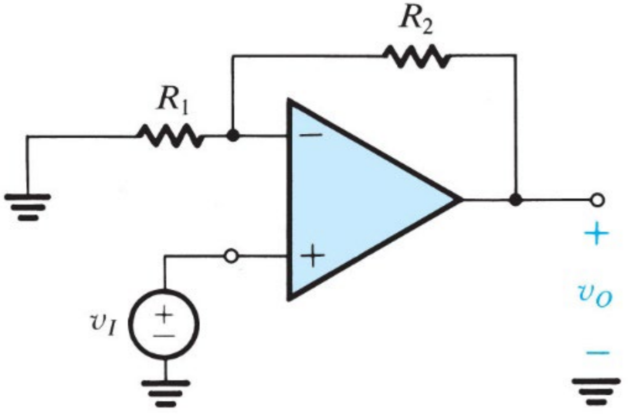


Figure 2.12 The noninverting configuration.

- 2.3.1 Close-loop gain ($A_v = \frac{v_O}{v_I}$)

Ohm's law: $i_1 = \frac{v_I}{R_1}$ (Where does this current come from?)

Ohm's law: $i_2 = \frac{v_O - v_I}{R_2}$

Thus, $\frac{v_O}{v_I} = 1 + \frac{R_2}{R_1}$

$v_I = \frac{R_1}{R_1+R_2} v_o$ (like a voltage divider)

Applications: Voltage Amplifier 3V-6V

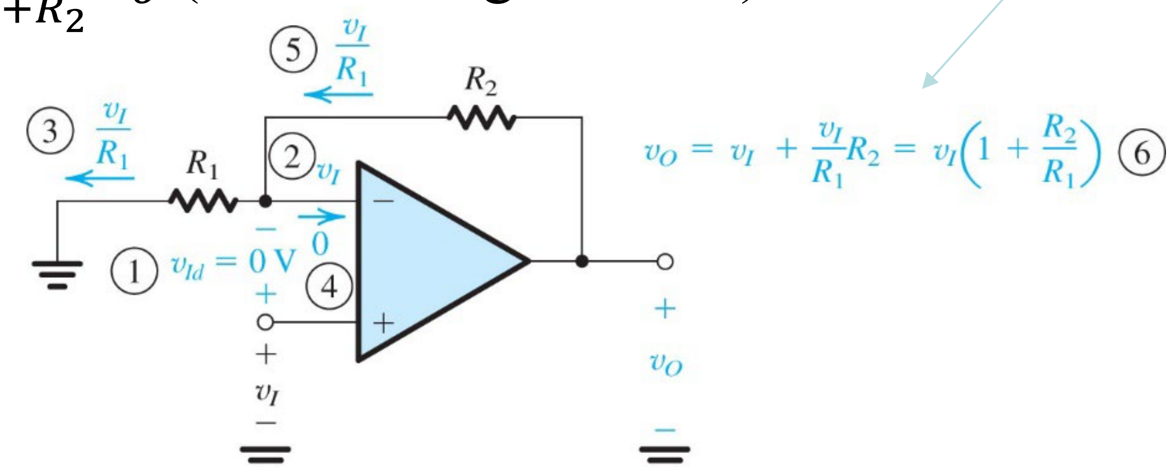
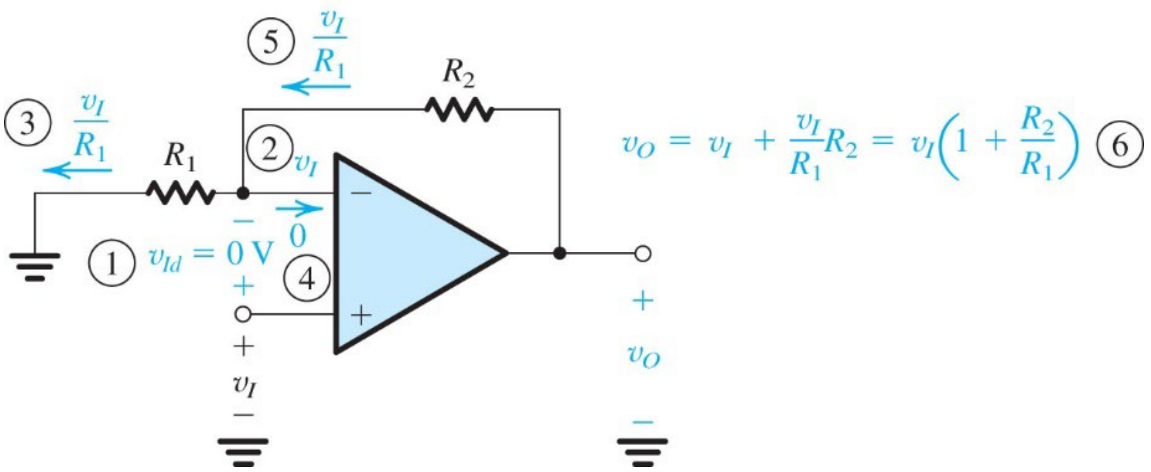
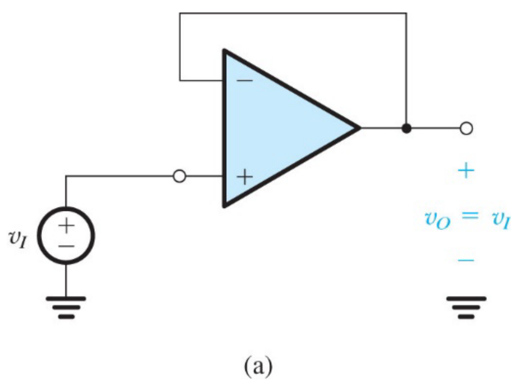


Figure 2.13 Analysis of the noninverting circuit. The sequence of the steps in the analysis is indicated by the circled numbers.

- 2.3.3 Input and output resistance
  - The input resistance is infinite with no current flows into the positive input terminal.
  - Output resistance: 0 with the ideal voltage source $A_{vo}(v_2 - v_1)$



- 2.3.3 The voltage follower/buffer
  - $R_2 = 0$ and $R_1 = \infty$, $v_O = v_I$
  - Ideal case: $v_O = v_I$, $R_{in} = \infty$ and $R_{out} = 0$
  - Applications: isolation circuit/power amplifier (input current is 0)



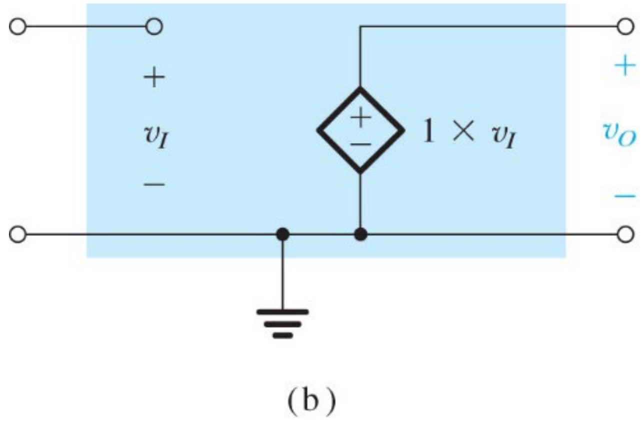


Figure 2.14 (a) The unity-gain buffer or follower amplifier. **(b)** Its equivalent circuit model.

- Exercise D2.9
  - Use the superposition principle to find the output voltage of the circuit in Fig. E2.9.

Find contribution of v_1 to the output v_o, we set $v_2 = 0V$

$$v_+ = \left(\frac{3k\Omega}{2k\Omega + 3k\Omega}\right) v_1 = 0.6v_1, \text{ thus } v_{o1} = \left(1 + \frac{9k\Omega}{1k\Omega}\right) v_+ = 6v_1$$

Find contribution of v_2 to the output v_o, we set $v_1 = 0V$

$$v_+ = \left(\frac{2k\Omega}{2k\Omega + 3k\Omega}\right) v_2 = 0.4v_2, \text{ thus } v_{o2} = \left(1 + \frac{9k\Omega}{1k\Omega}\right) v_+ = 4v_2$$

Hence, $v_o = v_{o1} + v_{o2} = 6v_1 + 4v_2$

**Superposition Principle: For linear systems, the output response caused by two or more SOURCES is the sum of the responses caused by each SOURCE individually.

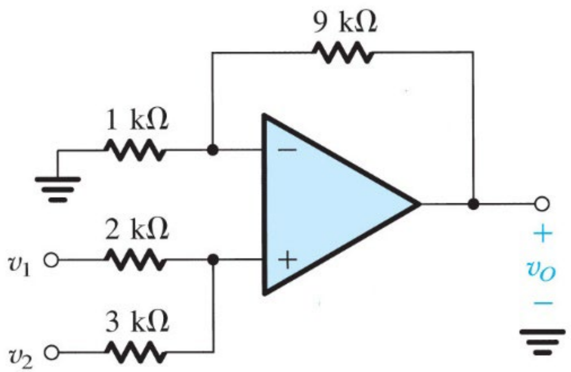


Figure E2.9

2.5 Integrators and Differentiators

- Op-Amp-RC in frequency domain
- 2.5.1 The inverting configuration with general impedances

$$\frac{V_o(w)}{V_i(w)} = -\frac{Z_2(w)}{Z_1(w)}, \quad (Z_1(w) = R_1, Z_2(w) = R_2||(1/jwC_2),)$$

Thus, $\frac{V_o(w)}{V_i(w)} = -\frac{R_2||(1/jwC_2)}{R_1} = -\frac{R_2}{R_1}\frac{1}{1+jwC_2R_2} = -\frac{R_2}{R_1}\frac{1}{1+\frac{jw}{1/C_2R_2}}$

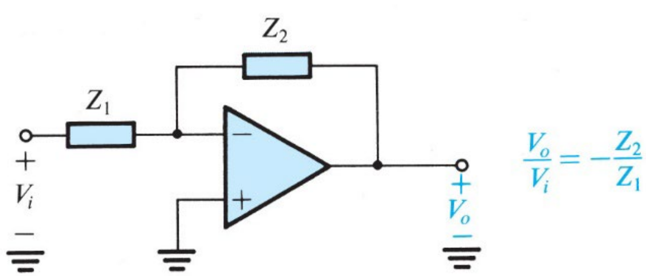
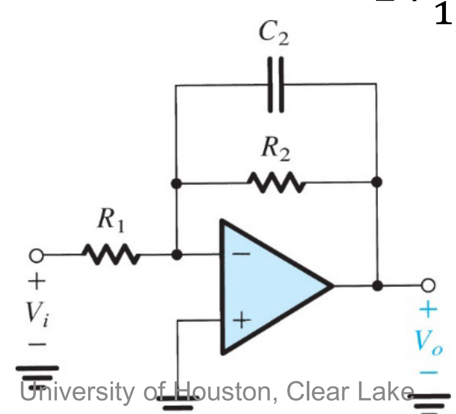


Figure 2.22 The inverting configuration with general impedances in the feedback and the feed-in paths.

Figure 2.23 Circuit for Example 2.4.



- Example 2.4

  1) Find the DC gain and the 3dB frequency

  2) Design the circuit to obtain a DC gain of 40 dB, a 3-dB frequency of 1kHz, and an input resistance of R_1=1$K\Omega$

  3) At what frequency does the magnitude of transmission become unity?

$$\frac{V_o(jw)}{V_i(jw)} = -\frac{R_2}{R_1}\frac{1}{1+\frac{jw}{1/C_2R_2}}$$

1) DC gain = $\frac{R_2}{R_1}$ and 3-dB frequency $\omega_0 = 1/C_2R_2$

2) 40dB, so $\frac{R_2}{R_1} = 100$, $R_1 = 1K\Omega$, so $R_2 = 100K\Omega$

$2\pi \times 1KHz = \frac{1}{C_2 \times 100K\Omega}$, so $C_2 = 1.59nF$

3) -20dB/decade, two decade to reach 0 (100KHz)

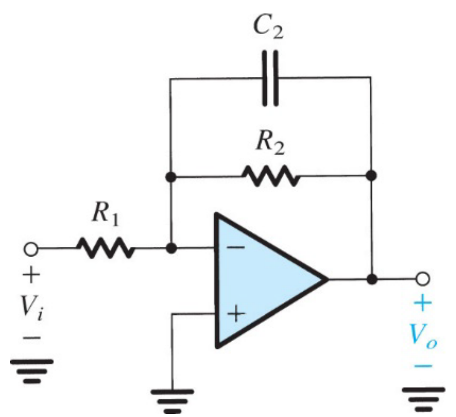


Figure 2.23 Circuit for Example 2.4.

2.8 Large-Signal Operation of Op Amps

- 2.8.1 Output voltage saturation
  - Output voltage will be less than DC power supplies
    - e.g.: Op Amps operating from $\pm 15V$ will saturate when output voltage reaches $\pm 13V$
    - The voltage over $\pm 13V$ will be clipped off

- 2.8.2 Output current limits
  - Output current is limited to a specified maximum
    - e.g.: Op Amps 741 is specified to have a maximum output current of $\pm 20mA$
  - Contains both load and feedback current

- # Example 2.7

Gain ($1 + R_2/R_1$=10V/V), V_I: V_P(peak voltage), Load R_L

Saturation voltage: $\pm$13V, current limits:$\pm$20mA

(a) $V_P = 1V$, $R_L = 1K\Omega$, specify output signal

(i) Output sine-wave will be amplified with peak value of 10V.

(ii) $i_L(\text{peak}) = \frac{10V}{1K\Omega} = 10mA$ $\quad i_F(\text{peak}) = \frac{10V}{1K\Omega + 9K\Omega} = 1mA$

$$i_o(\text{peak}) = i_L(\text{peak}) + i_F(\text{peak}) = 11mA < 20mA$$

(20mA is the current limitation)

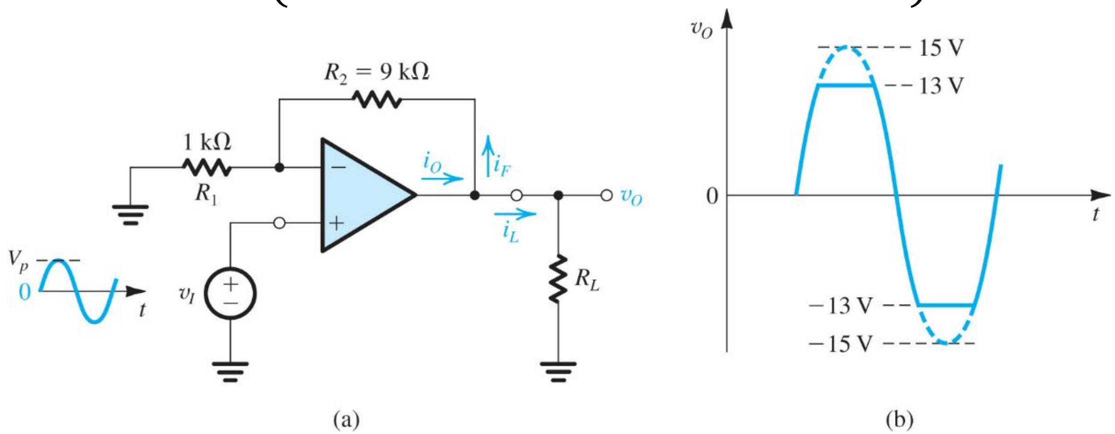


Figure 2.42 (a) A noninverting amplifier with a nominal gain of 10 V/V designed using an op amp that saturates at ±13-V output voltage and has ±20-mA output current limits. **(b)** When the input sine wave has a peak of 1.5 V, the output is clipped off at ±13 V.

- Example 2.7 Cont.

Gain ($1 + R_2/R_1$=10V/V), V_I: V_P(peak voltage), Load R_L

Saturation voltage: $\pm$13V, current limits:$\pm 20mA$

(b) $V_P = 1.5$V, $R_L = 1K\Omega$, specify output signal

(i) Output sine-wave will be clipped off as 13V peak voltage

(ii) $i_L(\text{peak}) = \frac{13V}{1K\Omega} = 13mA$ $\quad i_F(\text{peak}) = \frac{13V}{1K\Omega + 9K\Omega} = 1.3mA$

$i_o(\text{peak}) = i_L(\text{peak}) + i_F(\text{peak}) = 14.3mA < 20mA$

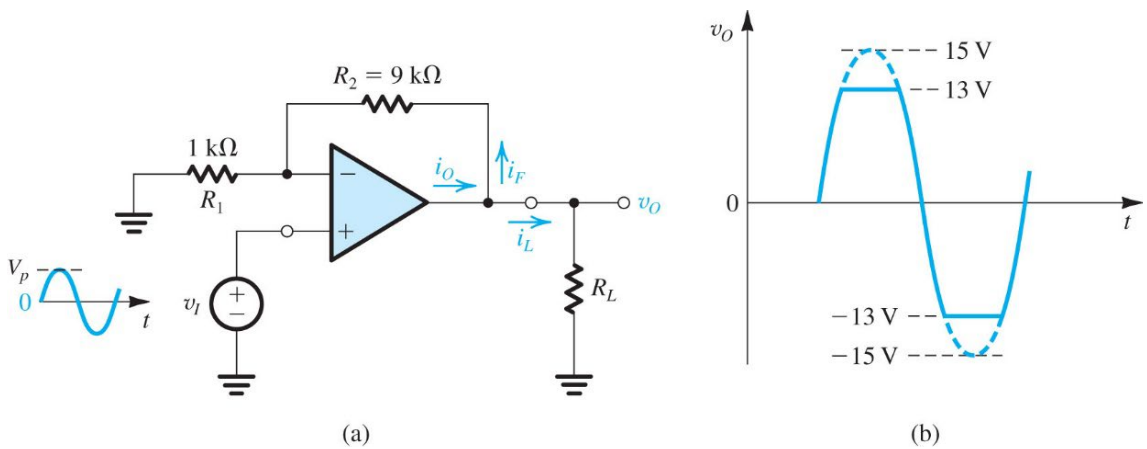


Figure 2.42 (a) A noninverting amplifier with a nominal gain of 10 V/V designed using an op amp that saturates at ±13-V output voltage and has ±20-mA output current limits. **(b)** When the input sine wave has a peak of 1.5 V, the output is clipped off at ±13 V.

- # Example 2.7 Cont.

Gain ($1 + R_2/R_1$=10V/V), V_I: V_P(peak voltage), Load R_L

Saturation voltage: ± 13V, current limits:$\pm 20mA$

(c) $R_L = 1K\Omega$, what is the maximum value of V_P for which an undistorted sine-wave output is obtained?

(d) $V_P = 1$V, what is the lowest value of R_L for which an undistorted sine-wave output is obtained?

(c) The maximum value of $V_P = 1.3V$

$i_o(peak) = 14.3mA < 20mA$

(d) $i_{omax} = 20mA = \frac{10V}{9K\Omega + 1K\Omega} + \frac{10V}{R_{Lmin}}$

$R_{Lmin} = 526\Omega$

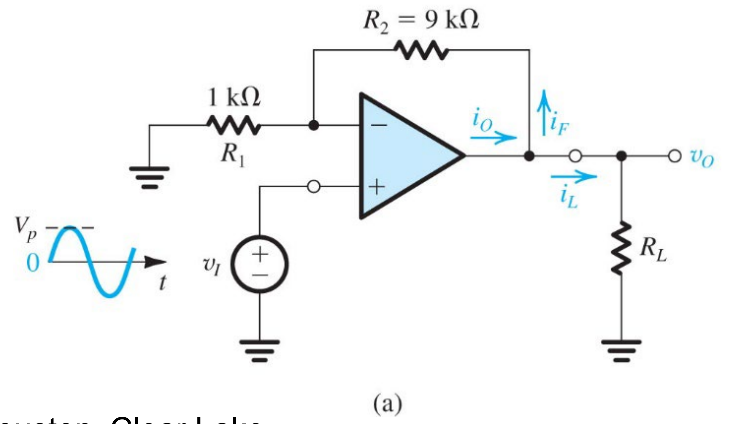


Figure 2.42 (a) A noninverting amplifier with a nominal gain of 10 V/V designed using an op amp that saturates at ±13-V output voltage and has ±20-mA output current limits.

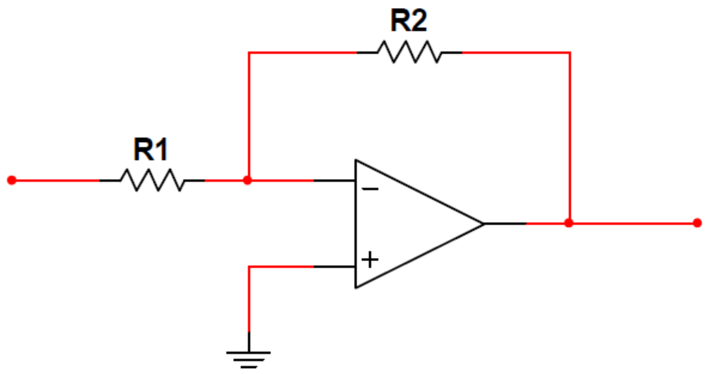
- Experiment 4.1

$v_{in}(t) = V_p \sin(\omega t)\ \ volts\,, V_p = 100mV, f = 100Hz.$

Try to make $|A_v|$ close to 10, 100, $10^3, 10^4, 10^5$. How high can you go?

Monitor the amplitude of the output signal to avoid distortion.

Measure and **graph** $v_{o(p-p)}$.

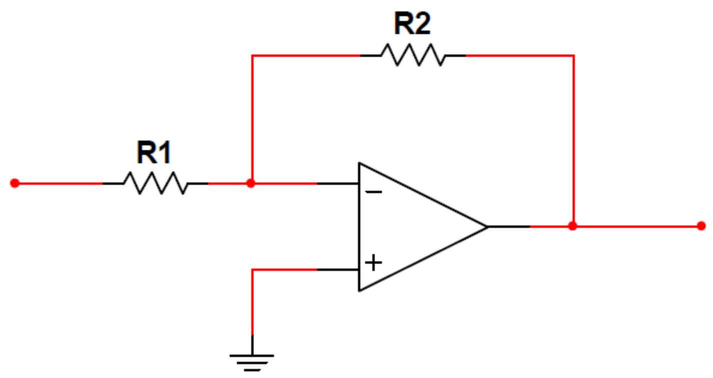


$\lvert A_v \rvert$	R_1	R_2	$v_{o(p-p)}$
10?	100Ω	$1k\Omega$	
100?		$10k\Omega$	
10^3?		$100k\Omega$	
10^4?		$1M\Omega$	

- Experiment 4.2

Increase the amplitude of the input signal until you observe clipping. Continue increasing the amplitude and observe the results.

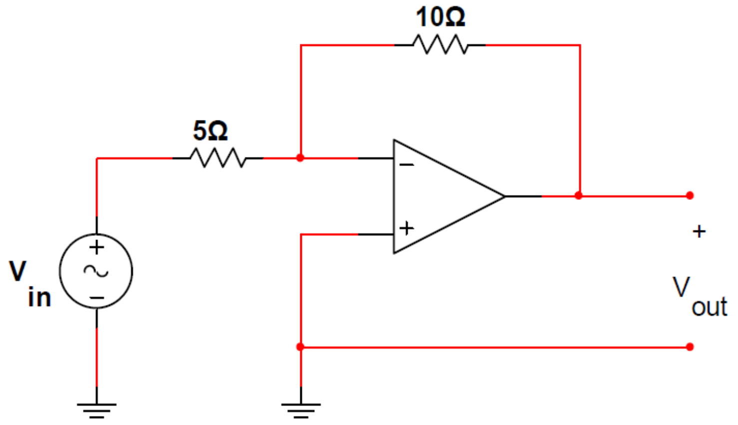
Measure and **graph** $v_{o(p-p)}$.



$\lvert A_v \rvert$	R_1	R_2	v_p	$v_{o(p-p)}$
-10	100Ω	$1k\Omega$	$100mV$	
			$1V$	
			$2V$	
			$4V$	

- Experiment 4.3

For the same amplifier as 2, reduce the value of R_1 (5Ω) and R_2 (10Ω) until the Op-Amp will be current limited. Observe the amplitude of the output signal.



$\lvert A_v \rvert$	R_1	R_2	v_p	$v_{o(p-p)}$
2?	5Ω	10Ω	$1V$	
			$5V$	

HW2

- Problems:
  - PP.118, 2.15 – The inverting configuration
  - PP.121, 2.38 – The inverting configuration: weighed summing circuit
  - PP.133, 2.122 – Large-signal operation of Op-Amps
- Submission requirement:
  - Add the cover page!!!
  - Print the HW2.pdf out and answer all the questions (download on the blackboard)