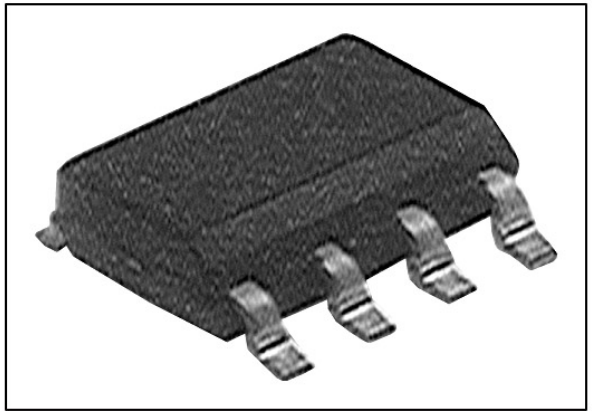
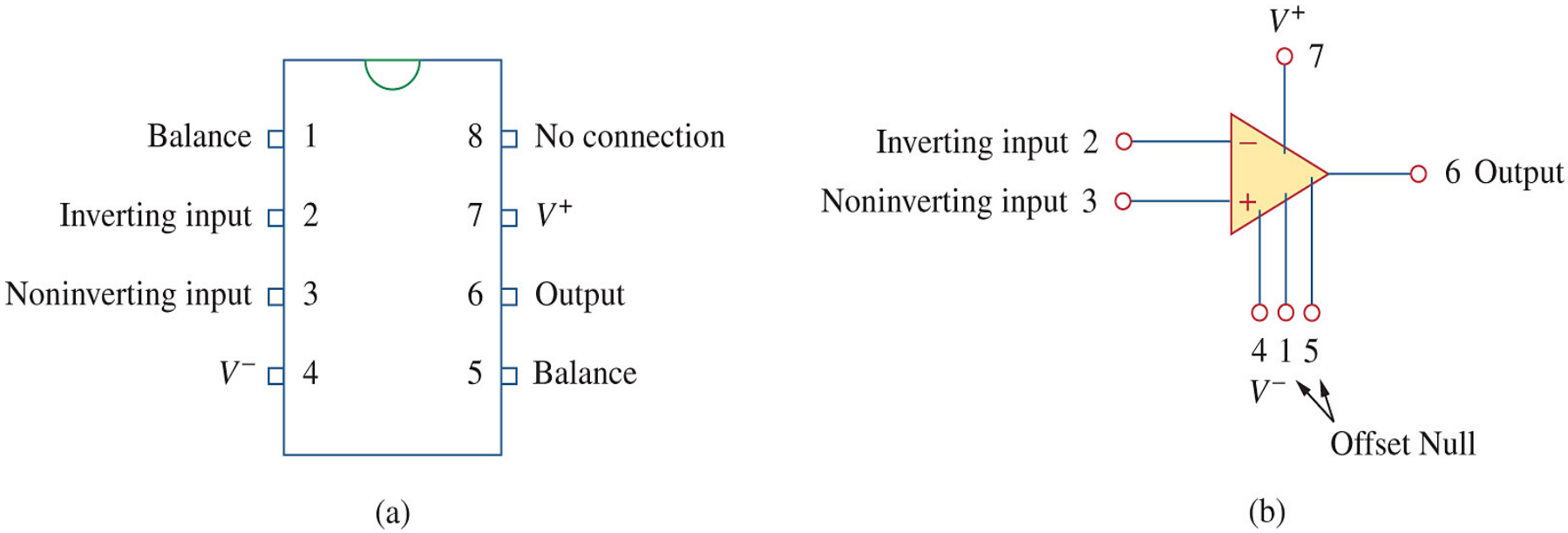
OPERATIONAL AMPLIFIERS

Introduction

- An electronic unit that behaves like a voltage-controlled voltage source.
- An active circuit element that amplifies, sums, subtracts, multiply, divide, differentiate or integrates a signal

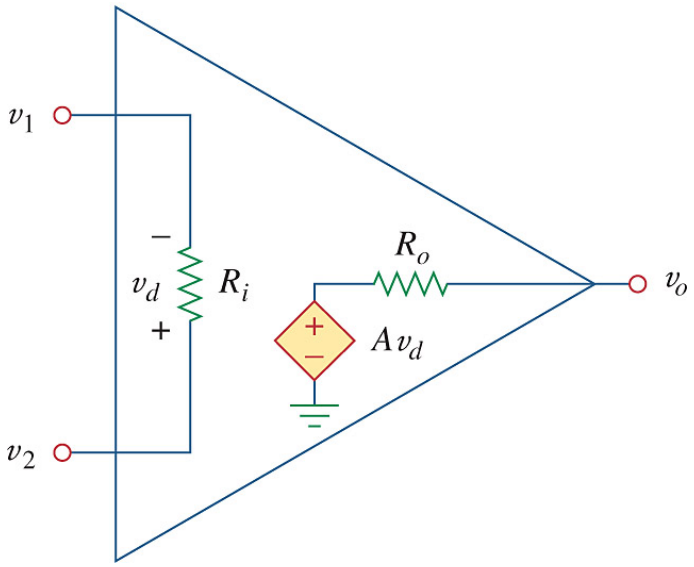


Introduction

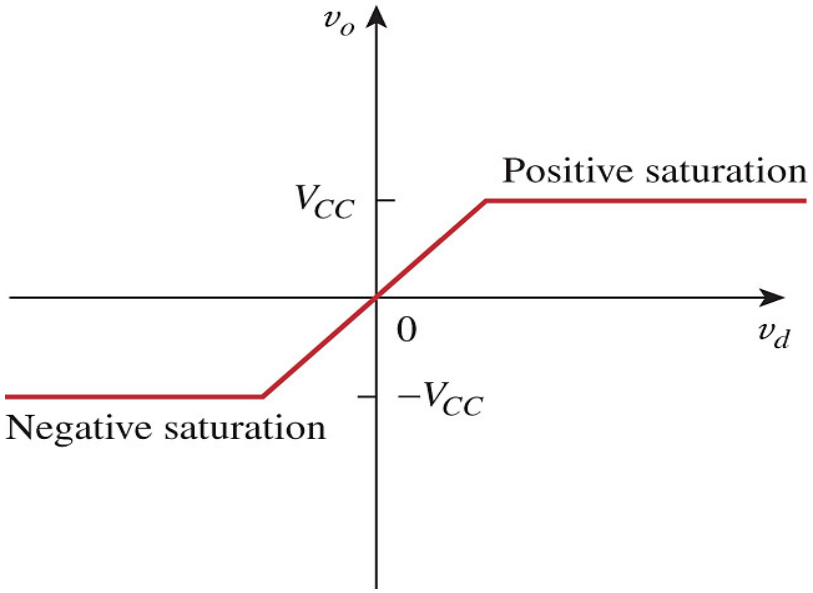


A typical op amp: (a) pin configuration, (b) circuit symbol

Introduction



The equivalent circuit
Of the non-ideal op amp



Op Amp output:
v_o as a function of V_d

$$v_d = v_2 - v_1; \quad v_o = Av_d = A(v_2 - v_1)$$

Introduction

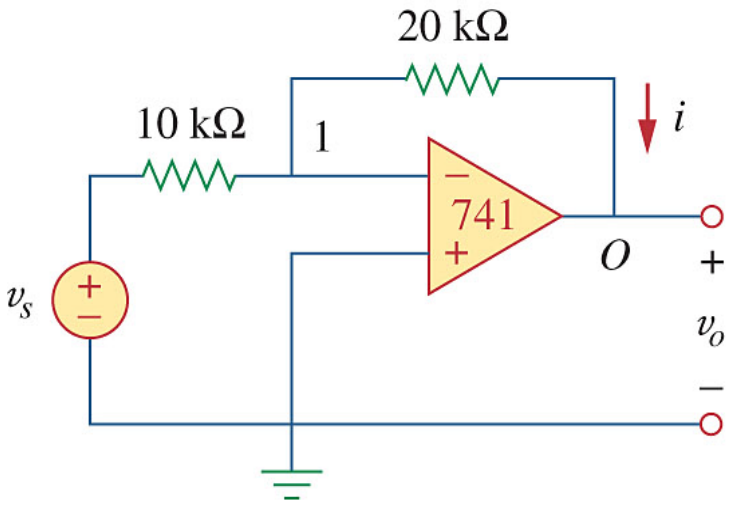
Typical ranges for op amp parameters

Parameter	Typical range	Ideal values
Open-loop gain, A	10^5 to 10^8 Ω	∞
Input resistance, R_i	10^5 to 10^{13} Ω	∞ Ω
Output resistance, R_o	10 to 100 Ω	0 Ω
Supply voltage, V_{CC}	5 to 24 V	

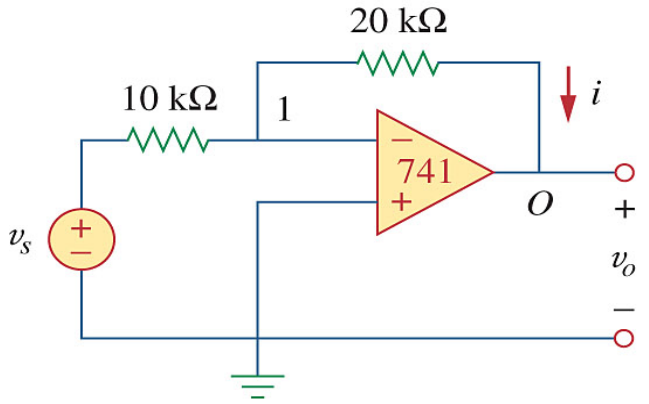
Op-amp (Introduction)

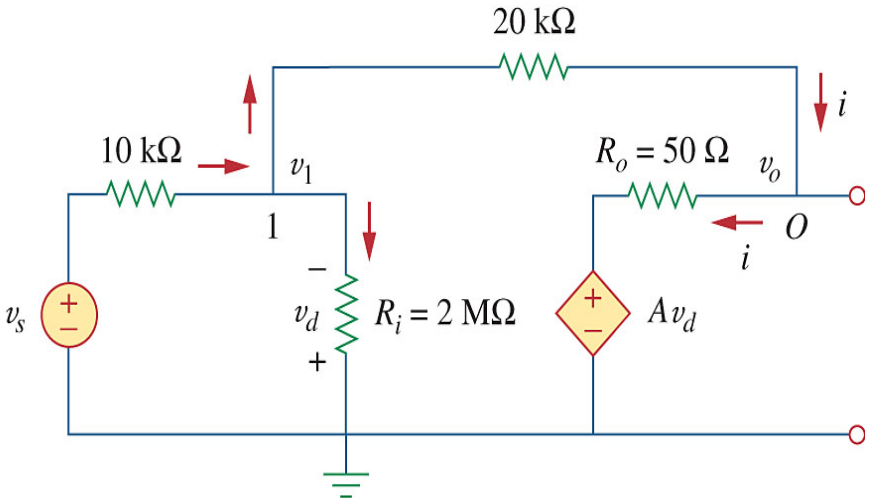
Example 5.1

A 741 op amp has an open-loop gain of 2 X 10E5, input resistance of 2 megaohm and output resistance of 50 ohm. The op amp is used in the circuit below. Find the close-loop gain v_0/v_s. Determine the current i when v_s is 2 V.



Op-amp (Introduction)

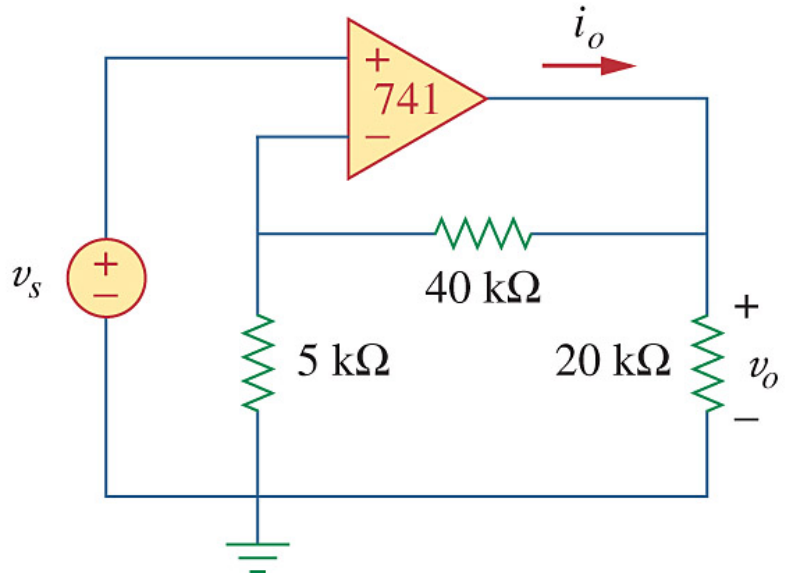




Op-amp (Introduction)

Practice Problem 5.1

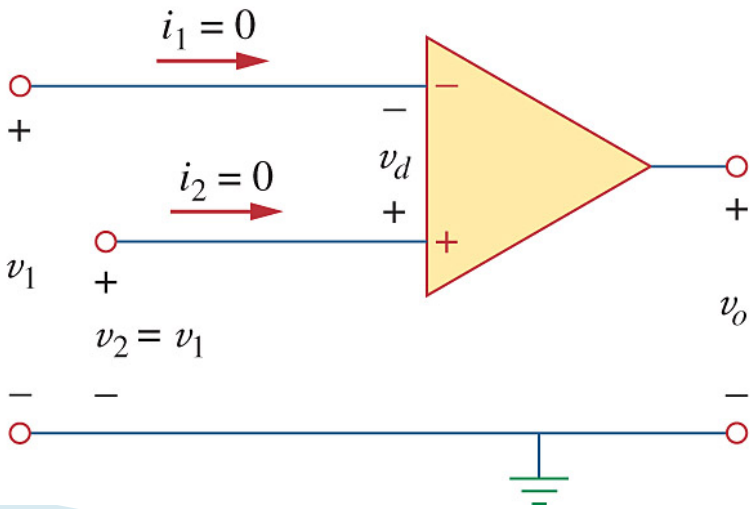
A 741 op amp has an open -loop gain of 2 X 10E5, input resistance of 2 megaohm and output resistance of 50 ohm. The op amp is used in the circuit below. Find the close-loop gain v_0/v_s. Determine the current I when v_s is 1 V.



IDEAL OP AMP

An Ideal op amp has the following characteristics:

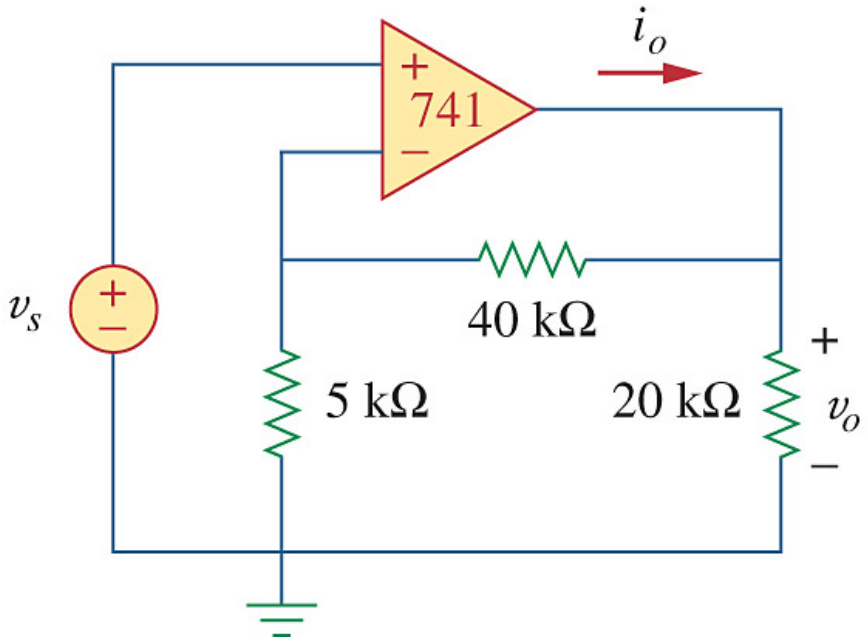
1. Infinite open-loop gain, $A \approx \infty$
2. Infinite input resistance, $R_i \approx \infty$
3. Zero output resistance, $R_o \approx 0$
4. Current into both input terminals are zero
5. Voltage across the input terminals is equal to zero



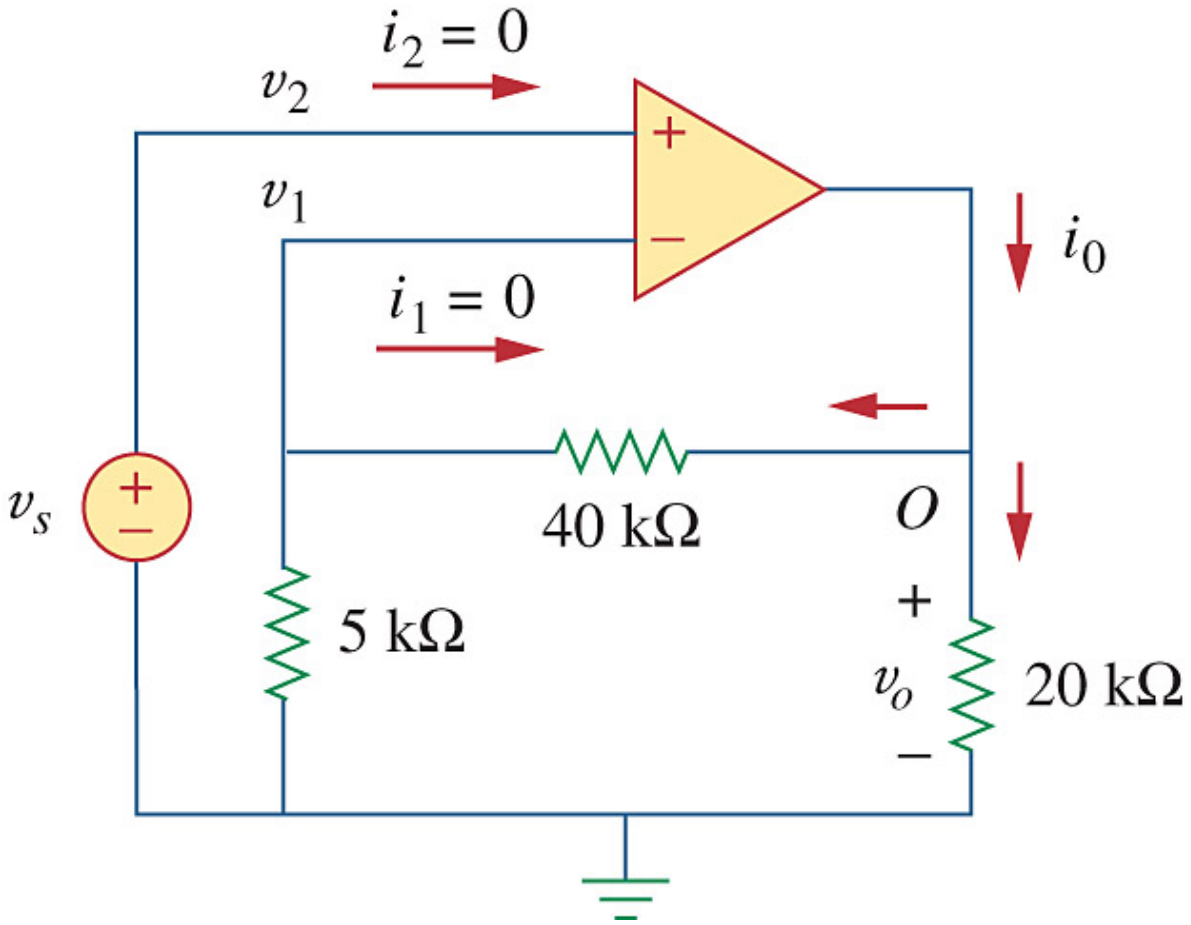
Op amp

Example 5.2

Find the close-loop gain and i_0 in the circuit below using the ideal op amp model



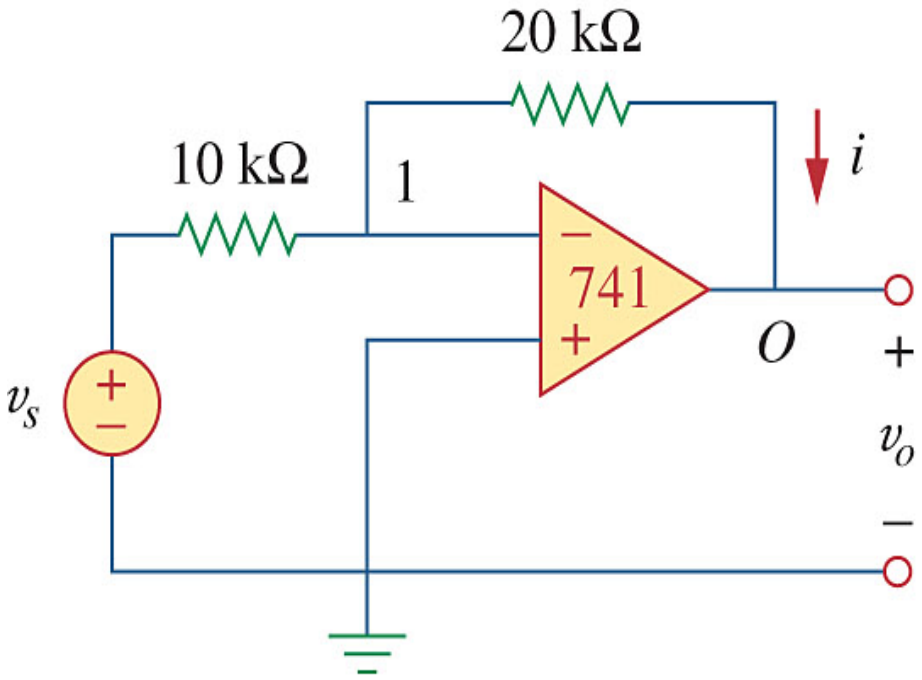
Op amp



Op amp

Practice Problem 5.2

Repeat example 5.1 using the ideal op amp model *(Q: Find the close-loop gain v_0/v_s. Det. Current i when v_s = 2 V)*



Tutorial (Non-ideal op amps)

1. The output voltage of an op amp is -4 V when the non-inverting input is 1 mV. If the open-loop gain of the op amp is 2×10^6, what is the inverting input? (Prob 5.4)
2. For the op amp circuit of Fig. 5.44, the op amp has an open-loop gain of 100,000, an input resistance of 10 kΩ, and an output resistance of 100 Ω. Find the voltage gain v_o/v_i using the non-ideal model of the op amp. (Prob. 5.5)
3. The op amp in Fig. 5.46 has $R_i = 100$ kΩ, $R_o = 100$ Ω, $A = 100{,}000$. Find the differential voltage v_d and the output voltage v_o. (Prob. 5.7)

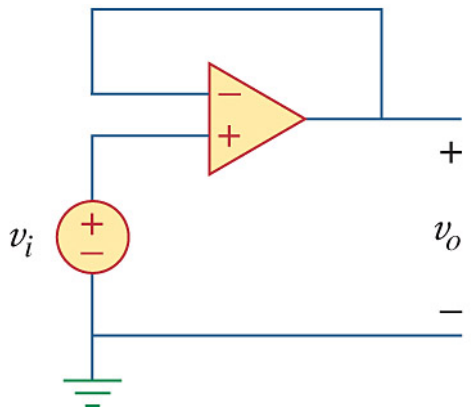


Fig. 5.44

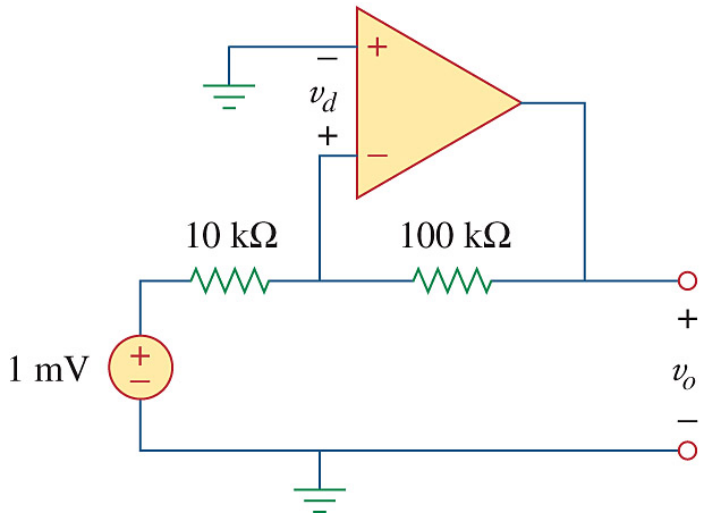


Fig. 5.46

Tutorial (Ideal op amps)

1. Calculate the voltage ratio v_o/v_s for the op amp circuit of Fig. 5.51. Assume that the op amp is ideal. (Prob 5.12)
2. Determine the output voltage v_o in the circuit of Fig. 5.53. (Prob. 5.14)

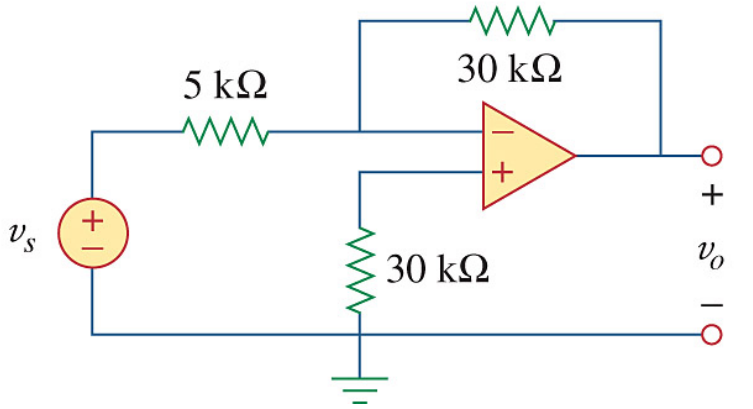


Fig. 5.51

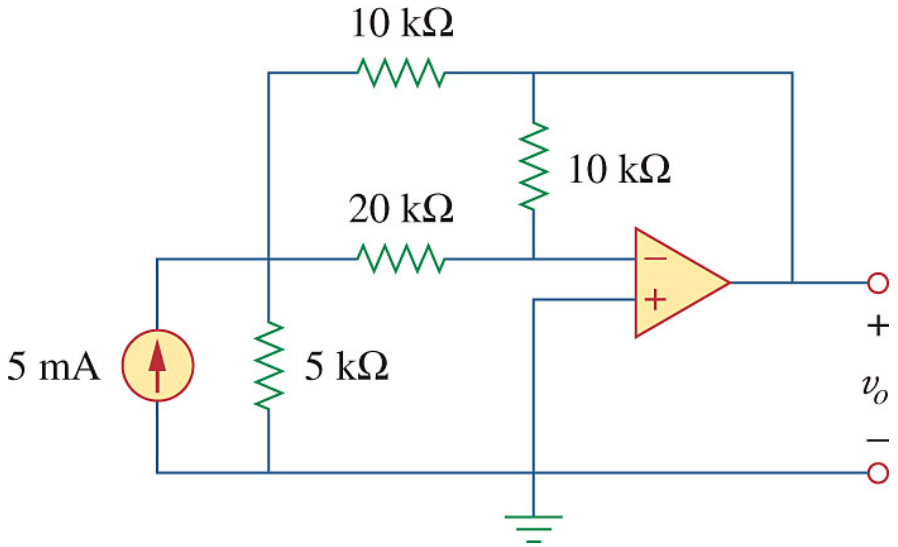


Fig. 5.53

INVERTING AMPLIFIER

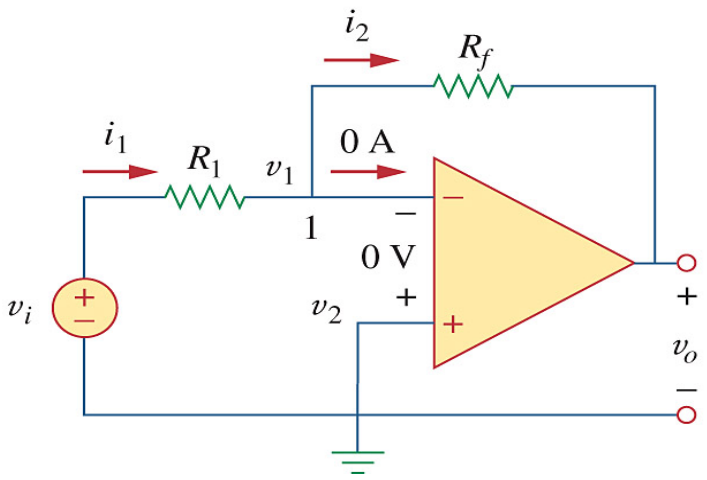


Fig.: Inverting Amplifier

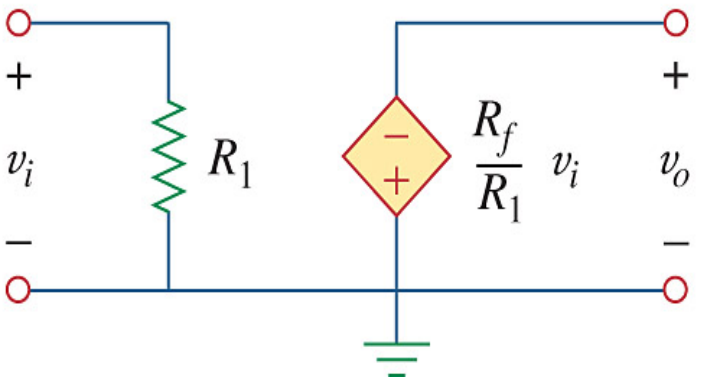


Fig.: Equivalent model

Characteristics:

- Non-inverting input is connected to the ground
- Input voltage v_i is connected to the inverting input through R_1
- A feedback resistor R_f is connected between the inverting input and output

Key feature: Both its input signal and feedback are applied at its inverting input

Inverting Amplifier

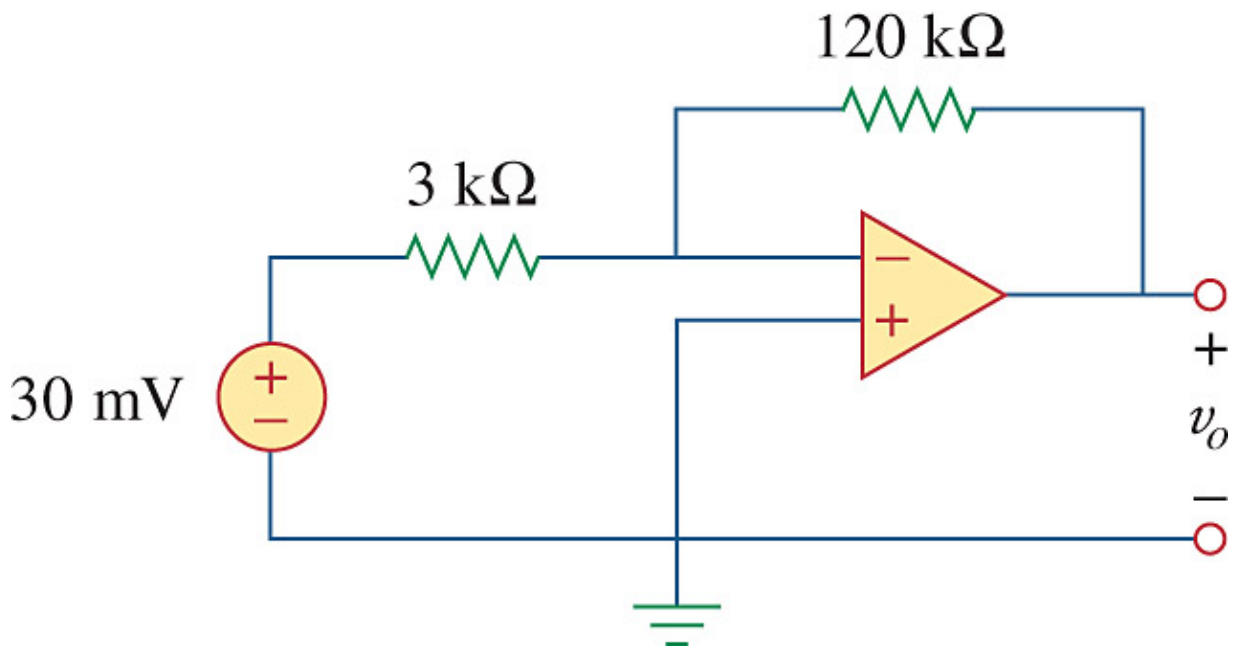
$$v_o = -\frac{R_f}{R_1} v_i$$

An inverting amplifier reverses the polarity of the circuit while amplifying it

Inverting Amplifier

Practice Problem 5.3

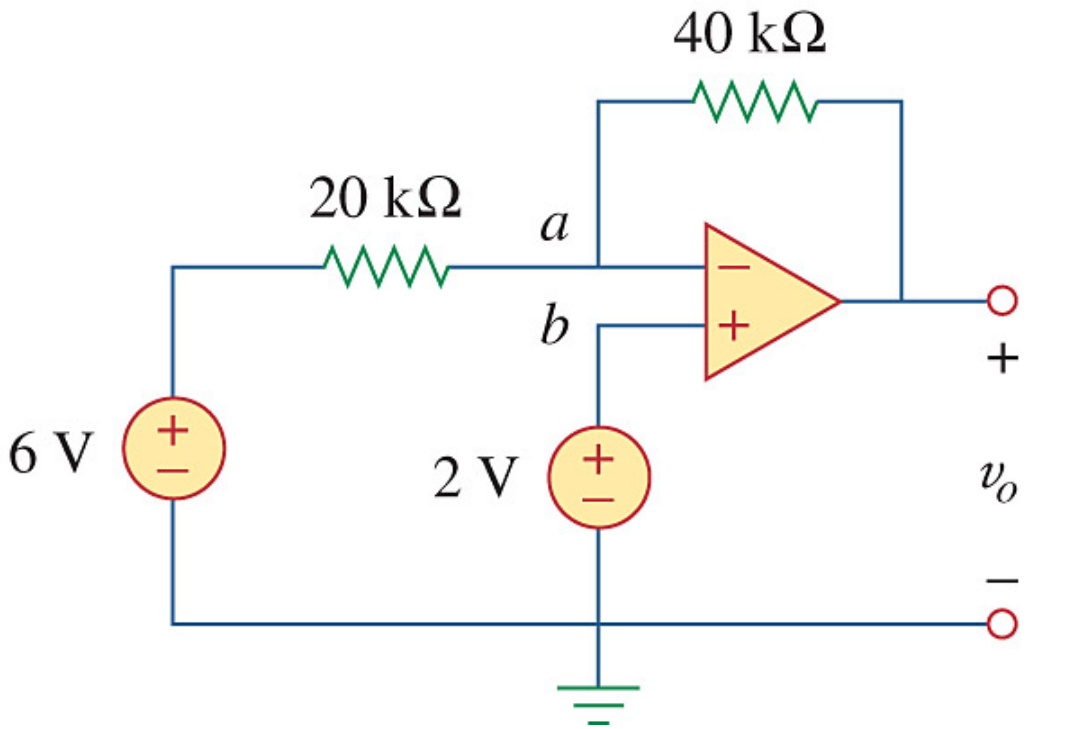
Find the output of the op amp circuit shown below. Calculate the current through the feedback resistor.



Inverting Amplifier

Example 5.4

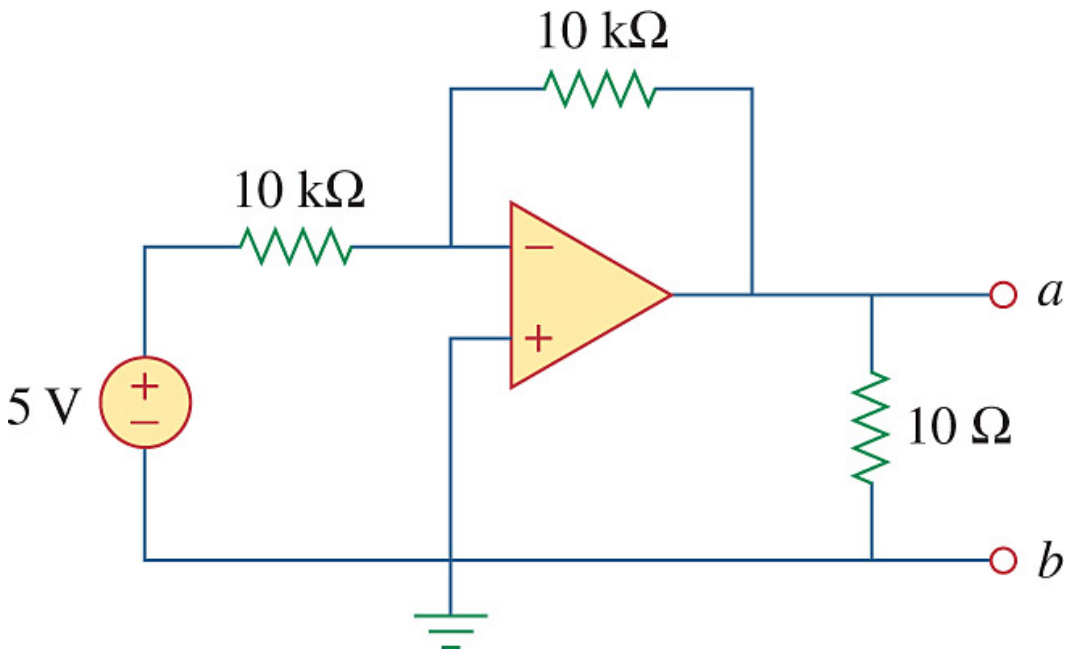
Determine v_0 in the op amp below



Tutorial (Inverting Amplifiers)

Problem 5.18

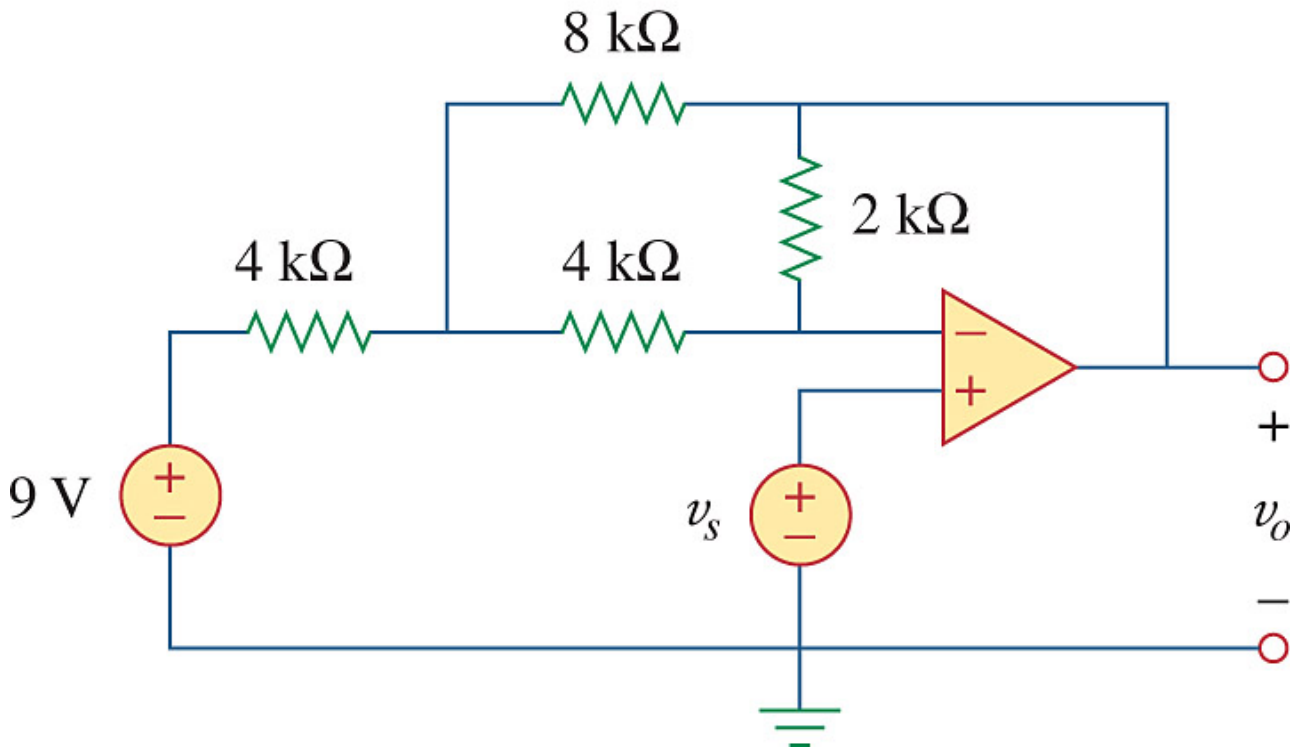
Solve the thevenin equivalent looking into the terminal A and B of the circuit below



Tutorial (Inverting Amplifiers)

Problem 5.20

In the circuit below, calculate V_0 of $V_s = 0$

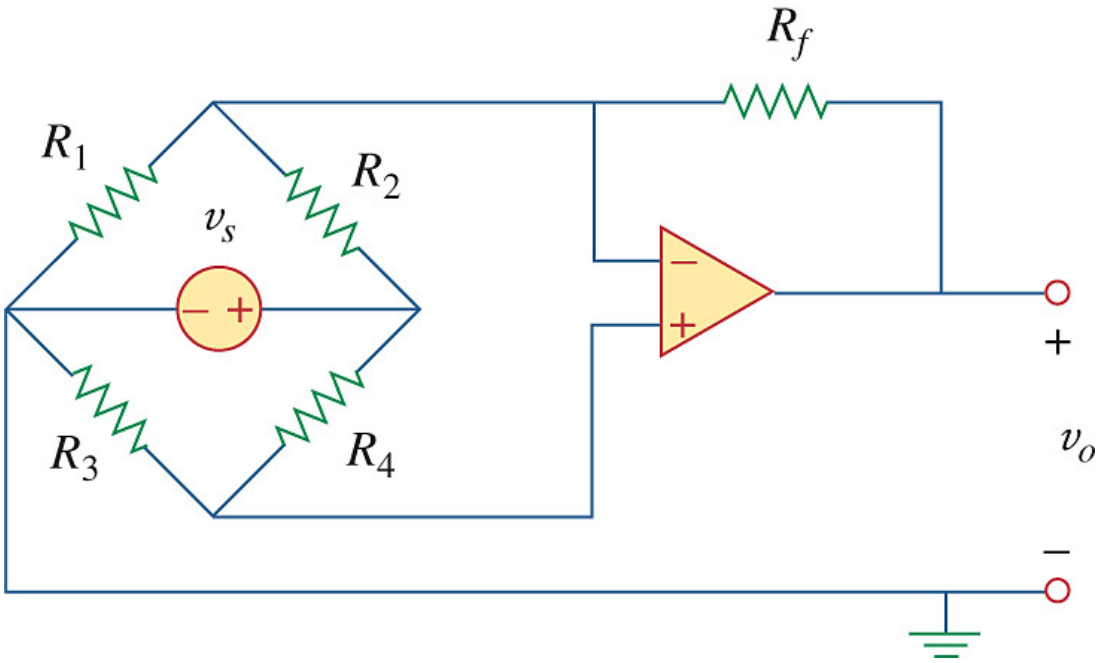


Tutorial (Inverting Amplifiers)

Problem 5.24

In the circuit below, find *k* in the voltage transfer function

$v_0 = kv_s$



NON-INVERTING AMPLIFIER

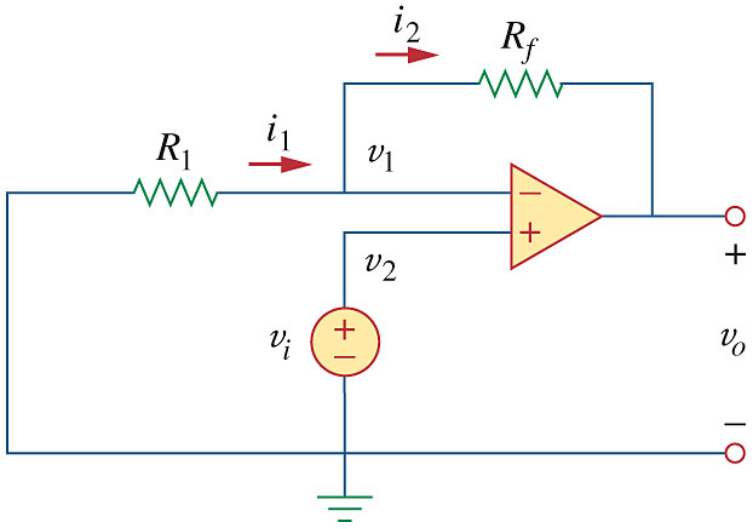


Fig.: Non-inverting Amplifier

Characteristics:

- Resistor R_1 is connected between the ground and the inverting terminal.
- Input voltage v_i is connected to the non- inverting input.
- A feedback resistor R_f is connected between the inverting input and output

Non-inverting Amplifier

$$v_o = \left(1 + \frac{R_f}{R_1}\right) v_i$$

An non-inverting amplifier is designed to provide a positive voltage gain

Non-inverting Amplifier

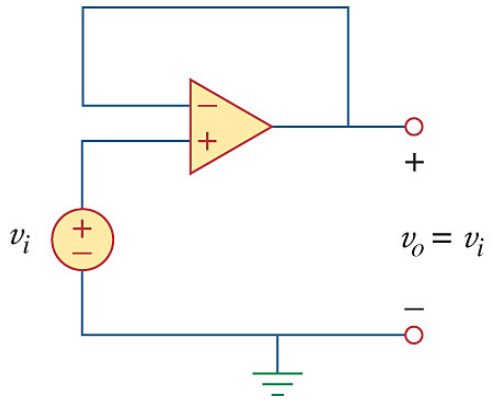


Fig.: Voltage follower

- Voltage follower circuits have high input impedance.
- Application: Used to isolate one circuit from another as they minimize interaction between circuits thus eliminating interstage loading.

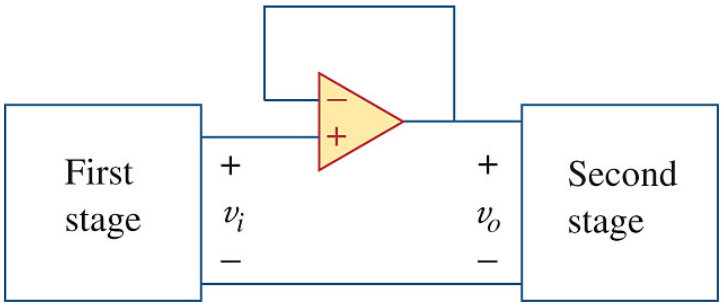
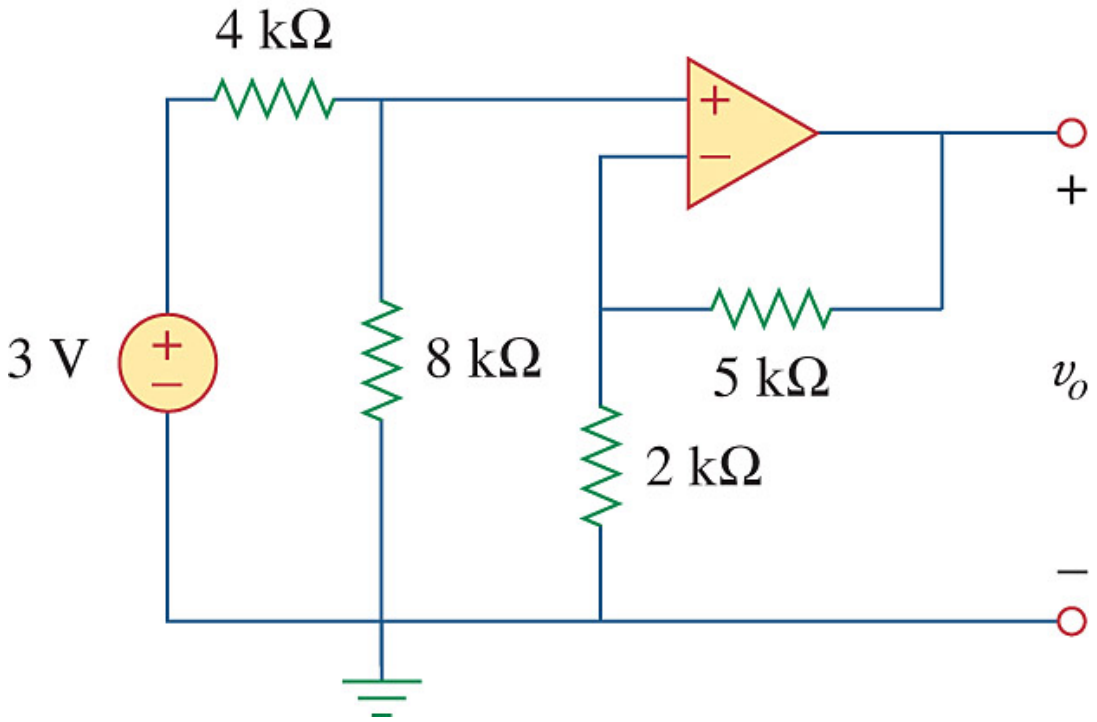


Fig.: Voltage follower used to isolate two cascaded stages of a circuit

Non-inverting Amplifier

Practice Problem 5.5

Determine v_0 in the circuit below



SUMMING AMPLIFIER

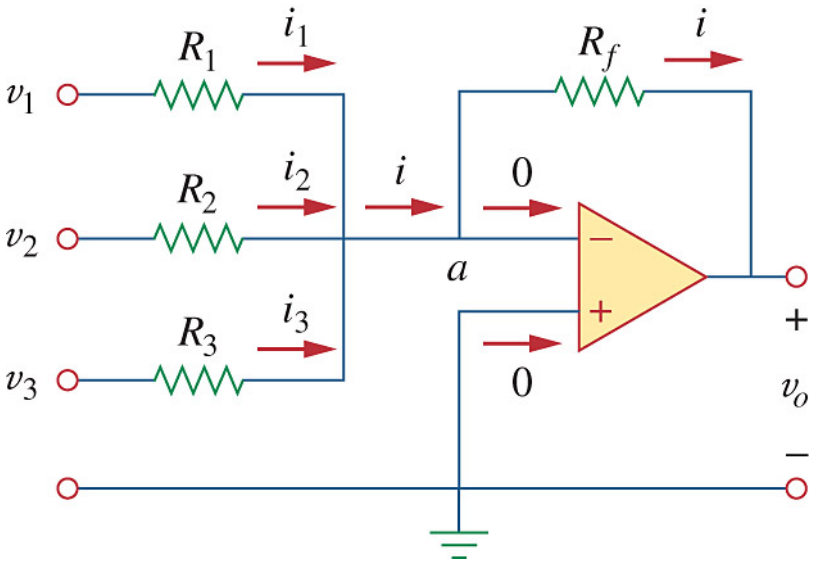


Fig.: Summing Amplifier

- Is a variation of the inverting amplifier.
- Takes the advantage of the fact that the inverting configuration can handle many inputs at the same time

Summing Amplifier

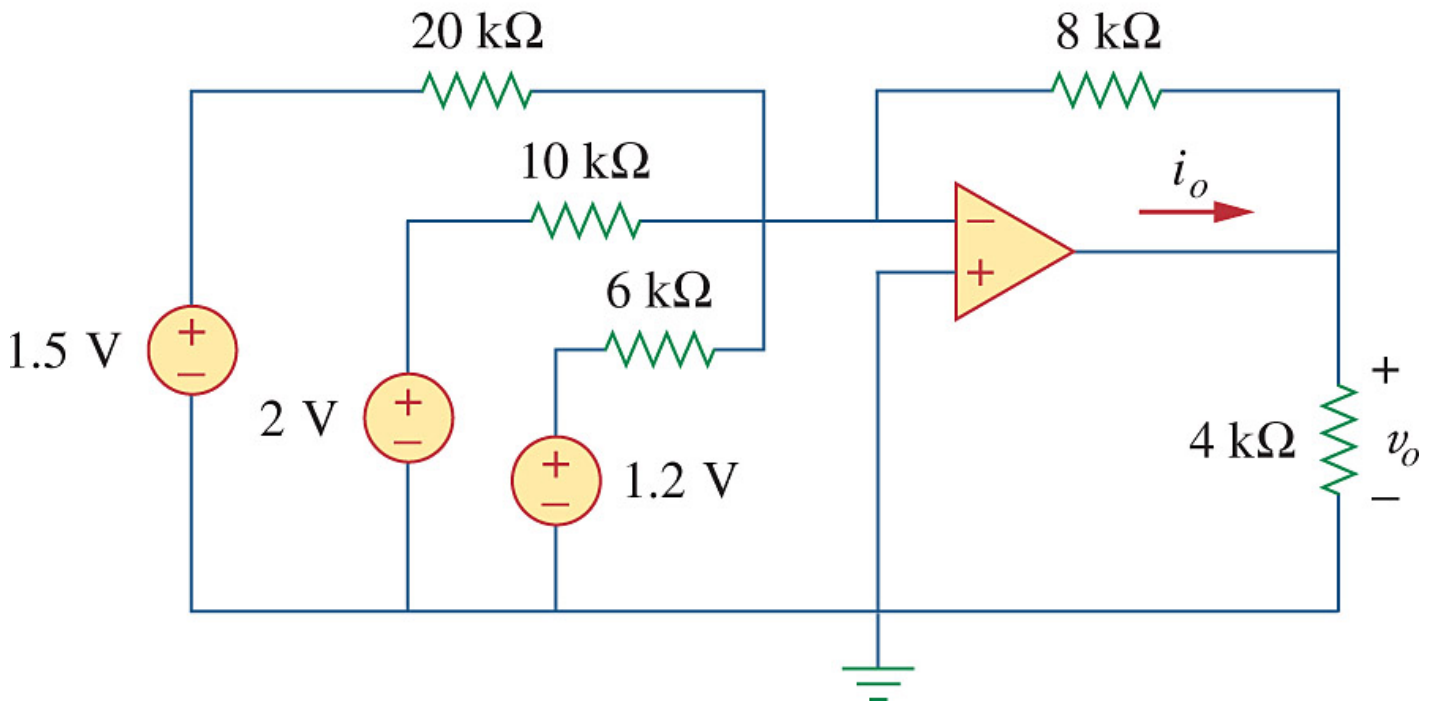
$$v_o = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3 \right)$$

A summing amplifier combines several inputs and produces an output that is the weighted sum of the inputs

Summing Amplifier

Practice Problem 5.6

Determine v_o and i_o in the circuit below



DIFFERENCE AMPLIFIER

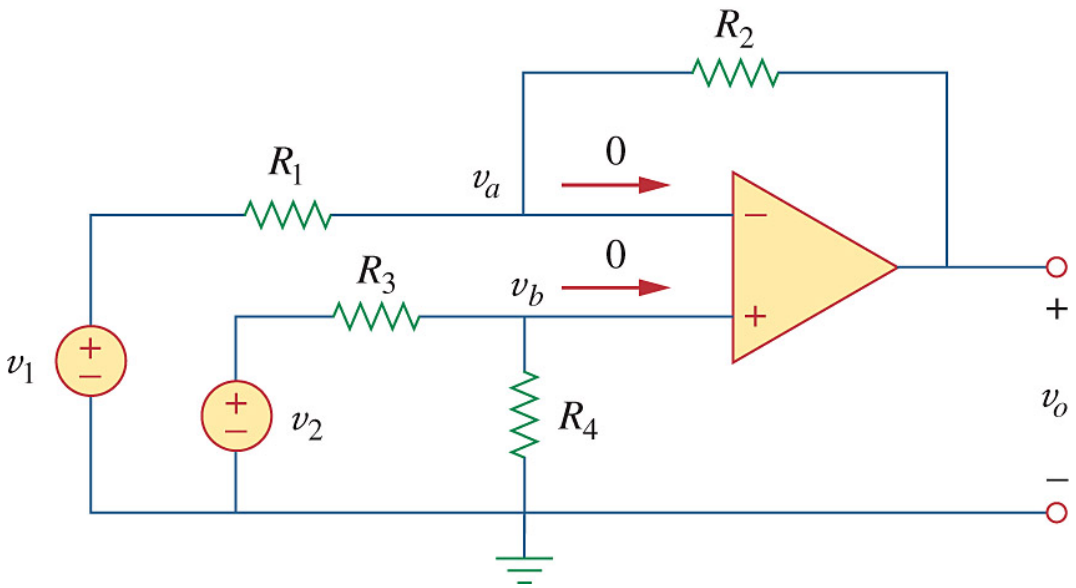
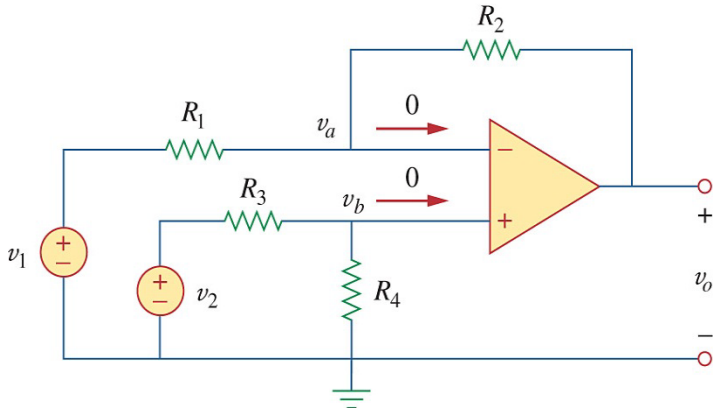


Fig.: Difference Amplifier

A difference amplifier amplifies the difference between two inputs but rejects any signals common to the two inputs

Application: amplifying the difference between two input signals

Difference Amplifier



Applying KCL at node a,

$$\frac{v_1 - v_a}{R_1} = \frac{v_a - v_0}{R_2}$$

$$v_0 = \left(\frac{R_2}{R_1} + 1\right) v_a - \frac{R_2}{R_1} v_1 \qquad (1)$$

Applying KCL at node b,

$$\frac{v_2 - v_b}{R_3} = \frac{v_b - 0}{R_4}$$

$$v_b = \frac{R_4}{R_3 + R_4} v_2 \qquad (2)$$

Substituting (2) into (1) since $v_a = v_b$

$$v_0 = \left(\frac{R_2}{R_1} + 1\right) \frac{R_4}{R_3 + R_4} v_2 - \frac{R_2}{R_1} v_1$$

$$v_0 = \frac{R_2(1 + R_1/R_2)}{R_1(1 + R_3/R_4)} v_2 - \frac{R_2}{R_1} v_1$$

For difference amplifier, when $v_1 = v_2$, v_o must be zero, this condition exists when

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Therefore, for a difference amplifier,

$$v_0 = \frac{R_2}{R_1}(v_2 - v_1)$$

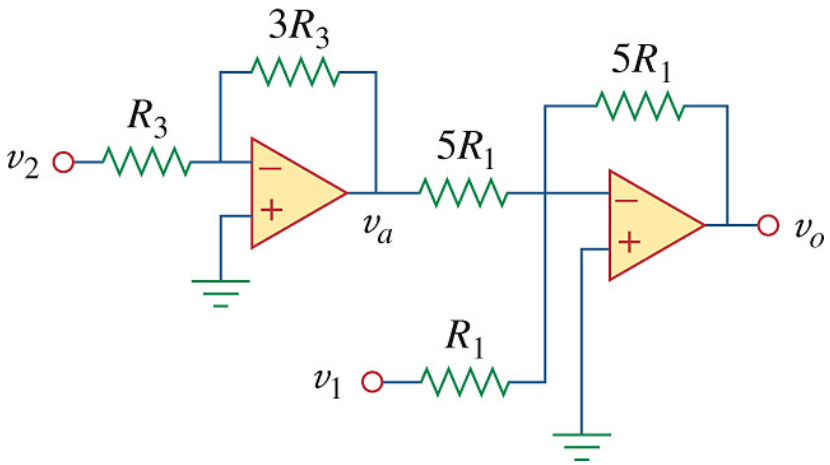
If $R_2 = R_1$ and $R_3 = R_4$, the difference amplifier becomes a ***SUBTRACTOR***

$$v_0 = (v_2 - v_1)$$

Difference Amplifier

Example 5.7

Design an op amp circuit with inputs v_1 and v_2 such that $v_0 = -5v_1 + 3v_2$



Practice Probem 5.7

Design a difference amplifier with gain 5

CASCADED OP AMP CIRCUIT

- It is a head-to-tail arrangement of two or more op amp circuits such that the output to one is the input of the next

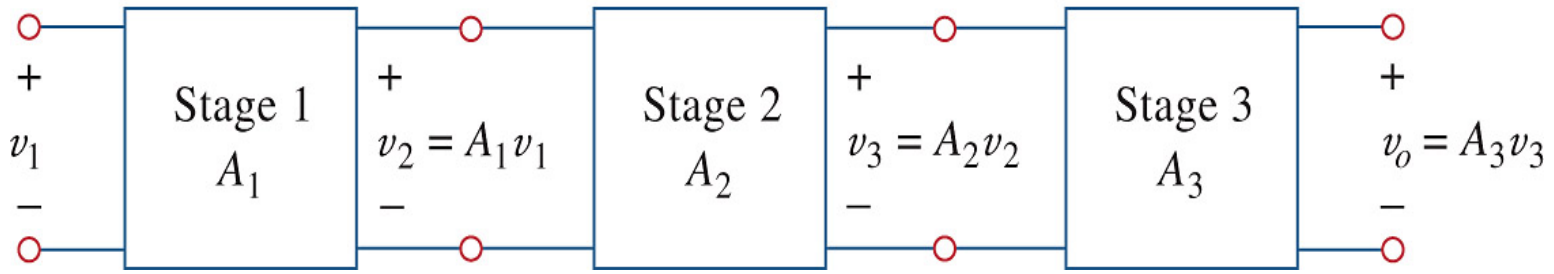


Fig.: A three stage cascaded connection

Characteristics:

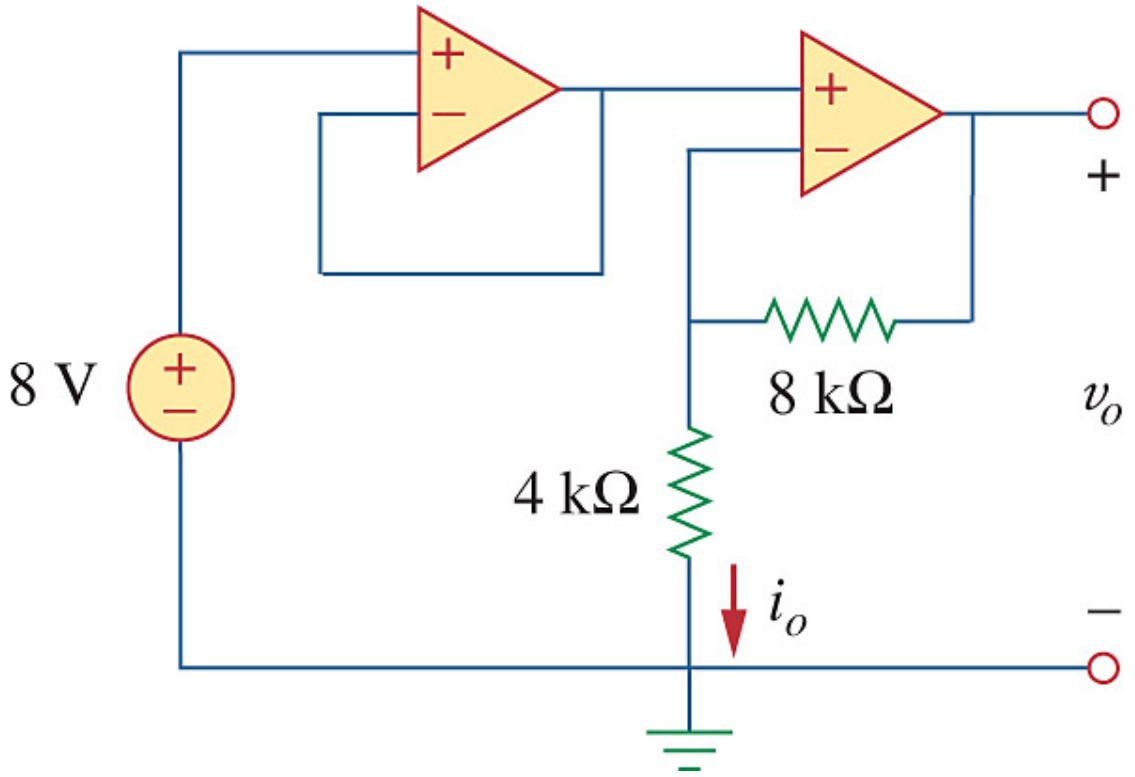
- The original input signal is increased by the gain of the individual stage
- Each op amp circuit is ideal, thus can be cascaded with another without change the input-output relationship

Caution: when cascading op amp circuits, in actual op amp design, care should be taken such that the load due to the next stage in the cascade does not saturate the op amp

Cascaded Op amp circuits

Practice Problem 5.9

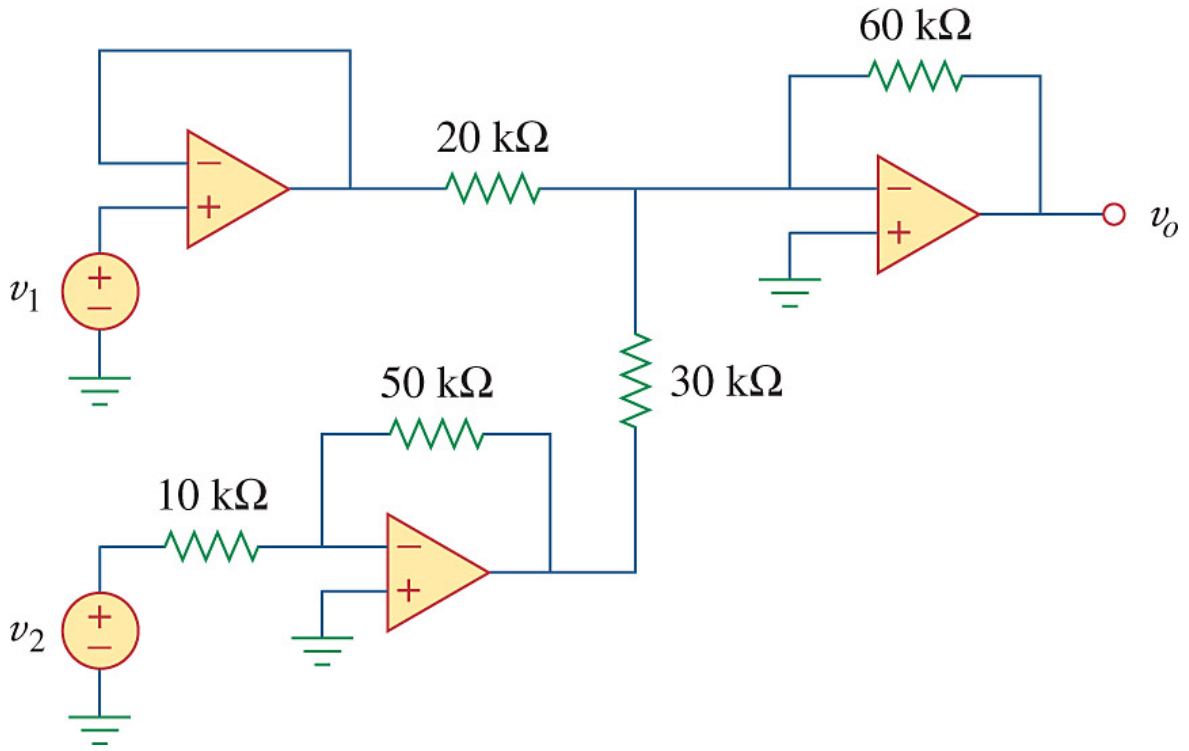
Determine v_o and i_o in the circuit below



Cascaded Op amp circuits

Practice Problem 5.10

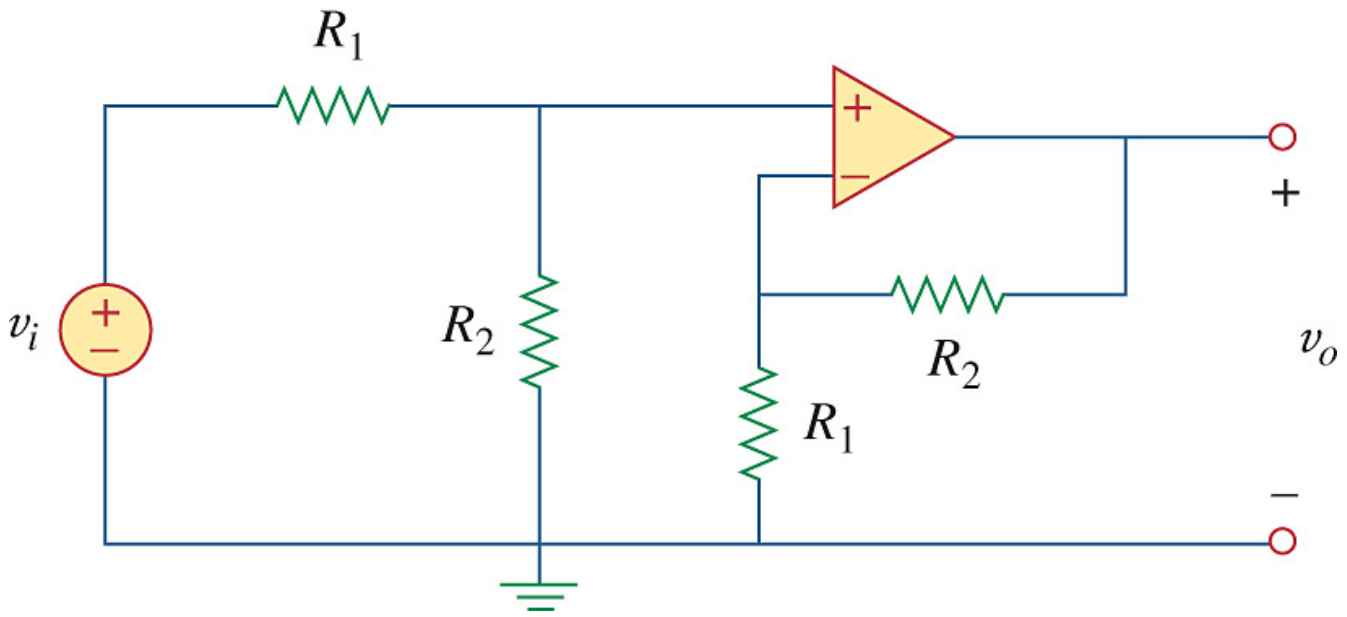
If $v_1 = 4$ V and $v_2 = 3$ V, find v_0 in the op amp circuit below:



Tutorials

Problem 5.29

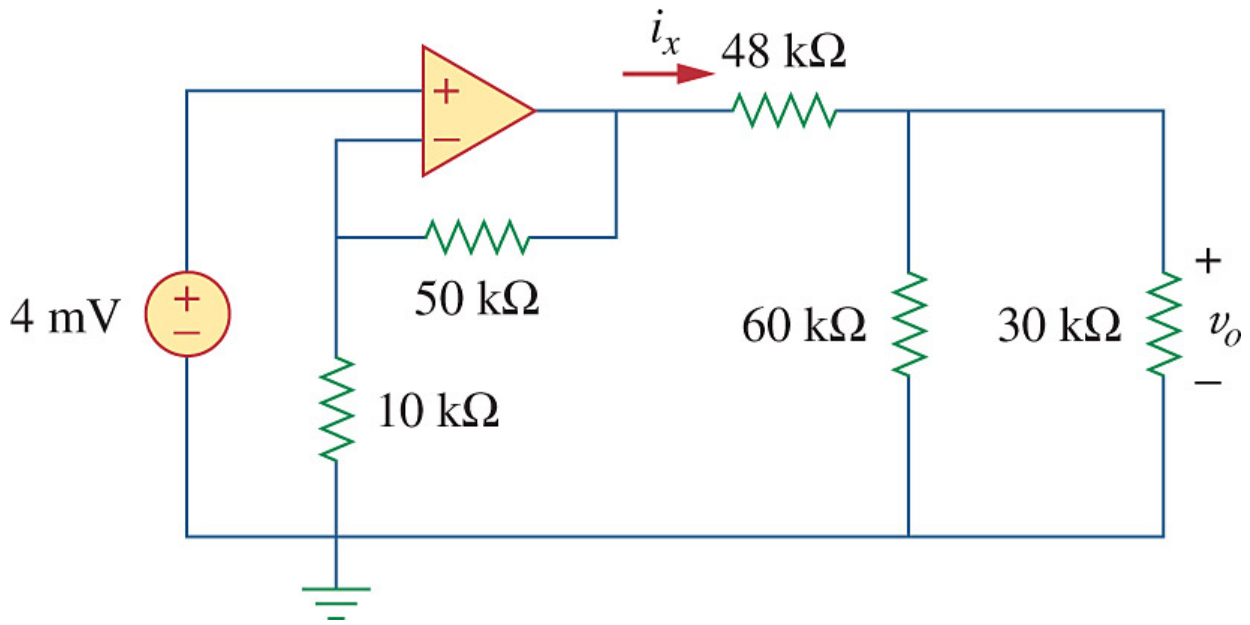
Determine the voltage gain v_0/v_i of the op amp circuit below



Tutorials

Problem 5.32

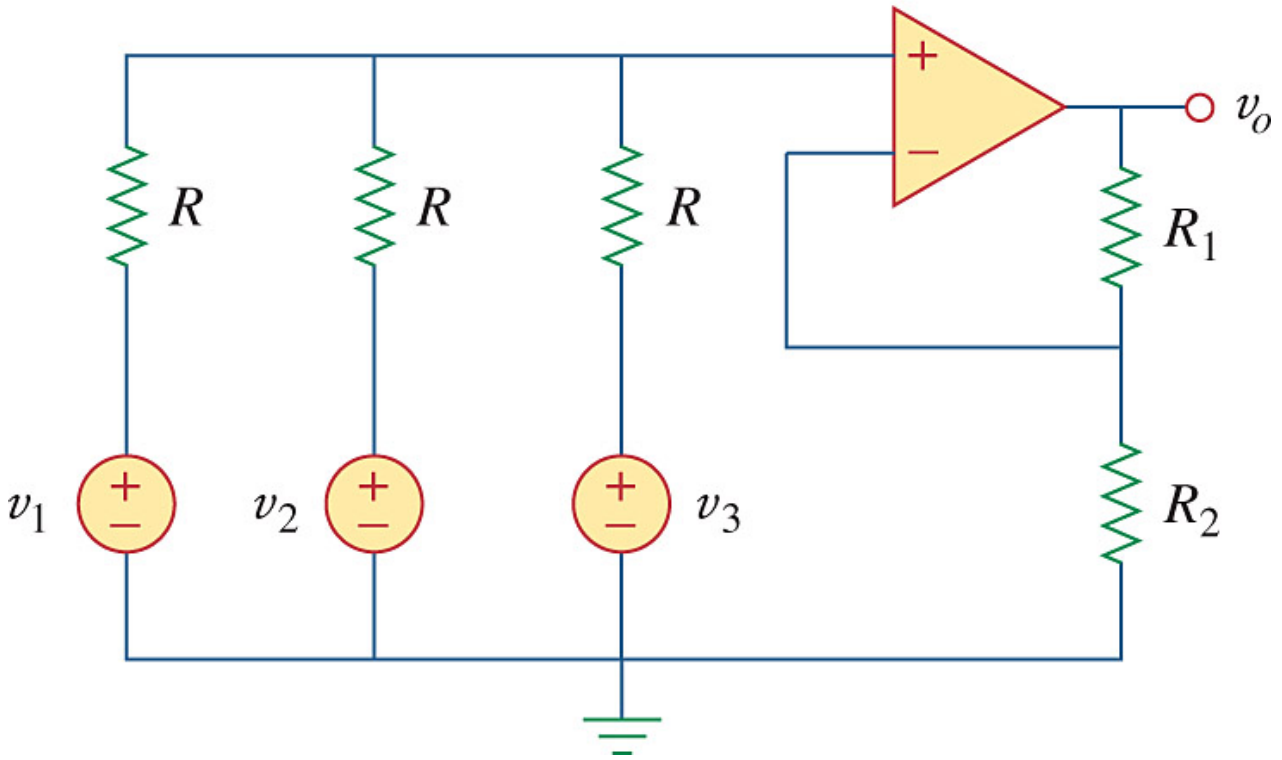
Calculate i_x and v_0 in the circuit below. Find the power dissipated by the 30-kiloohm resistor



Tutorials

Problem 5.40

Find v_0 in terms of v_1, v_2, v_3 in the circuit below

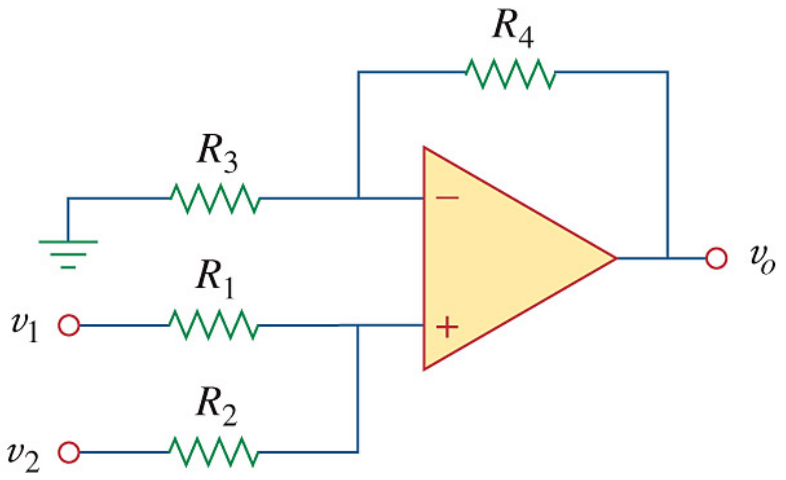


Tutorials

Problem 5.44

Show that the output voltage v0 of the circuit below is

$$v_0 = \frac{(R_3 + R_4)}{R_3(R_1 + R_2)}(R_2 v_1 + R_1 v_2)$$



Tutorials

1. Using only 2 op amps, design a circuit to solve

$$-v_{out} = \frac{v_1 - v_2}{3} + \frac{v_3}{2}$$

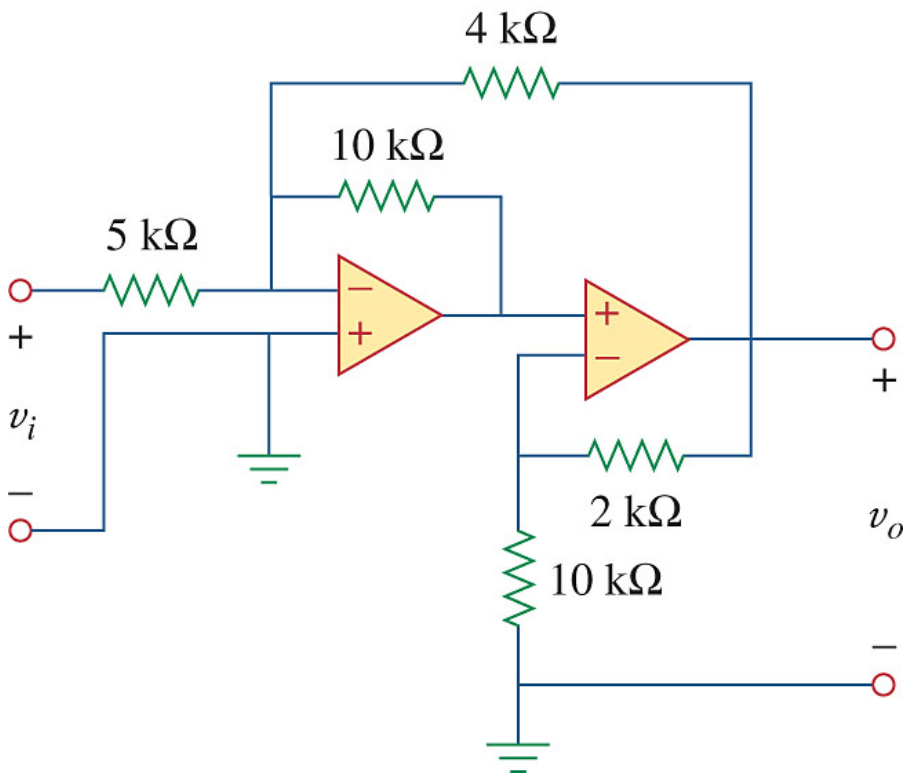
2. Design an op amp to perform the following operation:

$$v_0 = 5v_1 + 4v_2 - 2v_3$$

Tutorials

Problem 5.60

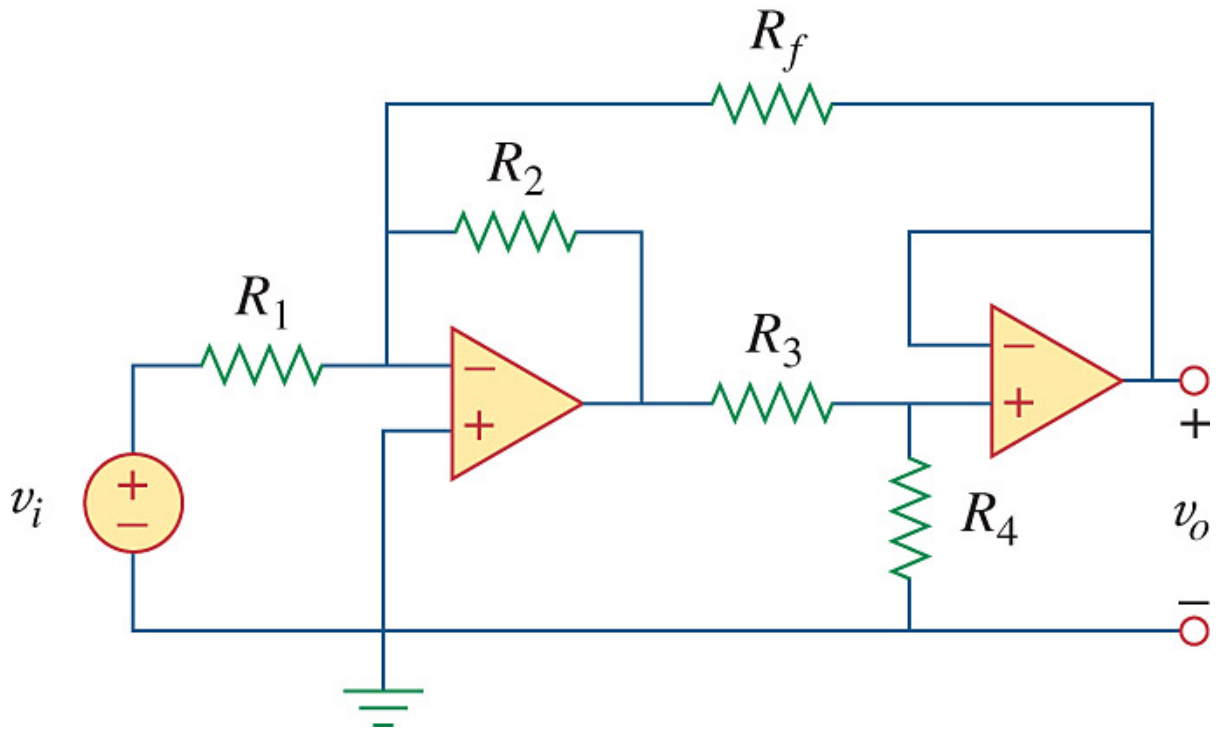
Calculate v_0/v_i in the op amp circuit below:



Tutorials

Problem 5.63

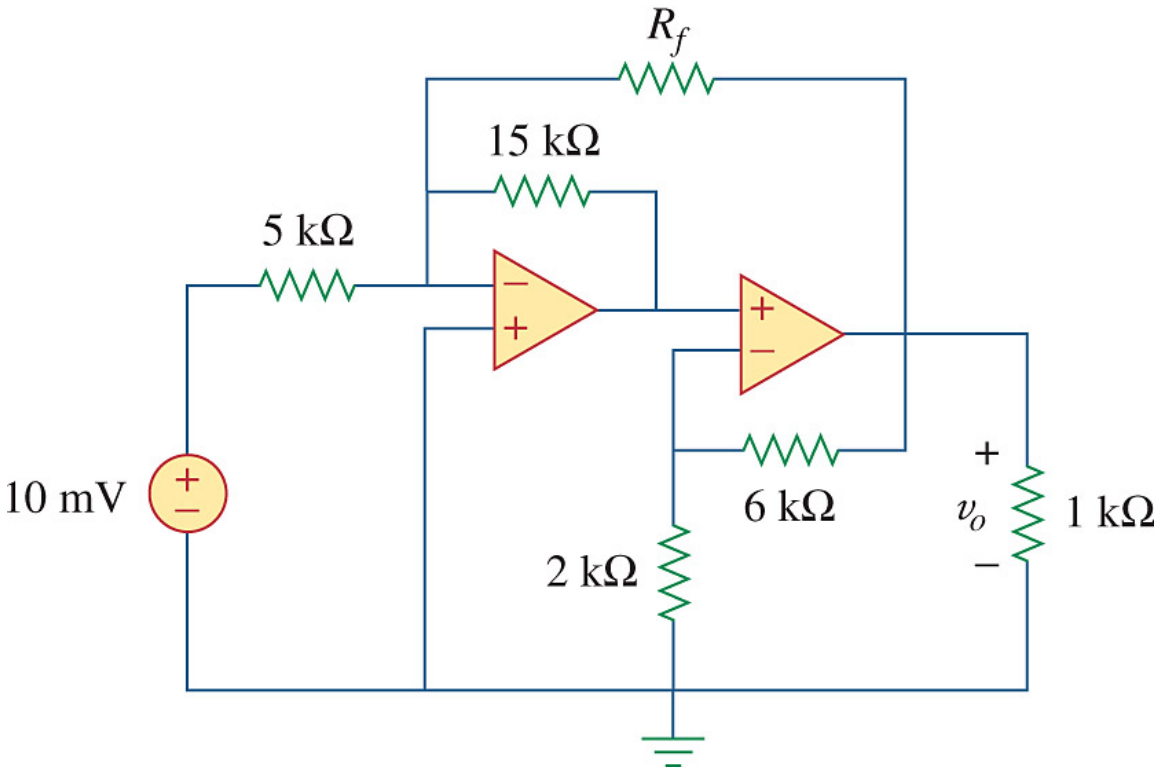
Determine the gain v_0/v_i in the op amp circuit below:



Tutorials

Problem 5.69

Find v_0 in the circuit below if R_f is 10 kiloohm



Tutorials

Problem 5.71

Determine v_0 in the circuit below