Operational Amplifiers

Last Topic of the Semester!!!!

Brief Summary

In this lecture we will

- **Learn the characteristics of ideal operational amplifiers**
- **Identify negative feedback in op-amp circuits**
- **Select op-amp circuit configurations suitable for various applications**
- **Use op-amps to design useful circuits.**
- **Work with instrumentation amplifiers.**
- **And more…**

Basics

Previously, we have discussed

- The external characteristics of amplifiers in general, and
- How basic amplifiers can be build using transistors

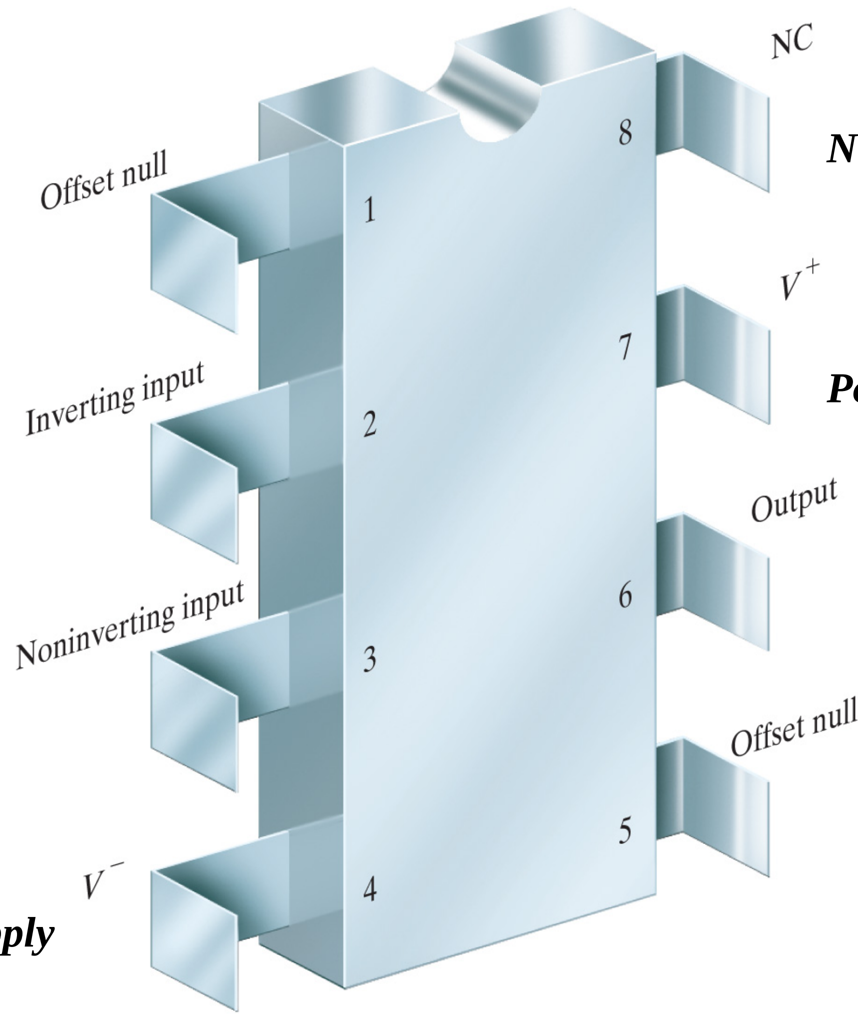
In this lecture we introduce an important device known as the operational amplifier (op-amp)

- An op-amp is a circuit composed of several transistors and other passive elements (resistors, capacitors)
- These components are manufactured concurrently on a single piece of silicon crystal (i.e. chip) by a sequence of processing steps

Operational Amplifiers

- An amplifier is a device that accepts a varying input signal and produces a similar output signal with a larger amplitude.
- The name "operational amplifier" comes from the fact that they were originally used to perform mathematical operations such as integration, differentiation, addition, sign changing, and scaling.
- Most Op-Amps behave like voltage amplifiers. They take an input voltage and produce a scaled version as output.
- They are the basic components used to build analog circuits.

Op Amp Chip example



No connection

Positive power supply

Negative power supply

Figure: 05-01

Circuit Symbols

- Circuit symbols for an op amp that contains the five terminals of primary interest.

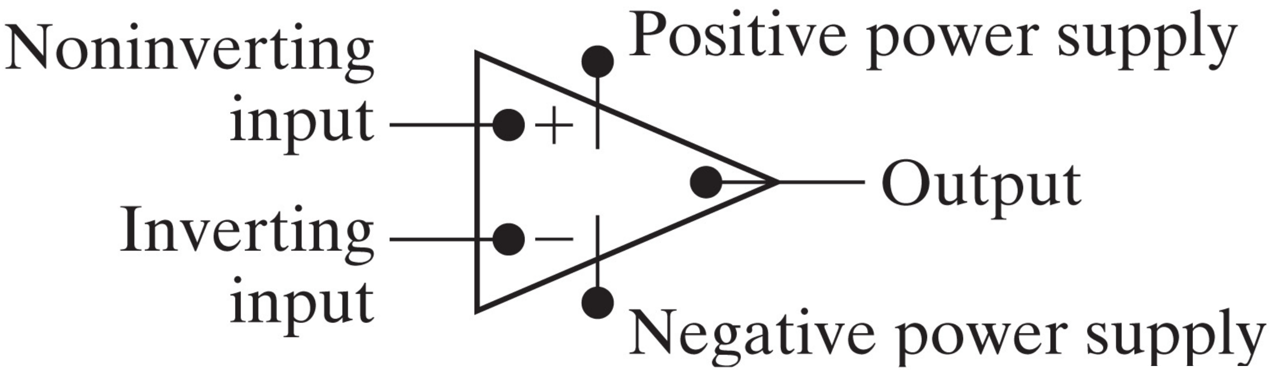


Figure: 05-02

Since we usually do not write the terminals' names we prefer this symbol in our circuits.

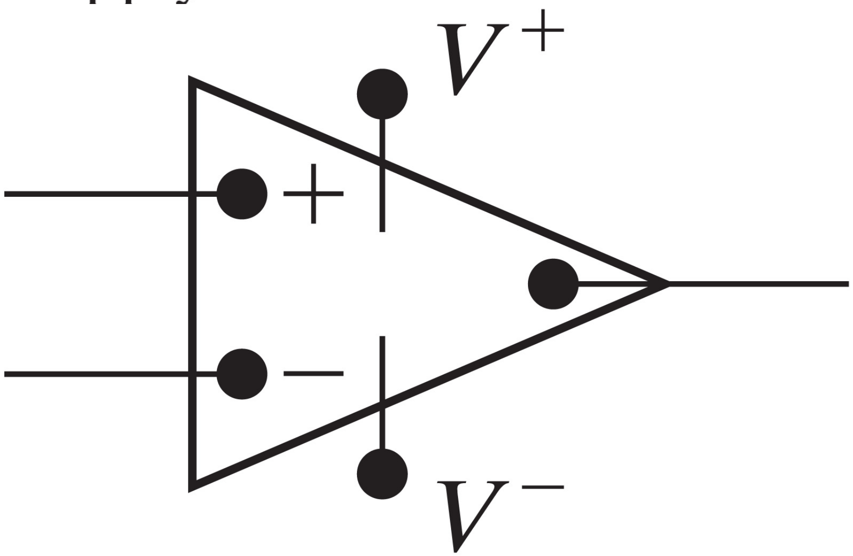


Figure: 05-03

Terminal Voltages and Currents

- Terminal voltage variables

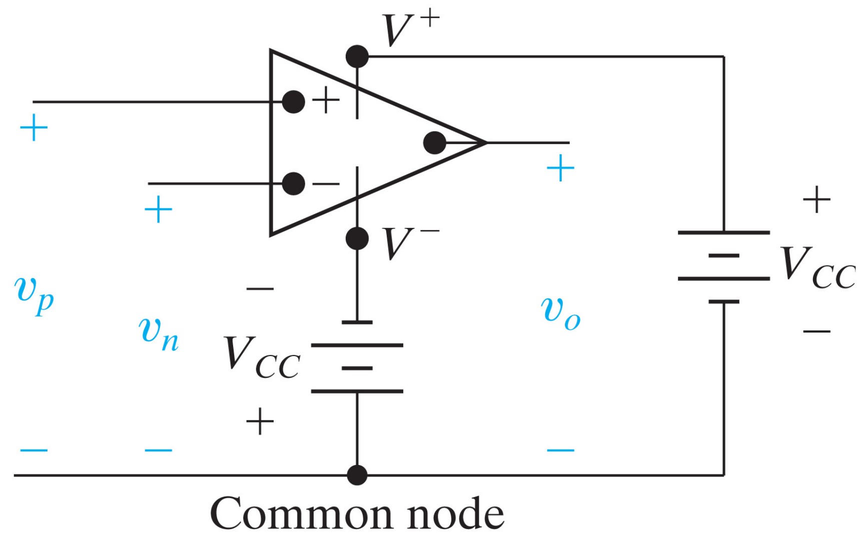


Figure: 05-04

- Terminal current variables

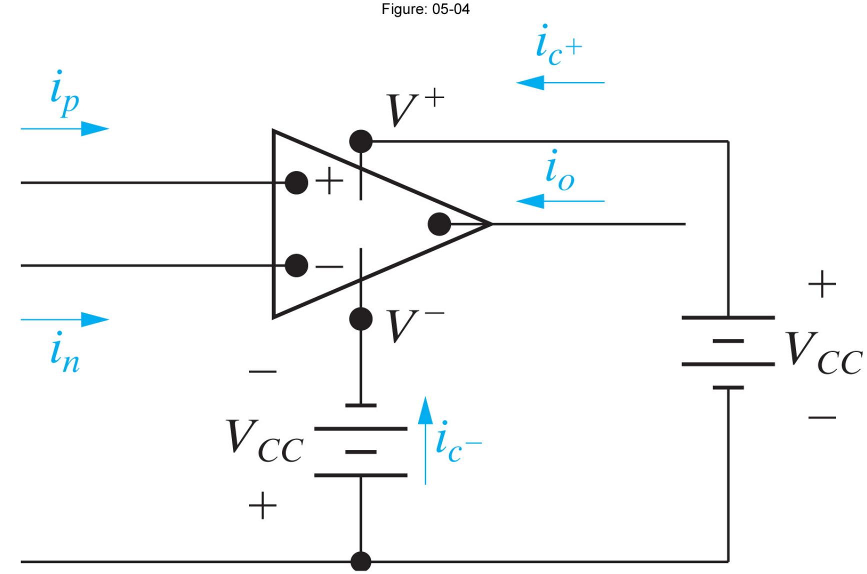


Figure: 05-05

Voltage Transfer Characteristics

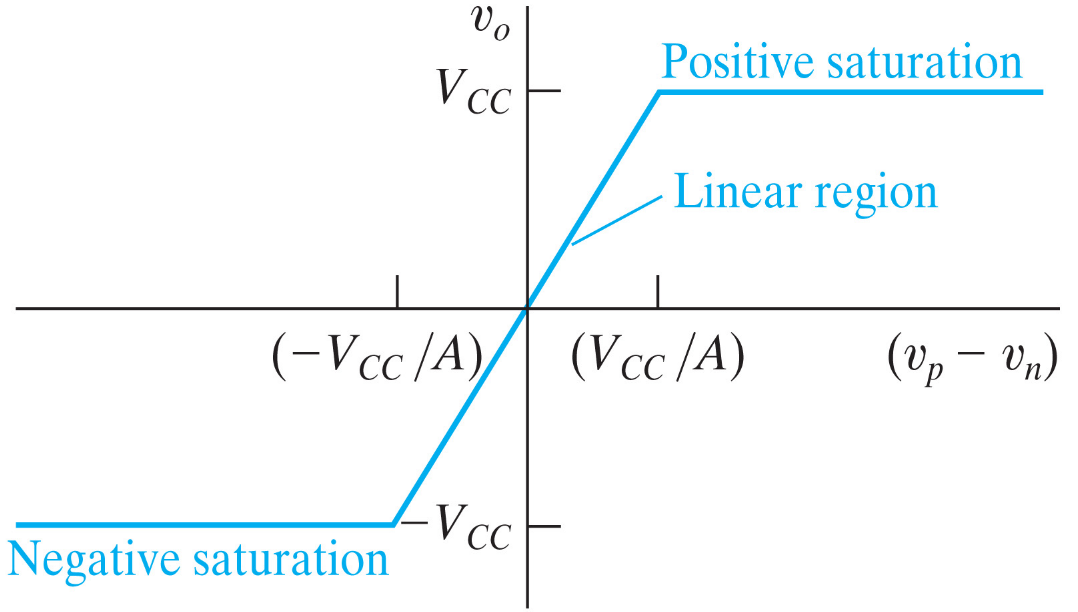


Figure: 05-06

$$v_0 = \begin{cases} -V_{CC} & A(v_p - v_n) < -V_{CC} \\ A(v_p - v_n) & -V_{CC} \le A(v_p - v_n) \le +V_{CC} \\ +V_{CC} & +V_{CC} < A(v_p - v_n) \end{cases}$$

Ideal Operational Amplifiers

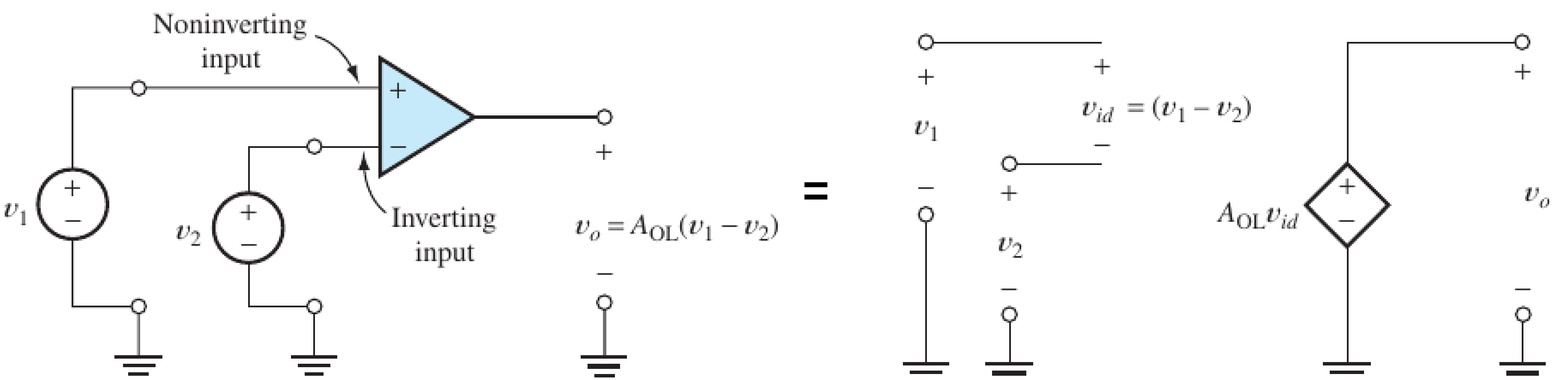
An ideal operational amplifier has

– Infinite input impedance

– Infinite gain for the differential input signal

– Zero gain for the common-mode input signal

– Zero output impedance



Equivalent circuit for an op amp

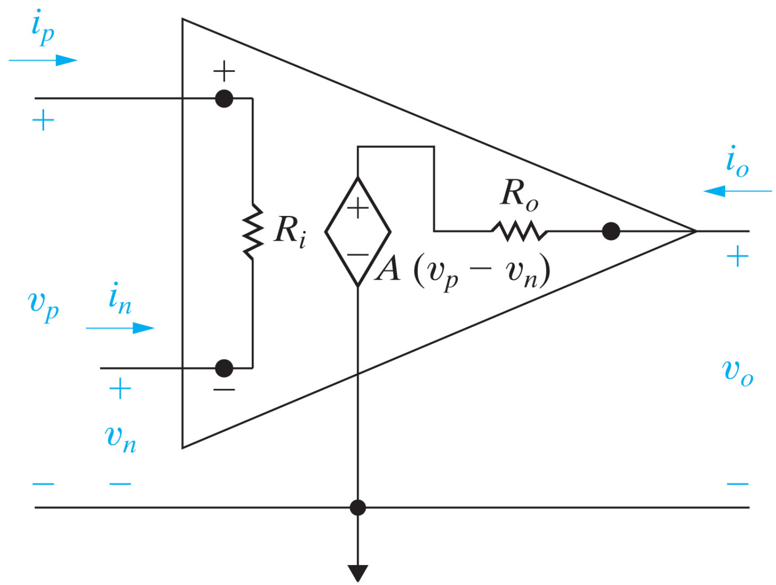
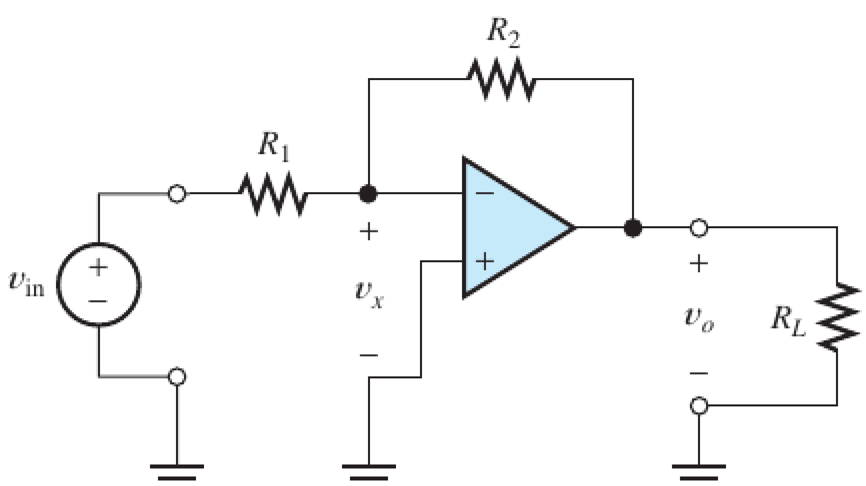


Figure: 05-15

- Circuit symbols for an op amp that contains the five terminals of primary interest.

Inverting Amplifiers

Most common usage for op-amps (with negative feedback) is as inverting amplifiers. Frequently, the op-amp circuits are analyzed by assuming ideal op-amp and then a concept called summing-point is employed.



Inverting Amplifier

$$A_v = v_o / v_{in}$$

Inverting Amplifiers

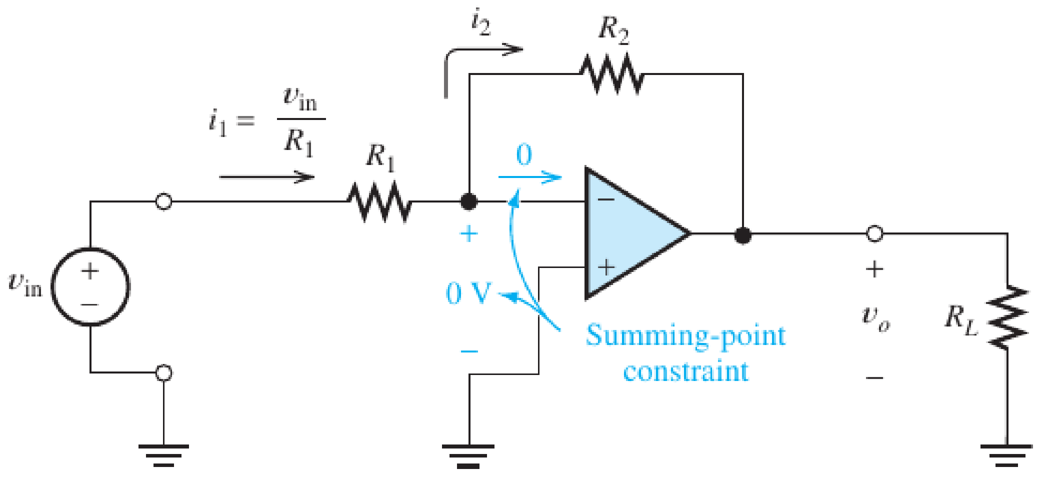
In a negative feedback system, the ideal op-amp output voltage attains the value needed to force the differential input voltage and input current to zero. This fact is called the “summing point” constraint.

Analyzing Ideal Op-Amps

Ideal op-amp circuits are analyzed using the following steps :

1. Verify that negative feedback is present
2. Assume that the differential input voltage and the input current of the op-amp are forced to zero (*)
3. Apply standard circuit analysis techniques (Ohm's law, Kirchhoff's voltage and current laws) to solve for the quantities of interest.

Back to Inverting Amplifiers



No current is flowing to the amplifier therefore :

$$i_1 = \frac{v_{in}}{R_1} \Rightarrow i_2 = i_1 \Rightarrow i_2 = \frac{v_{in}}{R_1}$$

From the output circuit $v_o + R_2 i_2 = 0$

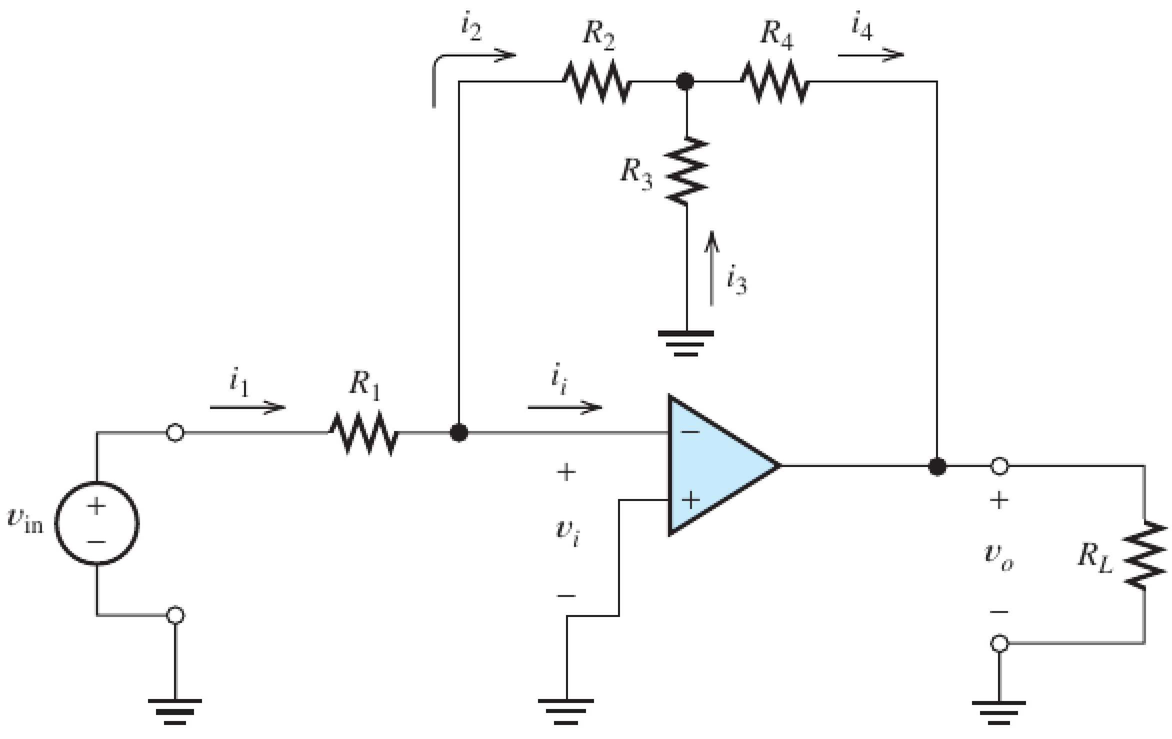
Therefore we can obtain : $v_o = -\frac{R_2}{R_1} v_{in}$

$$A_v = \frac{v_o}{v_{in}} = -\frac{R_2}{R_1}$$

Example

For the circuit given below, derive an expression for the voltage gain under ideal op-amp assumption. Evaluate the results for

$R_1 = R_3 = 1\ \text{k}\Omega$ and $R_2 = R_4 = 10\ \text{k}\Omega$.



Example: Solution

Solution :

Notice that for the ideal amplifier $v_i = 0 \quad \text{and} \quad i_i = 0$

Now apply Kirchhoff's current law on the input side to obtain

$$i_1 = \frac{v_{\text{in}}}{R_1} \qquad \text{also} \qquad i_2 = i_1 \Rightarrow i_2 = \frac{v_{\text{in}}}{R_1}$$

Then we have $i_4 = i_2 + i_3$ and $R_2 i_2 = R_3 i_3 \Rightarrow i_3 = v_{\text{in}} \frac{R_2}{R_1 R_3}$

$$\Rightarrow i_4 = v_{\text{in}} \left(\frac{1}{R_1} + \frac{R_2}{R_1 R_3} \right)$$

One more step is left : calculate the output voltage in terms of the resistors

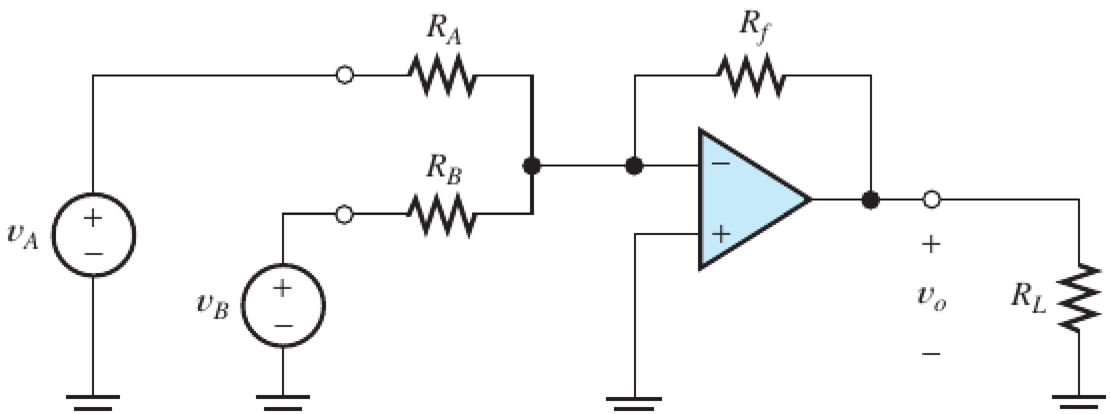
$$v_o = -R_4 i_4 - R_3 i_3$$

Plug in for the current values to obtain

$$v_o = -v_{\text{in}} \left(\frac{R_2}{R_1} + \frac{R_4}{R_1} + \frac{R_2 R_4}{R_1 R_3} \right) \Rightarrow A_v = \frac{v_o}{v_{\text{in}}} = -\left(\frac{R_2}{R_1} + \frac{R_4}{R_1} + \frac{R_2 R_4}{R_1 R_3} \right) = -120$$

Example

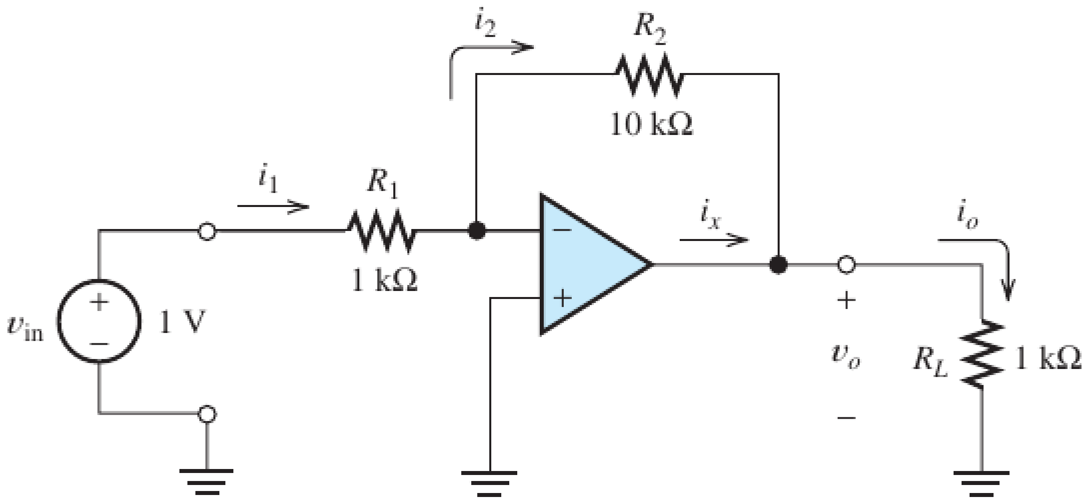
For the circuit given below, using the ideal op-amp assumption, solve the output voltage in terms of the input voltage and resistor values.
What is the input resistance seen by v_A ?
What is the output resistance seen from R_L ?



Answer **a.** $v_o = -(R_f/R_A)v_A - (R_f/R_B)v_B$; **b.** the input resistance for v_A is equal to R_A; **c.** the input resistance for v_B is equal to R_B; **d.** the output resistance is zero.

Example

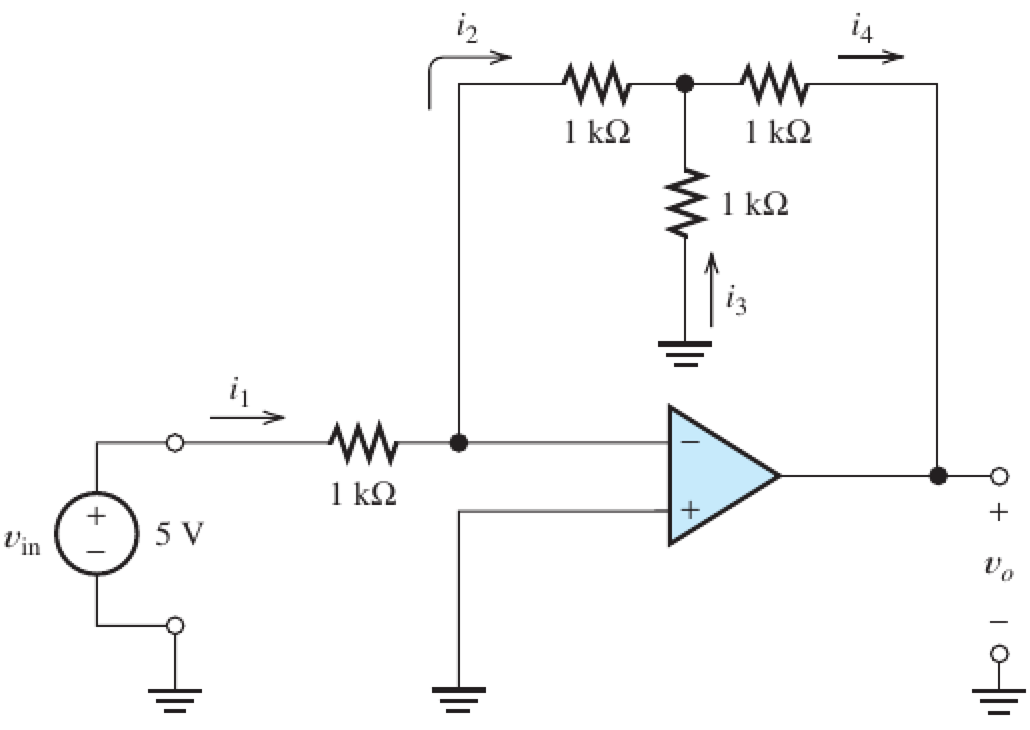
Assuming ideal op-amp solve for the currents labeled on the circuitry given below



Answer $i_1 = 1\text{ mA}, i_2 = 1\text{ mA}, i_o = -10\text{ mA}, i_x = -11\text{ mA}, v_o = -10\text{ V};$

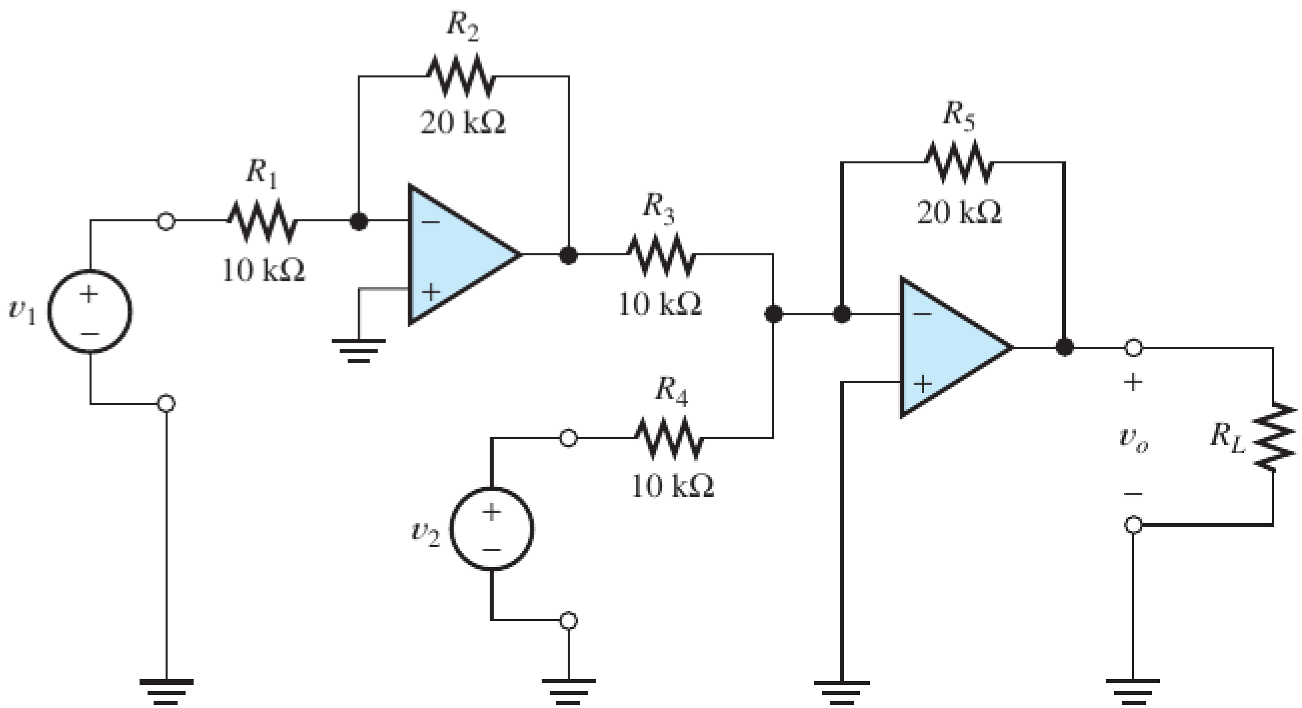
Example

Assuming ideal op-amp solve for the currents labeled on the circuitry given below



Example

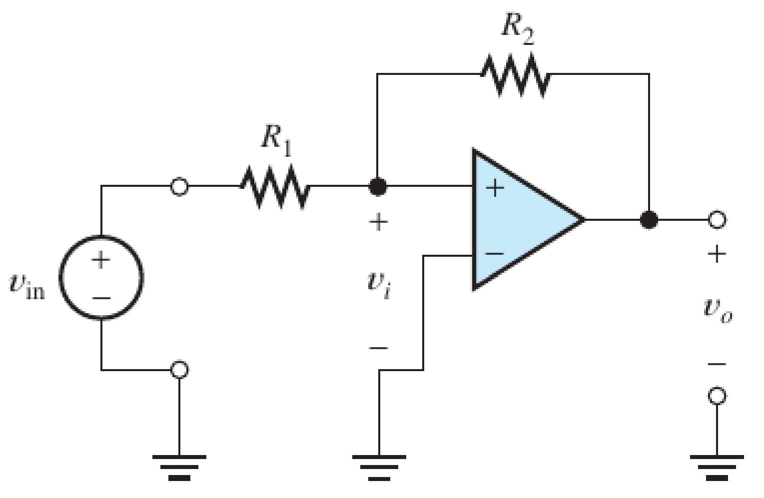
Find an expression for the output voltage in terms of the input voltages



Answer $v_o = 4v_1 - 2v_2$.

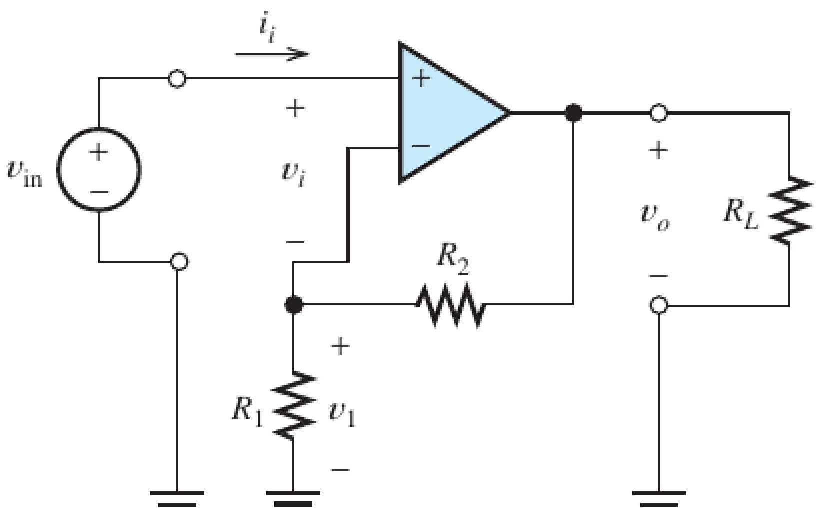
Positive Feedback

Consider the inverting amplifier configuration with the input terminals of the op-amp interchanged as in the figure. In this case the feedback is positive, that is the feedback signal aids the input signal.



Non-inverting Amplifiers

The circuit configuration of a non-inverting amplifier is given below. Input voltage is applied to the + side of the amplifier



$$v_{in} = v_1$$

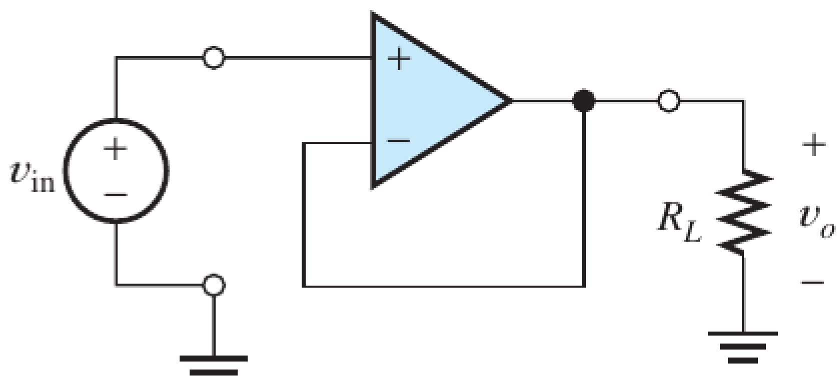
Notice that

$$v_1 = \frac{R_1}{R_1 + R_2} v_o \quad \Rightarrow \quad \boxed{A_v = \frac{v_o}{v_{in}} = 1 + \frac{R_2}{R_1}}$$

A_v is POSITIVE

Voltage Follower

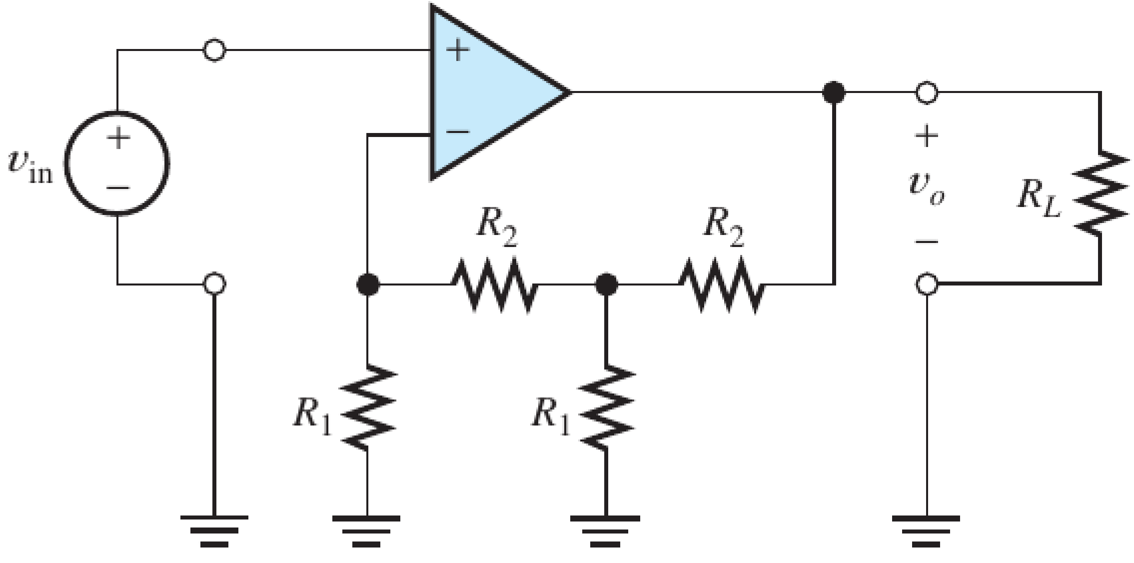
The minimum gain for a non-inverting amplifier given in the previous slide is 1 (when $R_2 = 0$) . When R1 is set to be open circuit we end up with a circuit configuration referred as **voltage follower** as shown in the figure



$$A_v = +1$$

Example

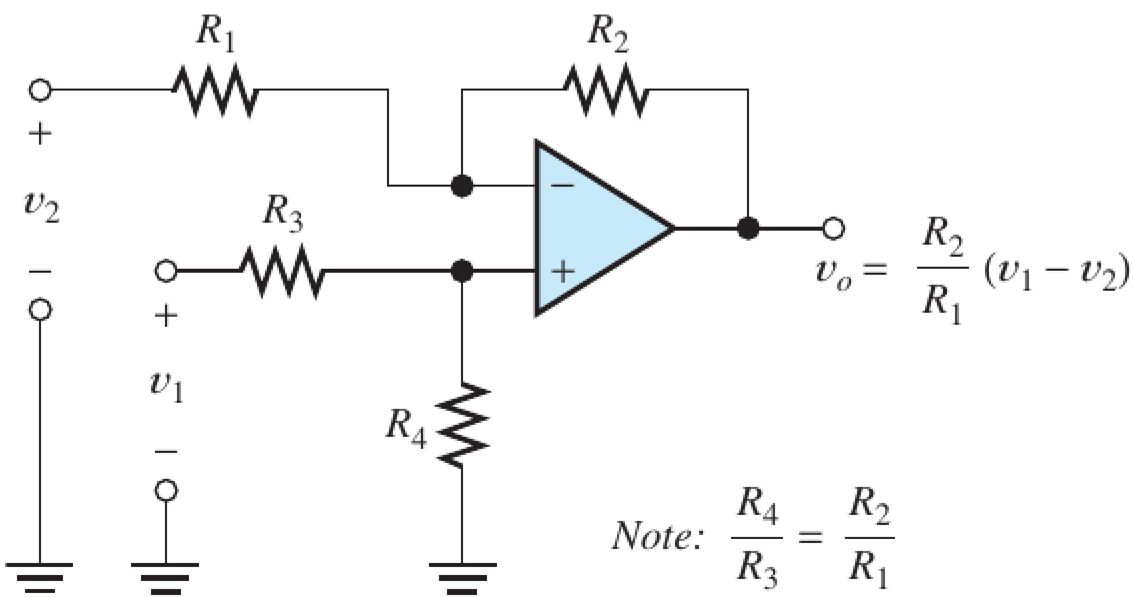
Derive an expression for the voltage gain for the given circuit



$$A_v = 1 + 3(R_2/R_1) + (R_2/R_1)^2$$

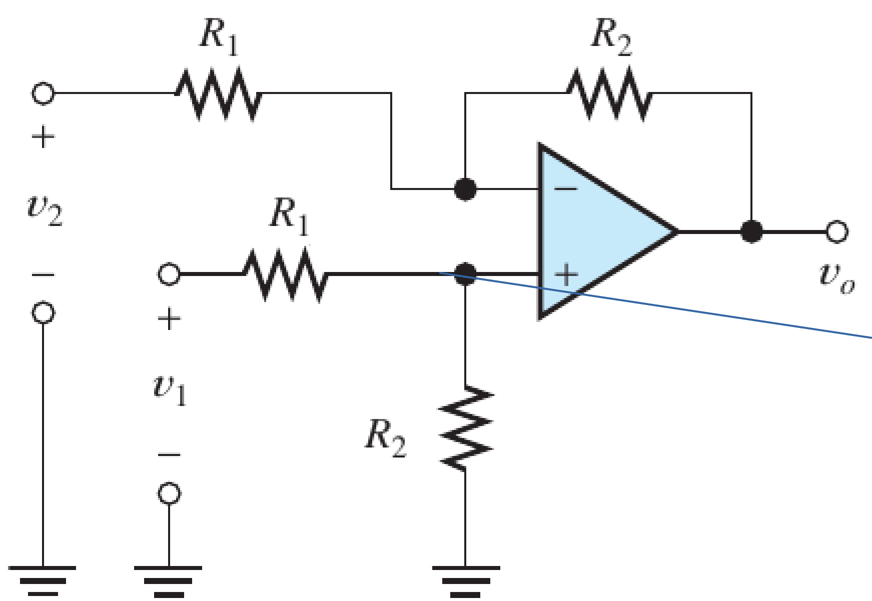
Differential and Instrumentation Amplifiers

Figure illustrates a differential amplifier. Assuming ideal op-amps and $R_4/R_3 = R_2/R_1$ the output voltage is a constant times the differential input. To minimize the effects of bias currents mostly we select $R_2 = R_4$ and $R_1 = R_3$



Differential and Instrumentation Amplifiers

But, How ???



$$\frac{v_1 - v_x}{R_1} = \frac{v_x - v_o}{R_2}$$

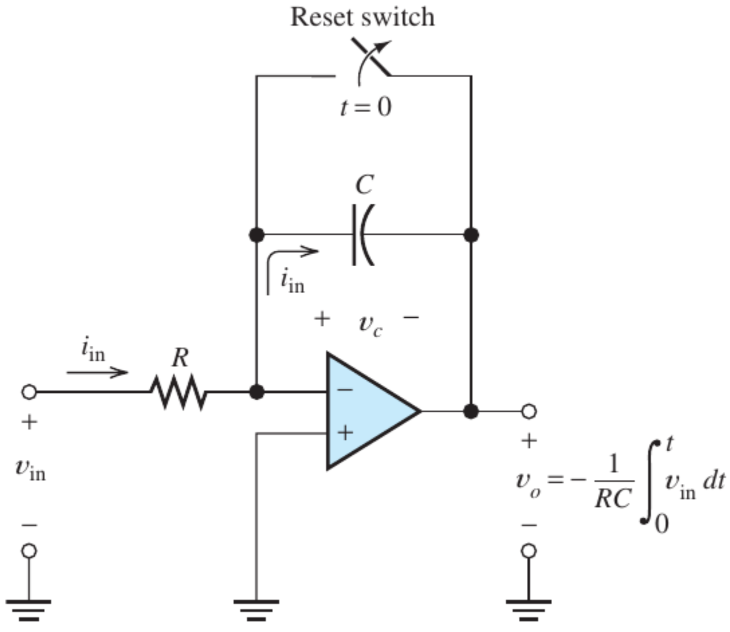
$$v_x = \frac{R_2}{R_1 + R_2} v_1$$

Plug in the values to obtain

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

Integrators

Figure shows the diagram of an integrator, which produces an output voltage proportional to the running-time integral of the input voltage



$$i_{in}(t) = \frac{v_{in}(t)}{R}$$

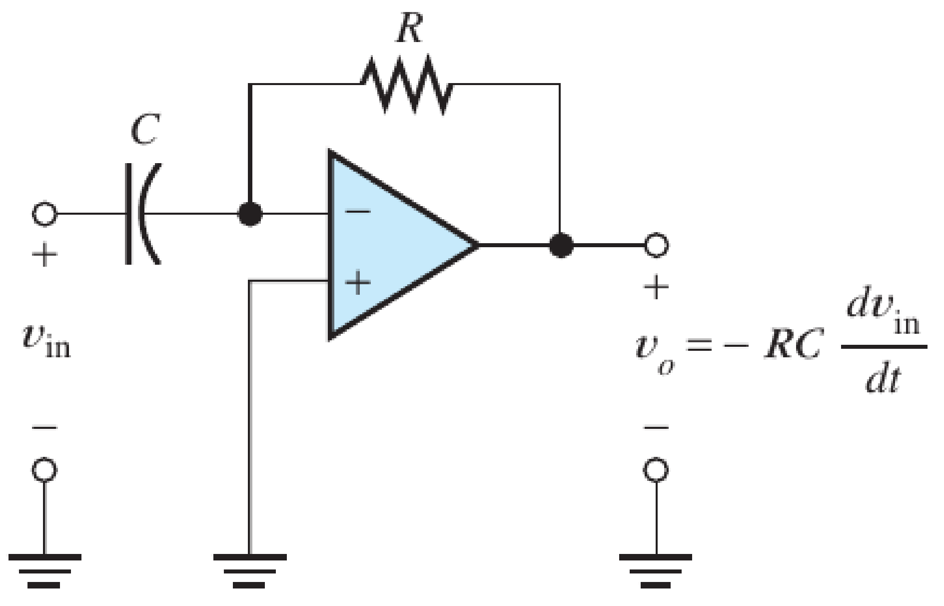
$$v_C(t) = \frac{1}{C}\int_0^t i_{in}(t)\, dt$$

$$v_o(t) = -v_C(t)$$

$$v_o(t) = -\frac{1}{RC}\int_0^t v_{in}(t)\, dt$$

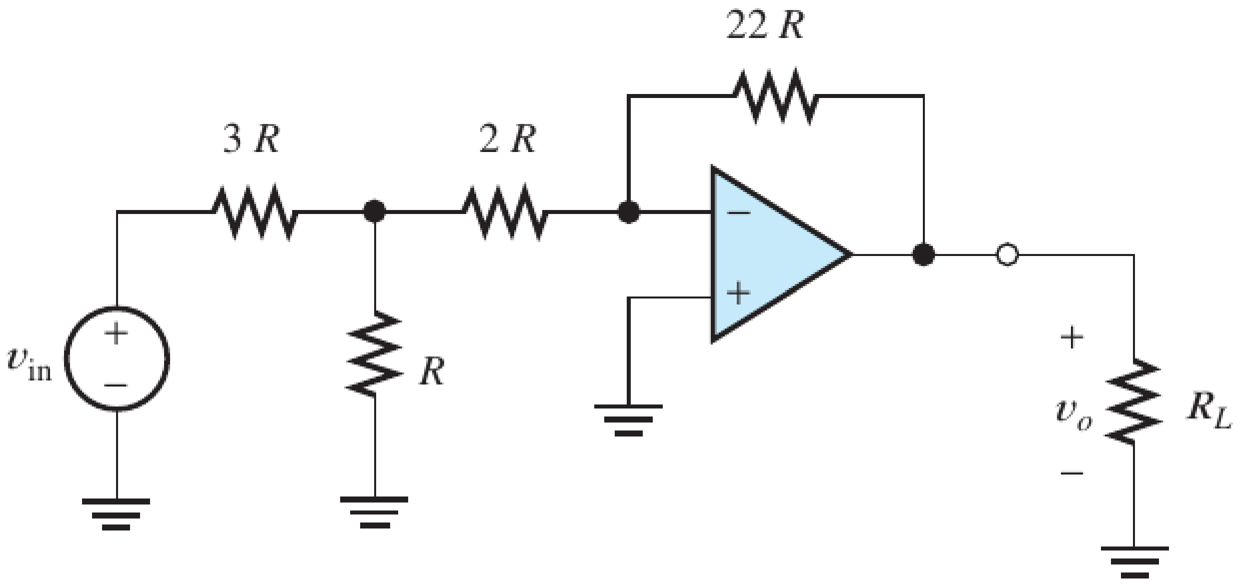
Differentiator

The circuit representation of an differentiator is given below. Analysis is left to the students :) .



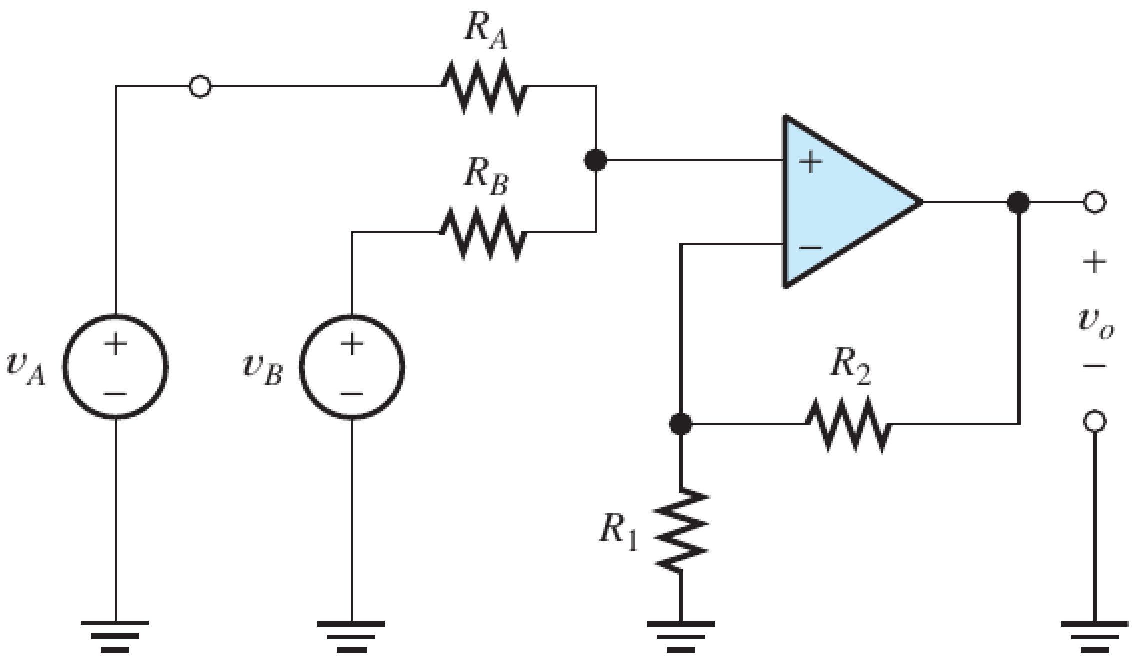
Example

Derive an expression for the voltage gain for the given circuit



Example

Obtain the output voltage in terms of the input voltages and the resistor values



$$v_o = \left(\frac{R_1 + R_2}{R_1}\right)\frac{v_A R_B + v_B R_A}{R_A + R_B}$$