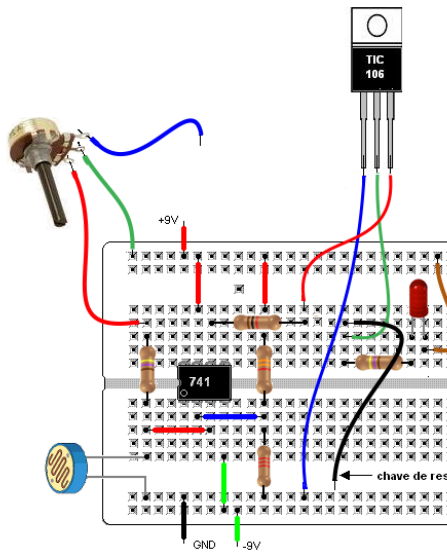
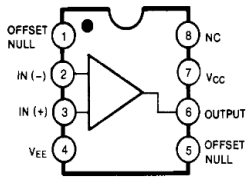


Prof. Rômulo Oliveira Albuquerque

Operational Amplifier Theory, Practice, Simulation and Exercises



About the e-Book

This is a basic theoretical and practical course on one of the most commonly used components in electronics, the Operational Amplifier (OA or Op Amp). The content is simplified, but essential. All experiments are performed on a breadboard with illustrations that allow them to be performed even by beginners. Basic knowledge of electricity and electronics is recommended.

11 exercises solved step by step and 11 proposed exercises complete the content.

For some experiments, there are links to simulations in [Multisim On Line](#) and [Tinkercad](#). See more at www.eletronica24h.net.br

About the Author

Graduated in Electrical Engineering from EEM ([Mauá Engineering School](#) - São Caetano do Sul - SP) in 1977. He established Fatec ([Technology College](#)) in São Bernardo do Campo and was director from 2005 to 2010. He is currently a professor.

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Analysis of Circuits in Continuous Current

[Analysis of Circuits in Alternating Current](#)

Circuits in Alternating Current (out of print)

Analysis and Simulation of Circuits on the Computer - EWB5 (out of print)

Analysis and Simulation of Circuits on the Computer - MultiSIM2001 (out of print)

[Using Electronics with AO, SCR, TRIAC, UJT, PUT, CI 555, LDR, LED, FET, IGBT](#)

Master's degree from the [Polytechnic School of USP](#) (São Paulo Brazil) where he defended the dissertation "INTEGRATION OF TOOLS TO HELP THE DESIGN OF INTEGRATED CIRCUITS FOR TEACHING MICROELECTRONICS" at the Polytechnic School of USP (University of São Paulo), obtaining the degree of Master

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Practice and Theory with Operational Amplifier

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Experiment 01: Operational Amplifier in open loop

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Objectives

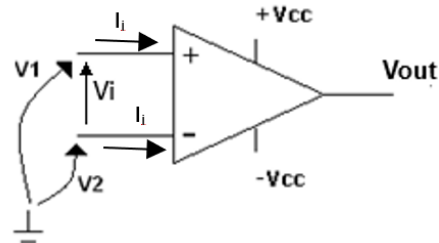
1. Verify the behavior of an Operational Amplifier in open loop.
2. Measure the positive and negative saturated output.

Materials Used

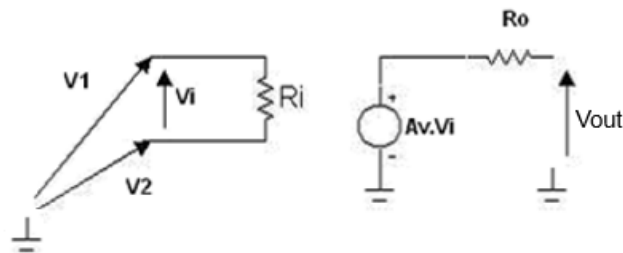
- 2x9 V batteries with terminals
- 1 Digital multimeter
- 1 Breadboard

Theoretical Introduction

The operational amplifier (Op Amp) is an integrated circuit (IC) device with wide applications in practically all areas of electronics. The model (equivalent circuit) shown in Figure 1b is used to study it, which is suitable for most applications. Figure 1a shows the symbol of the Op Amp and Figure 1b the simplified equivalent circuit.



(a)



(b)

Figure 1 – Operational amplifier – (a) Symbol and (b) equivalent circuit

In Figure 1, V_1 is the voltage applied to the non-inverting input (+) and V_2 is the voltage applied to the inverting input (-).

$V_i = V_1 - V_2$ is the error signal or difference signal

R_i is the input resistance without feedback

R_o is the output resistance without feedback

A_v is the open-loop voltage gain (gain without feedback)

$+V_{cc}$ is the value of the positive source and $-V_{cc}$ is the negative source, known as a symmetrical source.

With no load connected to the output:

$$V_{out} = A_v \cdot V_i = A_v \cdot (V_1 - V_2),$$

The Ideal Operational Amplifier

An Op Amp should ideally have the following characteristics:

- a) Infinite input resistance (R_i)
- b) Zero output resistance (R_o)
- c) Infinite open-loop voltage gain (A_v)
- d) Infinite bandwidth (BW)
- e) No offset at the output ($V_{out} = 0$ if $V_1 = V_2$)
- f) Infinite slew rate (SR)

As a result of the characteristics of an ideal Op Am, it results:

$$A_v = \frac{V_{out}}{V_1 - V_2} = \frac{V_{out}}{V_i} \quad \text{or} \quad V_i = \frac{V_{out}}{A_v}$$

Since A_v is infinite, $V_i=0$, in practice V_i is in the order of microvolts

Como the input resistance (R_i) is ideally infinite, the currents at both inputs of the Op Amp are zero, $I_i=0$.

In practice, considering the Op Amp 741, the values are approximately:

- a) $R_i = 1 \text{ M}\Omega$
- b) $R_o = 75 \Omega$
- c) $A_v = 100,000$
- d) $BW = 10 \text{ Hz}$ (Bandwidth)
- e) $V_{io} = 2 \text{ mV}$
- f) $SR = 0.7 \text{ V}/\mu\text{s}$

There are several [types of operational amplifiers](#), one for each type of application, and the simplest and best known Op Amp is the [741](#), which can have [two types of encapsulation](#), the DIP (Dual In Line Package) and the TO-99, with the 8-pin. DIP being the most common, Figure 2.

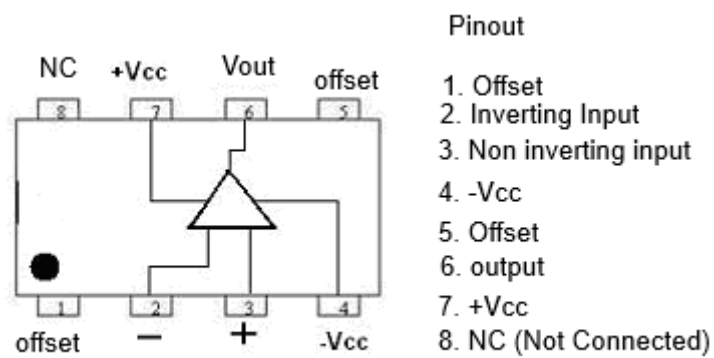


Figure 2 – 741 Dual in line package - DIP

Open Loop Operational Amplifier

Open loop means that there is no feedback (output connected to one of the inputs). In this condition the output voltage is given by:

$$V_{out} = A_v \cdot (V_+ - V_-) = A_v \cdot (V_1 - V_2)$$

Since the open loop gain value (A_v) is very high (typically equal to 100,000), for application as an amplifier it is necessary to apply negative feedback between the output and the input. Without this type of feedback the output saturates easily, that is, it reaches the highest negative or positive value, called negative saturation and positive saturation, respectively.

The maximum voltage, saturation voltage, is limited to the supply, if the symmetrical supply is $\pm 12\text{ V}$ the output will be approximately $+12\text{ V}$ or -12 V . For example, if the non-inverting input (+) is supplied with 3 V and the inverting input (-) is grounded, Figure 3, then $V_1 = 3\text{ V}$ and $V_2 = 0\text{ V}$ therefore $V_1 - V_2 = 3\text{ V}$ and as the gain is very high, for example 100,000, the output will be limited to approximately $V_{out} = 100,000 \cdot 3\text{ V} \approx +12\text{ V}$, that is, it saturates!

On the other hand, if the non-inverting input is zero and the inverting input is 3 V , $V_1 - V_2 = -3\text{ V}$, the output saturates at approximately -12 V , Figure 3b.

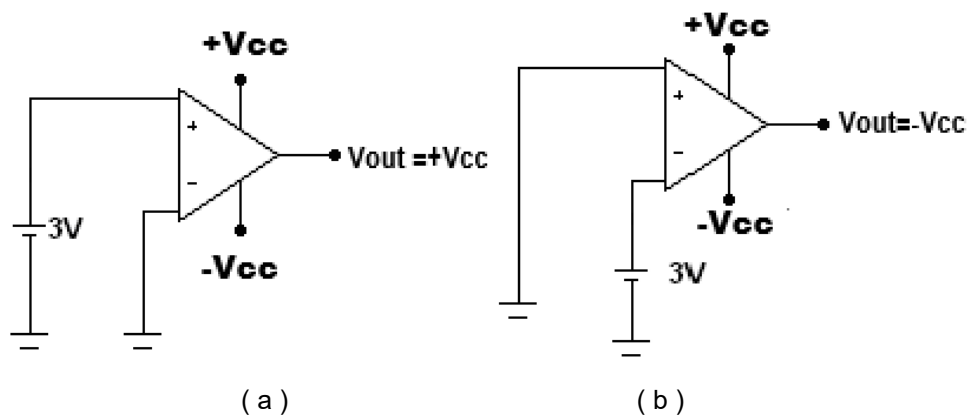


Figure 3 – Open loop operational amplifier

Figure 4 shows how to simply and cheaply obtain a symmetrical 9 V source from two 9 V batteries.

Experimental Procedure

- 1) In most cases, the Op Amp is powered by a symmetrical source, and there are several ways to build a symmetrical source. In this course, two 9 V batteries will be used (It's cheaper). Figure 4 shows the two 9 V batteries that will be used to power the Op Amp. In the case of Figure 4a, the negative terminal of one is connected to the positive terminal of the other battery. The common point is ground (GND or 0 V) but note that the two batteries can be separate and you will have to connect the two grounds in the breadboard, as shown in Figure 4c.

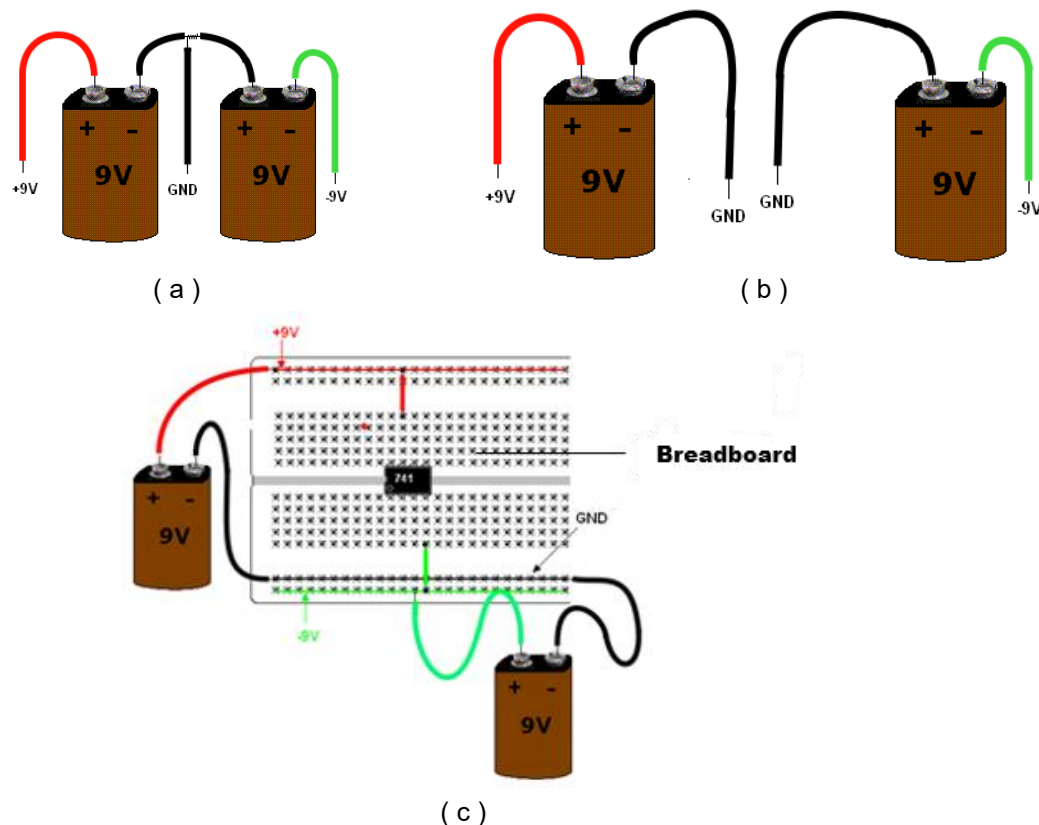


Figure 4 – (a) and (b) Symmetrical 9 V source (c) Op Amp being powered by the symmetrical 9 V source

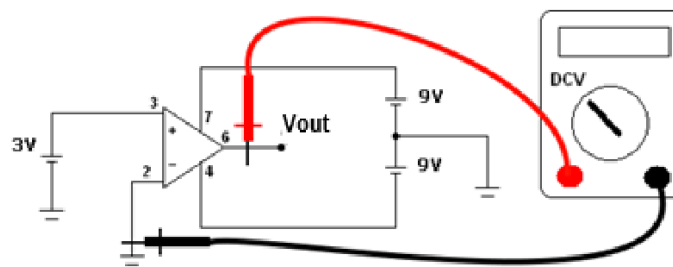
[Link to Simulator1](#)

[Link to Simulator2](#)

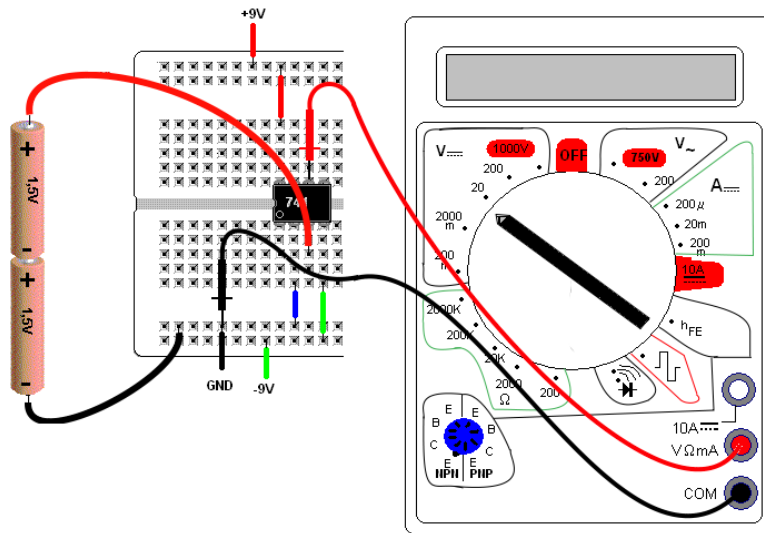
- 2) Assemble the circuit in Figure 5a according to the layout in Figure 5b, and measure the output voltage (V_{Out}), this value is the positive saturation voltage.

Note that the batteries do not appear, but rather the terminal points (+9 V, GND and -9 V).

$V_{out} \text{ (Measured)} = V_{sat(+)} =$



(a)



(b)

Figure 5 – Open-loop operational amplifier (a) circuit (b) Breadboard layout non-inverting input 3 V / inverting input 0 V

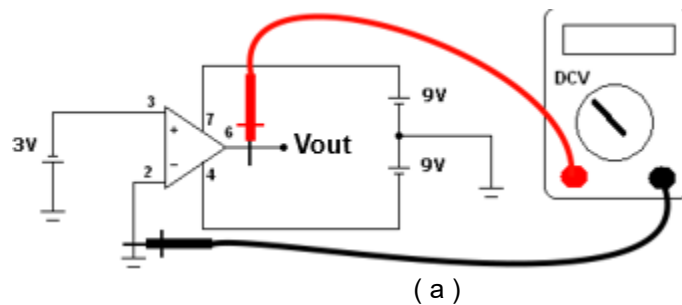
[Link to Simulator1](#)

[Link to Simulator2](#)

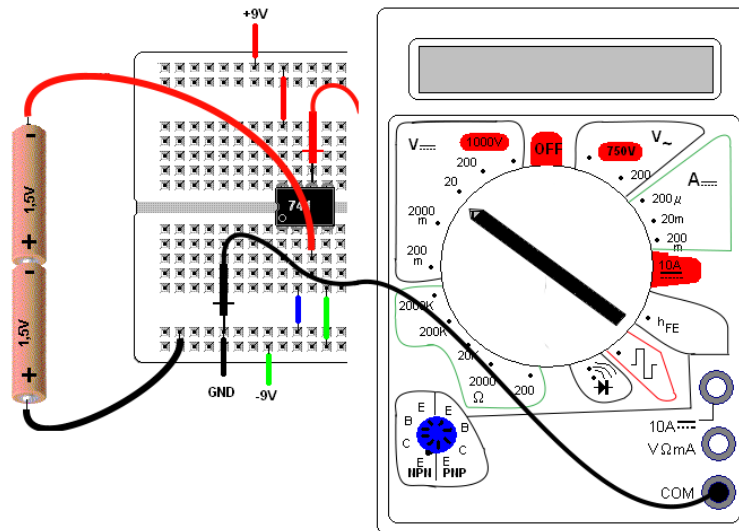
- 3) Repeat step 2 considering that the voltage at the non-inverting input is -3 V with the inverting input grounded, to do this invert the terminals of the battery as indicated in Figure 6.

$$V_{out}(\text{Measured}) = V_{\text{Sat}(-)}$$

Note: In Multisim, instead of inverting the battery, write the value -3V



(a)



(b)

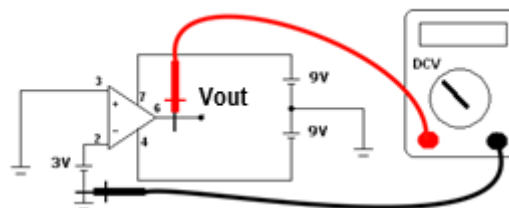
Figure 6 – Open-loop operational amplifier (a) circuit (b) Breadboard layout – non-inverting input at -3 V and inverting at 0 V

[Link to Simulator1](#)

[Link to Simulator2](#)

- 4) Repeat step 2 assuming that the voltage at the inverting input is 3 V and the non-inverting input is zero. Measure the voltage at the output and write it down.

$V_{out}(\text{measured}) =$



(a)

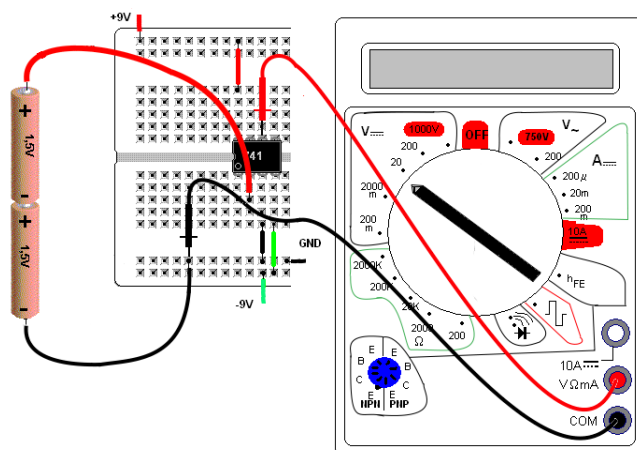


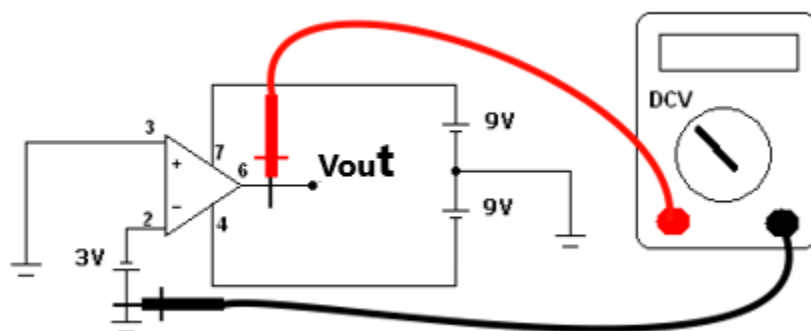
Figure 7 – Open loop operational amplifier (a) circuit (b) Breadboard layout – inverting input at 3 V and Non-inverting input at 0

[Link to Simulator1](#)

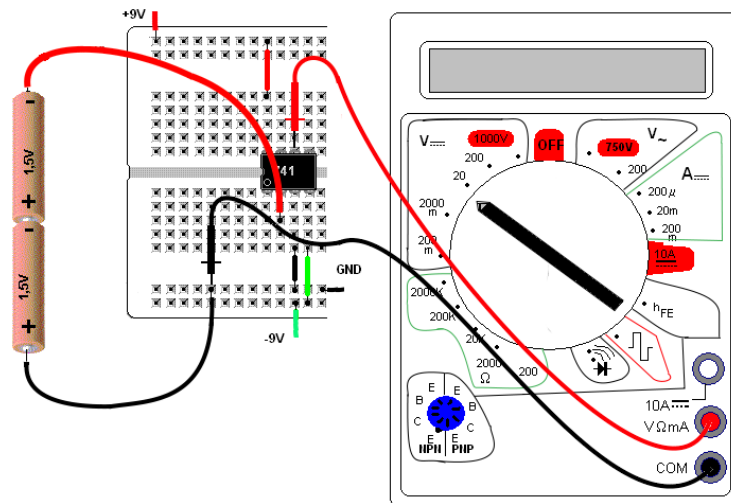
[Link to Simulator2](#)

- 5) Now consider that the voltage at the inverting input is -3 V with the non-inverting input grounded. Measure the voltage at the output.

$V_{out}(\text{measured}) =$



(a)



(b)

Figure 6 - Open loop operational amplifier (a) circuit (b) breadboard layout – inverting input at -3V

[Link to Simulator1](#)

[Link to Simulator2](#)

- 6) Based on the measurements and observations made, write your conclusion.

Experiment 02: Inverter Amplifier

Index

Objective

1. Experimentally determine the gain of a DC inverting amplifier.

Material Used

2x9 V batteries with terminals
 1 Battery holder for 1 1.5 V batteries.
 1 1.5 V batteries
 1 Digital multimeter
 1 Breadboard
 1 IC 741
 Resistors: 2.2k/4.7k/22k
 Connection wires

Theoretical Introduction

The inverting amplifier is a circuit with negative feedback, obtained through the resistor network R_2 and R_1 , Figure 1. The feedback is negative because the output connects to the inverting input. All linear applications (amplifiers) must have negative feedback. The name inverter is because the output voltage is inverted 180 degrees in relation to the input, so if $V_{in} > 0$ the output, $V_{out} < 0$ and if $V_{in} < 0$, $V_{out} > 0$.

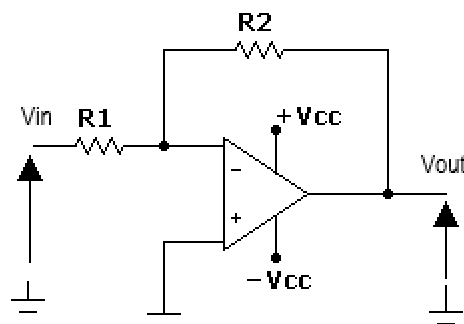


Figure 1 – Inverting amplifier

For the circuit in Figure 1, the feedback gain expression (A_{vf}) is given by:
 :

$$A_{Vf} = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

Note: The letter f in Avf stands for feedback

The negative sign indicates a 180° phase shift between Vin and Vout, so if the gain is -5 it means that if the input voltage is 1 V the output will be equal to -5 V, on the other hand if the input is -1 V the output will be equal to 5 V.

Saturation Voltage

The maximum output voltage is limited to approximately +Vcc and the minimum to approximately -Vcc.

Experimental Procedure

- 1) For the circuit in Figure 2, calculate the gain (Avf) and then the output voltage. Write these values down as Avf (calc.) and Vout(calc.).

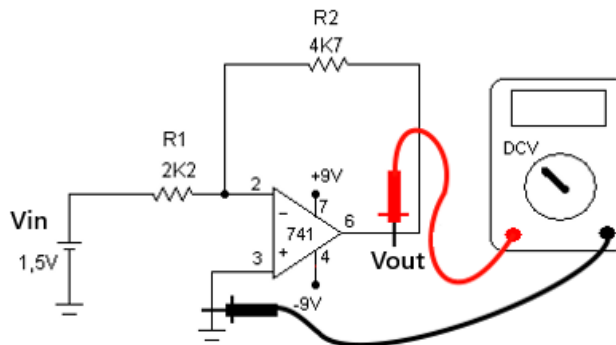


Figure 2 – Experimental circuit – inverting amplifier with Vin=1.5 V

$$A_{vf} \text{ (calc.)} = -\frac{R_2}{R_1} =$$

$$V_{out} \text{ (calc.)} = A_{vf} \text{ (calc.)} \cdot V_{in} =$$

- 2) Assemble the circuit in Figure 2 on the breadboard according to the suggestion in Figure 3. Measure the exact value of the battery voltage and write it down as Vin (effective). Measure the output voltage and write it down.

$$V_{in} \text{ (effective)} =$$

$$V_{out} \text{ (measured)} =$$

Note: $V_{in}(\text{effective})$ is the actually measured battery voltage which may be different from 1.5 V.

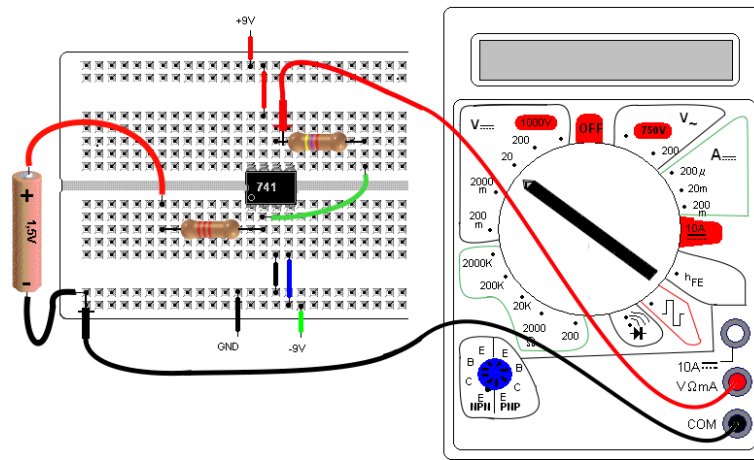


Figure 3 – DC inverter amplifier– layout on breadboard – $V_{in}=1.5\text{ V}$

[Link to Simulator1](#)

[Link to Simulator2](#)

3) Determine the effective gain $A_{Vf}(\text{effective})$ by:

$$A_{Vf}(\text{effective}) = \frac{V_{out}(\text{measured})}{V_{in}(\text{effective})} =$$

4) Invert the input voltage of the circuit in Figure 2, resulting circuit in Figure 4. Calculate the output voltage and record it as $V_{out}(\text{calc.})$.

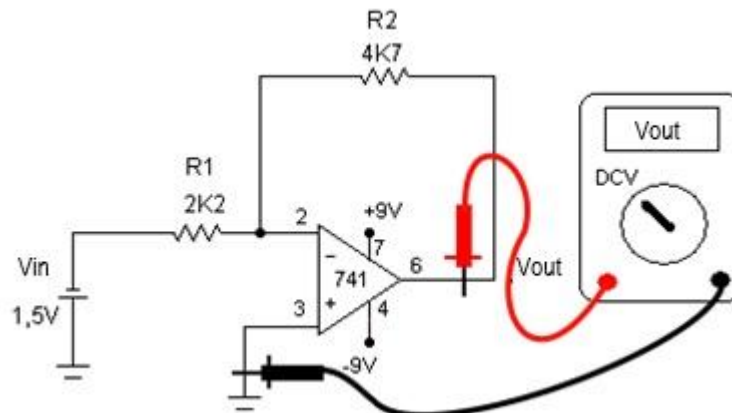


Figure 4 – Experimental circuit – inverting amplifier with $V_{in}= - 3\text{ V}$

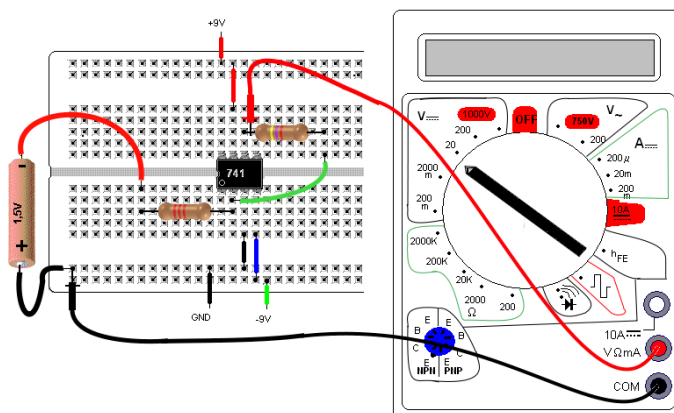


Figure 5 – Experimental circuit with inverter – layout on breadboard – $V_{in} = -1.5\text{ V}$

[Link to Simulator1](#)

[Link to Simulator2](#)

$$A_{vf}(\text{calc.}) = -\frac{R_2}{R_1} =$$

$$V_{out}(\text{calc.}) = A_{vf}(\text{calc.}) \cdot V_{in} =$$

- 5) Assemble the circuit in Figure 4 on the breadboard according to the suggestion in Figure 5. Measure the voltage at the output.

$$V_{out}(\text{measured}) = \underline{\hspace{2cm}}$$

Determine the effective gain by:

$$A_{vf}(\text{effective}) = \frac{V_{out}(\text{medido})}{V_{in}(\text{effective})} =$$

- 6) In the circuit in Figure 5, replace the 4k7 resistor with a 22 K resistor and measure the voltage at the output and write it down.

$$V_{out}(\text{measured}) = \underline{\hspace{2cm}} \quad V_{sat}(+) = \underline{\hspace{2cm}}$$

–

- 7) Reverse the polarity of the input voltage and repeat step 6.

$$V_{out}(\text{measured}) = \underline{\hspace{2cm}} \quad V_{sat}(-) = \underline{\hspace{2cm}}$$

- 8) Based on the results, write your conclusions.

Experiment 03: Non-Inverting Amplifier

Index

Objectives

1. Understand how a non-inverting DC amplifier works.
2. Experimentally determine the gain of a non-inverting amplifier.

Material Used

2x9 V batteries with terminals
 1 Battery holder for 1 1.5 V batteries.
 1 1.5 V batteries
 1 Digital multimeter
 1 Breadboard
 1 IC 741
 Resistors: 2X2k/4.7k/22k ¼ W
 Connection wires

Theoretical Introduction

In this circuit, the output voltage, V_{out} , will be in phase with the input voltage, V_{in} , Figure 1 and as we can see, the feedback continues to be negative, but the signal to be amplified (V_{in}) is applied to the non-inverting input (V_+).

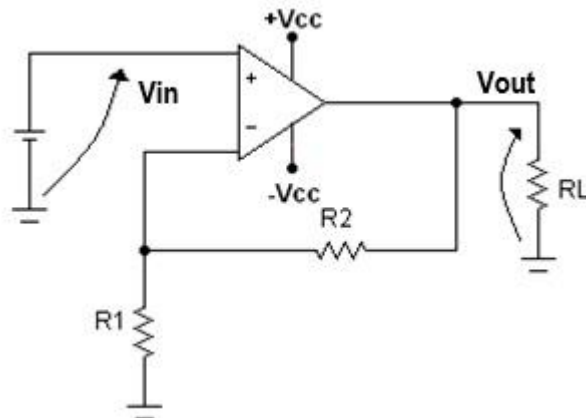


Figure 1 – Non-inverting amplifier

In the circuit in Figure 1, the relationship between the output (V_{out}) and the input (V_{in}), the gain (A_{vf}) is given by:

$$A_{vf} = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

This circuit is characterized by having a very high input resistance and a very low output resistance

If $R_1=R_2$ the gain will be equal to 2 and if $V_{in}=1.5\text{ V}$ the output will be equal to 3 V and if $V_{in}=-1.5\text{ V}$ the output will be -3 V, that is, the output is in phase with the input.

Experimental Procedure

- 1) For the circuit in Figure 2, calculate the gain (A_{vf}) and then calculate the output voltage, V_{out} , for the values indicated. Record these values as A_{vf} (calc.) and V_{out} (calc.).

A_{vf} (calc.)=

V_{out} (calc.)=

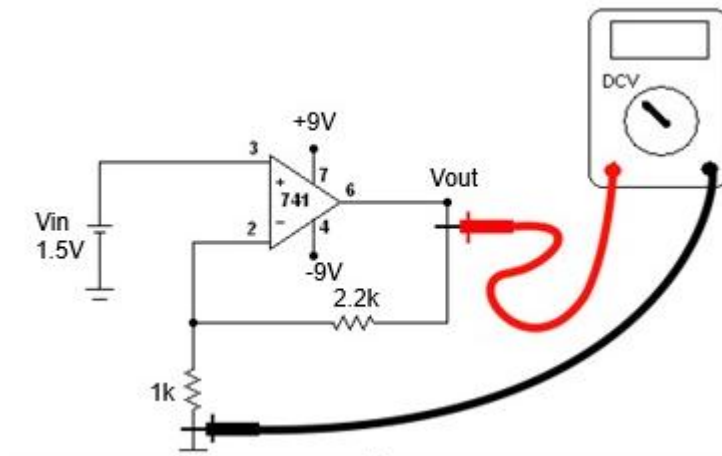
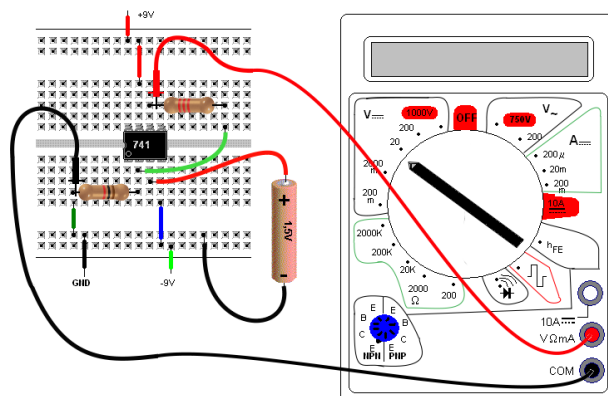


Figure 2 – Non-Inverting Amplifier for experiment

- 2) Assemble the circuit in Figure 2 on the breadboard according to the suggestion in Figure 3. Measure the exact value of the battery voltage and write it down as V_{in} (effective). Measure the output voltage and write it down.

V_{in} (effective)=

V_{out} (measured)=

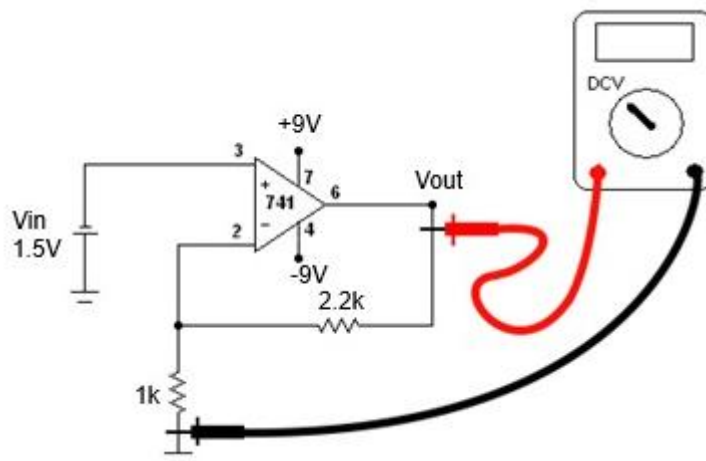
Figure 3 – Non-Inverting Amplifier $V_e=1.5V$
[Link to Simulator1](#)
[Link to Simulator2](#)

3) Determine the gain by:

$$A_{vf(effective)} = \frac{V_{out(measured)}}{V_{in(effective)}} =$$

4) Invert the input voltage of the circuit in item 2, resulting in the circuit in Figure 4. Repeat the previous items.

$$A_{vf(effective)} = \frac{V_{out(measured)}}{V_{in(effective)}} =$$

Figure 4 – Non-Inverting Amplifier – circuit with negative input $V_{in}=-1.5V$

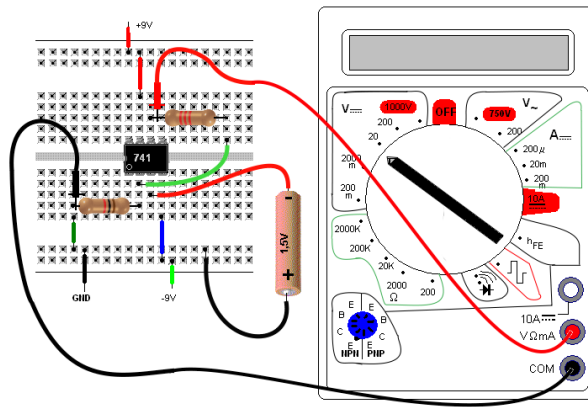


Figure 5 – Non-Inverting Amplifier $V_{in} = -1.5V$

[Link to Simulator1](#)

[Link to Simulator2](#)

5) Based on the results obtained, write your conclusions.

Experiment 04: Buffer or Voltage Follower

Index

Objectives

1. Understand the Buffer or Voltage Follower circuit.
2. Experimentally determine the Buffer gain.

Material Used

2x9 V batteries with terminals
 1 Holder for 1 1.5 V battery
 1 1.5 V battery
 1 Digital multimeter
 1 Breadboard
 1 IC 741
 Resistors – 1 k/10 k

Theoretical Introduction

This circuit, also called a voltage follower, is obtained from the inverting amplifier by making $R_2=0$ and R_1 infinity, resulting in the circuit in Figure 1. The gain of this circuit will be:

$$A_{vf} = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1} = 1$$

That is, $V_{out}=V_{in}$

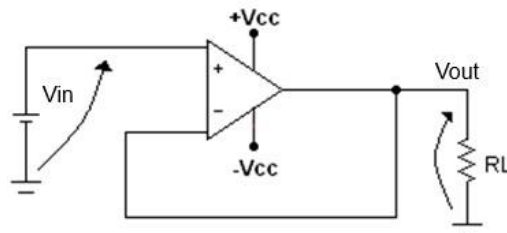


Figure 1 – voltage follower or buffer

The main characteristics of a buffer are, very high input impedance (hundreds of Megaohms), very low output impedance (thousandths of Ohms) and unity gain ($V_{out} = V_{in}$). The main application of a Buffer is to isolate one circuit from another. They are also used as an interface between circuits that do not have current capacity with a circuit that drains a high current.

Procedimento Experimental

- 1) For the voltage divider circuit in Figure 2, calculate the voltage across the load (1 k). Use the voltage divider expression.

$$V_{RL} = \frac{R_L}{R_L + R_S} \cdot 9$$

$V_{RL}(\text{calc.}) =$

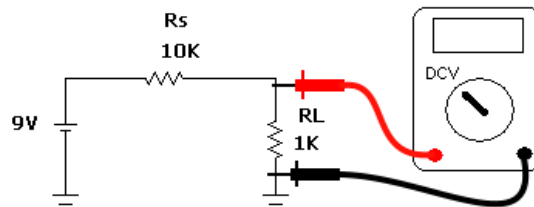


Figure 2 – Voltage divider - Circuit

- 2) Assemble the circuit in Figure 2 according to the layout suggestion in Figure 3, measure the voltage across the load (1 k).

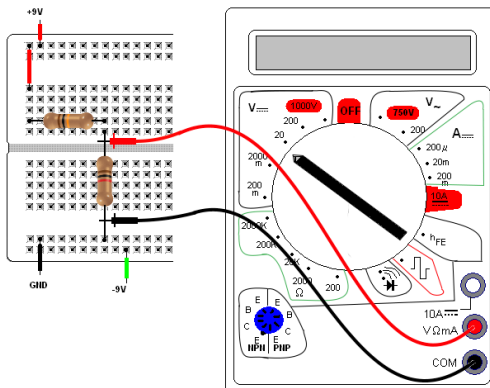


Figure 3 – Voltage divider in breadboard

[Link to Simulator1](#)

[Link to Simulator2](#)

$$V_{RL}(\text{Measured}) =$$

- 3) The circuit in Figure 4 is a Buffer that isolates a 1 k R_L load from a circuit whose output resistance is 10 k. Calculate the voltage across R_L in the circuit in Figure 4. Note as $V_{RL}(\text{calc.})$

$$V_{RL}(\text{calc.}) =$$

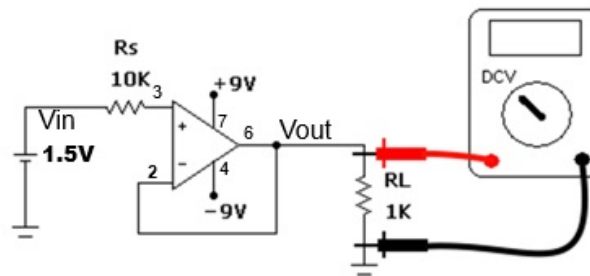


Figure 4 – Buffer Circuit

- 4) Assemble the circuit in Figure 4 on the breadboard according to the layout suggestion in Figure 5 and measure the voltage across the 1k load.

$$V_L(\text{measured}) =$$

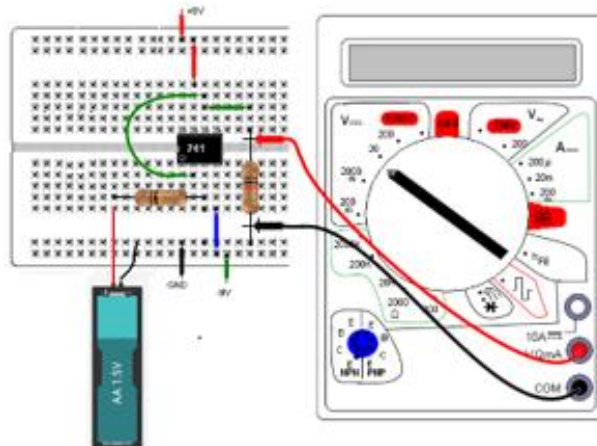


Figure 5 – Buffer with Op Amp

[Link to Simulator1](#)

[Link to Simulator2](#)

Calculate the gain measured by:

$$A_{vf} = \frac{V_{out}}{V_{in}} =$$

- 9) Based on the results, write a conclusion.

Experiment 05: Summing Amplifier

Index

Objectives

1. Experimentally verify the relationship between the output voltage and the inputs in an inverting adder circuit.
2. Experimentally verify the relationship between the output voltage and the inputs in a non-inverting adder circuit.

Material Used

2x9 V batteries with terminals
 4x1.5 V batteries
 2xHolder for 1 1.5 V batteries
 2xHolder for 2 1.5 V batteries
 1 Digital multimeter
 1 Breadboard
 1 IC 741
 Resistors: 3x2.2k
 Connection wires

Theoretical Introduction

Os circuitos somadores são derivados dos circuitos inverso e não inversor. A Figura 1 mostra o circuito somador inversor derivado do amplificador inversor, neste caso com três entradas (V_{in1} , V_{in2} e V_{in3}).

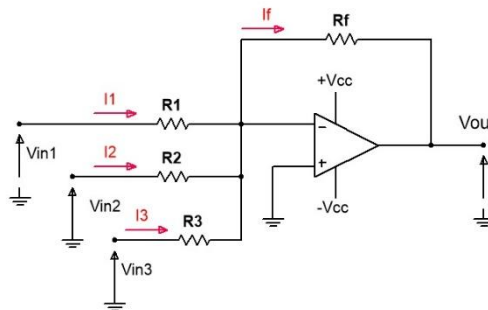


Figure 1 – Inverting summing amplifier

For this circuit, the expression of the output as a function of the inputs is given by:

$$V_{out} = -R_f \cdot \left(\frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2} + \frac{V_{in3}}{R_3} \right)$$

That is, the output voltage is a linear combination of the input voltages.

If we do $R_1 = R_2 = R_3 = R$ it will result in:

$$V_{out} = -\frac{R_f}{R} \cdot (V_{in1} + V_{in2} + V_{in3})$$

And if $R_f=R$ the expression results:

$$V_{out} = -(V_{in1} + V_{in2} + V_{in3})$$

that is, the output voltage is the inverted sum of the input voltages.

Non-Inverting Summing Amplifier

It is a non-inverting amplifier derivative circuit. For this particular case, with three inputs, the expression of the output (V_{out}) as a function of the inputs ($V_{in1}, V_{in2}, V_{in3}$) is:

$$V_{out} = V_{in1} + V_{in2} + V_{in3}$$

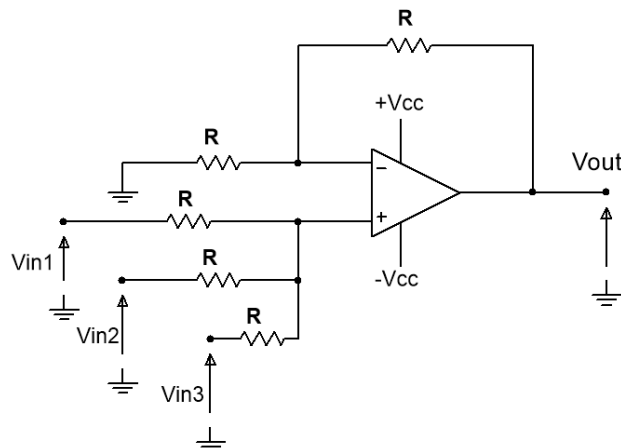


Figure 2 – Non-inverting summing amplifier

Experimental Procedure

- 1) For the circuit in Figure 3, calculate the output voltage (V_{out}) for each of the combinations of input voltages (V_{in1} , V_{in2}) in Table 1.

Table 1 – Inverting summing amplifier - calculated values

V_{IN1} (V)	V_{IN2} (V)	V_{OUT} (V)
1.5	1.5	
-1.5	-1.5	
-1.5	3.0	
-1.5	-3.0	
1.5	3.0	
0	0	

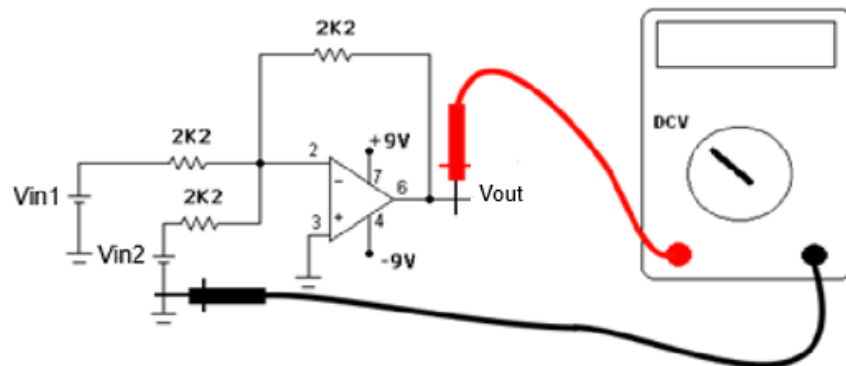


Figure 3 – Inverter adder circuit

- 2) Assemble the circuit in Figure 3 in the breadboard according to the layout suggestion in Figure 4. Measure the voltage at the output, V_{out} , for each of the combinations of inputs (V_{in1} , V_{in2}) in Table 2.

Note: indicate in Table 2 the effective values of the battery voltages, for example the effective value of battery 1 is 1.45 V, of battery 2 is 1.47 V, of the combination of two batteries is 2.9 V, etc.

Table 2 – Inverting summing amplifier – measured values

Vin1 (V)	Vin2 (V)	Vout(V)
1.5*	1.5*	
-1.5*	-1.5*	
-1.5*	3.0*	
-1.5*	-3.0*	
3.0*	3.0*	
0	0	

* Values actually measured with real batteries

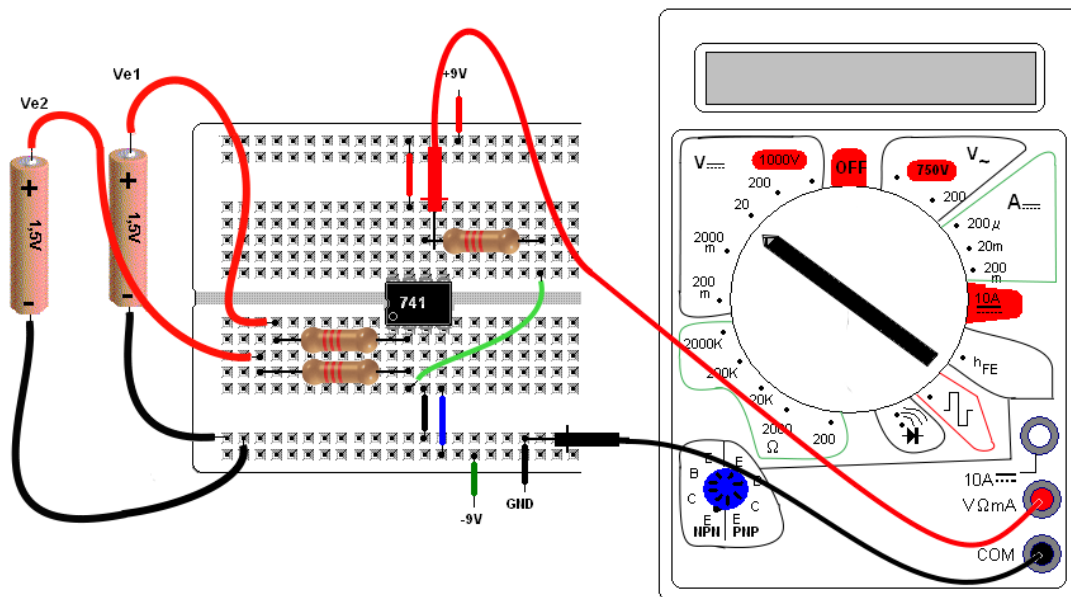


Figure 4 – Inverting summing amplifier - suggested layout on the breadboard

[Link to Simulator1](#)

[Link to Simulator2](#)

- 3) For the circuit in Figure 5, a non-inverting adder, calculate the output voltage for each of the combinations of input voltages in Table 3.

Table 3 – Non-inverting summing amplifier – calculated values

V_{in1} (V)	V_{in2} (V)	V_{out} (V)
1.5	1.5	
-1.5	-1.5	
-1.5	3.0	
-1,5	-3,0	
1.5	3.0	
0	0	

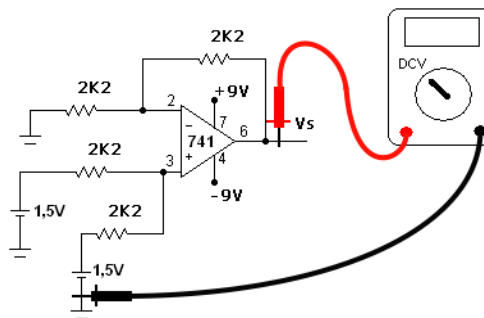


Figure 5 – Non-inverting adder circuit

- 4) Assemble the circuit in Figure 5 in accordance to the layout suggestion in Figure 6. Measure the output voltage for each of the input combinations in Table 4. *Note: indicate the effective values of the battery voltages (measured value) in the table.*

Table 4 – Non-inverting summing amplifier – measured values

V_{in1} (V)	V_{in2} (V)	V_{out} (V)
1.5*	1.5*	
-1.5*	-1.5*	
-1.5*	3.0*	
-1.5*	-3.0*	
1.5*	3.0*	
0	0	

*Note: * effective value*

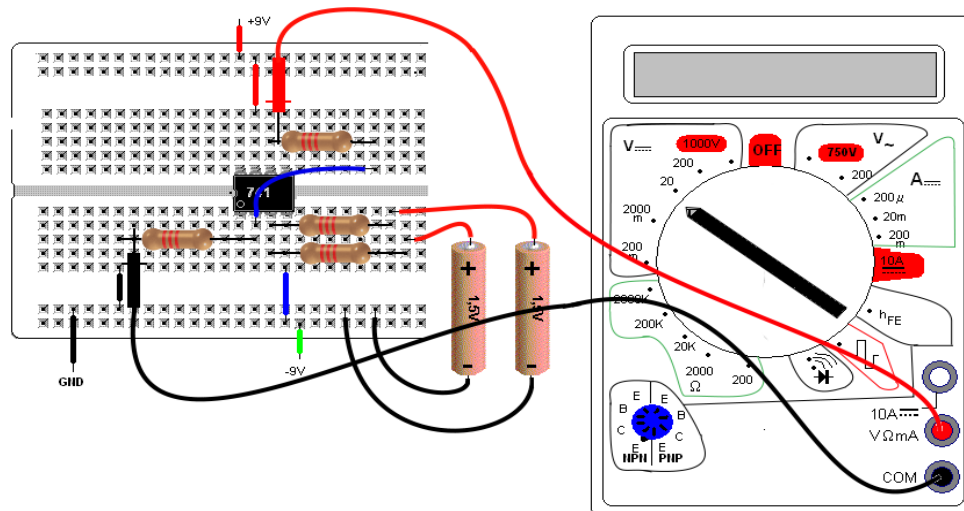


Figure 6 – Non-inverting summing amplifier on the breadboard
[Link to Simulator1](#) [Link to Simulator2](#)

5) Write your conclusion based on the calculated and measured results.

Experiment 6: Differential Amplifier – Subtractor Circuit

Index

Objectives

1. Experimentally determine the gain of a Differential Amplifier.
2. Experimentally verify the equation of a Subtractor circuit

Materials used

2x9 V batteries with terminals
 1 Digital multimeter
 6x1.5 V batteries
 1 Holder for 1 1.5 V battery
 1 Holder for 2 1.5 V batteries
 1 Holder for 4 1.5 V batteries
 1 Breadboard
 1 IC 741
 Resistors: 4x1 k/4x2.2k 1/4W

Theoretical Introduction

By definition, a Differential Amplifier amplifies the difference between two voltages.

Figure 1 shows the basic circuit.

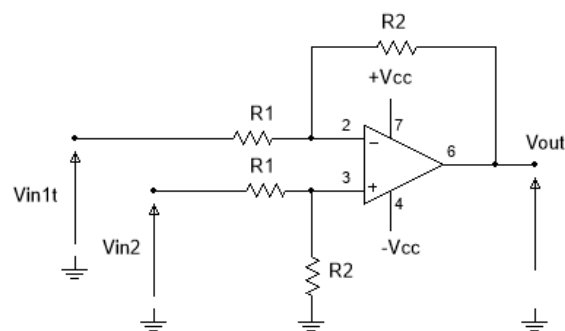


Figure 1 – Differential amplifier

For the circuit in Figure 1, the output voltage as a function of the inputs is given by:

$$V_{out} = \frac{R_2}{R_1} \cdot (V_{in2} - V_{in1})$$

Where differential gain is given by:

$$A_d = \frac{R_2}{R_1}$$

If $V_{in2}=V_{in1}$ the output is zero, but in practice this is not true due to several factors such as mismatch between the resistances (resistances that should be equal and are not) and a non-ideal Op Amp.

This circuit also has limitations, mainly in relation to the input resistance at both inputs, which is low. Another limitation of the circuit is the difficulty in varying the gain (two resistances must vary at the same time).

Subtractor Amplifier

If in the circuit in Figure 1 all the resistances are equal, the differential gain will be equal to 1 and the output will be given by:

$$V_{out} = V_{in2} - V_{in1}$$

that is, the circuit performs analog subtraction between two voltages.

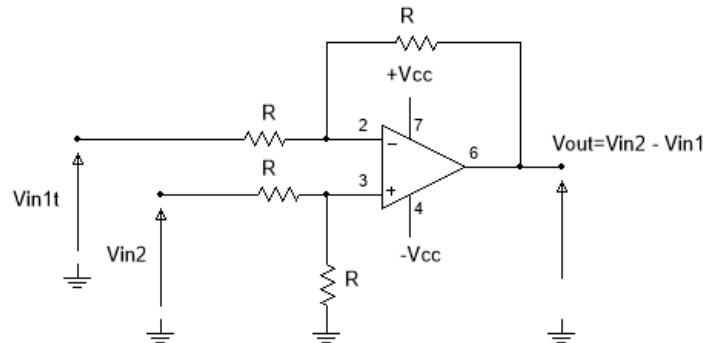


Figure 2 – Subtractor Amplifier

Differential Instrumentation Amplifier

Instrumentation amplifiers are essentially differential amplifiers, but without the disadvantages of the circuit in Figure 1. Figure 3 shows a simplified circuit of an instrumentation amplifier.

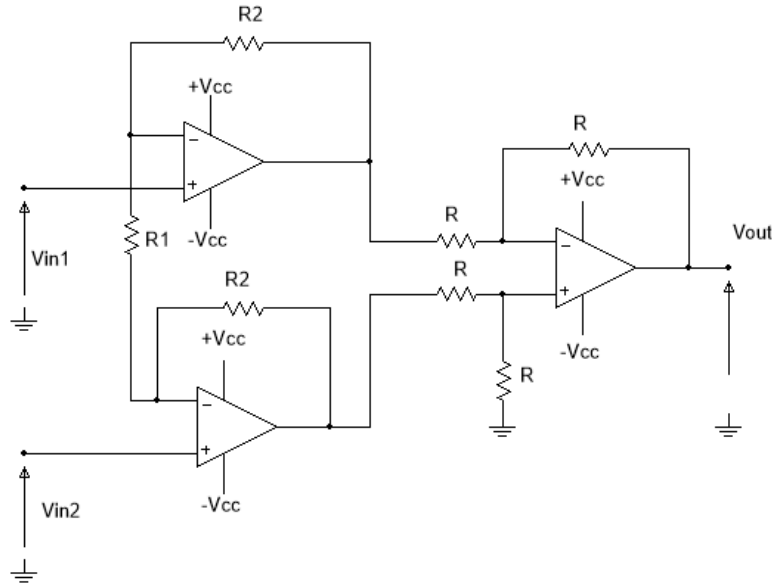


Figure 3 – Differential instrumentation amplifier

The circuit gain is given by:

$$A_{vf} = \frac{V_{out}}{V_{in}} = 1 + \frac{2.R_2}{R_1}$$

Where $V_{in} = V_{in2} - V_{in1}$

From the gain expression (A_{vf}) we conclude that if R_1 is variable the gain will be variable with only one resistance. The resistance at the inputs is typically of the order of 10^9 Ohms. The other resistances must have a tolerance of less than 1%.

In practice, we do not need to build an instrumentation amplifier, since it is already integrated with three Op Amps in the same package. Figure 4 shows an example of this instrumentation amplifier. The [ADC620](#), from Analog Devices, allows the gain to be varied through an external resistor R_G and since the amplifier comes perfectly balanced from the factory, we do not need to worry about adjusting the offset, Figure 4.

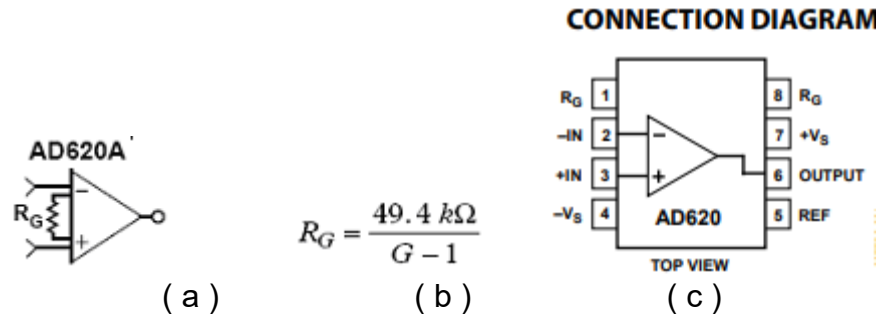


Figure 4 – Example of instrumentation amplifier (a) symbol (b) equation for calculating external resistance (R_G) (c) pinout

For example, if a gain of 100 is desired, the external R_G value will be:

$$R_G = \frac{49,4k}{G-1} = \frac{49400}{100-1} \cong 500$$

Note: $\cong$ approximately

Experimental Procedure

- 1) Calculate the output voltage (V_{out}) of the circuit in Figure 5 for each of the input voltage combinations in Table 1.

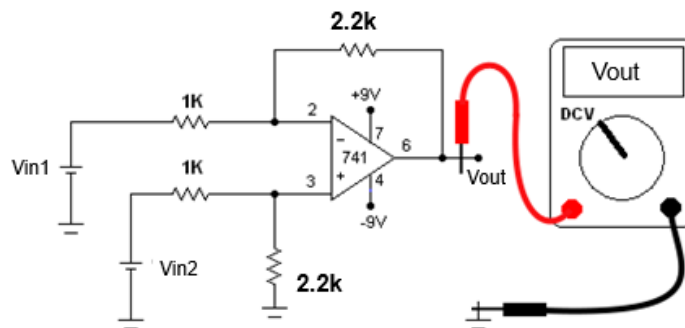


Figure 5 – Differential amplifier

Table 1 – Differential amplifier – calculated values

$V_{in2}(V)$	$V_{in1}(V)$	$V_{out}(V)$
3.0	1.5	
-3.0	1.5	
1.5	3.0	
0	0	
-3.0	-1.5	
-1.5	3.0	

- 2) Assemble the circuit in Figure 5 on the breadboard and for each of the combinations of input voltages (V_{in1} and V_{in2}) in Table 2, measure the voltage at the output (V_{out}).

Note: To obtain negative values, simply invert the battery (or combination). Important!! Indicate the effective values in the table, that is, if the measured value of one battery resulted in 1.47 V, this is the value that should be included. Two batteries measured resulted in 2.9 V, this is the value that should be indicated in table 2.

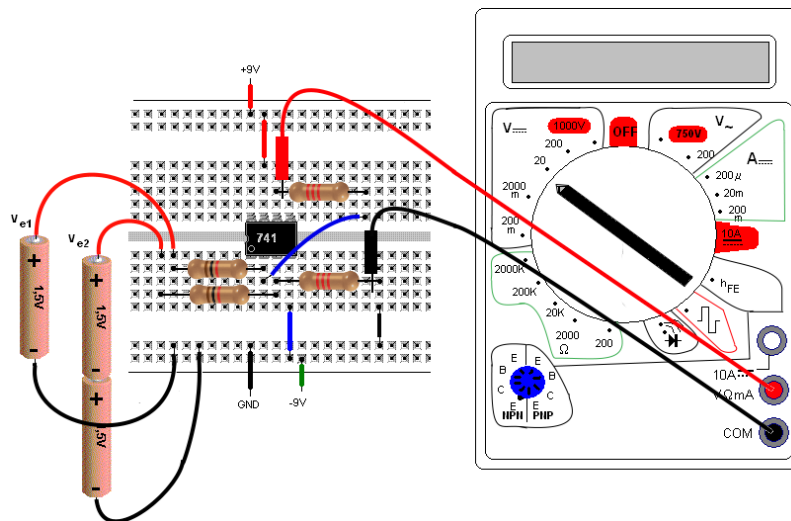


Figure 6 – Differential amplifier layout on the breadboard
[Link to Simulator1](#) [Link to Simulator2](#)

Note: Don't forget, the values given in table 2 are actually measured values.

Table 2 – Differential amplifier – measured values

$V_{in2}(V)$	$V_{in1}(V)$	$V_{out}(V)$
3.0	1.5	
-3.0	1.5	
1.5	3.0	
0	0	
-3.0	-1.5	
-1.5	3.0	

- 3) The circuit in Figure 7 works as a subtractor circuit, that is, it subtracts one voltage from another. Calculate the output voltage of the circuit in Figure 7 for each of the input voltage combinations in Table 3.

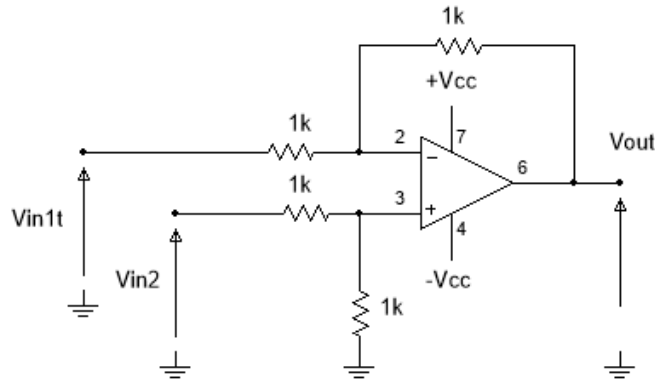


Figure 7 – Subtractor circuit

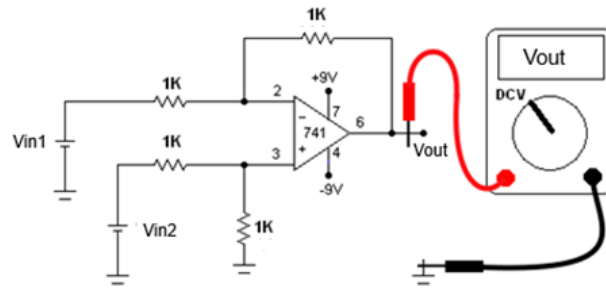
Note: The value of 6V is obtained with 4 1.5V batteries in series

Table 3 – Subtractor Circuit - calculated values

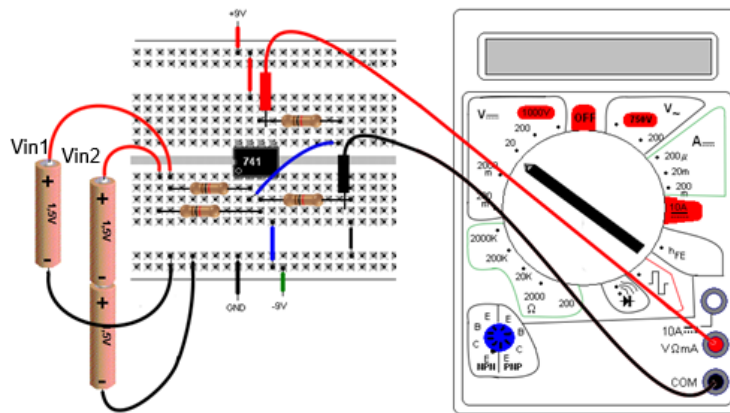
$V_{in2}(V)$	$V_{in1}(V)$	$V_{out}(V)$
3.0	1.5	
-3.0	1.5	
1.5	3.0	
0	0	
6.0	3.0	
3.0	6.0	

- 4) Assemble the circuit in Figure 8a on the breadboard according to the layout in Figure 8b, and for each of the combinations of input voltages (V_{in1} and V_{in2}) in Table 4, measure the voltage at the output.

Note: To obtain negative values, simply invert the source (or association). Important!! Indicate the effective values in the table, that is, if one measured battery resulted in 1.47 V, this is the value that should be included. Two measured batteries resulted in 2.9 V, this is the value that should be indicated in table 4.



(a)



(b)

Figure 8 – Subtractor circuit

[Link para Simulador1](#)
[Link para Simulador2](#)

Table 4 – Subtractor Circuit – measured values

$V_{IN2}(V)$	$V_{IN1}(V)$	$V_{out}(V)$
3.0	1.5	
-3.0	1.5	
1.5	3.0	
0	0	
-3.0	-1.5	
-1.5	3.0	

5) Based on the measurements and observations, write your conclusions.

Experiment 07: Zero Comparators

Index

Objectives

1. Experimentally verify the behavior of an inverting zero comparator.
2. Experimentally verify the behavior of a non-inverting zero comparator.

Materials Used

2x9 V batteries with terminals
 1xSupport for 1 1.5 V battery
 1x1.5 V battery
 1 Digital multimeter
 1 Breadboard
 1 IC 741
 1 LED
 Wires for connections

Theoretical Introduction

Comparator circuits work based on the very high open-loop gain ($>10^5$) of an Op Amp. Figure 1 shows the open-loop transfer characteristic ($V_{out} \times V_i$) curve of a typical Op Amp. The graph shows that there is a region of linear behavior, but it is very narrow.

For $-0.1\text{mV} < V_{in} < 0.1\text{mV}$ the output will be $V_{out} = 100,000 \cdot V_{in}$ and outside this range the Op Amp saturates. In practice, if the input voltage, in module, is much higher than 0.1mV the transfer characteristic curve approaches the ideal (red line).

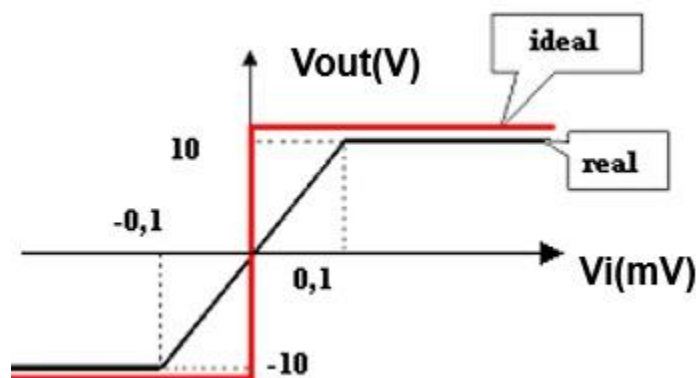


Figure 1 – Open loop transfer characteristic curve ideal (black) e curve real (red)

Non-Inverting Zero Comparator

In this circuit, the voltage applied to the non-inverting input, V_{in} , is compared with the voltage applied to the inverting input, which is zero. If it is greater than zero (positive), the output saturates positively ($+V_{sat}$), if V_{in} is less than zero (negative), the output saturates negatively ($-V_{sat}$). Figure 2 shows this behavior.

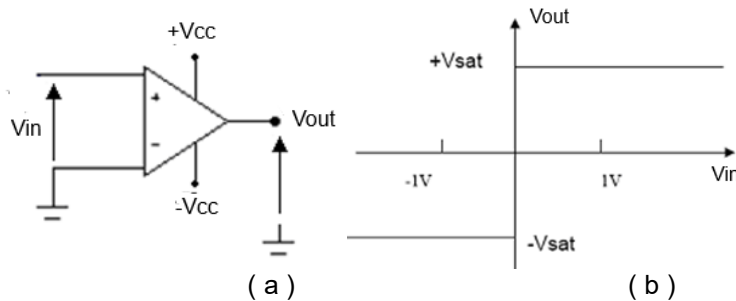


Figure 2 – (a) Non-inverting zero comparator (b) transfer characteristic

For example, if $V_{in}=1V$ in Figure 2a the output will be positive and equal to $+V_{sat}$ ($\approx +V_{cc}$). If $V_{in}= -1V$ the output saturates negatively and will be equal to $-V_{sat}$ ($\approx -V_{cc}$).

Note: $\approx$ means approximately

Inverter Zero Comparator

It is similar to the non-inverting one, but the signal is applied to the inverting input, Figure 3.

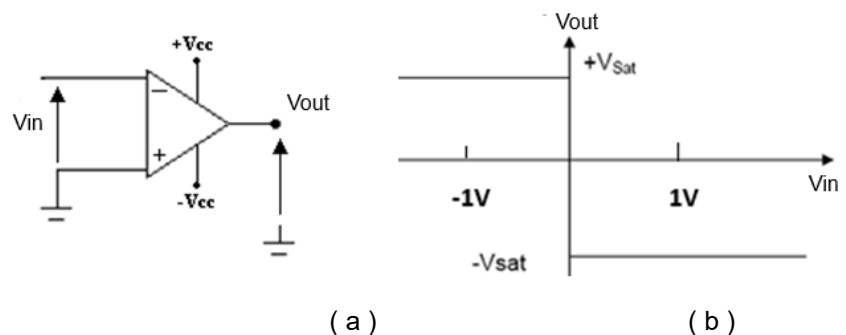


Figure 3 – (a) Inverting zero comparator (b) transfer characteristic.

For example, if $V_{in}=1V$ in the circuit in Figure 3a, the output voltage, V_{out} , will be equal to the saturation voltage, $-V_{sat}$, whose value depends on the power supply V_{cc} . If $V_e=-1V$ the output voltage will be $+V_{cc}$.

These circuits are used to detect the crossing of zero of an alternating voltage, since when changing polarity there is a voltage variation from $-$ to $+$ or from $+$ to $-$ and this can be detected by a circuit called a differentiator.

Experimental Procedure

- 1) Assemble the circuit in Figure 4 (non-inverter comparator) on the breadboard, Figure 5 and measure the voltage at the output for the two input values in Table 1.

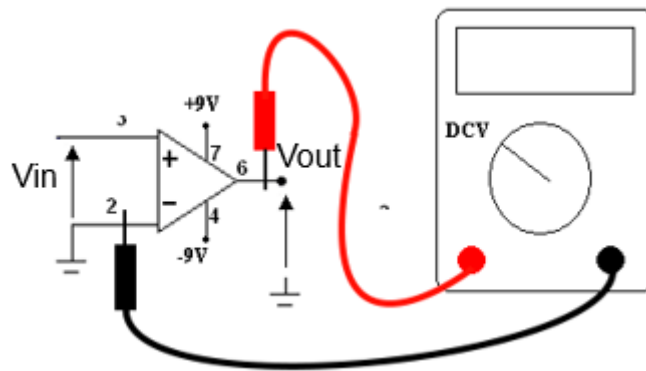
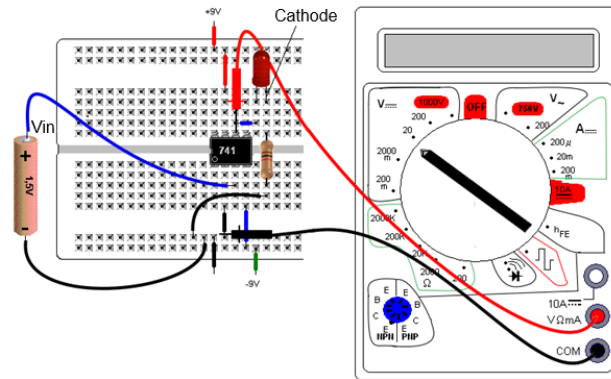


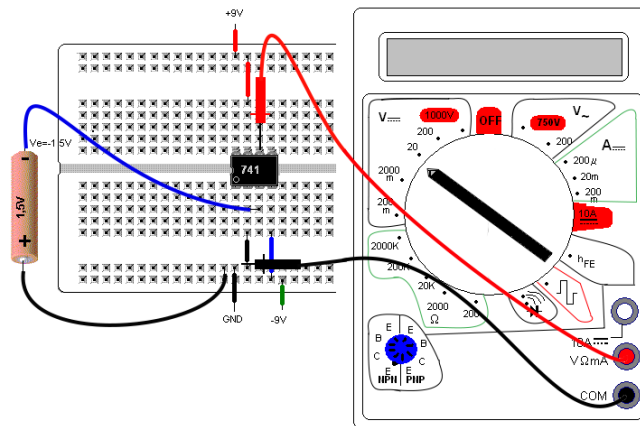
Figure 4 – Non-inverting zero comparator

Table 1 – Measured values – non-inverting zero comparator

Measured values	
$V_{in}(V)$	$V_{out}(V)$
1.5	
-1.5	



(a)



(b)

Figure 8 – Non-inverting zero comparator (a) $V_{in}=1.5\text{ V}$ (b) $V_{in}=-1.5\text{ V}$ [Link to Simulator1](#)[Link to Simulator2](#)

- 2) Assemble the circuit in Figure 9 (inverter comparator) on breadboard and measure the voltage at the output for the two input values in Table 2.

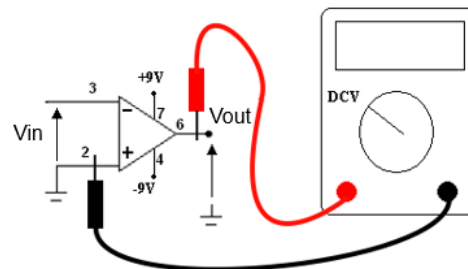


Figure 9 – Inverter zero comparator

Table 2 – Measured values – Inverter zero comparator

Measured values	
Vin(V)	Vout(V)
1.5	
-1.5	

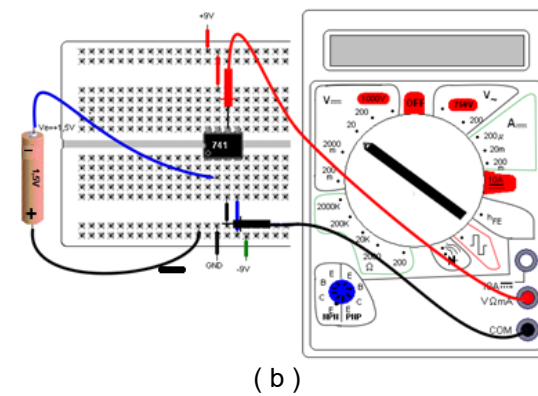
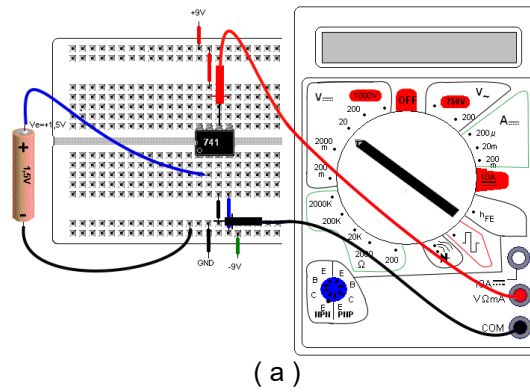


Figura 9 – Comparador de Zero inversor (a) $V_{in}=1.5\text{ V}$ (b) $V_{in}=-1.5\text{ V}$ - Layout no breadboard
[Link to Simulator1](#) [Link to Simulator2](#)

Experiment 8: Level Comparators

Index

Objectives

1. Verify the operation of a level comparator.

Materials Used

2x9 V batteries with terminals

1 Holder for 1 1.5 V battery

1 1.5 V battery

1 Digital multimeter

1 Breadboard

1 IC 741

Resistors: 3x1k/2k2/10 k

1 LDR

1 LED

Wires for connections on the breadboard

Theoretical Introduction

The level comparator is similar to the zero comparator. The difference is that the input voltage (V_{in}) is compared with a reference voltage V_R . If $V_{in} > V_R$ the Op Amp output saturates positively, if V_i is applied to the non-inverting input. If $V_{in} < V_R$ the Op Amp output saturates negatively. This is shown graphically in the transfer curve Figure 1b.

The voltage V_{in} can be associated with a temperature obtained from a temperature sensor. For example, the voltage obtained in a voltage divider where one of the resistors is a thermistor PTC or NTC.

Level Comparator

In a level comparator the input voltage (V_{in}) is compared with a reference voltage V_R instead of ground, Figure 1a. In practice this can be used to determine whether a physical quantity (level of a reservoir, temperature, light, etc.) has reached a predetermined level. In the circuit of Figure 1a if the input voltage is less than V_R the output saturates negatively otherwise it saturates positively.

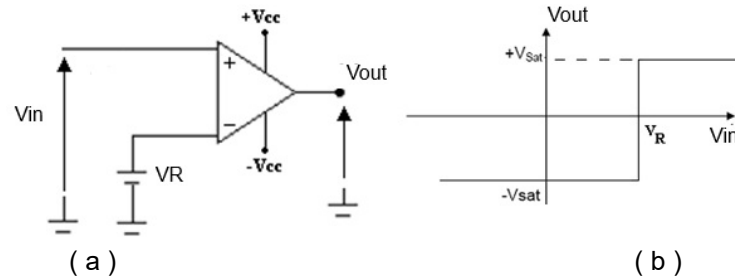


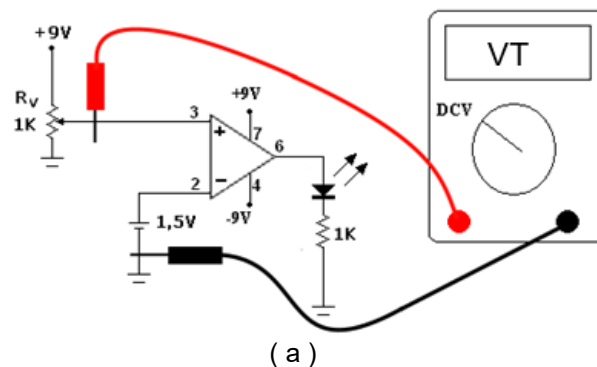
Figure 1 – Non-inverting level comparator and transfer characteristic curve ($V_{out} \times V_{in}$)

Experimental Procedure

- 1) Assemble the circuit in Figure 2a, level comparator, on the breadboard according to the suggested layout in Figure 2b. Vary the potentiometer, checking what happens to the LED at the output.
- 2) Place the voltmeter between the central terminal (cursor) of the potentiometer and ground and note the voltage value to which the output changes (LED condition changes). Note this value as V_T (transition voltage).

Note: V_R = effective value, is the value actually measured (1.5V, 1.48V, 1.52V etc)

$V_T =$



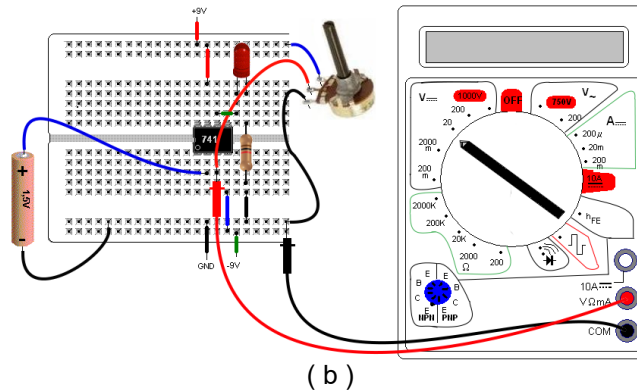


Figure 2 – Comparing the cursor voltage with 1.5V (a) Circuit (b) Breadboard assembly

[Link to Simulator1](#)

[Link para Simulador2](#)

- 3) In practice, a battery is not used to provide the reference voltage (V_R), but a voltage divider (two resistors in series).
- 4) For the circuit in Figure 3a, calculate the value of the reference voltage applied to the inverting input. Write this value down as V_R .

$$V_R(\text{calc.}) =$$

Note: Don't forget 2k2 and 1k are a [voltage divider](#)!

- 5) Now, calculate what value the resistance between the non-inverting input (+) and ground must have so that the voltage at the non-inverting input is equal to V_R . Write this value down as R_T (transition resistance).

$$R_T(\text{calc.}) =$$

- 6) Assemble the circuit in Figure 3a according to the layout in Figure 3b on the breadboard. Measure the voltage at the inverter input and write it down as $V_R(\text{measured})$. Remember, if $V > V_R$, $V_{out} = +V_{sat}$, if $V < V_R$, $V_{out} = -V_{sat}$

$$V_R(\text{measured}) =$$

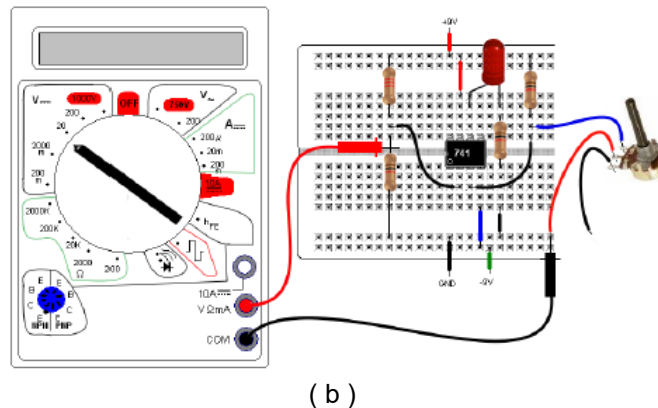
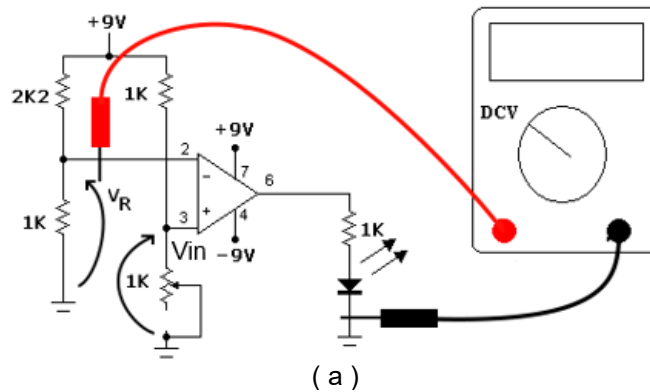


Figure 3 – Level comparator with voltage divider (a) Circuit (b) Breadboard assembly

[Link to simulator1](#)

[Link to simulator2](#)

- 7) Vary the potentiometer from zero to the maximum value, observing what happens to the LED at the output. When the output changes, remove the potentiometer and measure the value resistance between cursor (red wire) and the other terminal (blue wire), Figure 4. Write down this value as R_T (measured).

Note: Do not forget that the potentiometer is not precision, that is, when it varies, the resistance variation is relatively large. To measure accurately, a multiturn potentiometer must be used!

R_T (measured)=

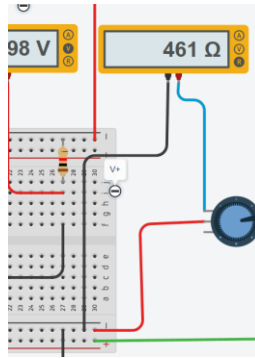


Figure 4 – Measuring resistance R_T

8) Based on the measurements and observations, write your conclusions.

Experiment 09: Light Comparator

Index

Objectives

1. To learn about a light sensor, the LDR.
2. To experimentally verify the operation of a light detector circuit using LDR and Op Amp.

Materials Used

2x9 V batteries with terminal
 1 Holder for 1 1.5 V battery
 1 1.5 V battery
 1 Potentiometer de 4.7k
 1 Digital multimeter
 1 breadboard
 1 IC 741
 Resistors: 3x1k/2.2k/10 k $\frac{1}{4}$ W
 1 LDR 5mm
 1 Red LED
 Wires for connections on the breadboard

Theoretical Introduction

This circuit aims to turn on a lamp at dusk and turn it off at dawn. To do this, it is necessary to have a light sensor, the best known is the LDR (Light Dependent Resistor) or photorresistor, Figure 1 shows the symbol and physical appearance of the LDR.

Note: LDR stands for Light Dependent Resistor

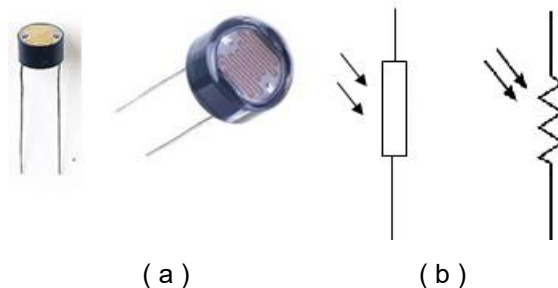


Figure 1 – LDR (a) Physical appearance (b) Symbols

When illuminated the resistance is low as 200 Ohms, and in the dark it can reach 200 kOhms.

Figure 2 shows a voltage divider, where one of the resistors is an LDR. What happens to the voltage across the LDR (V_{LDR}) when illuminated and in the dark?

For example, consider that when illuminated the resistance of the LDR is $R_{LDR}=500$ Ohms and in the dark $R_{LDR}=180k$. What is the voltage value across the LDR in each case?

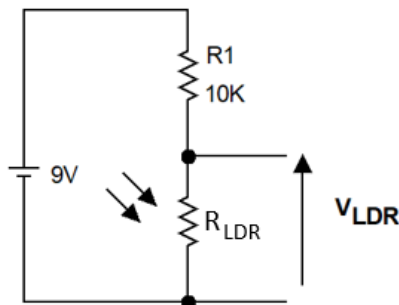


Figure 2 – LDR in voltage divider

In the dark:

$$V_{LDR(dark)} = \frac{180k \times 9V}{10k + 180k} = 8.5V$$

the LDR under light:

$$V_{LDR(light)} = \frac{0.5k \times 9V}{10k + 0.5} = 0.428V$$

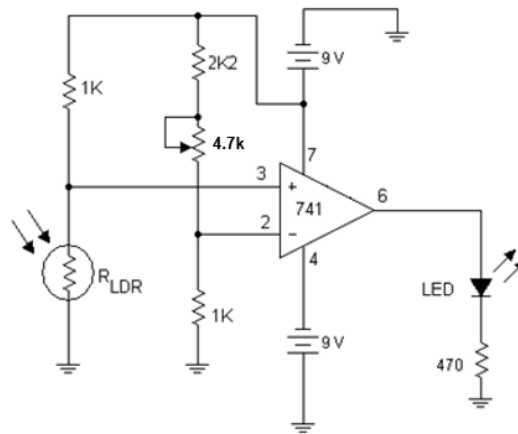
Experimental Procedure

- 1) Assemble the circuit in Figure 3a (light detector) according to the layout in Figure 3b. Adjust the potentiometer so that the LED turns off (the output is - 9 V) when the LDR is illuminated (the voltage at the inverting input must be greater than the voltage at the non-inverting input). Remember: In the dark, R_{LDR} is very high, around 180 kΩ. On the other hand, when well lit, R_{LDR} is very low, around 200 Ohms. The voltage at the Non-Inverting input (+) can be calculated by:

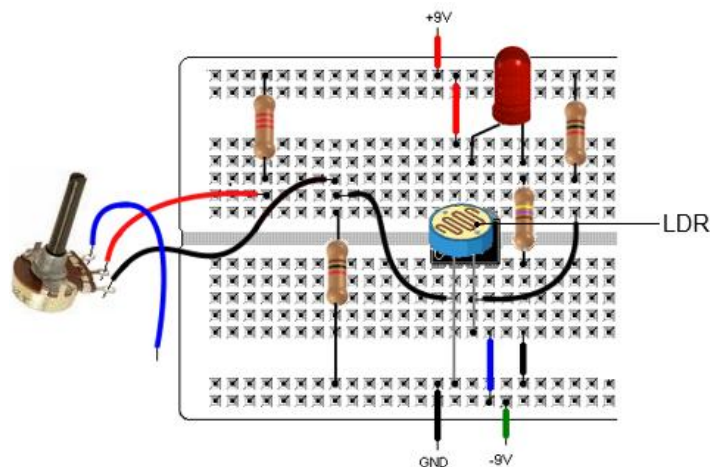
$$V_+ = \frac{R_{LDR}}{R_{LDR} + 1k} \cdot 9V$$

The voltage at the input (-) must be adjusted, using the 4.7 k potentiometer, so that with the LDR illuminated the LED at the output does not light up, for this $V_- > V_+$. As soon as it gets dark $V_+ > V_-$ making the Op Amp output go to $+V_{sat}$ turning on the LED. At the same time observe the V_{in} and V_{out} measurements.

Note: To illuminate, use the cell phone lamp and to darken, place your hand on top of the LDR



(a)



(b)

Figure 3 – Luminosity detector (a) circuit (b) Layout in breadboard

[Link to simulator1](#)

[Link to Simulator2](#)

- 2) What happens if light up the LDR again? Can the circuit be used as an burglar alarm? Justify.
- 3) Based on the measurements and observations, write your conclusions.

Experiment 10: Op Amp and SCR in Direct Current - Alarm

[Index](#)

Objective

1. Experimentally verify the operation of an SCR (Si Controlled Rectifier) in DC.
2. Assemble a comparator circuit with Op Amp and SCR, verifying the SCR's locking action.
3. Assemble a light detector circuit with SCR.
4. Assemble a light detector circuit with Op Amp and SCR

Materials Used

2x9 V batteries with terminals
 1 Digital multimeter
 1 Breadboard
 1 SCR TIC106B or BT151
 1 Op Amp 741
 Resistors: 4x470/2x1k/2.2k/3.3k $\frac{1}{4}$ W
 1 1k linear potentiometer
 1 4.7k linear potentiometer
 1 47k linear potentiometer
 1 5 mm LED

Theoretical Introduction

The SCR or Silicon Controlled Rectifier is a semiconductor constructed with 4 alternating layers (PNPN) and with three terminals: Anode (A), Cathode (K) and Gate (G). Figure 1 shows the simplified physical aspect, the symbol and the characteristic curve.

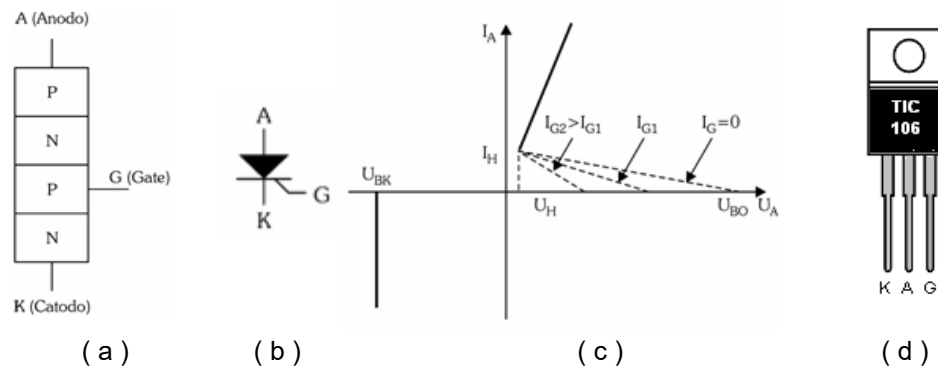


Figure 1 – SCR (a) physical structure (b) symbol (c) characteristic curve (d) physical appearance

Considering that the gate current is zero, the three operating regions are defined:

Reverse Blocking

If the anode is negative with respect to the cathode, the SCR behaves as an open switch (current is practically zero) just like a common diode. If the reverse voltage is greater than V_{BK} (breakdown voltage) or V_{RRM} , the device will be destroyed. This information is usually given on the body of the SCR as a letter (A=100 B=200 V, C=300 V, D=400 V, etc.)

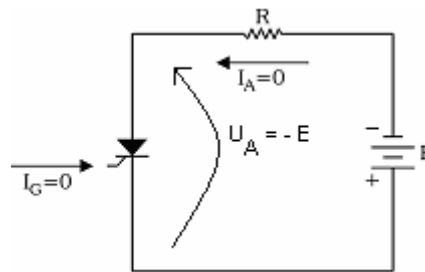


Figure 2 – SCR in reverse block

Direct Blocking

If the voltage applied between anode and cathode is positive, but lower than a V_{BO} value (breakover voltage) or V_{DRM} , the SCR remains cut off (open switch).

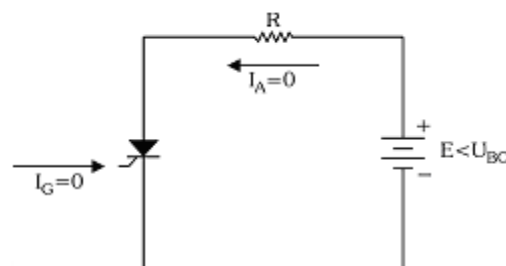


Figure 3 – SCR in direct blocking

Triggering and Conduction

If the voltage applied in Figure 3 exceeds V_{BO} or V_{DRM} , the SCR triggers, that is, changes condition abruptly. The voltage across the SCR drops to approximately 1 V (the exact value depends on the current intensity). Practically all of the source voltage drops across the resistance.

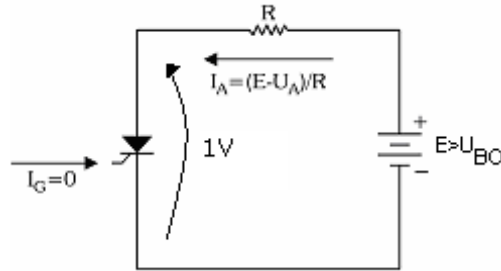


Figure 4 – Forward biased SCR after triggering.

After triggering, the SCR will cut off again if the voltage (current) between the anode and cathode falls below a value called the maintenance voltage (current) V_H (I_H).

The Gate

The function of the gate is to trigger the SCR at voltages below V_{BO} . The higher the current injected into the gate, the lower the voltage required to trigger. Importantly, the gate is only used for triggering, to turn off the SCR, the anode voltage (current) must fall below the maintenance voltage (current) V_H (I_H).

See more about SCR and more virtual experiments at

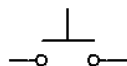
<http://www.eletronica24h.net.br/aulaei06.html>

Experimental Procedure

- 1) Assemble the circuit in Figure 6a on breadboard according to the layout suggestion in Figure 6b. Check the circuit operation using the S1 (to trigger) and S2 (to reset) switches. Measure the voltage across the 470 Ohm resistor, the SCR and the LED and write it down.

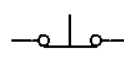
Note: You can replace the wires with normal open push button, Figure5a.

Push Button normal open.



(a)

Push Button normal closed.



(b)

Figure 5 – Push Button (a) Normal open (b) Normal closed

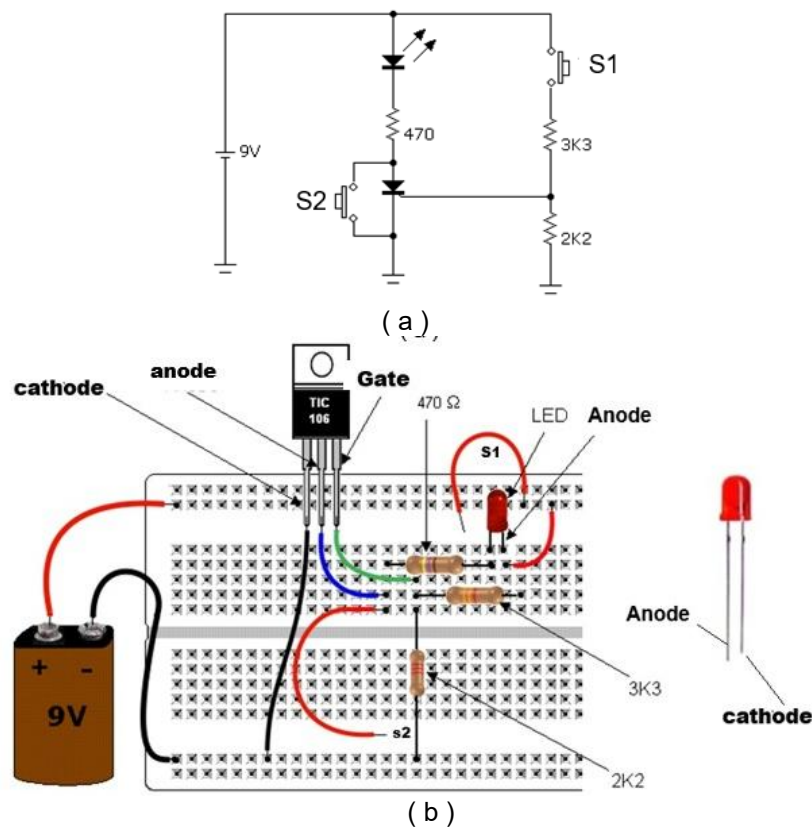


Figure 6 – SCR in DC (a) circuit (b) Circuit on breadboard

[Link to Simulator2](#)

Note: Tinkercad does not have SCR

$V_{470} =$ _____ $V_{SCR} =$ _____ $V_{LED} =$ _____

- 2) The circuit in Figure 6a is an Op Amp comparator, the output will be high (+9 V) if $V_+ > V_-$ and will be low (-9 V) if $V_+ < V_-$. The voltage at the non-inverting input is fixed at half the battery voltage, but the voltage at the inverting input depends on the value of R_V , which in practice can be a potentiometer, an LDR, a phototransistor, an NTC, a PTC or any device whose resistance can be varied when a physical quantity varies. The objective is to build an alarm associated with the physical quantity in question, light.
- 3) Assemble the circuit in Figure 6a according to the layout in Figure 6b. Measured the voltage at the non-inverting input and record it as V_+ .

$V_+(\text{Measured}) =$

- 4) Adjust the potentiometer so that the voltage at the inverting input is slightly higher than the voltage at the non-inverting input. Under these conditions, the Op Amp output is negative and the SCR should be cut off and LED is on (if the LED is on, reset the SCR using switch S1).
- 5) After adjustment, slowly vary the potentiometer until the LED lights up (SCR trigger). Disconnect one of the potentiometer terminals and measure its resistance, noting it as $R_{\text{transition}}$.

$R_{\text{transition}} =$

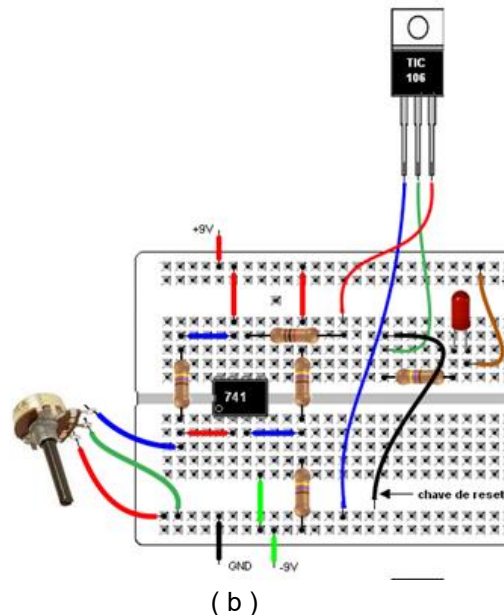
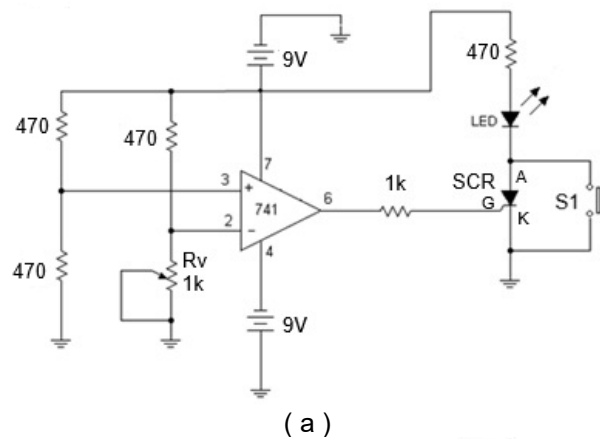


Figure 6 – Circuit with Op Amp and SCR (a) circuit (b) Suggested layout on the breadboard.

[Link to Simulator2](#)

Note: Tinkercad does not have SCR

- 6) The circuit in Figure 7a is a practical application of the circuit in Figure 6. It is an alarm.
- 7) Assemble the circuit of Figure 7a in breadboard according to the layout of Figure 7b. Adjust the 47 k Ω potentiometer so that the Op Amp output is low (-Vcc) when the LDR is illuminated (use cell phone light), that is, the voltage at the non-inverting input is slightly lower than that at the inverting input. Under these conditions, the SCR will be cut off and the LED will be off.

NOTE: Since there is no LDR (photoresistor) in Multisim, two resistors of 100 ohms (light) and 200 k Ω (dark) will be used to simulate the LDR.

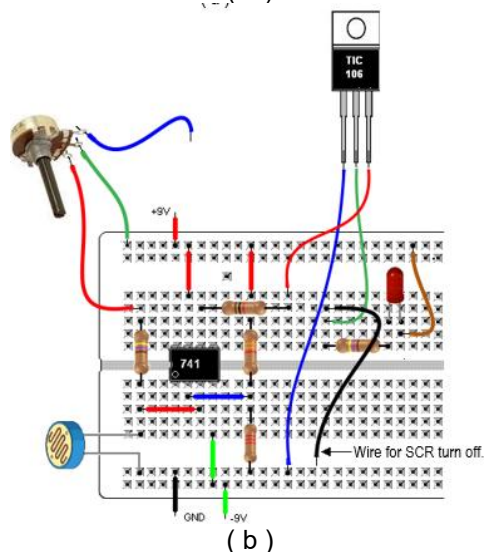
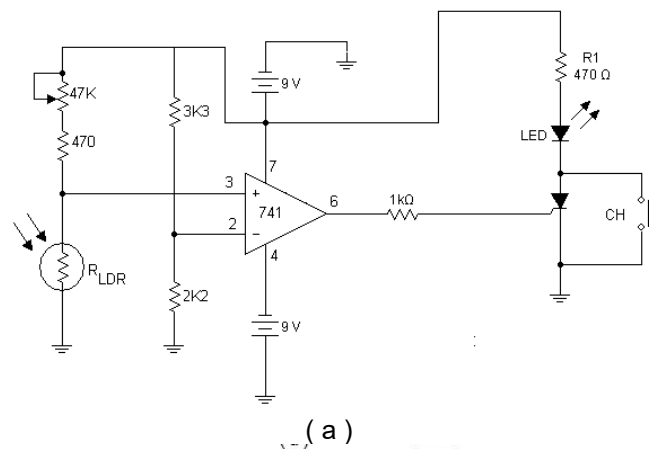


Figure 7 – Alarm with SCR, Op Amp and LDR (a) circuit (b) Layout on breadboard

[Link to Simulator2](#)

Note: Tinkercad does not have SCR Multisim does not have LDR.

LDR, in the circuit, will be represented by two resistors, R_{night} and R_{day} .

$R_{night}=180$ $R_{day}=200$

- 8) Make a shadow over the LDR, for this use your hand. What happens? If necessary, repeat the experiment, and to do so, reset the SCR (by momentarily pressing the S1 key), with the LDR illuminated.
- 9) Based on the measurements taken and observations made, write your conclusions regarding item 8

Bibliography:

SEDRA, A. **Microelectronic Circuits**

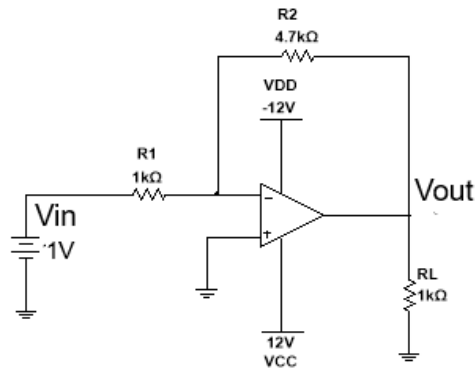
STOUT, David F. **Handbook of Operational Amplifier Circuit Design**

<http://www.eletronica24h.net.br/aulaao002.html>

Solved Exercises

These exercises complement the experimental part.

- 1) Calculate the voltage at the output of the Op Amp (V_{out}), the current at the output of the Op Amp (I_{out}) and the load (I_L) in the circuit.



Solved Exercise1 1

Solution: $V_{in} = 1\text{ V}$ Closed loop gain: $A_{vf} = -4\text{K}7/1\text{K} = -4.7$

Therefore **$V_{out} = A_{vf} \times V_e = -4.7 \cdot 1\text{V} = -4.7\text{ V}$**

Since $V_i = 0$, then $V_{R1} = V_{in} = 1\text{V}$, thus $I_{R1} = 1\text{V}/1\text{k} = 1\text{mA}$

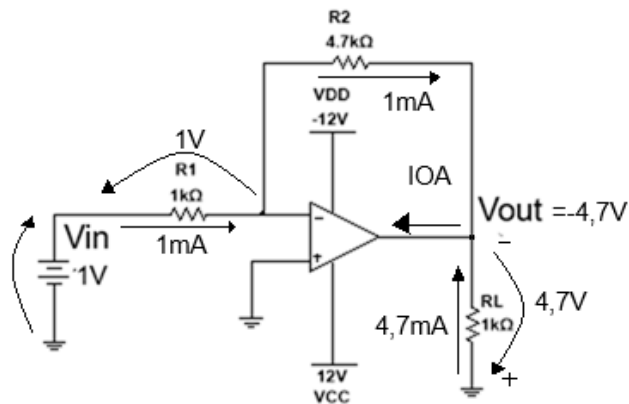
Since R_i is infinite and $I_i = 0$, then $I_{R2} = I_{R1} = 1\text{mA}$

Since the output voltage, V_{out} , is -4.7V (negative output in relation to ground), the current in the load (R_L) has the direction indicated as in the figure and has the value:

$$I_L = 4.7\text{V}/1\text{k} = 4.7\text{mA}$$

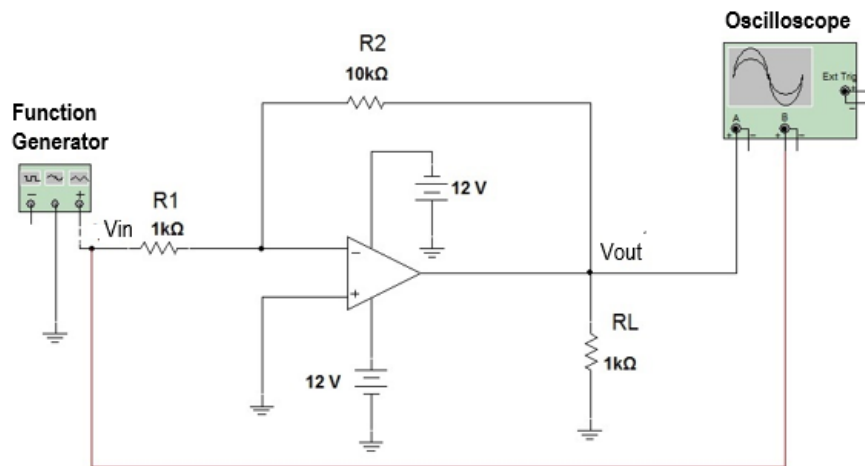
The current at the Op Amp output ($I_{OP} = I_{out}$) is:

$I_{op}=I_{out}= 1mA+4.7mA=5.7mA$ (Kirchhoff's First Law). This information is important because every Op Amp has an output current limit. For example, the 741 has a maximum output current of 20mA (Leaving or entering.).



2) For the circuit you are asked for::

- Draw the graphs of $V_{out}(t)$ and $V_{in}(t)$ if $V_{in}(t) = 1.\sin\omega t(V)$
- Draw the transfer characteristic curve ($V_{out} \times V_e$) if the saturation voltage is given $V_{sat} = \pm 12V$.
- Draw the output voltage graph if $V_e = 2.\sin\omega t(V)$



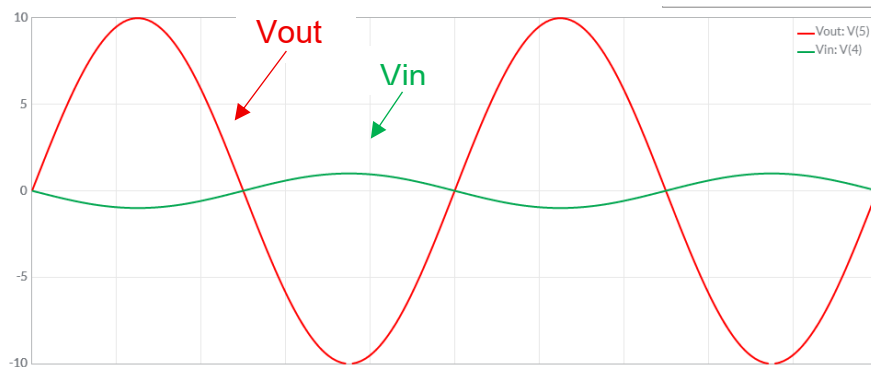
[SolvedExercices2a](#)

Solution:

- a) The circuit gain is $A_{vf} = -10k/1k = -10$ the output is ten times greater than the input and out of phase by 180° .

$$V_{in} = 1 \cdot \sin(\omega t) \text{ (V)} \quad \mathbf{V_{out} = -10 \cdot \sin(\omega t) \text{ (V)}}$$

The graphs of $V_{in}(t)$ and $V_{out}(t)$ are:



- b) The transfer characteristic curve of any device relates the input Variable to the output variable. For example, in a motor the input variable may be voltage in the winding and the output variable, the rotation on the shaft.

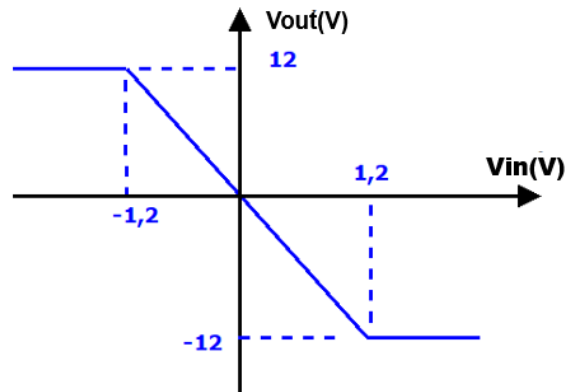
In the case of exercise 2, the input is a voltage (V_{in}) and the output is a voltage (V_{out}).

The transfer curve is basically the graphical representation of the equation

$$V_{out} = -10 \cdot V_{in}$$

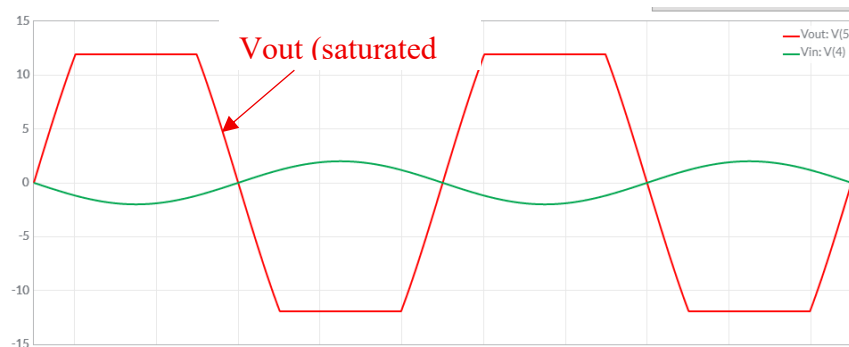
within the linear region, that is, to saturate (reach 12 V at the output) the input must be ± 1.2 V. Mathematically, we write:

$V_{out} = -10 \cdot V_{in}$ is valid for **$-1.2 \text{ V} < V_{in} < 1.2 \text{ V}$** the graph shows this condition.



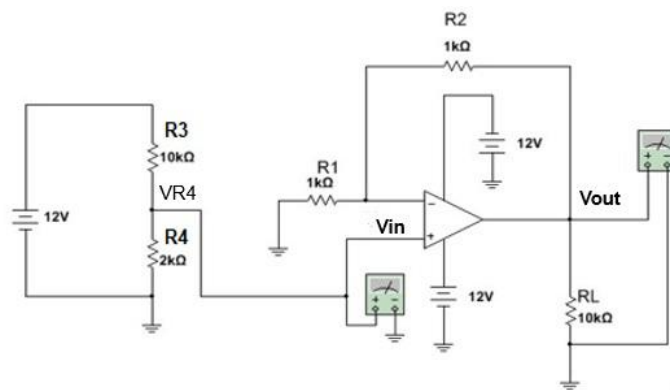
[SolvedExercices2b](#)

- c) The maximum output voltage (saturation) depends on the value of the symmetrical power supply. It is normally slightly lower, in module, than the power supply. If the maximum output is $V_{sat} = \pm 12V$, when $V_{in} = 2V$ the output will not be $-20V$, saturating before. In this case the sinusoid peaks will be cut at approximately $+12V$ and $-12V$ as in the graph



[SolvedExercices2c](#)

- 3) In the circuit determine the output voltage, V_{out} .



[SolvedExercices3](#)

Solution: In the circuit the voltage in the voltage divider $V_{R4}=V_{in}$.

$$V_{R4} = \frac{2k}{10k + 2k} \cdot 12V = 2V = V_{in}$$

The circuit with the Op Amp is a Non-Inverting amplifier with gain $(1+R_2/R_1)$ equal to 2. The output voltage, V_{out} , will be equal to:

$$V_{out} = \text{Gain} \cdot V_{in} = (2) \cdot 2V = 4V$$

- 4) In relation to the circuit of Exercise 3 determine:
- What is the maximum amplitude that the input voltage V_{in} can have, in Exercise 3, so that the output does not saturate?
 - What should be the value of R_4 in item a)?
 - Draw the transfer curve, $V_{out} \times V_{in}$

Given: $V_{sat} = \pm 12V$

Solution:

- a) The maximum output amplitude is 12 V, and since the gain is

$$A_{vf} = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1} = 2 \quad \text{or} \quad V_{out} = 2 \cdot V_{in}$$

The maximum input amplitude will be:

$$V_{inMax} = \frac{V_{outMax}}{2} = \frac{12V}{2} = 6V$$

- b) Applying the value of a) to the voltage divider, that is:

$$6 = \frac{R_4}{R_4 + 10k} \cdot 12V$$

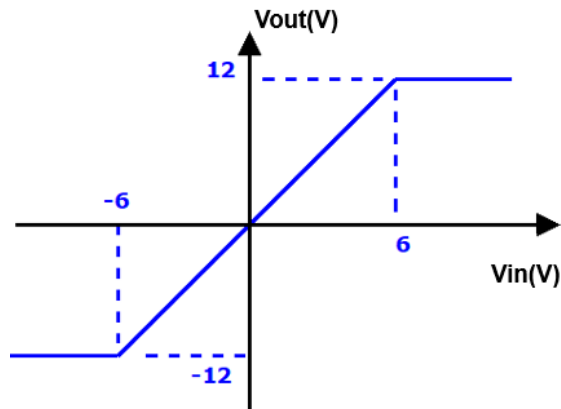
developing the expression results :

$$6 \cdot (R_4 + 10k) = 12 \cdot R_4 \quad \Rightarrow \quad 6 \cdot R_4 + 60 = 12 \cdot R_4 \quad \Rightarrow \quad 60 = 12 \cdot R_4 - 6 \cdot R_4$$

Finally: $R_4 = 60/6 = 10k$

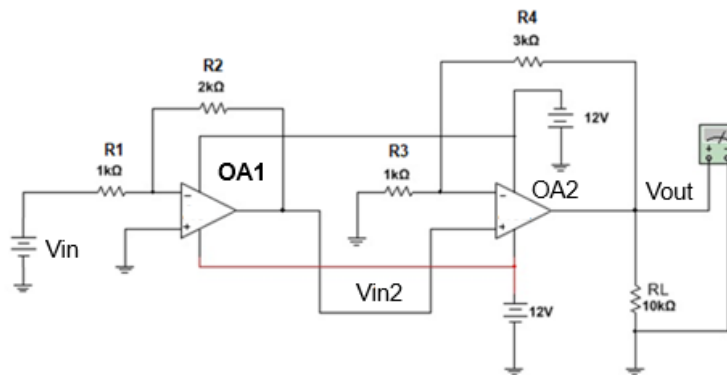
Note: Try changing $R_4=2k$ to $R_4=10k$ and see what happens in simulation

c) As the gain is 2 to saturate $V_{in} \geq 6V$ (in module) the graph will result.



[SolvedExercices4c](#)

5) What is the value of V_{in} that results in an output (V_{out}) equal to 8 V in the circuit? $R_1=1k$ $R_2=2k$ $R_3=1k$ $R_4=3k$ $R_L=10k$



[SolvedExercices5](#)

Solution:

The gain of the 2nd stage (OA2) is

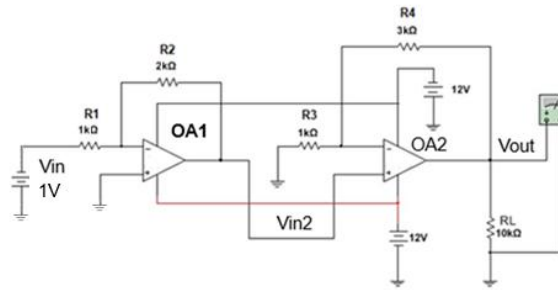
$$A_{vf2} = 1 + \frac{3k}{1k} = 4 = \frac{V_{out}}{V_{in2}}$$

Since $V_{out}=8V$ $V_{in2} = 8V/4 = 2V = V_{out1}$

The gain of the first (OA1) is

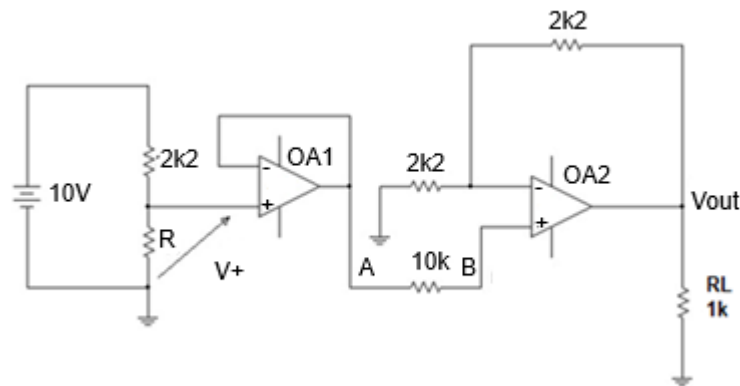
$$A_{vf1} = \frac{V_{in2}}{V_{in}} = -\frac{R_2}{R_1} = -\frac{2k}{1k} = -2 \quad V_{in} = \frac{2V}{-2} = -1V$$

Therefore of polarity opposite to that indicated in the circuit.



Solved Exercises 5

- 6) In the circuit, what is the value of R so that $V_{out}=6\text{ V}$?



Solved Exercises 6

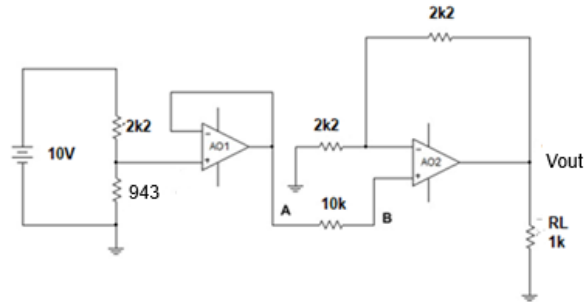
Solution:

The voltage at point A is equal to the voltage at point B (the current through the 10 k is zero). Since the gain of the second Op Amp is 2, with $V_{out} = 6\text{ V}$ the voltage at the input (point B) will be equal to:

$$V_B = 6\text{ V} / 2 = 3\text{ V}.$$

The first Op Amp is a buffer, its output voltage (V_A) is equal to the input voltage (V_+), therefore:

$$V_+ = \frac{R}{R+2.2k} \cdot 10\text{ V} = 3\text{ V} \quad \text{Developing results } \mathbf{R=943\text{ Ohms}}$$



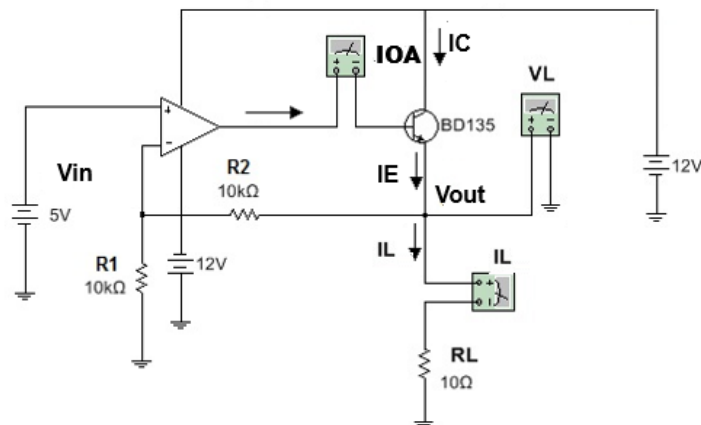
SolvedExercices6

- 7) The circuit allows the non-inverting amplifier with Op Amp to power a load (R_L) with a current higher than the maximum allowed in an Op Amp (20mA).

It is requested to calculate:

- Load current (I_L)
- Current at the Op Amp output (I_{OA})
- Power dissipated in the load (P_{RL}) and in the transistor (P_{TR})

Given: $\beta = 125$



SolvedExercise7

Solution:

- a) Because of the virtual short circuit between the (+) and (-) inputs $V_{R1} = V_{in} = 5\text{ V}$ therefore:

$$I_{R1} = V_{R1}/R_1 = 5\text{V}/10\text{ k} = 0.5\text{ mA} = I_{R2} \quad \text{then} \quad V_{R2} = 10\text{k} \cdot 0.5\text{ mA} = 5\text{ V}$$

as $V_L = V_{out} = V_{R1} + V_{R2} = 5 + 5 = 10 \text{ V}$ therefore $I_L = 10\text{V}/10 \text{ Ohms} = 1 \text{ A}$.

$$\text{b) } I_E = I_{R2} + I_L = 0.5\text{mA} + 1000\text{mA} = 1000.5 \text{ mA} \approx 1\text{A}$$

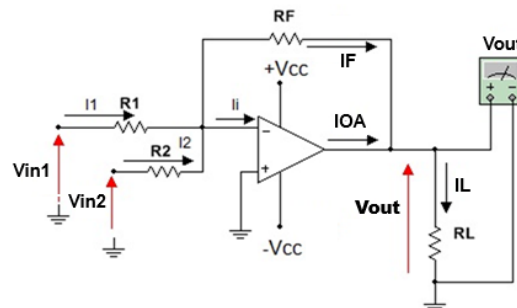
$$I_{OA} = I_B = I_C/\beta = 1000.5\text{mA}/125 = 8 \text{ mA}$$

$$\text{c) } P_{RL} = V_L \cdot I_L = 10\text{V} \cdot 1 \text{ A} = 10 \text{ W}$$

$$V_{CE} + V_L = 12\text{V} \quad \text{then} \quad V_{CE} = 12\text{V} - 10\text{V} = 2\text{V}$$

$$P_{TR} = V_{CE} \cdot I_C = 2\text{V} \cdot 1\text{A} = 2\text{W}$$

- 8) Calculate the output voltage, V_{out} , in the circuit if $R_1=1\text{k}$, $R_2=2\text{k}$, $R_L=1\text{k}$, $R_F=3\text{k}$, $V_{in1}=2 \text{ V}$ and $V_{in2} = -2 \text{ V}$.



SolvedExercise7

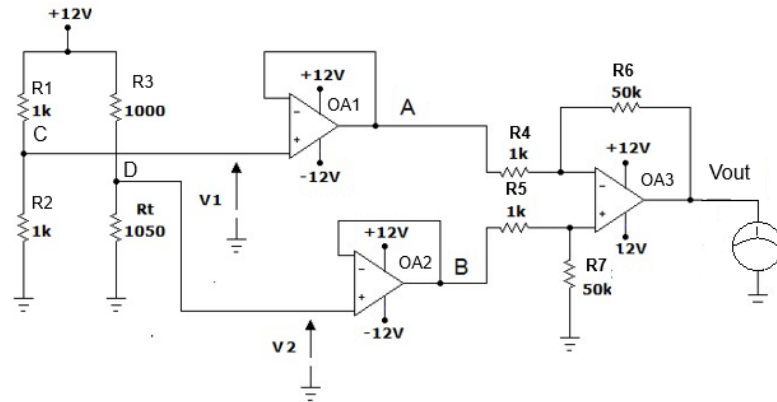
Solution:

For the circuit, the expression of the output voltage, V_{out} , as a function of the inputs, V_{in1} , and V_{in2} is:

$$V_{out} = -R_F \cdot \left(\frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2} \right)$$

$$V_{out} = -3\text{k} \cdot \left(\frac{2\text{V}}{1\text{k}} - \frac{2\text{V}}{2\text{k}} \right) = -3\text{V}$$

- 9) In the circuit, R_1 , R_2 , R_3 and R_t are a Wheatstone bridge where R_t is a resistance that varies with temperature. Calculate the output voltage, V_{out} , for two values of R_t , 1050 ohms and 1060 ohms.



Solved Exercise9

Note: Operational Amplifiers OA1 and OA2 are in Buffer configuration and OA3 is a differential amplifier.

Solution:

Considering $R_t = 1050$ Ohms and the circuit values:

$$V_1 = \frac{1k}{1k + 1K} \cdot 12V = 6V = V_A$$

The input voltage V_2 is:

$$V_2 = \frac{1,05k}{1k + 1,05K} \cdot 12V = 6,146V = V_B$$

Since the gain of the differential amplifier is 50, the value of the voltage at the output (V_{out}) will be equal to:

$$V_{out} = 50 \cdot (V_2 - V_1) = 50 \cdot (6.146 - 6) = \mathbf{7.3\ V}$$

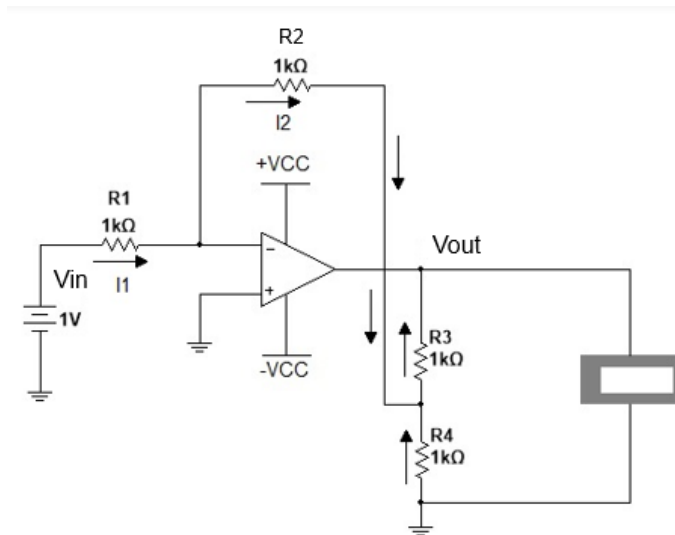
Considering $R_t = 1060$

$$V_1 = \frac{1k}{1k + 1K} \cdot 12V = 6V = V_A$$

$$V_2 = \frac{1.06k}{1k + 1,06K} \cdot 12V = 6.174V = V_B$$

$$V_{out} = 50 \cdot (V_2 - V_1) = 50 \cdot (6.174 - 6) = \mathbf{8.7\ V}$$

10) In the circuit determine the output voltage V_{out} .



Solved Exercise 10

Solution:

Calculation of current I_1 . Because of virtual ground:

$$V_{R1} = V_{in} = 1V$$

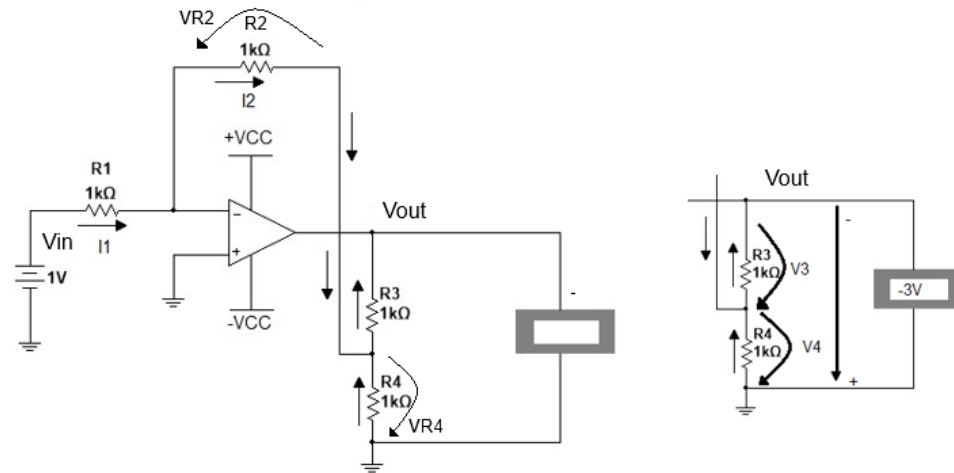
$$I_1 = \frac{V_{R1}}{R_1} = \frac{1V}{1k} = 1mA = I_2 \text{ because of the infinite input impedance.}$$

The voltage in R_2 , $V_2 = 1k \cdot 1mA = 1V = V_4$ because of the virtual ground and with the positive pole on the ground generating a current in R_4 of:

$$I_4 = \frac{1V}{1k} = 1mA, \text{ upwards as indicated}$$

$I_3 = I_2 + I_4 = 1 + 1 = 2mA$ upwards, so the voltage across R_3 is:

$$V_3 = 1k \cdot 2mA = 2V$$



SolvedExercise10

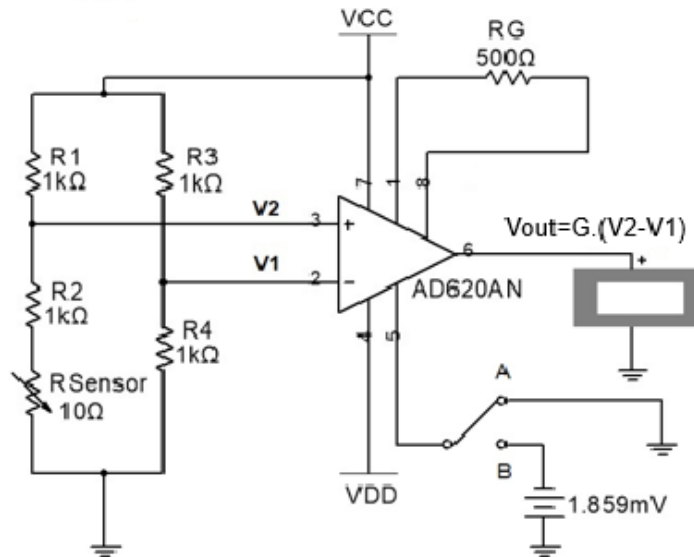
and the voltage at the output (V_{out}) with the positive on the ground, therefore negative:

$$V_{out} = V_4 + V_3 = 1V + 2V = 3V$$

- 11) The circuit is an instrumentation amplifier using an AD620 connected to a Wheatstone bridge ($R_1, R_2, R_3, R_4, R_{sensor}$). To use it, the offset adjustment is first made, which consists of applying a voltage to pin 5 equal to the output voltage, V_{out} , when $V_1 = V_2$, and with opposite polarity to pin 5 (REF) of the AD620. The gain (G) is given by:

$$R_G = \frac{49.4 k\Omega}{G - 1}$$

No circuito, o ganho desejado é 100, resultando $R_G = 500 \text{ ohms}$



SolvedExercise11

Solution:

If $R_{\text{sensor}}=0$ then $V_1=V_2=6V$ (voltage divider) therefore $V_2-V_1=0$ and $V_{\text{out}}=100.(V_2-V_1)=0$

$R_{\text{sensor}}=10 \text{ Ohms}$

$$V_2 = \frac{1010}{1000 + 1010} \cdot 12V = 6.0298V$$

$$V_1 = \frac{1000}{1000 + 1000} \cdot 12V = 6.0000V$$

With $R_G=500 \text{ Ohms}$ the gain is 100 therefore

$$V_{\text{out}}=100.(6.0298-6.0000)=\mathbf{2.985 \text{ V}}$$

$R_{\text{sensor}}=20 \text{ Ohms}$

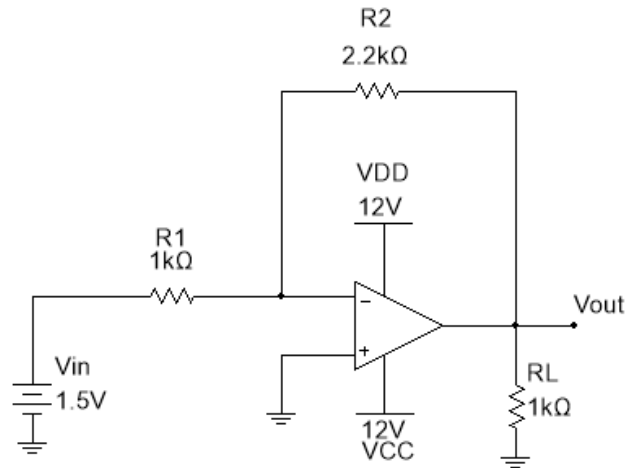
$$V_2 = \frac{1020}{1000 + 1020} \cdot 12V = 6.0594V$$

$$V_{out}=100.(6.0594V - 6.0000)=5.94 V$$

Proposed Exercises

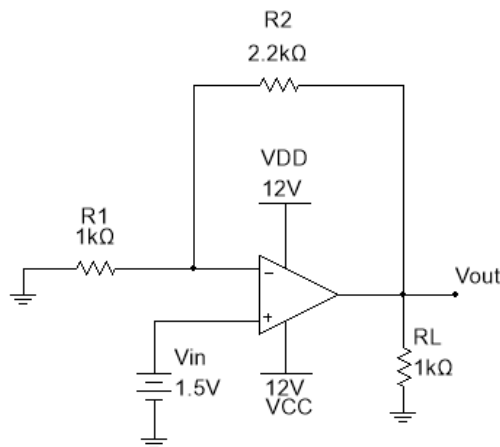
1) Determine the value of the output voltage, V_{out} , current at the OpAmp output, I_{oa} and current at the input, I_{in} , in each case.

1a



Proposed Exercises1a

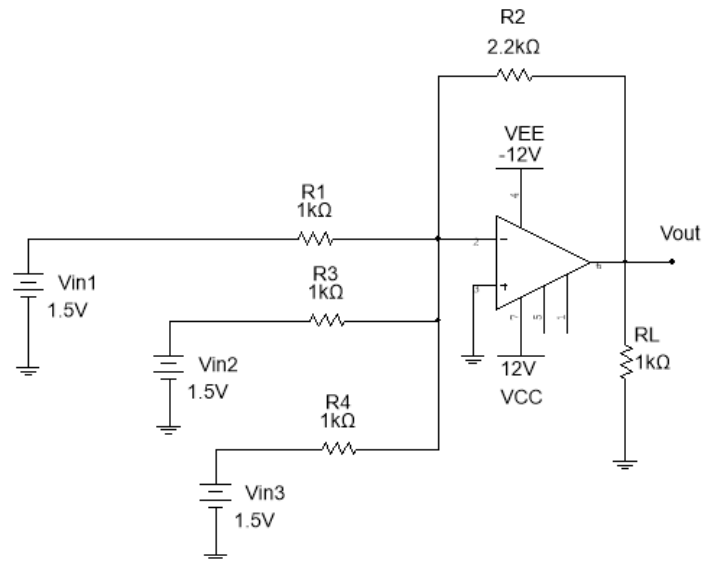
1b



Proposed Exercises1b

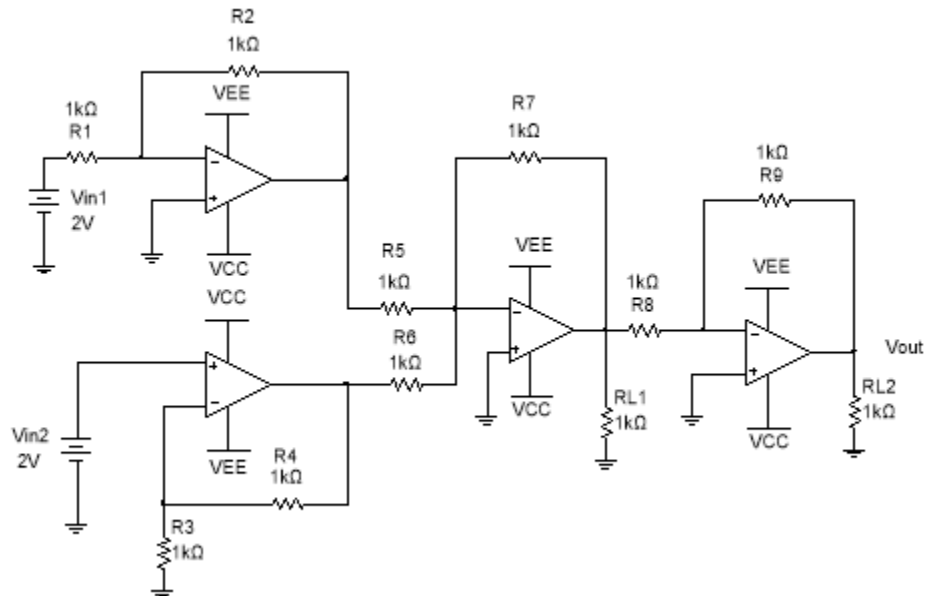
1) Determine the value of the output voltage, V_{out} , in each case.

2a



Proposed Exercises 2a

2b



Proposed Exercises 2b

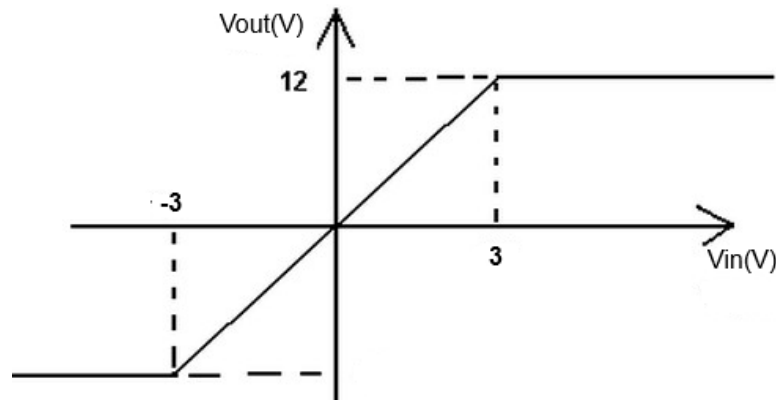
- 2) In question 2a, what is the expression for V_{out} in terms of V_{in1} and V_{in2} and V_{in3} ?

3) In question 2b, what is the expression for V_{out} in terms of V_{in1} and V_{in2} ?

4) Obter um circuito com Op Amp que tenha a expressão

$$V_{out} = 2.(V_2 - V_1) + V_3$$

5) The graph represents the output voltage (V_{out}) as a function of the input voltage (V_{in}) of a circuit with Op Amp. This circuit is:

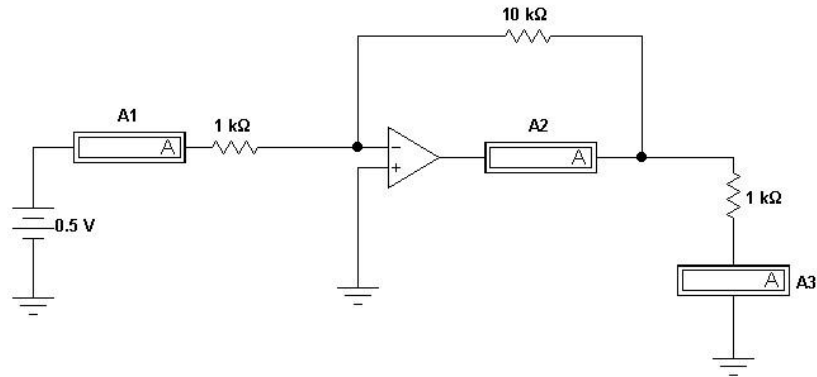


- a) Inverting amplifier
- b) Non-Inverting Amplifier
- c) Summing Amplifier
- d) Differential amplifier

6) The gain (V_{out}/V_{in}) of the amplifier in question 5 is:

- a) 4
- b) -4
- c) 2
- d) -2

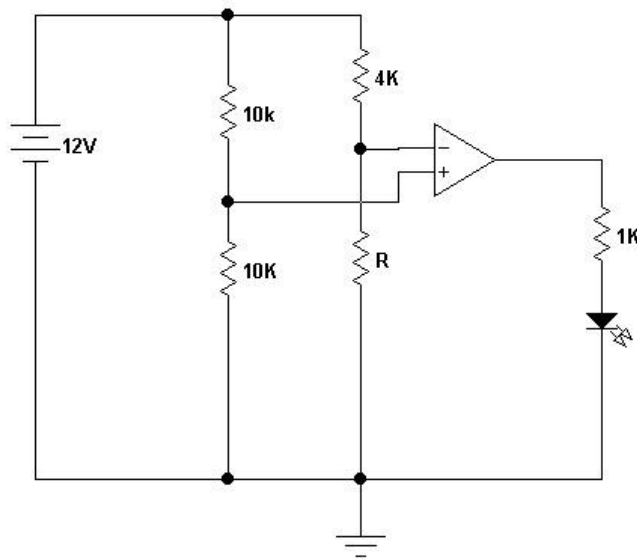
5) Regarding the circuit, the indication of instruments A1, A2 and A3, in module, are respectively:



ProposedExercise5

- a) 0,5 mA; 5 mA; 5,5 mA
- b) 0,5 mA; 5,5 mA; 5 mA
- c) 0,5 mA; 4,5 mA; 5 mA
- d) 0,5 mA; 5mA; 4 mA

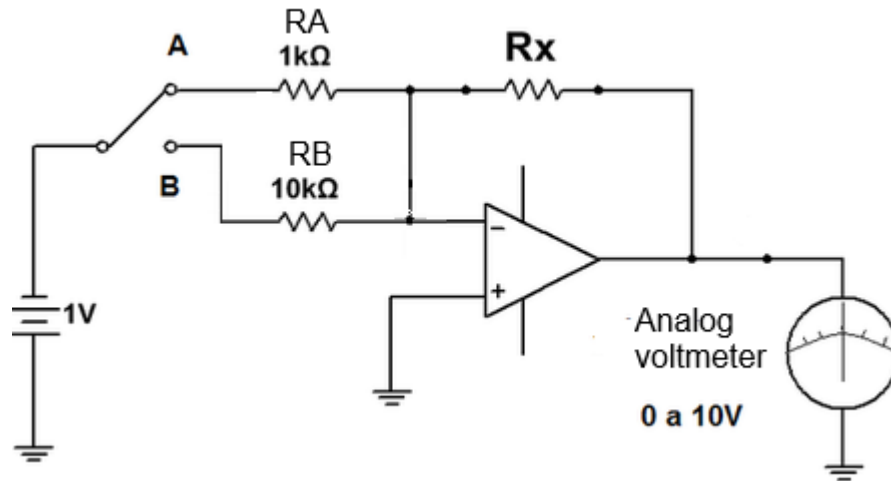
6) For what range of R values does the LED light up?



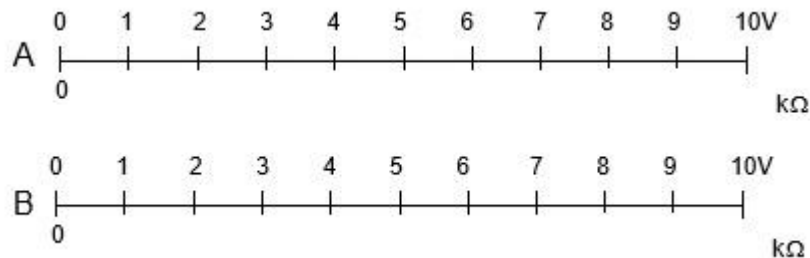
ProposedExercise6

- a) Greater than 10 k
- b) Less than 10 k
- c) Greater than 4 k
- d) Less than 4 k

- 7) The circuit is an analog ohmmeter. An analog voltmeter is placed at the output that measures from 0 to 10V. Considering the ideal Op Amp, what is the maximum resistance R_x that can be measured with the switch in A and B? Build a resistance scale considering the key in A and in B.

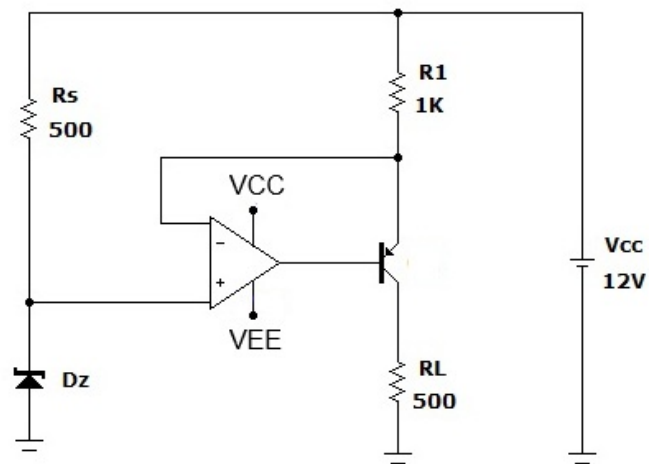


ProposedExercise7



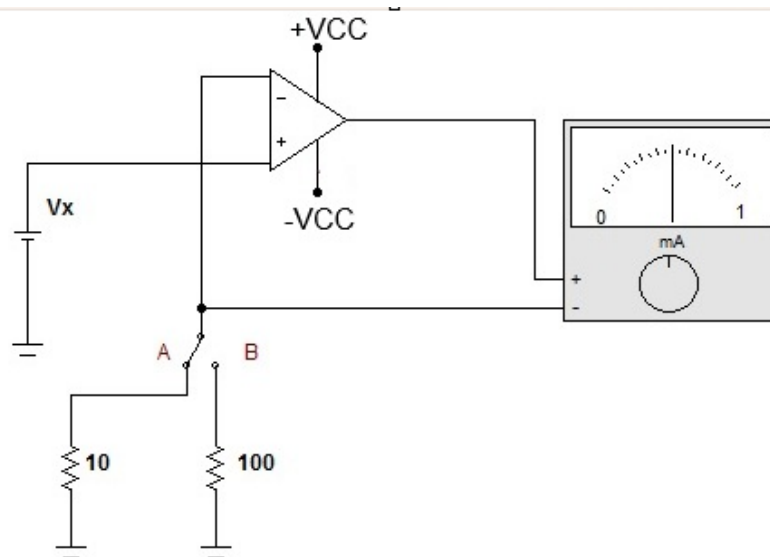
- 8) In question 7) a scale from 0 to 500 Ohms is desired. What is the value of the input resistance (R_C)?
- 9) The circuit works as a constant current source (even if the load changes value, the current value does not change). The following is required:
- Value of the current in the load (I_L), considering a load of 500 ohms.
 - What are the limits that R_L can have, in practice, so that the circuit can work as a current source?

Data: Zener diode $V_Z = 6\text{ V}$, $V_{ECsat} = 0\text{ V}$

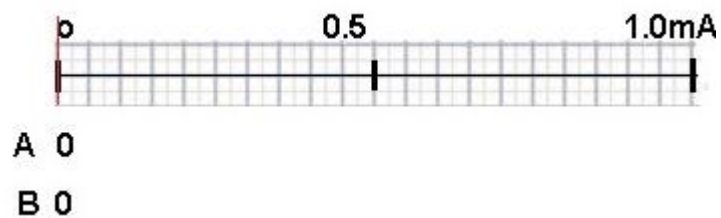


Proposed Exercise 9

- 10) The circuit is a precision voltmeter. The circuit uses a 1 mA full-scale milliammeter. What is the full-scale of the millivoltmeter for each switch position? Construct a scale for both switch positions.



Proposed Exercise 10



- 11) In the circuit, the resistance R varies with temperature according to the equation $R = 6000 + 0.004.T$ where R is specified in Ohms and T in degrees Celsius. At the output is a 10 V full-scale analog voltmeter. a) What is the maximum temperature it can measure? b) What temperature corresponds to 4V?

