ENGR 206

Experiment 8
Operational Amplifiers, II

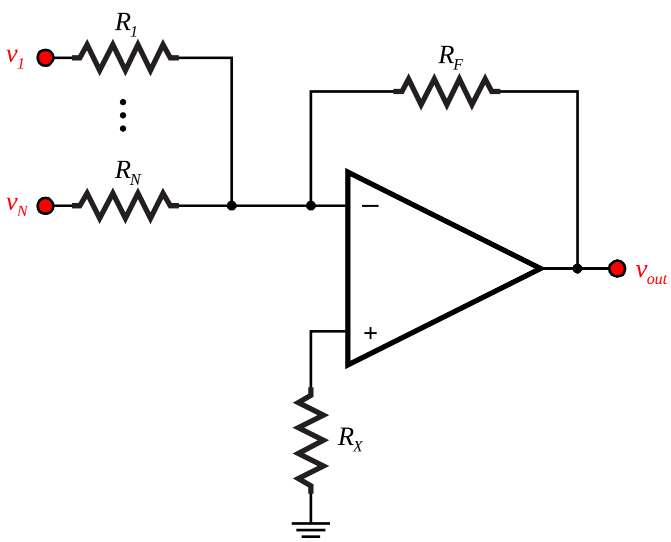
Objective

To experiment with operational amplifiers connected in summing and differential configurations. To understand negative resistance and current-to-voltage conversion.

Introduction

In the previous laboratory, we investigated basic inverting and non-inverting amplifier circuits using operational amplifiers (op amps). In this laboratory, we'll look at a number of further applications that exploit the capabilities of these remarkable circuit elements.

a) Summing amplifier



b) Differential amplifier

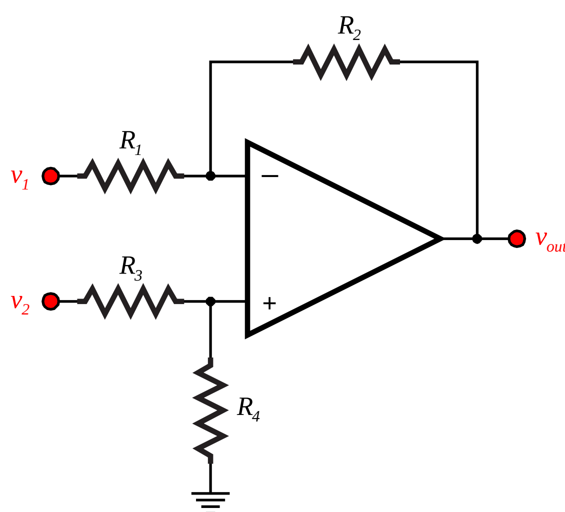


Figure 1: Summing and differential amplifier

Summing amplifier

Figure 1a shows the circuit of an op amp configured as a summing amplifier. The output of the amplifier is proportional to the sum of the N inputs, $v_1, \cdots v_N$. Notice that the summing amplifier is basically just the inverting amplifier with more than one input connected to the inverting terminal. The analysis of this amplifier configuration is identical to that of the inverting amplifier. Since no current flows into the terminals of the op amp, the non-inverting terminal is at ground, which makes the inverting terminal a "virtual ground". Applying KCL at the inverting terminal gives

$$\frac{v_1}{R_1} + \cdots + \frac{v_N}{R_N} + \frac{v_{out}}{R_F} = 0\,.$$

So,

$$v_{out} = -\frac{R_F}{R_1} v_1 - \cdots - \frac{R_F}{R_N} v_N = -R_F \left(\frac{v_1}{R_1} + \cdots + \frac{v_N}{R_N} \right)$$

We attach a resistor of value $R_x = (R_1 \parallel \cdots R_N \parallel R_F)$ to the non-inverting terminal to compensate for the input offset current, an effect we discussed in the last laboratory.
When the input resistors, $R_1, \cdots, R_N$ have different values, this circuit provides the sum of the individually scaled inputs. In the particular case in which all the input resistors are equal, $R_{in} \triangleq R_1 = \cdots = R_N$, then the output is scaled sum of the inputs,

$$v_{out} = -\frac{R_F}{R_{in}}(v_1 + \cdots + v_N) ,$$

and further, if $R_F = R_{in}$, then the output is just a unity-gain sum of the inputs.

Each input of the summing amplifier is effectively isolated from the other inputs, because even though all the inputs are tied together through their input resistors at the inverting terminal, the inverting terminal is effectively at ground. Summing amplifiers are useful in many applications, including audio mixers, and digital-to-analog (D/A) converters.

<u>Differential amplifier</u>
The differential amplifier, shown in Figure 1b, produces an output that is proportional to the difference of two input signals. You can view it as a hybrid of the inverting and non-inverting amplifiers, since inputs are presented to both terminals. At the non-inverting terminal,

$$v_+ = v_2 \frac{R_4}{R_3 + R_4} ,$$

and by KCL at the inverting terminal,

$$\frac{v_1 - v_-}{R_1} + \frac{v_{out} - v_-}{R_2} = 0 .$$

By the golden rules of op amps, $v_- = v_+$. A bit of algebra yields,

$$\begin{aligned} v_{out} &= v_2 \left(\frac{R_4}{R_3 + R_4} \right) \left(\frac{R_1 + R_2}{R_1} \right) - v_1 \frac{R_2}{R_1} = v_2 \left(\frac{1 + R_2/R_1}{1 + R_3/R_4} \right) - v_1 \frac{R_2}{R_1} \\ &= v_2 \frac{R_2}{R_1} \left(\frac{1 + R_1/R_2}{1 + R_3/R_4} \right) - v_1 \frac{R_2}{R_1} \end{aligned} . \qquad (1)$$

In the case where $R_1/R_2 = R_3/R_4$, then the output of the circuit is the scaled difference between the two inputs:

$$v_{out} = \frac{R_2}{R_1}(v_2 - v_1) ,$$

When $R_1 = R_2 = R_3 = R_4$, the circuit is a unity gain difference “amplifier”: $v_{out} = v_2 - v_1$.

Note that if v_1 is grounded, the differential amplifier reduces to a non-inverting amplifier (with a voltage divider at the input). If v_2 is grounded, the differential amplifier reduces to an inverting amplifier.

<u>Negative resistance</u>
An op amp circuit can be set up to look like a negative resistance. Consider the circuit of Figure 2a.

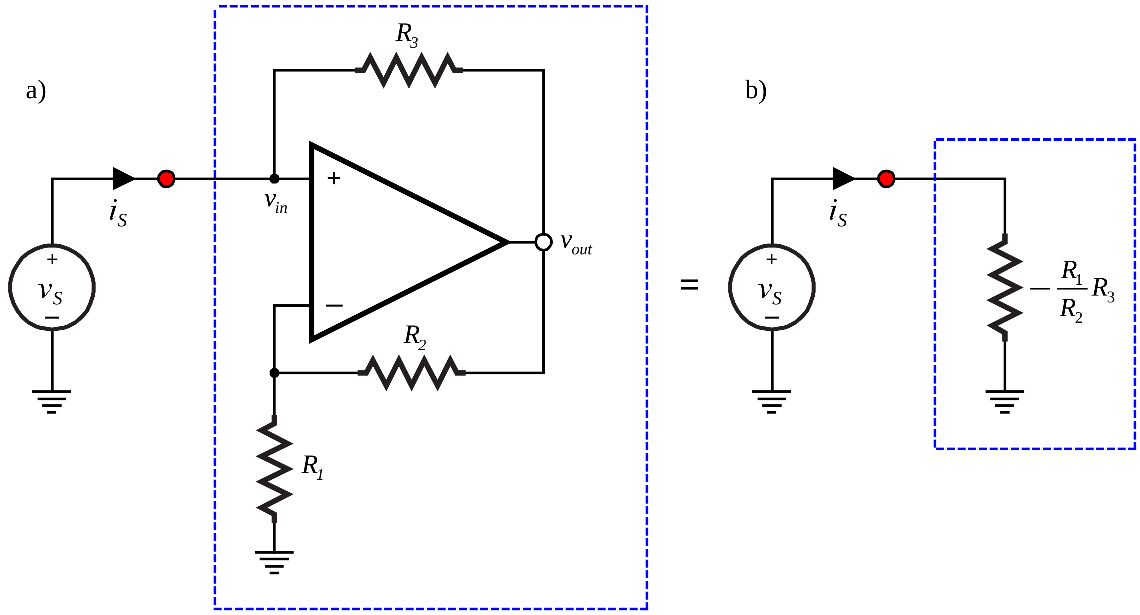


Figure 2: Negative resistance converter

It is basically a non-inverting amplifier with an additional resistor, R_3, between the v_{out} and v_{in}. In order to find the Thévenin equivalent of the circuit in the dotted box, we hook up a voltage source, v_s, and measure the current flowing into the circuit, is. Here, $v_{in} = v_s$, so for a non-inverting amplifier, the output is

$$v_{out} = v_s\left(1+\frac{R_2}{R_1}\right),$$

and by KCL at the non-inverting terminal,

$$i_s = \frac{v_s - v_{out}}{R_3} = v_s\frac{-\left(\frac{R_2}{R_1}\right)}{R_3}.$$

Hence, the circuit in the box is equivalent to a *negative* resistor of value

$$R_{eq} = \frac{v_s}{i_s} = -\frac{R_1}{R_2}R_3.$$

If we select $R_1 = R_2$, then $R_{eq} = -R_3$.

For any resistor with voltage, *V*, across it, the power dissipated is V^2/R. For a normal passive resistor, *R* is positive, so power is always being *consumed* by the resistor. However, in this circuit, *R* is negative, which means the power is being *supplied* to the circuit by the "resistor" rather than dissipated!

<u>Voltage-controller current source</u>

Figure 3a shows a key application of the negative resistance converter: a voltage-controlled constant-current source.

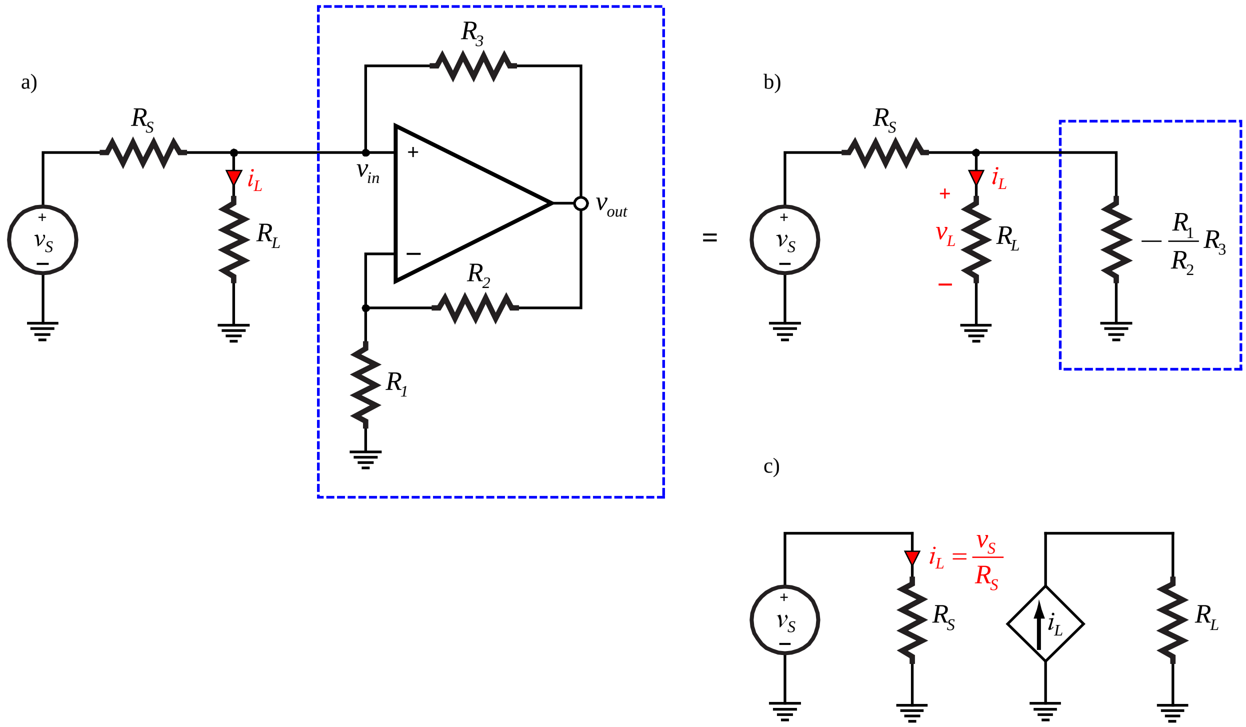


Figure 3: Voltage-controlled current source

The purpose of a current source is to provide a constant current, i_L, to a load, which we model by a resistor of value R_L. Constant current means that i_L is independent of the value of R_L. To analyze this circuit, replace the circuit in the box by its equivalent negative resistor, as shown in Figure 3b. Now, v_L, the voltage across R_L is given by a simple voltage divider formed by R_S and the parallel combination of the negative resistor and R_L:

$$v_L = v_S \frac{R_L \,\|\left(-\frac{R_1}{R_2}R_3\right)}{R_S + R_L \,\|\left(-\frac{R_1}{R_2}R_3\right)}.$$

A bit of algebra gives

$$i_L = \frac{v_L}{R_L} = v_S \frac{1}{R_S + R_L\left(1 - \frac{R_2 R_S}{R_1 R_3}\right)}.$$

In order that i_L be independent of the load, R_L, we require

$$\frac{R_2 R_S}{R_1 R_3} = 1 \text{ or } \frac{R_S}{R_3} = \frac{R_2}{R_1}.$$

Then the value of i_L is determined only by the value of voltage source, v_S and series resistor, R_S:

$$i_L = \frac{v_S}{R_S},$$

so the equivalent circuit is a voltage-controlled constant-current source, as shown in Figure 3c. If we've already selected $R_1 = R_2$, then we only need choose $R_3 = R_S$.

Current-to-voltage converter

The current-to-voltage (I-V) converter can be viewed as a simple extension of the inverting op amp and is shown in Figure 4a.

a) I-V converter b) Photo converter

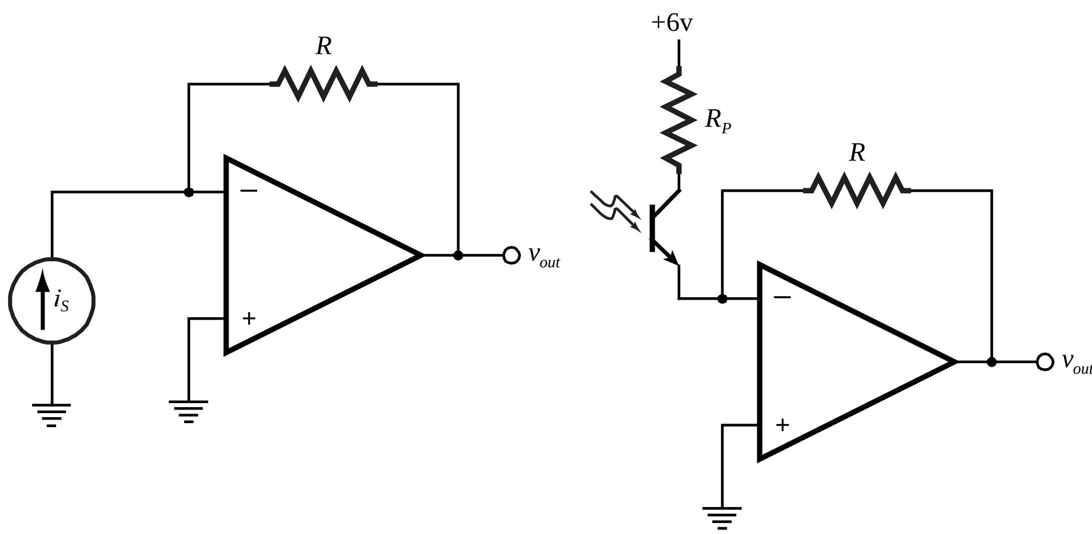


Figure 4: I-V converter

Since the inverting terminal is a virtual ground, solving KCL yields

$$v_{out} = -i_s R .$$

Figure 4b shows an application of the I-V converter. In this case, the source of current is a phototransistor, which basically converts incident light into a relatively small current. In this laboratory, we'll be using a phototransistor that is sensitive to light in the visible range. The data sheet is here.

Laboratory work

1. Set up op amp. Turn on the power supply and adjust the ±25V outputs for ±15V, then turn the power off while you connect the op amp. As a reminder, Figure 5a shows the pin configuration of the 741 op amp and Figure 5b shows the tidy way to connect the op amp to power and ground on your circuit board. Remember to bypass the ±15V supplies on the circuit board with $0.1\,\mu F$ capacitors to ground.

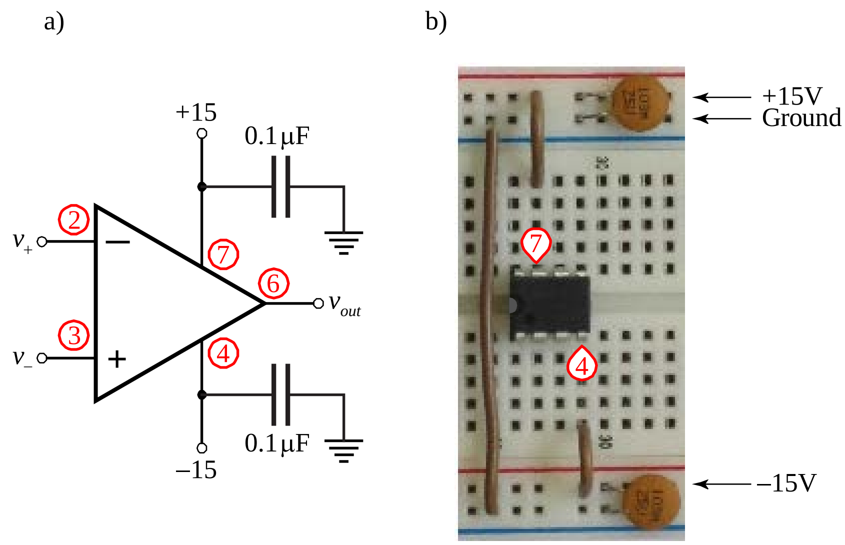


Figure 5: Op amp connections

2. Summing amplifier.
   a. Assemble the summing amplifier circuit shown in Figure 1a with only two inputs. Let $R_1 = 1\,K\Omega$, $R_2 = 3.3\,K\Omega$, $R_F = 10\,K\Omega$ and $R_X \approx R_1 \,||\, R_2 \,||\, R_F = 2.2\,K\Omega$.
   b. First, we will measure the gain of the amplifier with each input active separately. Connect input v_1 to a 1-kHz sinusoidal AC signal of 1V peak amplitude and 0V DC offset obtained from the function generator. Connect input v_2 to ground. Put the AC input on Ch1 of the scope and v_{out} on Ch2 and make sure both channels are DC coupled. Set the scope to trigger on Ch1, AC coupled. Measure the output, v_{out}, and calculate the gain for this input. Now, connect input v_1 to ground and connect input v_2 to the AC signal. Again, measure the output, v_{out}, and calculate the gain for this input. Do the gains you have measured make sense given the values of the resistors?
   c. Now we determine the output of the amplifier with two inputs connected. Connect input v_1 to the 1V peak AC signal and connect input v_2 to a +2V DC voltage obtained from the +6V supply the function generator. Measure the peak-to-peak and mean value of the output. Does the value you obtain correspond to what you expect?
   d. Slowly increase the DC offset of the function generator and note the value at which v_{out} begins to saturate. Does this value make sense? Now decrease the DC offset and again note the value at which v_{out} begins to saturate. Does this value make sense?
   e. Adjust the DC offset of the function generator to make v_{out} have a zero DC value (i.e. a mean value of zero). Does the value of the DC offset correspond to what you expect? Return the DC offset of the function generator to zero.
3. Difference amplifier.
   a. Assemble the difference amplifier circuit shown in Figure 1b with $R_1 = 1\,K\Omega$, $R_2 = 4.7\,K\Omega$, $R_3 = 6.8\,K\Omega$ and $R_4 = 3.3\,K\Omega$.
   b. We are now going to measure the gains of each input separately. Connect a 1-kHz sinusoidal AC signal of 1V peak amplitude and 0V DC offset to input v_1 and ground input v_2. Measure the gain of the op amp. Does it match your expectation given the values of the resistors?
   c. Now reverse the inputs: connect the AC signal to input v_2 and ground input v_1. Again measure the gain of the op amp. Does it match your expectation?

d. Now we connect both inputs. With the AC signal still connected to input v_2, connect a 1V DC signal to input v_1. Explain your output. Save a picture of the display for your report.

e. Leave resistors $R_1 = 1\,K\Omega$ and $R_2 = 4.7\,K\Omega$ in place. But in the place of R_3 and R_4, use a $10\,K\Omega$ potentiometer, as shown in Figure 6.

f. Attach the AC signal to both inputs of the amplifier. Adjust the wiper of the potentiometer so that the output of the amplifier is zero. Now carefully remove the connections from the potentiometer without disturbing the wiper position and measure both R_3 and R_4 with the ohmmeter. What is the relation between R_1/R_2 to R_3/R_4 and why?

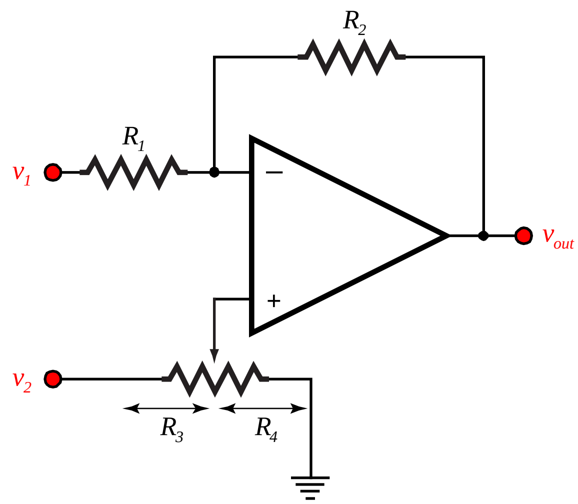


Figure 6: Difference amplifier

4. Negative resistance converter.
   a. Assemble the negative resistance converter shown in Figure 2 with $R_1 = 10\,K\Omega$, $R_2 = 10\,K\Omega$ and $R_3 = 4.7\,K\Omega$.
   b. Attach the adjustable +6V DC source to the input of the converter. Using your DMM, measure the source current, i_S, at six equally spaced values of v_S between 0 and +5V. Plot these data as an I-V curve. Explain the result
   c. Voltage-controlled current source
   d. Modify the negative resistance converter of the previous part to form the voltage controlled current source shown in Figure 3. Leave $R_1 = 10\,K\Omega$ and $R_2 = 10\,K\Omega$. Select $R_3 = 1\,K\Omega$. What is the value of R_S that will make this a constant current source? Select that value.
   e. Select $R_L = 1\,K\Omega$. Using your DMM, measure the load current, i_L, at six equally spaced values of v_S between 0 and +5V. Plot these data. Repeat with $R_L = 470\,\Omega$. What do you conclude about the capabilities of the constant current source?
5. Current-to-voltage converter.
   a. Assemble the current-to-voltage converter circuit shown in Figure 7a. The collector of the phototransistor, which has the shorter of the two leads, connects to a +6V DC source via a resistor of value $R_P = 1\,K\Omega$. The emitter of the transistor, which has the longer lead, connects to the inverting input of the op amp. The feedback resistor has value $R = 10\,K\Omega$.
   b. The phototransistor responds to light in the visible range by generating a current, which the I-V converter converts to a voltage. In this experiment, the light will come from an LED which you will connect to the function generator via a resistor of value $R_D = 1\,K\Omega$. The packages of the LED and the phototransistor look alike, but you can easily tell them apart if you look at them from the top. As shown in Figure 7b, the phototransistor has a small black square in the middle, whereas the LED has a small dot whose color will depend on the color of the LED you have. Set the function generator to produce v_S, a 3V p-p square-wave at 4 Hz. You should see the LED blink. To get the maximum response from the circuit, bend the leads of the phototransistor and the LED at 90° and orient the devices so that the tops of the two devices are pointing to each other, like two gentlemen bowing deeply to each other, with only a millimeter of separation between them.

c. Apply power to the circuit. Observe v_s on Ch1 of the oscilloscope and v_{out} on Ch2. What do you see on Ch2? How fast does the phototransistor respond to a change in the light? Increase the amplitude of v_S to 5V p-p. What happens? Change the frequency of the square wave to 100 Hz. Can the phototransistor follow?

d. To test whether the phototransistor is responding to light or perhaps to an induced electrical signal from the LED circuit, place an opaque object like your plastic student ID card between the LED and the phototransistor. What happens?

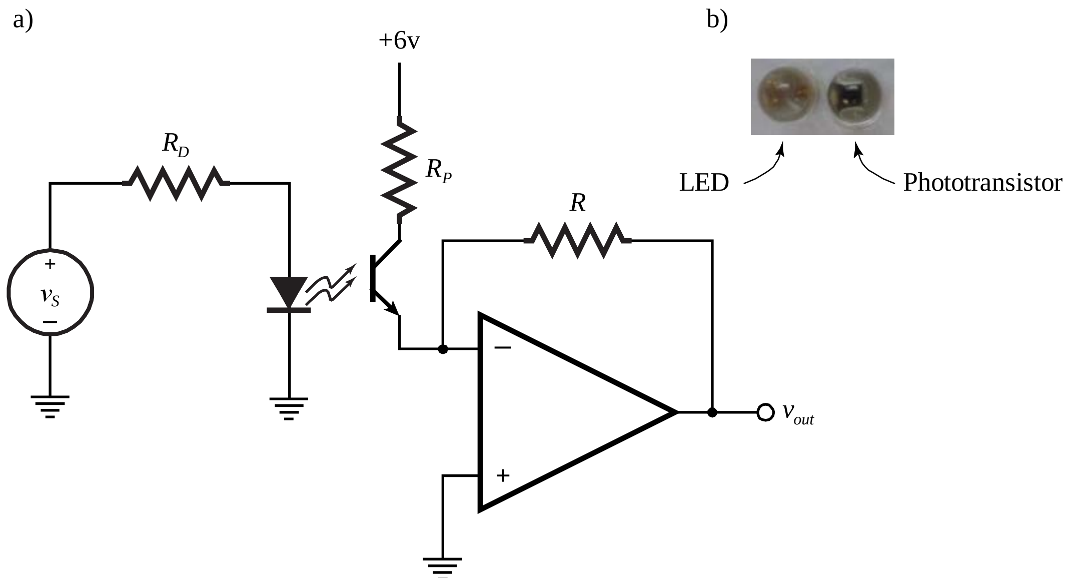


Figure 7: Phototransistor and LED circuit