

University of Portland
School of Engineering

EE 271–Electrical Circuits Laboratory
Spring 2014

Laboratory Manual
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**University of Portland
School of Engineering**

**EE 271 Electrical Circuits Laboratory Spring 2014
Syllabus**

Purpose: The goal of this laboratory is to teach the students how to construct and test simple electrical circuits, measure various physical quantities, such as voltage, current, and resistance, using different types of test instruments, and verify the relationships as well as observe and record the differences between theory and practice.

Learning Objectives: At the successful completion of this course, the student is expected to gain the following skills:

- Become familiar with the basic circuit components and know how to connect them to make a real electrical circuit;
- Become familiar with basic electrical measurement instruments and know how to use them to make different types of measurements;
- Be able to verify the laws and principles of electrical circuits, understand the relationships and differences between theory and practice;
- Be able to gain practical experience related to electrical circuits, stimulate more interest and motivation for further studies of electrical circuits; and
- Be able to carefully and thoroughly document and analyze experimental work.

Co-requisite: EE 261 Electrical Circuits

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Office: Shiley Hall 212

Lab Location: Shiley Hall 309

Textbook A lab manual will be provided.

Notebook: Every student is required to have a lab notebook to be used for reporting their lab work. The recommend lab notebook brand is *Roaring Spring* Compositions, which is a QUAD. RULED, 5 lines to 1", 9¾ in. X 7½ in., sewn-binding, 100-page notebook. It is available at UP Bookstore.

Lab Dates: The lab dates are tentatively scheduled as follows:

Experiment	Section A (Tuesday)	Section B (Thursday)
No Lab during first week	1/14/14	1/16/14
Exp. #0: Intro to EE271 Lab and Exp. #1: Ohm's & Kirchhoff's Laws	1/21/14	1/23/14
Exp. #2: Simple Resistive Circuits	1/28/14	1/30/14
Exp. #3: Wheatstone-Bridge Circuit	2/4/14	2/6/14
Fun Project #1*	2/11/14	2/13/14
Exp. #4: Electrical Circuit Theorems	2/18/14	2/20/14
Exp. #5: DAC R-2R Ladder Network (Formal Lab Report)	2/25/14	2/27/14
Fun Project #2*	3/4/14	3/6/14
No Lab during Spring Break	3/11/14	3/13/14
Exp. #6: Intro. to the Oscilloscope & Op- Amp Circuits	3/18/14	3/20/14
Exp. #7: First-Order RC Circuits	3/25/14	3/27/14
Exp. #8: Second-Order RLC Circuits	4/1/14	4/3/14
No Lab on Founders Day	4/8/14	N/A
Fun Project #3*	4/15/14	4/10/14
No Lab before Good Friday	N/A	4/17/14
Fun Project #4*	4/22/14	4/24/14

* Students are required to do any 3 of the 4 fun projects.

**Assessment/
Grades:**

The total score and grade for the course will be computed based on the following percentages:

- 25% for lab quizzes
- 45% for the lab notebook (based on performance on the pre-lab assignments, accuracy and presentation of the measurements, error analyses, discussions and conclusions; completeness, organization, and neatness of the lab notebook applies to both the pre-lab and the lab assessments)
- 15% formal lab report
- 10% fun projects
- 5% for lab performance

The final letter grade for the course is assigned based on the following total score/grade brackets over a scale of 100 possible points:

- 90–100 A⁻-A (Excellent Performance)
- 80–89 B⁻-B⁺ (Good Performance)
- 70–79 C⁻-C⁺ (Average Performance)
- 60–69 D⁻-D⁺ (Poor Performance)
- <60 F (Inadequate Performance)

Typically, the class average of the course grade is a B⁻.

**Pre-lab
Assignments:**

Pre-lab assignments will be assigned for each experiment. These pre-lab assignments are mandatory, that is, every student is expected to complete these assignments before coming to the lab.

Lab Quizzes:

There will be a 15-minute lab quiz at the beginning of most of the lab periods. The quizzes will cover the pre-lab assignment and previous labs.

**UP's Code of
Academic
Integrity:**

Academic integrity is openness and honesty in all scholarly endeavors. The University of Portland is a scholarly community dedicated to the discovery, investigation, and dissemination of truth, and to the development of the whole person. Membership in this community is a privilege, requiring each person to practice academic integrity at its highest level, while expecting and promoting the same in others. Breaches of academic integrity will not be tolerated and will be addressed by the community with all due gravity (taken from the University of Portland's Code of Academic Integrity).

The complete code may be found in the University of Portland Student Handbook and as well the Guidelines for Implementation. It is each student's responsibility to inform themselves of the code and guidelines.

**Accommodation
for Disability:**

If you have a disability and require an accommodation to fully participate in this class, contact the Office for Students with Disability (OSWD), located in the University Health Center (503-943-7134), as soon as possible.

Assessment

Disclosure: Student work products for this course may be used by the University for educational quality assurance purposes.

Diversity and Green

Dot Statement: All persons should feel safe to express their opinions in my class, regardless of their race, religion, political philosophy, gender, sexual orientation, or disability. In addition, I encourage anyone to speak up on behalf of themselves or others, if the classroom environment becomes uncomfortable for any reason.

Lab Safety: No one is allowed to work in the shops or labs without appropriate training from the shop technician and without instructor permission. No food or beverages are allowed in the lab.

Requirements for Laboratory Notebooks

In addition to keeping good records of what you have done for your own use, and the use of your company, it is necessary to keep records of your work in a way that would be effective to in defending against legal challenges to patent applications or in disputes over the ownership of intellectual property.

One of the goals of this course is to learn how to keep good records of laboratory work. You will find that accurate, readable records are extremely valuable in your work, and in some situations can make the difference between you or your company successfully defending a challenge to a patent or losing the patent.

The following is a list of requirements for the lab notebook:

1. Entries should be written in a bound lab notebook which gives some indication of tampering if pages are inserted or deleted, and keeps pages from being lost or from being re-ordered.
2. Write all data and notes directly into the lab notebook. Do not use scrap paper and later copy the data into your notebook. This saves time and eliminates the possibility of making a mistake while copying.
3. Use black permanent ink for all entries.
4. Do not erase or remove incorrect entries. Simply cross them out so that the incorrect entry is still readable.
5. Write the date with your initials at the top of each page.
6. Cross out any blank space that is more than about three lines.
7. Do not use the back of the pages.
8. Record the names of anyone who helps you perform the experiment.
9. If a separate sheet, such as a computer printout, needs to be inserted into the notebook, staple it to a blank page and make a note in the lab notebook describing the attachment.
10. Entries in the notebook should be clear and complete enough to allow others to repeat the work. Record what was done, when it was done, and who did it.
11. Entries should be signed and dated by a witness.
12. If additional information is added after the original date, that information should be signed and dated separately.

For more information, see *Successful Patents and Patenting for Engineers and Scientists*, Edited by Michael A. Lechter, IEEE Press, ISBN: 0-7803-1086-1, 1995, pp. 156-182.

Sample Write-Up Format for EE 271 Lab Experiments

The following is a sample write-up format for the EE 271 lab experiments. Please follow this format for all your write-ups in your lab notebooks this semester. Note that the write-up is provided in italics form.

SAMPLE LAB REPORT WRITE-UP

PROVIDE THE DATE! → *January 17, 2013*

PROVIDE YOUR INITIALS! → *BF*

PROVIDE THE TITLE! → *Experiment # 1: Ohm's Law and Kirchhoff's Laws*

I. Objective ← PROVIDE SUBTITLES!

In this experiment, the student will learn how to read resistor color codes and how to measure voltage, current, and resistance with the digital multimeter (DMM). The student will also build circuits and take measurements to verify Ohm's law, Kirchhoff's laws, and the conservation of energy.

I(a)-Prelab Assignment: ← PROVIDE SUBTITLES! *The color code for a 10 kΩ resistor with 5% tolerance will be Brown-Black-Orange-Gold.*

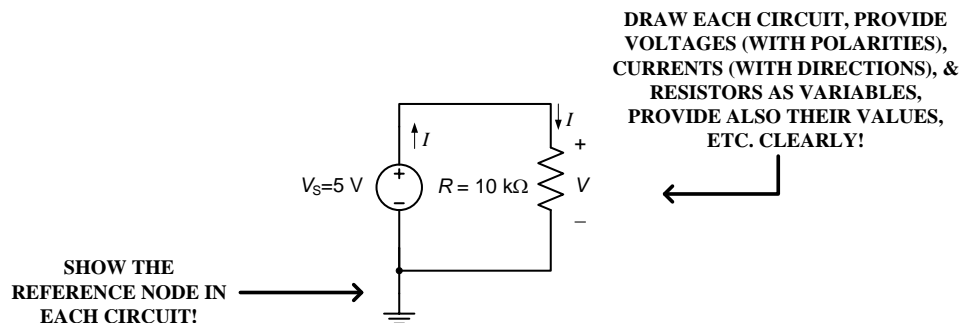


Figure 1. Circuit for pre-lab 1(a).

Note that in Figure 1, the resistor voltage $V=5\text{ V}$ based on KVL. In addition, note that the currents of the voltage source and the resistor are equal based on KCL. Using Ohm's law, we can find the current I as (next page)

$$I = \frac{V}{R} = \frac{5\text{ V}}{10\text{ k}\Omega} = 0.5\text{ mA} \leftarrow \text{PROVIDE APPROPRIATE UNITS!}$$

Next, the power absorbed by the resistor can be calculated as $p_R = I^2 R = (0.5 \text{ mA})^2 (10 \text{ k}\Omega) = 2.5 \text{ mW}$. Yes, it is safe to use resistors with 0.25 W power ratings in this experiment since $2.5 \text{ mW} < 0.25 \text{ W}$. The power supplied by the voltage source can be obtained as $p_S = V_S I = (5 \text{ V})(-0.5 \text{ mA}) = -2.5 \text{ mW}$. Note that the minus sign of the value of the source power indicates that this is supplied power. Since $p_S + p_R = -2.5 + 2.5 = 0$, the conservation of energy principle is satisfied.

1(a)-Lab Experiment: ←PROVIDE SUBTITLES!

We will construct the circuit shown in Figure 2. First, we start by measuring the actual value of the 10 kΩ resistor. Always measure the resistor value without it being connected to anything else! Never measure the resistor value while it is connected to the bread board!!

Measured value of the 10 kΩ resistor using the handheld DMM is $R_{\text{measured}} \cong 9.96 \text{ k}\Omega$. The percentage error in the resistor value can be calculated as

$$\% \text{ error in the resistor value} = \frac{|R_{\text{theoretical}} - R_{\text{measured}}|}{R_{\text{theoretical}}} \times 100 = \frac{10 \text{ k}\Omega - 9.96 \text{ k}\Omega}{10 \text{ k}\Omega} \times 100 \cong 0.40\%$$

Since $0.4\% < 5\%$, the percentage error is less than the specified tolerance of the resistor.

Construct the circuit shown in Figure 2 using the 5-volt DC supply in your lab kit (the red terminal).

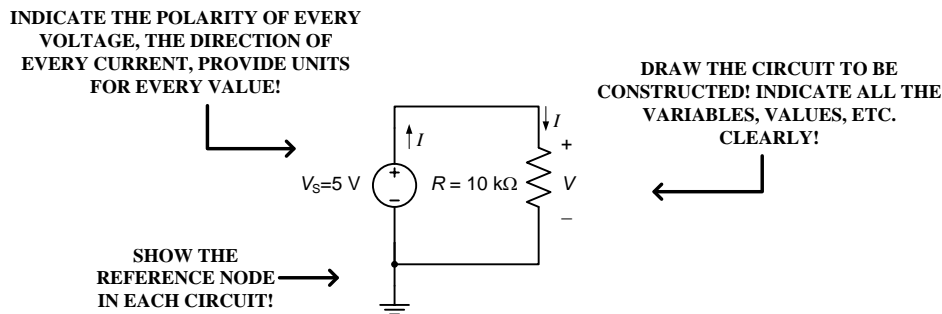


Figure 2. Circuit for lab experiment 1(a).

FIGURE NUMBER & CAPTION!

Measured V and I values using the handheld DMM in DC mode are $V \approx 5.00 \text{ V}$ and $I \approx 0.497 \text{ mA}$. The percentage error between the theoretical and measured values of the current I can be calculated as

$$\% \text{ error in the current value} = \frac{|I_{\text{theoretical}} - I_{\text{measured}}|}{I_{\text{theoretical}}} \times 100 = \frac{0.5 \text{ mA} - 0.497 \text{ mA}}{0.5 \text{ mA}} \times 100 \cong 0.60\%$$

The difference between the theoretical and measured values of current could be due to the additional resistance introduced by the connecting wires which was ignored in the theoretical calculations.

Using the measured values of V and R , the predicted value of I using Ohm's law can be calculated as

$$I_{\text{predicted}} = \frac{V_{\text{measured}}}{R_{\text{measured}}} = \frac{5\text{V}}{9.96\text{ k}\Omega} \cong 0.502\text{ mA} \leftarrow \text{PROVIDE APPROPRIATE UNITS!}$$

Table 1. Theoretical and measured resistor, voltage and current values.
(For circuit shown in Figure 2.)

R_{th} (k Ω)	R_m (k Ω)	V_{th} (V)	V_m (V)	I_{th} (mA)	I_{pr} (mA)	I_m (mA)
10	9.96	5.00	5.00	0.5	0.502	0.497

Next, we calculate the percentage error between the predicted and measured values of the current I as follows:

$$\% \text{ error in the current value} = \frac{|I_{\text{predicted}} - I_{\text{measured}}|}{I_{\text{predicted}}} \times 100 = \frac{0.502\text{ mA} - 0.497\text{ mA}}{0.502\text{ mA}} \times 100 \cong 1.00\%$$

The predicted and measured values for the current differ simply because the calculation of the predicted current doesn't take into account the resistances introduced by the connecting wires.

Using the measured values, the powers absorbed by the resistor and supplied by the voltage source can be calculated as $p_R = I^2 R = (0.497\text{ mA})^2 (9.96\text{ k}\Omega) = 2.46\text{ mW}$ and $p_S = V_S I = (5\text{V})(-0.497\text{ mA}) = -2.49\text{ mW}$ respectively. Yes, conservation of energy is approximately satisfied since $p_S + p_R \cong 0$. The difference between the two power values (which is $\sim 0.03\text{ mW}$) can be accounted as the power consumed by the wires and other parasitic resistances.

IV. Conclusion

The objective of this experiment was to construct simple resistive electric circuits to verify Ohm's law and Kirchhoff's laws. These laws were clearly used throughout this experiment. In general, our measured values agreed with our theoretical values. The differences were due to the accuracy of the instruments (the handheld DMM) used, parasitic resistances introduced by the conductor wires, etc. The maximum % error calculated was $\sim 1.00\%$. The errors between the measured and calculated values based on theory were mainly due to the inaccuracies introduced into the measured values by the handheld DMM, parasitic resistances introduced by the conductor wires, the conductors of the board, and other imperfections associated with the elements used to construct the circuits. In general, this experiment went very well and the goals of the experiment were achieved.

Checking Out the PB-503-C Lab Kit

In order to become familiar with the lab kit, and to ensure that it is operating properly, please read pages 4 and 5 in the PB-503-C Instruction Manual, do the following tests, and record your measurements and results in your lab notebook:

- Record the Kit number that is on the outside of the lab kit.
- Measure the voltage between the terminal indicated as +5 V (it's the red-colored terminal near the upper right hand corner) and the ground terminal (black-colored terminal near the upper right hand corner).
- Measure the minimum and maximum voltages available between the yellow-colored terminal near the upper right hand corner (labeled either +5 to 15 V or +1.3 to 15 V) and ground terminal while adjusting the +15 V adjustment knob (small black-colored knob near the top).
- Measure the minimum and maximum voltages available between the blue-colored terminal near the upper right hand corner (labeled either -5 to -15 V or -1.3 to -15 V) and ground terminal while adjusting the -15 V adjustment knob (small black-colored knob near the top).
- Test each LED by simply connecting its input to the +5 V terminal. Note that the other terminals of the LED's are connected to ground internally.
- Test the function generator by connecting the output (use the output on the right side, NOT the TTL output) to one of the speaker inputs, and connect the other speaker input to the ground terminal. Set the function generator switch on the left to KHz and the switch on the right to 1. Slide the FREQ control to 1.0 and slide the amplitude control to the top. Do you hear a tone? Switch the lower switch between square, triangle, and sine waveforms. Do you hear a difference? (You may want to display the different waveforms on the oscilloscope and measure the frequency.)
- Test the 10K potentiometer (labeled as 10K POT) by measuring the minimum and maximum resistance values between pins 1 and 2 while adjusting the knob. Also measure the minimum and maximum resistance between pins 2 and 3, and between pins 1 and 3.
- Test the 1K potentiometer (labeled as 1K POT) by measuring the minimum and maximum resistances available between pins 1 and 2 while adjusting the knob. Similarly, measure the minimum and maximum resistances between pins 2 and 3, and between pins 1 and 3.

Are you finished early? Try these **optional** experiments:

- Measure the maximum frequency that an LED can flash and still perceived to be as flashing by connecting the TTL output of the function generator to one of the LED's.
- Find the minimum and maximum frequencies that you can hear from the speaker by connecting the function generator output (use the output on the right side, NOT the TTL output) to one of the speaker inputs, connect the other speaker input to ground, and set the waveform to sine.

University of Portland
School of Engineering

EE 271–Electrical Circuits Laboratory

Lab Experiment #1: Ohm's Law and
Kirchhoff's Laws

Ohm's Law and Kirchhoff's Laws

I. Objective

In this experiment, the student will learn how to read resistor color codes and how to measure voltage, current, and resistance with the digital multimeter (DMM). The student will also build circuits and take measurements to verify Ohm's law, Kirchhoff's laws, and the conservation of energy.

II. Background: Resistor Color Codes

Standard resistors are labeled with a color code which indicates their resistance values. The value indicated by each color band is listed in Tables 1, 2, and 3, and the resistor's value can be computed by the following equation:

$$R = [(1\text{st Digit}) \times 10 + (2\text{nd Digit})] \times (\text{Multiplier})$$

Consider a resistor that has the following color bands: brown, green, orange, and silver. We first recognize that the silver band must be the tolerance band since the 1st Digit cannot be silver (see Tables 1 and 2). So the brown band must be the 1st band, which indicates that the value of the 1st Digit equals 1 (see Table 2). The second band, then, is green, which indicates that the value of the 2nd Digit equals 5 (see Table 2). The multiplier band is orange which indicates a value of 1 k (see Table 3). So the value of this resistor is $R = [(1) \times 10 + (5)] \times 1\text{k} = 15 \text{ k}\Omega$. Furthermore, the silver tolerance band indicates that the actual value of the resistance might deviate by $\pm 10\%$ (see Table 1).

A resistor with the bands red, violet, red, gold, would have a value of $R = [(2) \times 10 + (7)] \times 100 = 2700 \text{ }\Omega = 2.7 \text{ k}\Omega$ with a tolerance of $\pm 5\%$.

A resistor with the bands orange, orange, brown, gold, would have a value of $R = [(3) \times 10 + (3)] \times 10 = 330 \text{ }\Omega$ with a tolerance of $\pm 5\%$.

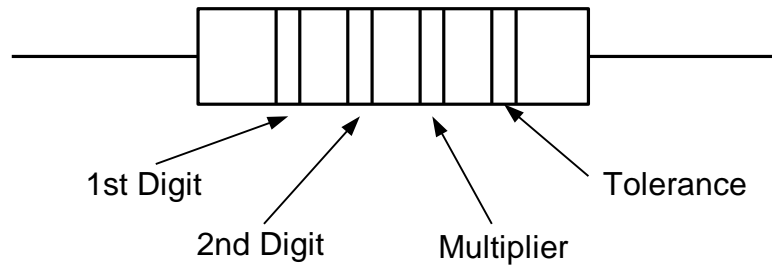


Figure 1. Resistor with 4 color bands.

Table 1. Tolerance band.

Color	Tolerance
Red	2%
Gold	5%
Silver	10%
none	20%

Table 2. 1st and 2nd digits.

Color	Value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

Table 3. Multiplier band.

Color	Value
Silver	0.01
Gold	0.1
Black	1
Brown	10
Red	100
Orange	1 k
Yellow	10 k
Green	100 k
Blue	1 M
Violet	10 M
Gray	100 M

III. Procedure

PART 1: Ohm's Law

1(a)-Pre-lab Assignment: Determine the color code for a 10 kΩ resistor with 5% tolerance. For the circuit shown in Figure 2, calculate the theoretical value of the current I (that is, I_{th}). Calculate the power absorbed by the resistor (P_R) and the power supplied by the voltage source (P_S). Show your work. Present all your results in table format using the appropriate tables provided. (You need to provide the following tables in your lab notebook to summarize your pre-lab calculation results.) The resistors we will use in the lab can safely handle 0.25 W. Is it safe to use a 0.25 W resistor for this circuit? State why. Is the conservation of energy satisfied in this circuit? State why.

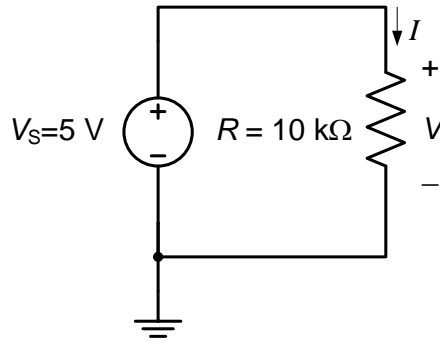


Figure 2. A simple resistive circuit.

Table 4. Color code for the 10 kΩ resistor (Figure 2 circuit).

First	Second	Third	Fourth

Table 5. Theoretical resistor, voltage and current values (Figure 2 circuit).

R_{th} (kΩ)	V_{th} (V)	I_{th} (mA)
10		

Table 6. Power values calculated (Figure 2 circuit).

P_R (mW)	P_S (mW)	Safe or not?	Energy conserved?

1(a)-Lab Experiment:

Provide the following table in your lab notebook including the measurements and calculated values related to the circuit shown in Figure 2.

Table 7. Theoretical and measured resistor, voltage and current values (Figure 2 circuit).

R_{th} (kΩ)	R_m (kΩ)	V_{th} (V)	V_m (V)	I_{th} (mA)	I_{pr} (mA)	I_m (mA)

Get a 10 kΩ resistor and measure its actual value by connecting it to the DMM and setting the DMM to DC mode to read resistance. Compute the % error of the resistance value as follows:

$$\% \text{ error} = \frac{R_{\text{theoretical}} - R_{\text{measured}}}{R_{\text{theoretical}}} \times 100 \text{ where } R_{\text{theoretical}} = 10 \text{ k}\Omega.$$

Is the % error less than the tolerance specified by the tolerance color band?

Table 8. Percentage error in the actual value of the 10 kΩ resistor (Figure 2 circuit).

R_{th} (kΩ)	R_{m} (kΩ)	% error	Less than tolerance value?
10			

Construct the circuit shown in Figure 2 using the 5-volt supply in your lab kit (the red terminal). Set the DMM to DC mode and use it to measure the actual values of the voltage V and the current I (represented by V_{m} and I_{m}). Be very careful to avoid setting your DMM to measure current while it is connected to the power supply or it will short out the power supply and burn up the fuse in the DMM!

Compare the measured value of I to the theoretical value from the pre-lab using percent error as follows:

$$\% \text{ error} = \frac{I_{\text{theoretical}} - I_{\text{measured}}}{I_{\text{theoretical}}} \times 100.$$

If the theoretical and measured values for the current I differ, explain why.

Now calculate the value of the current I predicted by Ohm's law using the **measured** values of the voltage and resistance: $I_{\text{predicted}} = \frac{V_{\text{measured}}}{R_{\text{measured}}}$. Compare the measured value of I

to the predicted value as follows:

$$\% \text{ error} = \frac{I_{\text{predicted}} - I_{\text{measured}}}{I_{\text{predicted}}} \times 100.$$

If the predicted and measured values for the current I differ, explain why. Box all your results.

Table 9. Percentage error in current values (Figure 2 circuit).

% error with respect to I_{th}	% error with respect to I_{pr}

Using your **measured** values, calculate the power absorbed by the resistor and supplied by the voltage source. Is conservation of energy satisfied in this circuit? State why.

Table 10. Power values calculated (Figure 2 circuit).

P_R (mW)	P_S (mW)	Energy conserved?

PART 2: Kirchhoff's Voltage Law

In this part of the experiment, we will add two more resistors (1.8 kΩ and 4.7 kΩ) to the circuit shown in Figure 2 to obtain the circuit shown in Figure 3.

2(a)-Pre-lab Assignment:

Determine the color codes for 1.8 kΩ and 4.7 kΩ resistors with 5% tolerance. What condition must always be satisfied by voltages indicated in Figure 3 based on Kirchhoff's voltage law (KVL)? (Box this condition.)

Table 11. Color codes for the 1.8 & 4.7 kΩ resistors (Figure 3 circuit).

R (kΩ)	First	Second	Third	Fourth
1.8				
4.7				

2(a)-Lab Experiment:

Provide the following table in your lab notebook to tabulate theoretical and measured resistor values related to the circuit shown in Figure 3.

Table 12. Theoretical and measured values of the resistors (circuit in Figure 3).

$R_{1,th}$ (kΩ)	$R_{1,m}$ (kΩ)	$R_{2,th}$ (kΩ)	$R_{2,m}$ (kΩ)	$R_{3,th}$ (kΩ)	$R_{3,m}$ (kΩ)
10		4.7		1.8	

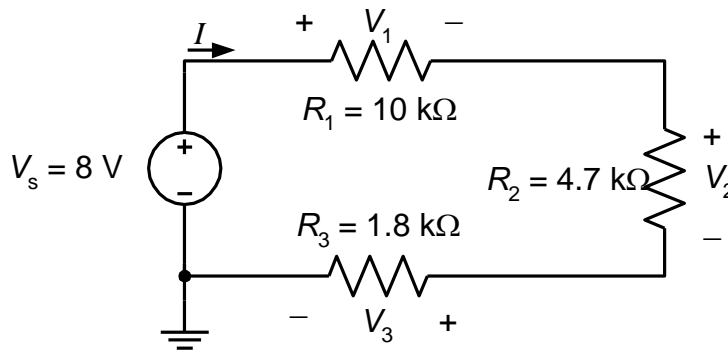


Figure 3. Resistors connected in series.

Measure the actual values of the 1.8 kΩ and 4.7 kΩ resistors in Figure 3 and calculate the % error for each resistor. Are all the % errors less than the tolerance specified by the tolerance color band? Present all your calculation results in table format.

Table 13. Percentage error in the values of 1.8 and 4.7 kΩ resistors (Figure 3 circuit).

R (kΩ)	% error	Less than tolerance value?
1.8		
4.7		

Provide the following table in your lab notebook to tabulate the measured voltage and current values in the circuit shown in Figure 3.

Table 14. Measured voltage and current values (circuit in Figure 3).

V_1 (V)	V_2 (V)	V_3 (V)	I (mA)	% KVL error	KVL satisfied?

Set the adjustable power supply (the yellow terminal labeled +1.3 to 15V) in your lab kit to 8V. Then construct the circuit shown in Figure 3. Measure the voltages V_s , V_1 , V_2 , and V_3 . Also measure the current I . Do the measured voltage values in this circuit satisfy KVL? Using the measured values, calculate the percentage error in KVL defined with respect to the source voltage as

$$\% \text{ error in KVL} = \frac{V_s - (V_1 + V_2 + V_3)}{V_s} \times 100$$

For each of the three resistors, calculate the value of the current into each resistor predicted by Ohm's law using the **measured** values of the voltage and resistance:

$I_{\text{predicted}} = \frac{V_{\text{measured}}}{R_{\text{measured}}}$. Compare the measured value of I to the predicted value as follows:

$$\% \text{ error} = \frac{I_{\text{predicted}} - I_{\text{measured}}}{I_{\text{predicted}}} \times 100.$$

Present your values in table format. Why do the

predicted and measured values for the current I differ, if they differ?

Table 15. Percentage errors in current values (circuit in Figure 3).

$I_{1,\text{pr}}$ (mA)	$I_{1,\text{m}}$ (mA)	% error in I_1	$I_{2,\text{pr}}$ (mA)	$I_{2,\text{m}}$ (mA)	% error in I_2	$I_{3,\text{pr}}$ (mA)	$I_{3,\text{m}}$ (mA)	% error in I_3

Design and perform an experiment to find out if changing the order in which the series components are connected in Figure 3 will change the voltage across the components or the current through the components. Document the experimental setup, results, and your conclusions.

PART 3: Kirchhoff's Current Law

In this part of the experiment, we will change the circuit shown in Figure 3 to the circuit shown in Figure 4.

3(a)-Pre-lab Assignment: What condition must the currents at node A (see Figure 4) always satisfy according to Kirchhoff's current law (KCL) ? (Box this condition.)

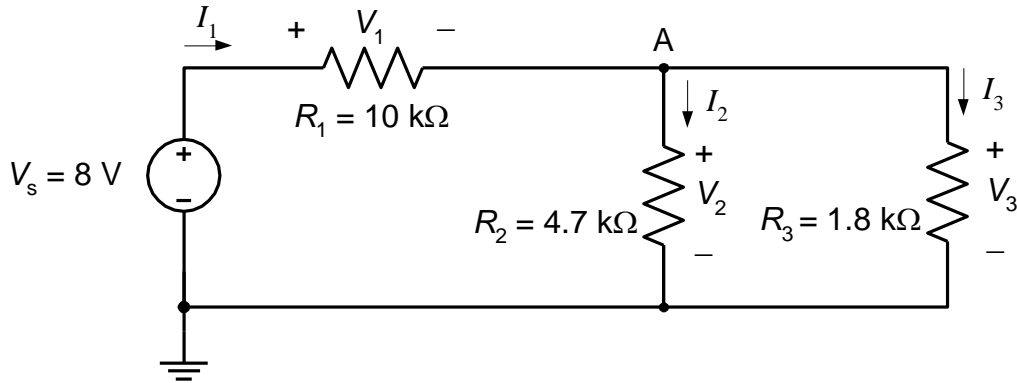


Figure 4. Parallel and series resistors.

3(a)-Lab Experiment:

Provide the following table in your lab notebook to tabulate measured current values in Figure 4.

Table 16. Measured current values (circuit in Figure 4).

I_1 (mA)	I_2 (mA)	I_3 (mA)	% error in I_1

Using the same resistors that you used in the last section, construct the circuit shown in Figure 4. Measure the currents I_1 , I_2 , and I_3 . Do the measured currents in this circuit satisfy Kirchhoff's current law at node A? Using the measured values, calculate the percentage error in KCL defined with respect to the current I_1 as

$$\% \text{ error in KCL} = \frac{I_1 - (I_2 + I_3)}{I_1} \times 100$$

Design and perform an experiment to find out if changing the order in which the parallel components (R_2 and R_3) are connected in Figure 4 will change the voltage across the components or the current through the components. Document the experimental setup, results, and your conclusion.

IV. Conclusion

Write a couple of paragraphs to summarize the following items:

1. What was the objective of this experiment and was the objective achieved?
2. Did your measured values agree with the theoretical values? What was the maximum % error in your calculations?
3. What sources of error may have contributed to the differences between the theoretical values and the measured values?
4. Other comments relevant to this experiment.

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**Lab Experiment #2: Simple Resistive
Circuits**

Simple Resistive Circuits

I. Objective

In this experiment, the students will design, build and/or experiment simple resistive electrical circuits to gain some experience in using Ohm's law, Kirchhoff's laws, and their extensions such as voltage and current divider principles to analyze circuits consisting of series- and parallel-connected resistors.

II. Procedure

PART 1: Voltage and Current Divider Principles

Part 1(a): Verification of the Voltage Divider Circuit

1(a)–Pre-lab Assignment: For the circuit shown in Fig. 1(a), using the voltage divider principle, provide a general equation for V_{out} and calculate its numerical value. Box your answer.

1(a)–Lab Experiment: Construct the circuit shown in Fig. 1(a). Using the handheld DMM in DC mode set to read resistance, measure and record the actual values of the resistors R_1 and R_2 used in your circuit in Table 1. Calculate the % error in each resistor value as follows:

$$\% \text{ error in } R \text{ value} = \frac{R_{\text{theoretical}} - R_{\text{measured}}}{R_{\text{theoretical}}} \times 100$$

Table 1. Resistor values and percentage errors. (Circuit in Figure 1(a).)

R_1 (k Ω) (theoretical)	R_1 (k Ω) (measured)	% error in R_1	R_2 (k Ω) (theoretical)	R_2 (k Ω) (measured)	% error in R_2

Provide the calculated percentage errors in the resistor values in Table 1. Measure and record the output voltage V_{out} . Also calculate the % error of the V_{out} value as follows:

$$\% \text{ error in } V_{out} \text{ value} = \frac{V_{out,prelab} - V_{out,measured}}{V_{out,prelab}} \times 100$$

Box your results. Comment on the differences between the theoretical and measured values.

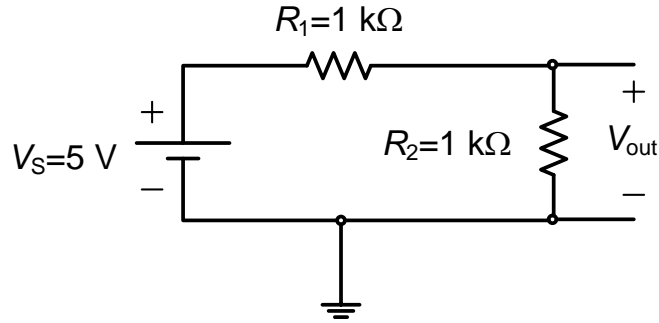


Figure 1(a). The voltage divider circuit.

Part 1(b): Verification of the Current Divider Principle

1(b)–Pre-lab Assignment: Connect a shunt resistor R_{shunt} across the $R_2=1\text{ k}\Omega$ resistance of Fig. 1(a), as shown in Fig. 1(b). Provide simplified general equations for currents I_2 and I_{shunt} flowing through the resistors R_2 and R_{shunt} and voltage V_{out} across R_2 and R_{shunt} in terms of V_S , R_1 , R_2 , and R_{shunt} . Using these equations, calculate the values of I_2 and I_{shunt} flowing through the resistors R_2 and R_{shunt} and the voltage V_{out} for three different values of R_{shunt} resistance which are $100\ \Omega$, $1\text{ k}\Omega$, and $10\text{ k}\Omega$ respectively. Present your calculated current and voltage values in a table as shown in Table 2.

Provide the following table in your lab notebook including the measurements and calculated values related to the circuit shown in Figure 2.

Table 2. Prelab values of R_{shunt} , I_2 , I_{shunt} , and V_{out} . (Figure 1(b) circuit).

R_{shunt} (kΩ)	I_2 (mA)	I_{shunt} (mA)	V_{out} (V)
0.1			
1.0			
10.0			

1(b)–Lab Experiment: Construct the circuit shown in Fig. 1(b). Measure and record the actual values of the resistors R_1 , R_2 and R_{shunt} used in your circuit in Table 2. Recalculate the values of currents I_2 and I_{shunt} and voltage V_{out} for three different cases using the measured values of the resistors R_1 , R_2 and R_{shunt} (for three different R_{shunt} values) and provide your recalculated values in Table 3.

Table 3. Recalculated values of I_2 , I_{shunt} , and V_{out} using actual R values.

R_1 (kΩ)	R_2 (kΩ)	R_{shunt} (kΩ)	I_2 (mA)	I_{shunt} (mA)	V_{out} (V)

Measure and record the values of the currents I_2 and I_{shunt} and the output voltage V_{out} for each R_{shunt} resistor connected across the R_2 resistance. Present your measured current and voltage values in a table as shown in Table 4.

Table 4. Measured values of R_{shunt} , I_2 , I_{shunt} , and V_{out} . (Figure 1(b) circuit).

R_{shunt} (k Ω)	I_2 (mA)	I_{shunt} (mA)	V_{out} (V)

Using the recalculated and measured values (given in Tables 3 and 4), calculate and present in a table (see Table 5) the percentage errors in the current and voltage values in each case and comment. Also, comment on what happens to the values of the two currents I_2 and I_{shunt} with respect to one another as R_{shunt} resistor increases? Why?

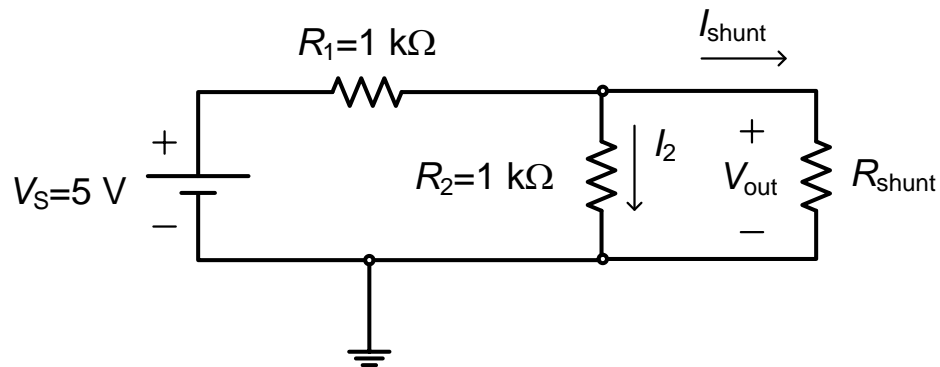


Figure 1(b). The current divider circuit.

Table 5. Percentage errors in measured values of I_2 , I_{shunt} , and V_{out} .

R_{shunt} (k Ω)	% error in I_2	% error in I_{shunt}	% error in V_{out}

PART 2: Design of a Voltage Divider Circuit

2(a)–Pre-lab Assignment: Design a voltage divider circuit similar to the one shown in Fig. 2 to convert a fixed power supply voltage of 5 V to a voltage equal to 2 V. For the circuit, all you have available are four 1 k Ω resistors. Show the circuit you designed on paper. (Note: More than one circuit design is possible.)

2(b)–Lab Experiment: Test your designed circuit in the lab. Measure and record the value of the output voltage in the circuit and verify your design.

2(c)–Lab Experiment: Next, to investigate loading effect, use the voltage divider circuit designed in Part 2(a) to supply 2 V to an unknown resistive load (which will be provided in the lab). Connect the unknown resistive load across the output

terminals of the voltage-divider circuit you designed and measure the voltage supplied to the unknown load in each circuit. Does your voltage divider circuit supply a 2 V voltage to the unknown load? If no, explain why.

2(d)–Lab Experiment: Measure the resistance of the unknown resistive load and redesign your voltage divider circuit accordingly so that your circuit takes the fixed 5 V voltage and supplies 2 V to the load. Again, as before, all you have are four 1 k Ω resistors. (Hint: If you design your voltage-divider circuit correctly, it only dissipates power when the load resistance is connected across it, otherwise, when the load is disconnected from the designed circuit, the power consumption in the voltage-divider circuit is zero.)

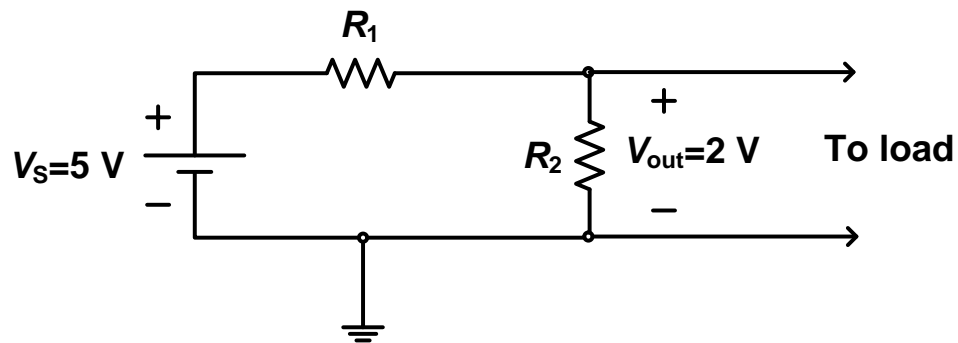


Figure 2. Voltage divider circuit.

III. Discussions & Conclusion

In this section, discuss the various aspects of Experiment #2 and make some conclusions. In your write-up, you should at least address the following questions:

1. What was the objective of this experiment and was the objective achieved?
2. Did any of your measurements have more than 5% error? What was your maximum % error?
3. What sources of error may have contributed to the differences between the theoretical values and the measured values?
4. Other comments relevant to this experiment.

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**Lab Experiment #3: Node Voltages of a
Wheatstone Bridge Circuit**

Node Voltages of a Wheatstone Bridge Circuit

I. Objective

In this experiment, the students will construct and test a Wheatstone bridge circuit. In addition, they will use a Wheatstone bridge circuit to measure the value of an unknown resistance.

II. History

Wheatstone bridge is an electrical circuit that can be used for measuring the value of an electrical resistance in a circuit. This circuit is named after Sir Charles Wheatstone (1802-1875), an English physicist and inventor who was a major figure in Victorian science. Wheatstone studied electricity and became a professor of experimental philosophy at King's College, University of London in 1834. He worked with William Cooke to produce the electric telegraph (1837), which some people refer to as the "Victorian Internet"! In 1838, he invented the stereoscope. Wheatstone is best remembered for the Wheatstone bridge circuit. The Wheatstone bridge circuit was first described by Samuel Hunter Christie (1784-1865) in his paper *Experimental Determination of the Laws of Magneto-electric Induction* published in 1833. Wheatstone introduced this circuit in his Bakerian Lecture on electrical measurements in 1843 and called it a Differential Resistance Measurer. In his lecture, although Wheatstone publicly stated that the principle of this circuit was not his own invention but it was rather an adaptation of a device originally suggested by Christie, the circuit was still named after him because he was the one who popularized it and put it in practical use. One such practical use is measurements using strain gauges that exhibit small changes in electrical resistance when strained as a result of stress.

III. Procedure

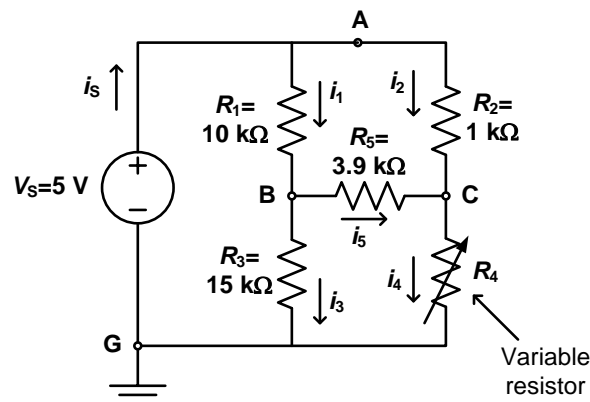


Figure 1. Wheatstone Bridge circuit.

Pre-lab Assignment 1: A Wheatstone bridge circuit is shown in Fig. 1. This circuit is said to be balanced Wheatstone bridge circuit when the current $i_5=0$. Determine the required relationship between the resistors R_1 , R_2 , R_3 , R_4 and R_5 needed to achieve this balanced circuit. (Hint: Note that $i_5=0$ means $V_B=V_C$. That is, resistor R_5 acts like an open circuit. This means one can remove resistor R_5 from the circuit as if nodes B and C are not connected at all. This removal will simply the circuit and make it much easier to determine the relationship needed between resistors R_1 , R_2 , R_3 , and R_4 to achieve $V_B=V_C$.)

Lab Experiment 1: Constructing and testing a Wheatstone bridge circuit.

Construct the Wheatstone bridge circuit shown in Fig. 1 on your circuit board. Record the actual values of all the resistors used in your circuit. Note that the resistor R_4 is a variable resistor. Use the following values for R_4 (measure and record their actual values): (a) $R_4=150 \Omega$, (b) $R_4=1.5 \text{ k}\Omega$, and (c) $R_4=15 \text{ k}\Omega$. For each R_4 value used, do the following:

1. Use your handheld DMM available in your lab-kit to measure and record the node voltages V_A , V_B , and V_C . Present your measurements in table form as shown.
2. Use the node voltages measured along with Ohm's law and the actual resistor values measured to calculate the currents i_1 , i_2 , i_3 , i_4 , and i_5 . For example, the current i_2 through the R_2 resistance is given in terms of the node voltages as $i_2 = (V_A - V_C)/R_2$. Present your calculated values in table form as shown.
3. Use the current values calculated in part 2 to verify Kirchoff's current law (KCL) at nodes B and C.

Table 1. Measured node voltage and calculated current values (Figure 1 circuit with $R_4 = 150 \Omega$).

V_A (V)	V_B (V)	V_C (V)	i_1 (mA)	i_2 (mA)	i_3 (mA)	i_4 (mA)	i_5 (mA)

Table 2. Measured node voltage and calculated current values (Figure 1 circuit with $R_4 = 1.5 \text{ k}\Omega$).

V_A (V)	V_B (V)	V_C (V)	i_1 (mA)	i_2 (mA)	i_3 (mA)	i_4 (mA)	i_5 (mA)

Table 3. Measured node voltage and calculated current values (Figure 1 circuit with $R_4 = 15 \text{ k}\Omega$).

V_A (V)	V_B (V)	V_C (V)	i_1 (mA)	i_2 (mA)	i_3 (mA)	i_4 (mA)	i_5 (mA)

Lab Experiment 2: Measuring the value of an unknown resistor using the Wheatstone bridge circuit.

Reconstruct the circuit shown in Fig. 1 by using $R_1=1 \text{ k}\Omega$, $R_2=10 \text{ k}\Omega$, $R_4=10 \text{ k}\Omega$ -potentiometer and replacing R_3 with an unknown

resistor to be provided, as shown in Fig. 2. Keep the resistor R_5 the same. Vary the potentiometer resistance R_4 until $i_5=0$. Measure and record the value of R_4 that balances the bridge. Compute the value of the resistor R_3 as determined by the Wheatstone bridge. Measure R_3 using the handheld DMM and compare it with the calculated value. Calculate the percentage error in the R_3 value using

$$\% \text{ error in } R_3 \text{ value} = \frac{|R_{3,\text{bridge}} - R_{3,\text{DMM}}|}{R_{3,\text{bridge}}} \times 100$$

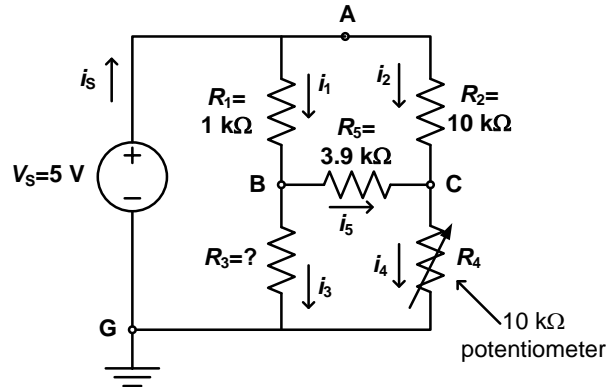


Figure 2. Wheatstone Bridge circuit for Lab Experiment 2.

Lab Experiment 3: Measuring small resistor values using the Wheatstone bridge circuit. Replace the resistor R_3 with a $4.7\text{-}\Omega$ resistor in Fig. 1, as shown in Fig. 3. Our goal is to measure the value of this small resistance using the Wheatstone bridge circuit. Resistors this small in value are hard to measure accurately. Choose the appropriate values of R_1 and R_2 so that you can precisely measure the value of R_3 using the Wheatstone bridge. Again, use a potentiometer for R_4 . Compare your measurement value obtained from the Wheatstone bridge circuit with measurements from your handheld DMM, the DMM on the lab bench, and the *LCR* meter. Again, calculate the percentage error in the R_3 value.

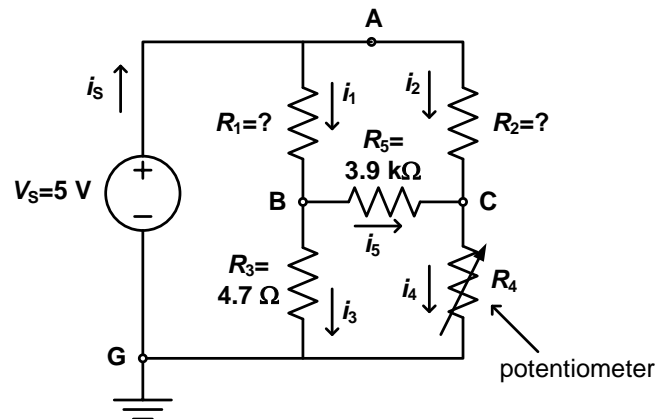


Figure 3. Wheatstone Bridge circuit for Lab Experiment 3.

IV. Discussions & Conclusion

In this section, discuss the various aspects of Experiment #3 and make some conclusions. In your write-up, you should at least address the following questions:

1. What was the objective of this experiment and was the objective achieved?
2. Did any of your measurements have more than 5% error? What was your maximum % error?
3. What sources of error may have contributed to the differences between the theoretical values and the measured values?
4. Other comments relevant to this experiment.

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Lab Experiment #4: Electrical Circuit
Theorems

Electrical Circuit Theorems

I. Objective

In this experiment, the students will analyze, construct and test dc resistive circuits to gain further insight and hands-on experience on electrical circuits as well as to verify some of the circuit theorems they learn in class such as the *Superposition Principle*, *Thevenin* and *Norton Equivalent Circuits* and *Maximum Power Transfer Theorem*.

II. Procedure

PART 1: Superposition Principle

Pre-lab Assignment 1.a: For the circuit shown in Fig. 1, calculate the voltage V_2 across the resistor R_2 using the superposition principle. Provide your work step by step and box your answers.

Pre-lab Assignment 1.b: For the circuit shown in Fig. 1, reverse the polarity of the 5 V dc voltage source and redo pre-lab assignment 1.1. (Hint: You can use the results of Pre-lab 1.a.) Box your answers.

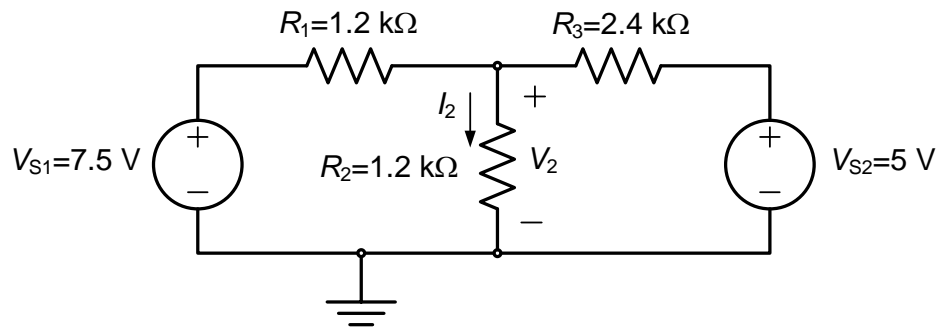


Figure 1. A resistive circuit excited by two dc voltage sources.

Lab Experiment 1.a: Construct the resistive circuit shown in Fig. 1. Using the *LCR* meter, measure and record the actual values of the resistors R_1 , R_2 , and R_3 used in your circuit. To verify the superposition principle, measure and record the voltage V_2 for three cases (record your measurements in Table 1 form as provided below):

- When V_{s1} voltage is on and V_{s2} is off. (Voltage source “off” means you disconnect the voltage source from the circuit and short the terminals in your

circuit where this voltage source was connected. Warning: Do not short the terminals of the voltage source itself!

- (b) When V_{s1} voltage is off and V_{s2} is on.
- (c) When both V_{s1} and V_{s2} voltages are on.

Table 1. Measured V_2 values in the circuit shown in Figure 1.

V_2 (V) (V_{s1} on and V_{s2} off)	V_2 (V) (V_{s1} off and V_{s2} on)	V_2 (V) (Both V_{s1} and V_{s2} on)

Check to see if superposition holds. Also check to see if your measured V_2 values agree with the V_2 values calculated in your pre-lab assignment 1.a (i.e., calculate percentage error between the calculated and the measured V_2 values).

Lab Experiment 1.b: Reverse the polarity of the 5 V voltage source in your circuit and repeat the same V_2 measurements done in Lab Experiment 1.a, parts (a), (b) and (c). Again record your measurements in Table 2 form as provided below.

Table 2. Measured V_2 values in the circuit shown in Figure 1 where the polarity of the 5 V voltage source is reversed.

V_2 (V) (V_{s1} on and V_{s2} off)	V_2 (V) (V_{s1} off and V_{s2} on)	V_2 (V) (Both V_{s1} and V_{s2} on)

Check to see if superposition holds. Also check to see if your measured V_2 values agree with the V_2 values calculated in your pre-lab assignment 1.b.

PART 2: Thevenin, Norton & the Maximum Power Transfer Theorem

Pre-lab Assignment 2.a: For the circuit shown in Fig. 2, find the Thevenin and Norton equivalent circuits seen between terminals **A** and **B**. Draw each equivalent circuit separately with the appropriate values provided. Provide your work step by step and box your results.

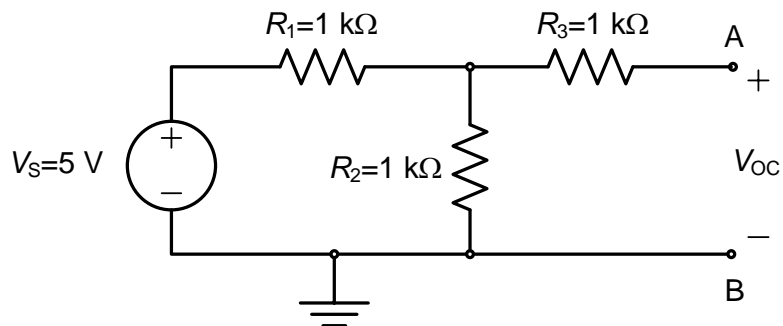


Figure 2. A resistive circuit excited by a dc voltage source.

Pre-lab Assignment 2.b: For the circuit shown in Fig. 2, find the optimum value of the external load resistance $R_{L,opt}$ to be connected between the terminals **A** and **B** so that it receives maximum power from the circuit. What is $P_{L,max}$? (Hint: Use the results of pre-lab assignment 2.a.)

Lab Experiment 2.a: Construct the circuit shown in Fig. 2. Using the *LCR* meter, measure and record the actual values of the resistors used in your circuit. Verify the Thevenin and Norton equivalent circuits obtained in pre-lab assignment 2.a by measuring the open-circuit voltage V_{OC} and short-circuit current I_{SC} between terminals **A** and **B**.

Table 3. Measured values of V_{OC} , I_{SC} and V_L , and calculated value of R_T (or R_N) and P_L in the circuit shown in Figure 2.

V_{OC} (V)	I_{SC} (mA)	R_T or R_N (Ω)	V_L (V)	P_L (mW)

Lab Experiment 2.b: Connect a load resistance with the optimum value $R_{L,opt}$ between terminals **A-B** in the original circuit shown in Fig. 2. Measure the voltage V_L across $R_{L,opt}$ and use it to verify the $P_{L,max}$ value calculated in pre-lab assignment 2.b.

PART 3: Maximum power to a load resistance with fixed value

Pre-lab Assignment 3: In Fig. 3, assume that the load resistance R_L has a fixed value given by $R_L=1\text{ k}\Omega$.

- (a) How much power is being delivered to R_L ? Show your work step by step.
- (b) Your job is to introduce a single external resistor R_{ext} into the circuit with an appropriate value to maximize power delivery to the $1\text{ k}\Omega$ load. What is the value of R_{ext} ? (Hint: The external resistor could even be a piece of wire.) Where should it be connected? With the external resistor properly connected to the circuit, what is $P_{L,max}$? (Note that this problem is different than the maximum power transfer theorem.) Show your work and box your results!

Lab Experiment 3: Verify the results of pre-lab assignment 3 experimentally. Measure and record the load voltage V_L and the current I_L with and without the external resistance connected and calculate the load power using $P_L = V_L I_L$ in each case. Approximately how much percent did the load power increase due to the introduction of the external resistance R_{ext} into the circuit?

Table 4. Measured values of V_L and I_L , and calculated values of P_L in the circuit shown in Figure 3.

V_L (V) (no R_{ext})	V_L (V) (with R_{ext})	I_L (mA) (no R_{ext})	I_L (mA) (with R_{ext})	P_L (mW) (no R_{ext})	P_L (mW) (with R_{ext})	% P_L increase

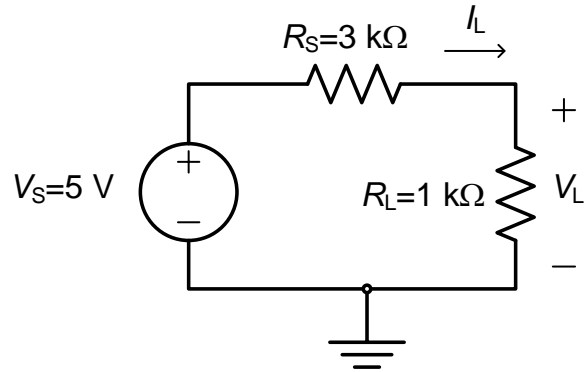


Figure 3. A circuit with a fixed load resistance having a value $R_L = 1\text{ k}\Omega$.

III. Discussions & Conclusion

In this section, discuss the various aspects of Experiment #4 and make some conclusions. In your write-up, you should at least address the following questions:

1. What was the objective of this experiment and was the objective achieved?
2. Did any of your measurements have more than 5% error? What was your maximum % error?
3. What sources of error may have contributed to the differences between the theoretical values and the measured values?
4. Other comments relevant to this experiment.

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Lab Experiment #5: DAC R-2R
Ladder Network

Digital-to-Analog Converter (DAC) R-2R Ladder Network

I. Objective

In this experiment, the students will analyze, construct and test a Digital-to-Analog Converter (DAC) R-2R Ladder Network to gain further insight and experience on electrical circuits and to verify some of the circuit theorems they learn in class such as the *Superposition Principle* and *Source Transformations*.

II. Introduction

A Digital-to-Analog Converter (DAC or D/A Converter) is an electronic circuit or a chip that is used to convert digital (usually binary) information or code (for example, from a CD or CD-ROM) into analog (usually a current or a voltage) information (such as sound or audio signals). DAC chips are currently being used in many applications involving modern communication and instrumentation systems. For example, all digital synthesizers, samplers and effect devices have DAC chips at their outputs to create audio signals. Some of the new DAC chips available in the high-tech market are designed in terms of highly complicated and sophisticated electronic circuits to be able to provide high speed and high resolution to the high performance communication/instrumentation systems.

A simple passive DAC circuit can be constructed with a network of resistors, usually a ladder consisting of two sizes of resistors, one twice the other, as shown in Fig. 1. The R-2R ladder network seen in Fig. 1 is an elegant implementation of a DAC. In this experiment, the students will construct this 3-bit DAC circuit consisting of only resistors, switches, and a single power supply.

III. Procedure

For the R-2R ladder network shown in Fig. 1, the switch positions S_3 , S_2 , and S_1 together represent a 3-digit binary number N given by $N=(S_3S_2S_1)_2$. Note that each switch can either be in position 0 (when connected to ground) or 1 (when connected to the power supply voltage V_S). Since there are $2^3=8$ different combinations, the 3-bit binary number N can take any value between $N=(000)_2=(0)_{10}$ to $N=(111)_2=(7)_{10}$. The R-2R ladder network shown in Fig. 1 is designed to convert the 3-bit binary (digital) number $N=(S_3S_2S_1)_2$ into its equivalent decimal (analog) number $N=(\bullet)_{10}$. The output voltage $V_{out}=(\bullet)_{10}$ measured between terminals A and B is in fact the decimal equivalent of the binary number $N=(S_3S_2S_1)_2$ set by the positions of the three switches. For example, if the switch positions are $S_3=1$, $S_2=0$, and $S_1=1$ which represents the binary number $N=(101)_2$, then, the decimal equivalent of this number should come out to be $V_{out}=5$.

Pre-lab Assignment 1: For the circuit shown in Fig. 1, find V_{out} in terms of V_S and R for each combination of the three switches. You will find 8 different expressions for V_{out} . Based on these expressions, you will be able to determine the appropriate value of the power supply voltage V_S needed to realize the goal of this design. (Hint: Transform the R - $2R$ ladder network shown in Fig. 1 to the equivalent circuit shown in Fig. 2. Note that the power supply voltages V_{S1} , V_{S2} , and V_{S3} can take a value equal to V_S or 0 depending on the position of the switches S_1 , S_2 , and S_3 in Fig. 1. Using this equivalent circuit and source transformation (or superposition principle), find the general expression for the output voltage V_{out} in terms of V_{S1} , V_{S2} , V_{S3} , and R . Then, use the general V_{out} expression to find the output voltage for each case.)

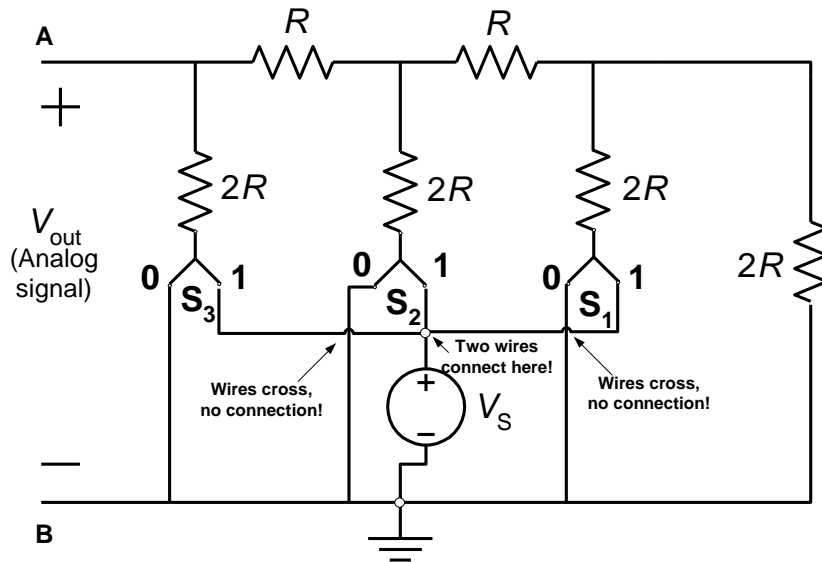
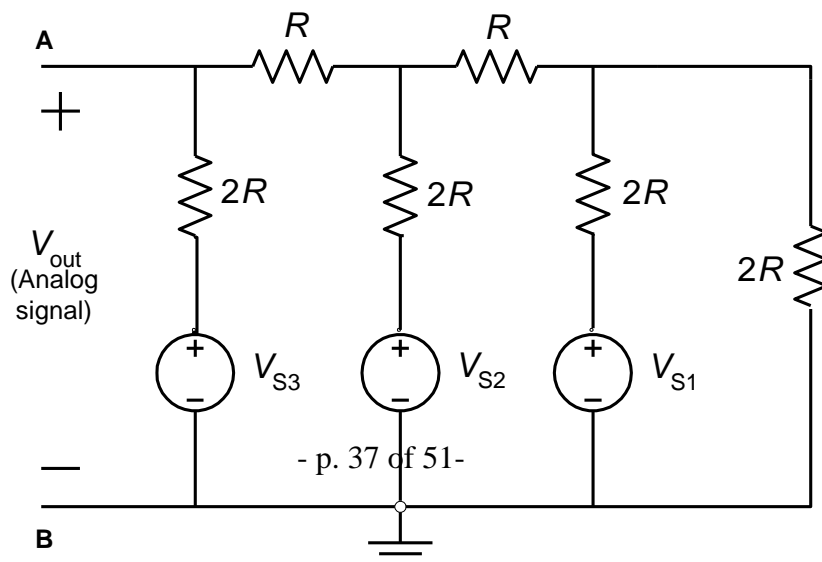


Figure 1. 3-bit binary to decimal R - $2R$ ladder network.

Figure 2. Equivalent circuit for the R - $2R$ ladder network shown in Figure 1.



Pre-lab Assignment 2: Can you redesign the circuit shown in Fig. 1 to be able to convert any 4-bit binary number into its decimal equivalent? If so, how many additional elements would you need and what will be the new value of the power supply voltage V_S ?

Lab Experiment: Select a value for the resistor R and construct the DAC circuit shown in Fig. 1. Set the power supply voltage V_S to the value you calculated in your pre-lab work. Measure and record the actual values of the resistors used in your circuit. Measure and record the value of the output voltage V_{out} in each one of the eight different switch combinations. Present your values in a table similar to Table 1 shown below.

Table 1. Predicted and measured output voltage values.

S_3	S_2	S_1	V_{out} (predicted) (V)	V_{out} (measured) (V)	Error (%)
0	0	0			
0	0	1			
0	1	0			
0	1	1			
1	0	0			
1	0	1			
1	1	0			
1	1	1			

IV. Discussions & Conclusion

In this section, discuss the various aspects of Experiment #5 and make some conclusions. In your write-up, you should at least address the following questions:

1. What was the objective of this experiment and was the objective achieved?
2. Did any of your measurements have more than 5% error? What was your maximum % error?
3. What sources of error may have contributed to the differences between the theoretical values and the measured values?
4. Other comments relevant to this experiment.

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Lab Experiment #7:
First-Order RC Circuits as Low-Pass and
High-Pass Filters

First-Order RC Circuits as Low-Pass & High-Pass Filters

I. Objective

In this experiment, the students will make measurements and observations on the step and sinusoidal steady-state responses of simple first-order RC circuits. They will also understand how first-order RC circuits can be used as low-pass or high-pass filters.

II. Procedure

PART 1: Step Excitation of First-Order RC Circuits

Pre-lab Assignment 1.a: A first-order capacitive circuit is excited by a periodic rectangular pulse train as shown in Fig. 1. The element values of the circuit are given by $R_1=10\text{ k}\Omega$ and $C_1=10\text{ nF}$ respectively. Calculate the following:

- The time constant τ of this circuit (call this time constant $\tau_{\text{pre-lab}}$ or τ_p).
- Approximate time it takes for the capacitor to fully charge or discharge. (The time for the capacitor to fully charge or discharge corresponds to the time it takes for the capacitor voltage to reach approximately 99% of its final value.)

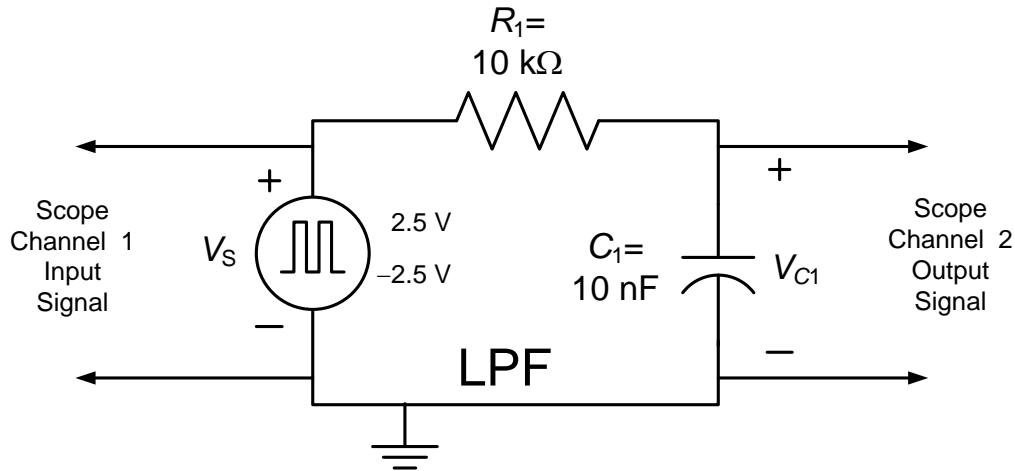


Figure 1. First-order RC circuit connected like a Low-Pass Filter (LPF).

Lab Experiment 1.a: Construct the first-order RC circuit shown in Fig. 1 using $R_1=10\text{ k}\Omega$ and $C_1=10\text{ nF}$. Using the digital LCR meter, measure and record the actual values of the resistor and the capacitor used in your circuit. Use these actual element values measured to recalculate the time constant τ (call this time constant τ_{actual} or τ_a). Use the function generator available on your bench to supply the periodic rectangular pulse train to the circuit. Set the function generator to provide the rectangular pulse train represented with source voltage $V_S(t)$ which oscillates between -2.5 V and 2.5 V (i.e., 5 V peak-to-peak) with frequency of

oscillation $f = 1/T = 500$ Hertz (Hz). (Note that $T=f^{-1}$ is the period of the periodic pulse train). Use the oscilloscope to monitor the source voltage $V_S(t)$ and the capacitor voltage $V_{C1}(t)$ simultaneously. Do the following:

- Measure the approximate value of the time constant τ of the circuit from the $V_{C1}(t)$ waveform (call this time constant τ_{measured} or τ_m). Note that over each $T/2$ time interval during which the source voltage $V_S(t)$ is either -2.5 V or 2.5 V, assuming $t=0$ to be the starting time of each one of these $T/2$ intervals, the capacitor voltage $V_{C1}(t)$ varies with respect to time as $V_{C1}(t) = V_{C1}(0)e^{-t/\tau_m} + V_{C1}(\infty)(1 - e^{-t/\tau_m})$ where $V_{C1}(0)$ is its initial value and $V_{C1}(\infty)$ is its final value. So, for example, the capacitor voltage at $t = \tau_m$ is approximately given by $V_{C1}(t = \tau_m) \cong 0.368V_{C1}(0) + 0.632V_{C1}(\infty)$. Refer to the middle portion of the $V_{C1}(t)$ sketch shown in Fig. 2 for which $V_{C1}(0) = -2.5$ V and $V_{C1}(\infty) = 2.5$ V. Substituting these values yield $V_{C1}(\tau_m) \approx 660$ mV. Using this portion of the $V_{C1}(t)$ waveform seen on the oscilloscope display, measure and record the approximate value of the time constant τ_m using the $V_{C1}(\tau_m)$ voltage point on the $V_{C1}(t)$ waveform.
- Calculate the percentage error in the τ_m value measured using

$$\% \text{ error in } \tau_m \text{ value} = \left| \frac{\tau_a - \tau_m}{\tau_a} \right| \times 100$$

- Compare $T/2$ (or $1/(2f)$) with $\sim 5\tau_m$ and comment on the two waveforms ($V_S(t)$ and $V_{C1}(t)$) observed simultaneously on the scope. (**Hint:** Does the capacitor have enough time to fully charge over the time interval $T/2$?)

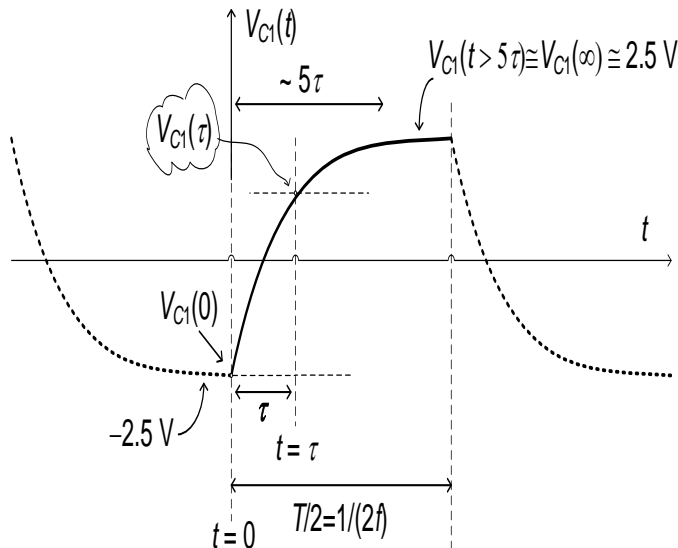


Figure 2. The capacitor voltage $V_{C1}(t)$ versus time t .

Lab Experiment 1.b: In Fig. 1, change the source frequency to $f = 5$ kHz and 50 kHz. Observe $V_S(t)$ and $V_{C1}(t)$ voltage waveforms simultaneously for each case.

Sketch and label the waveforms. Based on your observations, explain what happens and why this circuit is referred to as a Low-Pass Filter (LPF).

Lab Experiment 1.c: Switch the places of the 10 nF capacitor and 10 kΩ resistor as shown in Fig. 3 and use the oscilloscope to observe the voltage waveforms $V_S(t)$ and $V_{R1}(t)$ simultaneously for each one of the above source frequencies which are 500 Hz, 5 kHz, and 50 kHz. Sketch and label the waveforms. Explain why this circuit is referred to as a High-Pass Filter (HPF).

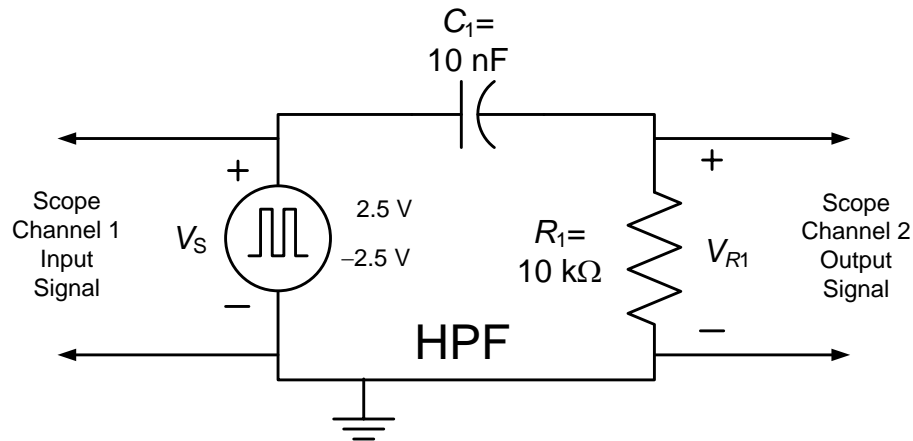


Figure 3. First-order RC circuit connected like a High-Pass Filter (HPF).

Pre-lab Assignment 1.d: For the first-order RC circuit considered in Fig. 1, introduce a second resistor $R_2=2.2\text{ k}\Omega$ in parallel with resistor $R_1=10\text{ k}\Omega$ as shown in Fig. 4. Calculate the value of the new time constant $\tau_{\text{pre-lab}}$ or τ_p for this circuit and the approximate time it takes for the capacitor to fully charge or discharge.

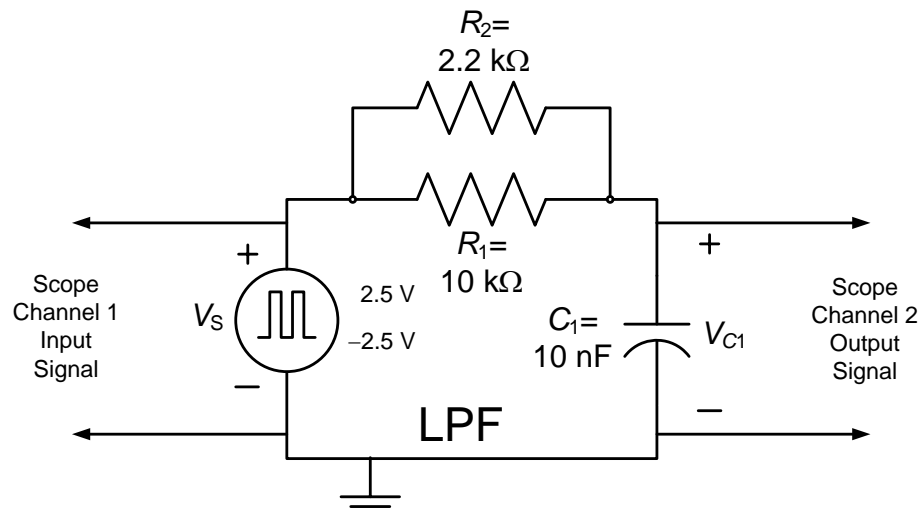


Figure 4. First-order RC circuit connected like a Low-Pass Filter (LPF).

Lab Experiment 1.d: For the first-order RC circuit shown in Fig. 4, measure and record the actual value of the $2.2\text{ k}\Omega$ resistor using the digital LCR meter. Recalculate the actual time constant τ_a using the actual element values measured. Set the source frequency to 500 Hz . Set-up the oscilloscope connections so that both $V_S(t)$ and $V_{C1}(t)$ waveforms appear on the screen simultaneously. Sketch and label the waveforms.

- Measure the time constant τ_m using the $V_{C1}(\tau)$ voltage point on the $V_{C1}(t)$ waveform seen on the oscilloscope display.
- Calculate the percentage error in the τ_m value measured using

$$\% \text{ error in } \tau_m \text{ value} = \left| \frac{\tau_a - \tau_m}{\tau_a} \right| \times 100$$

Pre-lab Assignment 1.e: For the first-order RC circuit considered in Fig. 1, introduce a second capacitor $C_2=100\text{ nF}$ in parallel with $C_1=10\text{ nF}$ as shown in Fig. 5. Calculate the new time constant $\tau_{\text{pre-lab}}$ or τ_p of the circuit and the approximate time it takes for the two capacitors to fully charge or discharge.

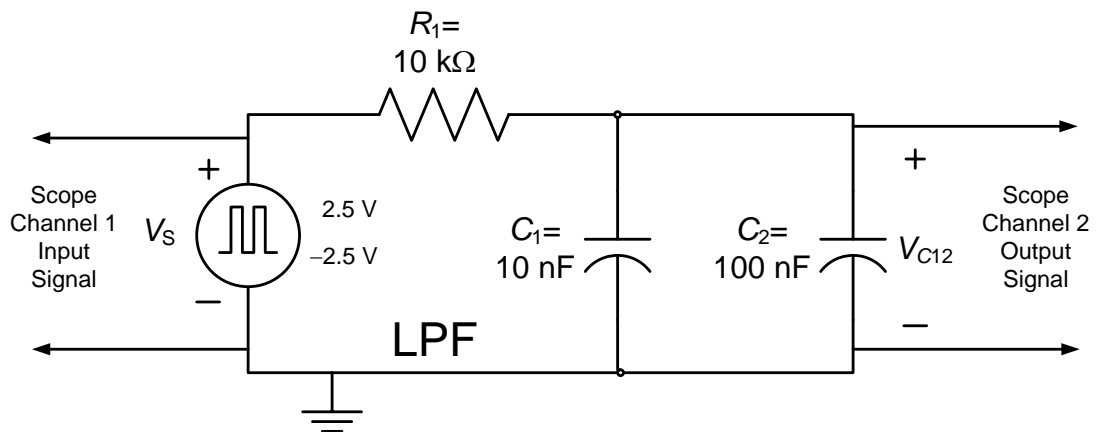


Figure 5. First-order RC circuit connected like a Low-Pass Filter (LPF).

Lab Experiment 1.e: Construct the first-order RC circuit shown in Fig. 5. Measure and record the actual value of the 100 nF capacitor using the digital LCR meter. Recalculate the actual time constant τ_a using the actual element values measured. Set the source frequency to 50 Hz . Observe both $V_S(t)$ and $V_{C12}(t)$ waveforms on the oscilloscope display simultaneously. Sketch and label the waveforms.

- Measure the time constant τ_m using the $V_{C12}(\tau)$ voltage point on the $V_{C12}(t)$ waveform seen on the oscilloscope display.
- Calculate the percentage error in the τ_m value measured using

$$\% \text{ error in } \tau_m \text{ value} = \left| \frac{\tau_a - \tau_m}{\tau_a} \right| \times 100$$

PART 2: Sinusoidal Excitation of First-Order RC Circuits (Optional)

Pre-lab Assignment 2: Replace the rectangular pulse source in the RC circuit in Fig. 1 with a sinusoidal source as shown in Fig. 6. Note that the *cutoff frequency* of this first-order LPF circuit is defined as the frequency at which the peak value of the output signal is $(1/\sqrt{2})$ (or ~ 0.707) times the peak value of the input signal and is given by $f_c = 1/(2\pi RC) = 1/(2\pi\tau)$ (in Hz). This means that a sinusoidal input signal V_S with an oscillation frequency below this cutoff frequency yields an output signal which is very close to the input signal (that is the input signal V_S applied at the input port of the circuit results in an output signal at the output port of the circuit which is almost identical to the input signal) whereas a sinusoidal input signal V_S with frequency above this cutoff frequency yields an output signal which has a much smaller peak value compared to the peak value of the input signal. Calculate the cutoff frequency of this LPF from the element values provided in the Fig. 6 using $f_c = 1/(2\pi RC)$.

Lab Experiment 2.a: Construct the circuit shown in Fig. 6. Observe both voltages $V_S(t)$ and $V_{C1}(t)$ on the scope simultaneously for 500 Hz, 5 kHz, and 50 kHz. Sketch and label the waveforms. Comment on your observations based on the cutoff frequency calculated in the pre-lab assignment.

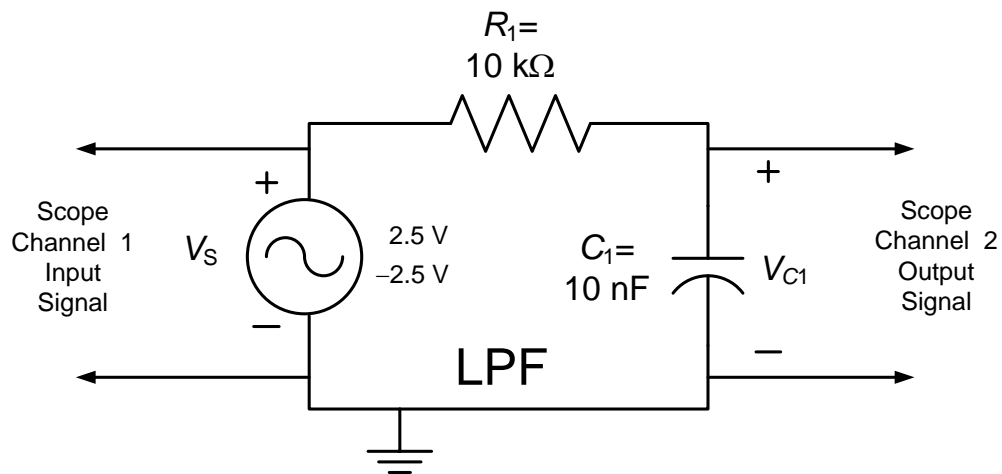


Figure 6. First-order LPF RC circuit excited by a sinusoidal source.

Lab Experiment 2.b: Construct the circuit shown in Fig. 7. Observe both voltages $V_S(t)$ and $V_{R1}(t)$ on the scope simultaneously for 500 Hz, 5 kHz, and 50 kHz. Sketch and label the waveforms. Comment on your observations based on the cutoff frequency calculated in the pre-lab assignment.

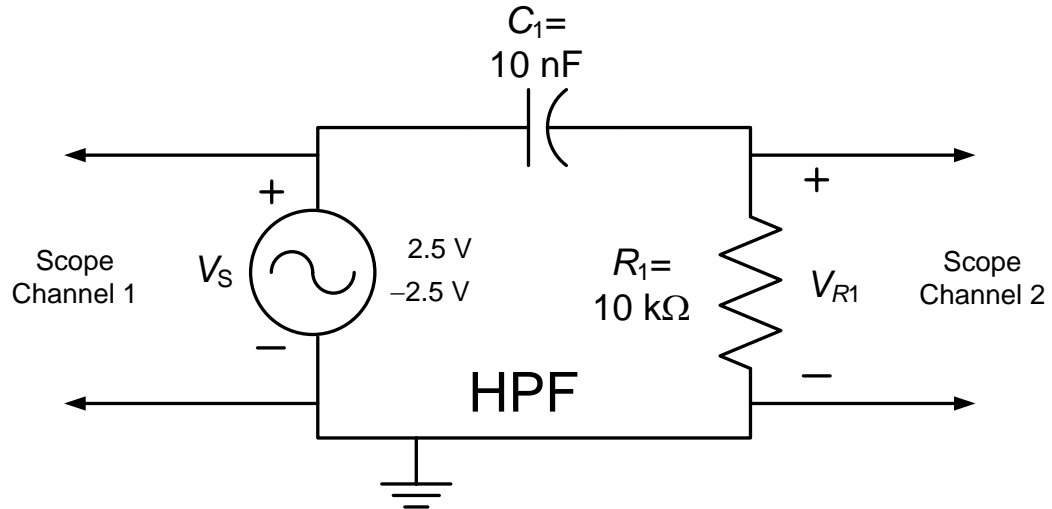


Figure 7. First-order HPF RC circuit excited by a sinusoidal source.

III. Discussions & Conclusion

In this section, discuss the various aspects of Experiment #8 and make some conclusions. In your write-up, you should at least address the following questions:

1. What was the objective of this experiment and was the objective achieved?
2. Did any of your measurements have more than 5% error? What was your maximum % error?
3. What sources of error may have contributed to the differences between the theoretical values and the measured values?
4. Other comments relevant to this experiment.

University of Portland
School of Engineering

EE 271–Electrical Circuits Laboratory

Lab Experiment #8:
Transient Response of First-Order RL
and Second-Order RLC Circuits

Transient Response of First-Order RL and Second-Order RLC Circuits

I. Objective

In this experiment, the students will make measurements and observations on the transient step response of simple RL and RLC circuits.

II. Procedure

PART 1: Step Excitation of First-Order RL Circuits

Pre-lab Assignment 1.a: A first-order inductive circuit is excited by a periodic pulse train as shown in Fig. 1. The values of the elements are given by $R_1=1\text{ k}\Omega$ and $L_{\text{coil}}=15\text{ mH}$ respectively. Assuming both the source and the inductor to be ideal (i.e., $R_S = 0$ and $R_{\text{coil}} = 0$), calculate the time constant (designate it with $\tau_{\text{pre-lab}}$ or τ_p) of this circuit. Approximately how long does it take for the inductor of this circuit to fully charge or discharge under pulse excitations? (Fully charge or discharge means the time it takes for the inductor current to reach approximately 99% of its final value.)

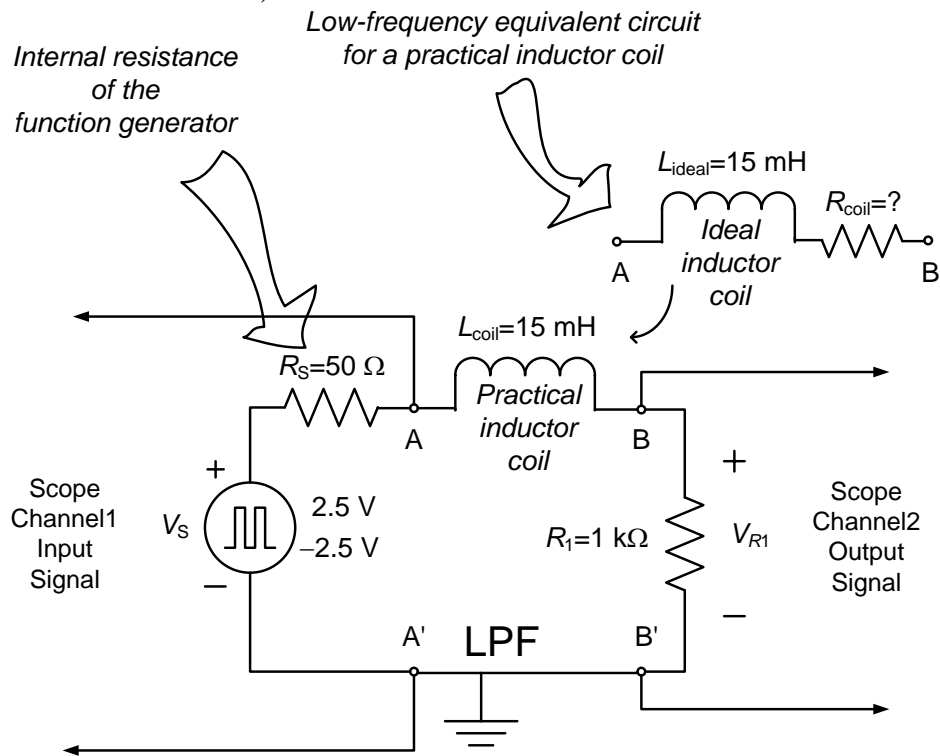


Figure 1. First-order RL circuit connected like a Low-Pass Filter (LPF). (Note that terminals A' and B' are the same.)

Lab Experiment 1.a: Construct the first-order RL circuit shown in Fig. 1 using $R_1=1\text{ k}\Omega$ and $L_{\text{coil}}=15\text{ mH}$. Do the following:

- Using the digital LCR meter, measure and record the actual values of R_1 and L_{coil} you use to build your circuit. Note that a practical inductor coil is not an ideal inductor. For low-frequency applications, a practical inductor can be represented in terms of an equivalent circuit model which consists of an ideal inductor with value $L_{\text{ideal}}=15\text{ mH}$ in series with the internal resistance R_{coil} of the inductor (see Fig. 1). Using the LCR meter, measure and record the internal resistance, R_{coil} , of the inductor coil.
- Also, assume the internal source resistance of the function generator R_S to be $50\ \Omega$.
- Use the actual element values measured to recalculate the time constant of this circuit (designate this time constant as τ_{actual} or τ_a).
- Next, use the function generator available on your bench to supply the periodic rectangular pulse train to the circuit. Set the function generator to provide the rectangular pulse train represented with the source voltage $V_S(t)$ which oscillates between -2.5 V and 2.5 V with frequency of oscillation $f = 1/T = 1\text{ kHz}$. Use the two channels of the oscilloscope to monitor the source voltage $V_S(t)$ and the resistor voltage $V_{R1}(t)$ across the resistor simultaneously.
- Measure the approximate value of the time constant τ of the circuit from the $V_{R1}(t)$ waveform (call this time constant τ_{measured} or τ_m). Note that over each $T/2$ time interval during which the source voltage $V_S(t)$ is either -2.5 V or 2.5 V , assuming $t=0$ to be the starting time of each one of these $T/2$ intervals, the resistor voltage $V_{R1}(t)$ varies with respect to time as $V_{R1}(t) = V_{R1}(0^+)e^{-t/\tau_m} + V_{R1}(\infty)(1 - e^{-t/\tau_m})$ where $V_{R1}(0^+)$ is its initial value and $V_{R1}(\infty)$ is its final value. So, for example, the resistor voltage at $t = \tau_m$ is approximately given by $V_{R1}(t = \tau_m) \cong 0.368V_{R1}(0^+) + 0.632V_{R1}(\infty)$. Refer to the middle portion of the $V_{R1}(t)$ sketch shown in Fig. 2 for which $V_{R1}(0^+) = -2.5\text{ V}$ initial and $V_{R1}(\infty) = 2.5\text{ V}$ final voltage values are indicated. Substituting these values yield $V_{R1}(\tau_m) \approx 660\text{ mV}$. Using this portion of the $V_{R1}(t)$ waveform seen on the oscilloscope display, measure and record the approximate value of the time constant τ_m using the $V_{R1}(\tau_m)$ voltage point on the $V_{R1}(t)$ waveform.
- Calculate the percentage error in the τ_m value measured using

$$\% \text{ error in } \tau_m \text{ value} = \left| \frac{\tau_a - \tau_m}{\tau_a} \right| \times 100$$

- Compare $T/2$ (or $1/(2f)$) with $\sim 5\tau_m$ and comment on the two waveforms ($V_S(t)$ and $V_{R1}(t)$) observed simultaneously on the scope. (Hint: Does the inductor have enough time to fully charge over the time interval $T/2$?)

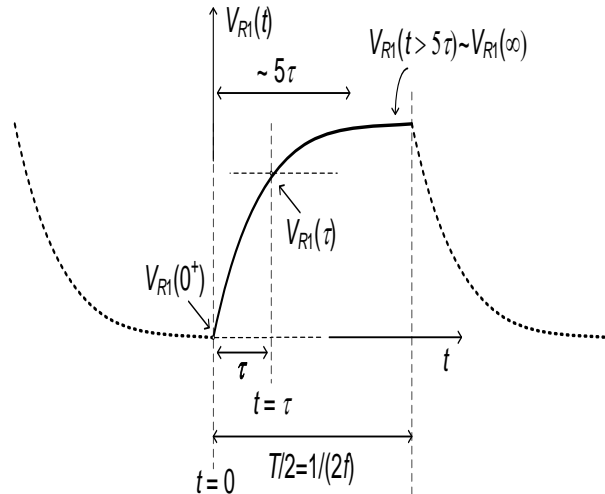


Figure 2. The resistor voltage $V_{R1}(t)$ versus time t .

Lab Experiment 1.b: Repeat Lab Experiment 1.a for the following source frequencies: $f = 5$ kHz, 30 kHz, 50 kHz, and 100 kHz. Observe $V_S(t)$ and $V_{R1}(t)$ waveforms simultaneously for each case. Sketch and label the waveforms. Explain what happens.

Lab Experiment 1.c: Switch the places of the 15 mH inductor and 1 k Ω resistor as shown in Fig. 3. Use the two oscilloscope channels to observe the voltage waveforms $V_S(t)$ and $V_{L1}(t)$ simultaneously at the same frequencies used in Lab Experiments 1.a and 1.b. Sketch and label the waveforms. Explain what this circuit does and why.

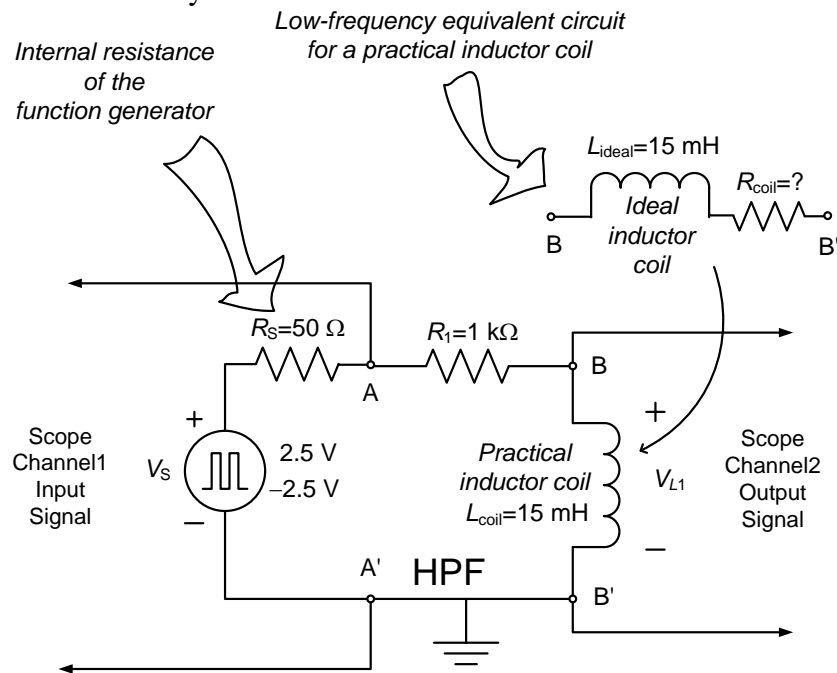


Figure 3. First-order RL circuit connected like a High-Pass Filter (HPF).

PART 2: Step Excitation of Second-Order RLC Circuits

Lab Experiment 2: Construct the second-order series *RLC* circuit shown in Fig. 4 using $L_{\text{coil}}=15$ mH and $C_1=10$ nF. Using the digital *LCR* meter, measure and record the actual value of the capacitor used. Using the actual element values of the circuit measured, do the following:

- Find the characteristic equation of this circuit. Note that the characteristic equation of this second-order series *RLC* circuit is given by

$$s^2 + (R_S + R_{\text{coil}})s/L_{\text{coil}} + 1/(L_{\text{coil}}C_1) = 0$$

- Find the roots of the characteristic equation and verify that the transient response of this circuit will be an under-damped response.
- Calculate the damping frequency f_d of the under-damped response by using the following expression:

$$f_d = \frac{1}{2\pi} \sqrt{\omega_0^2 - \alpha^2} = \frac{1}{2\pi} \sqrt{1/(L_{\text{coil}}C_1) - [(R_S + R_{\text{coil}})/(2L_{\text{coil}})]^2}$$

Next, set the function generator to provide the rectangular pulse train represented with the source voltage $V_S(t)$ which oscillates between -2.5 V and 2.5 V with frequency of oscillation $f = 1/T = 250$ Hz. Use the oscilloscope channels to observe the two voltage waveforms $V_S(t)$ and $V_{C_1}(t)$ simultaneously. Sketch and label the waveforms. Explain the difference between the voltage waveform $V_{C_1}(t)$ observed in this circuit versus in a first-order *RC* circuit (like the one used in Lab Experiment # 7). Measure the damping frequency f_d of the under-damped oscillations observed in the $V_{C_1}(t)$ waveform by measuring the damping period T_d and using $f_d = 1/T_d$. Calculate the percentage error in the measured value of f_d .

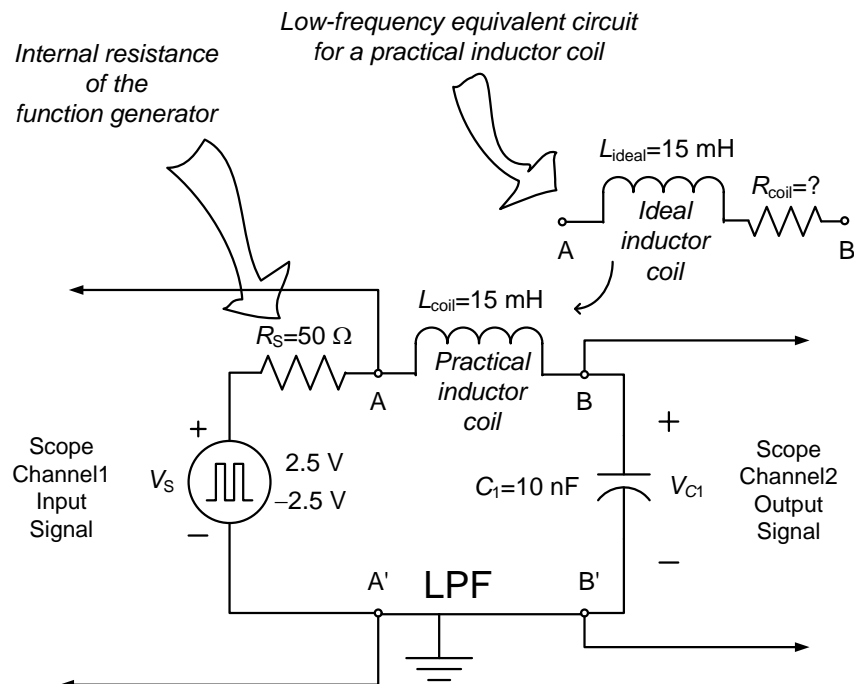


Figure 4. Second-order series *RLC* circuit.

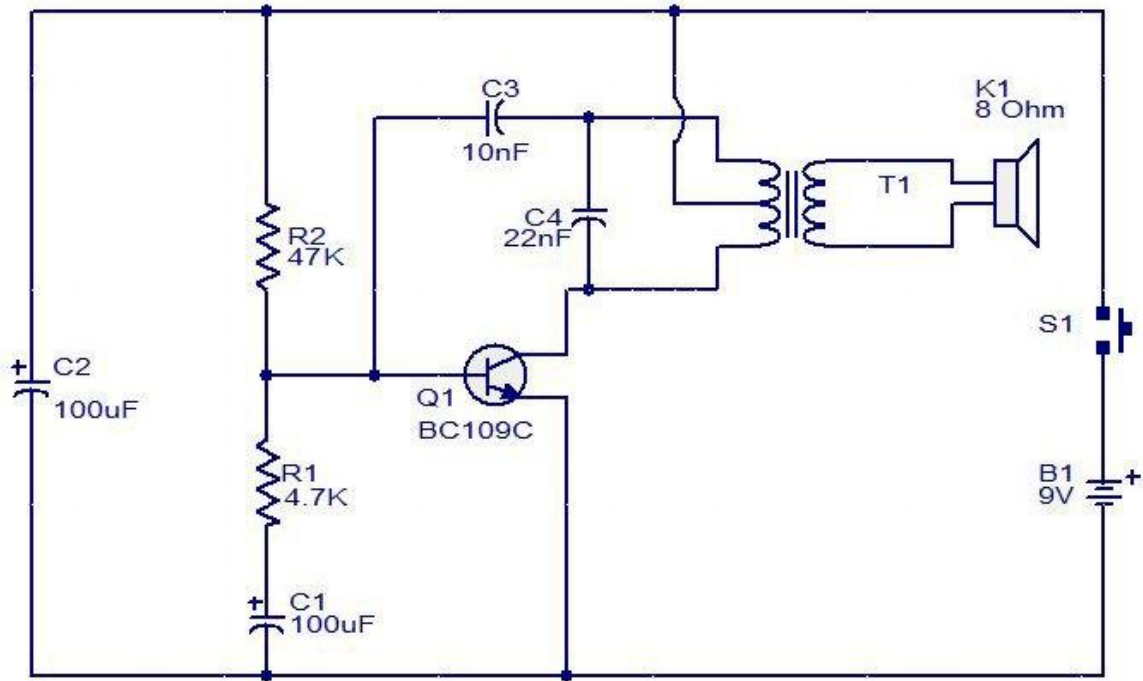
Repeat this experiment at 5 kHz, 10 kHz, and 20 kHz and observe the two voltage waveforms on the oscilloscope simultaneously in each case. Sketch and label the waveforms. Provide an explanation as to what happens to the two waveforms as the source frequency increases.

III. Discussions & Conclusion

In this section, discuss the various aspects of Experiment # 8 and state some conclusions. In your write-up, you should at least address the following questions:

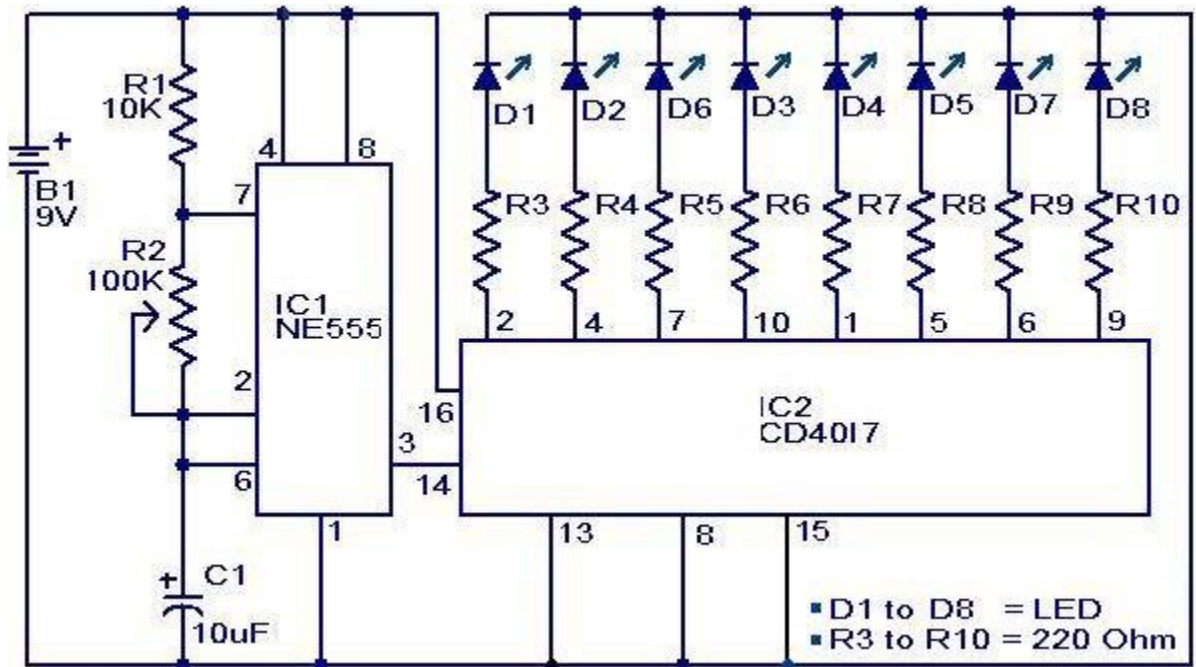
1. What was the objective of this experiment and was the objective achieved?
2. Explain how the output resistance of the function generator affected some of the waveforms observed on the scope and why. Why was this effect not observed in the first-order RC experiment (i.e., Experiment # 7)?
3. Did any of your measurements have more than 5% error? What was your maximum % error?
4. What sources of error may have contributed to the differences between the theoretical values and the measured values?
5. Other comments relevant to this experiment.

Fun Circuit 1

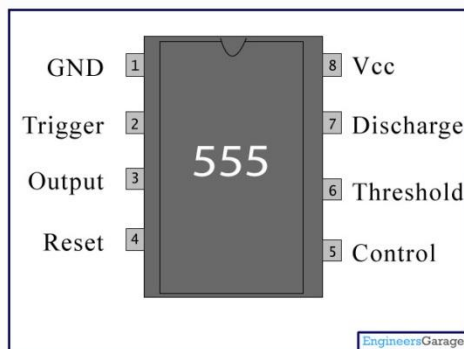


Fun Circuit 2

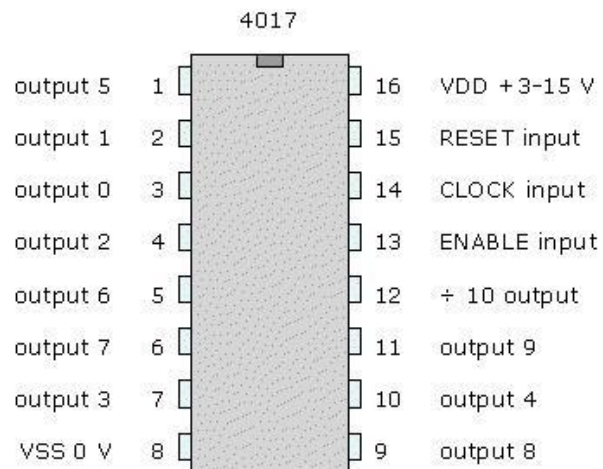
Circuit to Build:

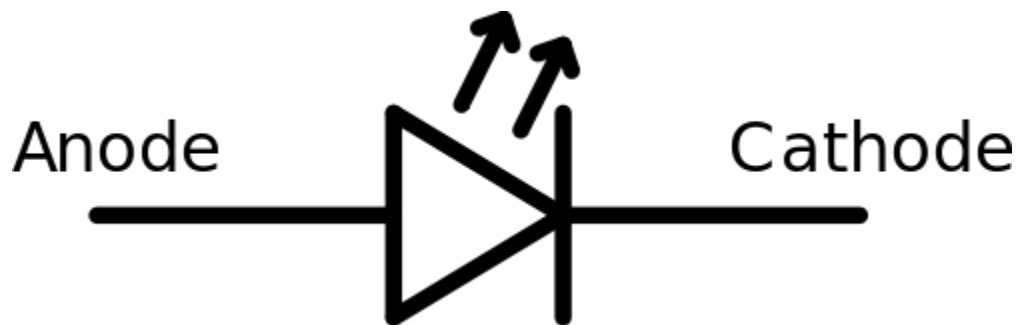
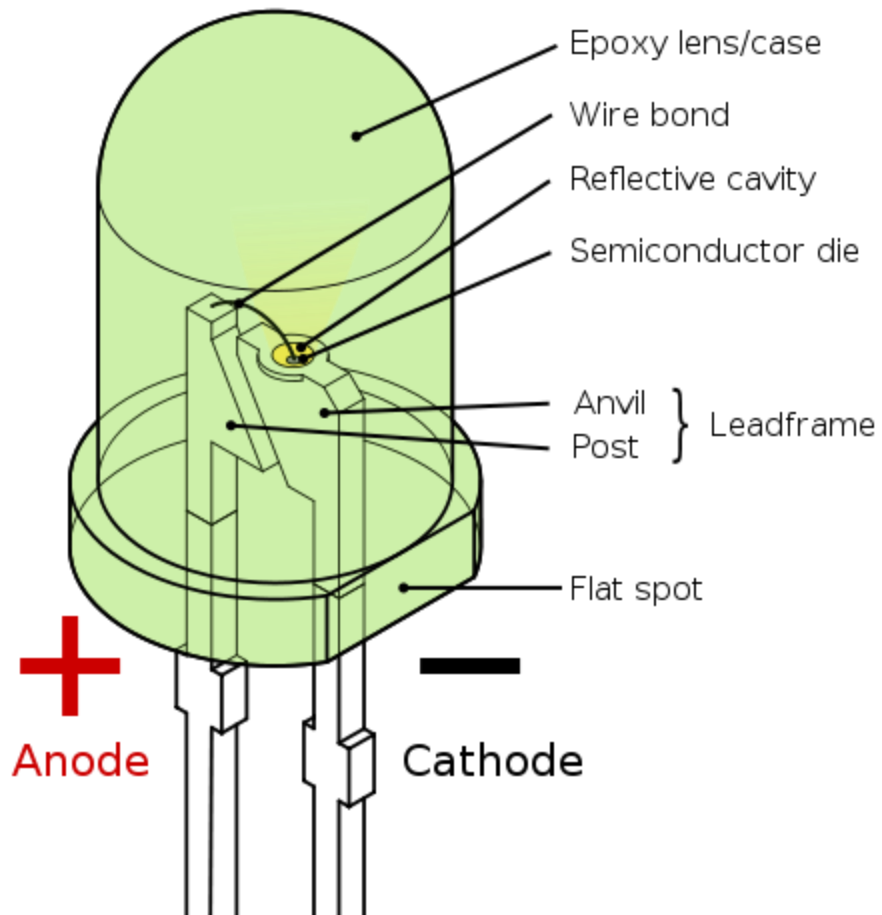


555 Pinout



4017 Pinout





Fun Circuit 3

The following is an excerpt of a lab from:

Worcester Polytechnic Institute
Department of Electrical and Computer Engineering
ECE3601 – Intro to Electrical Engineering
Laboratory Project 5: Operational amplifier I

Part II High-Gain Amplifier Stage

In this part of the laboratory you will build a more practical and more realistic amplifier circuit. This is a simple yet accurate heart rate sensor. The present circuit has recently been designed by Professor Stephen J. Bitar (ECE) for ECE3601-C09 (and ECE2011-C09).

The specific feature of this circuit is a rather challenging character of an input signal. The input signal is a low-voltage low-frequency pulse train with a very significant DC offset and a significant noise. Therefore, a more complicated circuitry is necessary to accurately amplify and record this signal.

The key to building more complicated circuits is the *block-by-block building procedure*. We build the circuit by blocks, starting with the sensor itself. Every block has a certain expected output. The output is tested with the oscilloscope. If the test is positive, we move to the next block. Otherwise, we debug the present block and eliminate the error.

Note: A faulty component is the unlikely source of circuit malfunctioning. Most likely error sources in this laboratory:

- i. the amplifier power is not connected;
- ii. the protoboard does not hold the amplifier or potentiometer well;
- iii. the amplifier pins are bent and are not in the board;
- iv. resistors are misplaced (e.g. $1\text{K}\Omega$ instead of $1\text{M}\Omega$);
- v. the power cables from the power supply are broken; etc.

1. Allocate space on the board

Disassemble the circuit from Part I, but leave the power supply connections unchanged. The final circuit design is given in Fig. 7 that follows. Looking at the board and at Fig. 7 estimate the space necessary for different blocks - five blocks total. Think about the amplifier placement. The output to the sensor - the green LED - should be possibly located further away from the sensor - the infrared emitter-to-collector pair within a PVC tube.

2. The sensor

The infrared sensor (operating wavelength of light is about 940 nm) of this laboratory project is used to measure the heart rate. The cardiovascular pulse results in a change in the volume of arterial blood with each pulse beat. The change in blood volume can be detected in peripheral parts of the body such as

the fingertip or ear lobe using a technique called Photoplethysmography. The device that detects the signal is called a plethysmograph (or 'Pleth' for short)¹.

The idea of the sensor is shown in Fig. 3. Infrared light is well absorbed in blood and weakly absorbed in tissue. Any changes in blood volume will be registered since increasing (or decreasing) blood volume will cause more or less light absorption. This principle is used to detect the heart rate.

The sensor includes the emitter (an infrared IR LED 940nm Digikey 751-1201-ND) and a detector (an infrared phototransistor or a photo BJT Digikey 160-1031-ND). Both are operating at 940 nm wavelength. The base current of the phototransistor is generated by incident infrared light. Therefore, the base is not connected in Fig. 3. When a finger is placed between the emitter and phototransistor, the collector current will slightly vary in response to the pulse beats. Our goal is to extract and amplify those variations.

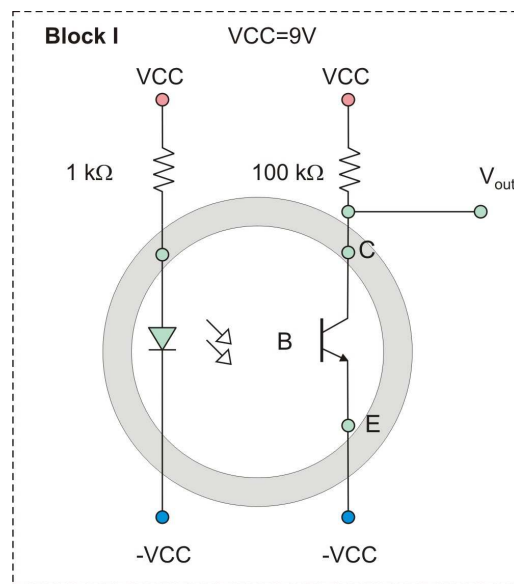


Fig. 3. Block I of the circuit - a sensor (top view). The blue LED is on the left.

Please build the circuit from Fig. 3 - Block I of the final circuit. Turn the power supply on. With CH 1 of the oscilloscope measure the output voltage v_{out} versus

¹ See, for example,
<http://electronicdesign.com/Articles/Index.cfm?AD=1&ArticleID=6343>
http://www.arborsci.com/Data_Sheets/Files/Sensor_Books/Heart_Rate1.pdf

the common bus. Use 5V per division (the y-axis) and 50 ms per division (the x-axis) resolution settings. When the finger is not in the PVC tube, the reading voltage should be low or close to -10V. The BJT base receives the photocurrent from the diode. The BJT is ON and the voltage drop across it is small (0.3-0.8V or so). With the finger in, a large fraction of the light flux is blocked. The BJT is almost OFF; the voltage across it significantly increases. It never reaches exactly +9V though. Record these two voltage values (approximate numbers are just fine) in your notes using MEASURE/MeanValue function of the oscilloscope.

If the circuit is not functioning, ask TA for help. *Once the circuit block is tested turn the power supply off.*

3. A “high-pass” filter

The voltage from the previous experiment usually does not indicate any sign of arterial blood pulse beats. The reason is a large DC voltage component, which is still present in the output signal. Small voltage changes are just not seen.

The circuit in Fig. 4 allows us to eliminate the DC component. The circuit in Fig. 4 is a *high-pass filter* to be studied in class. It blocks the DC voltage (the DC current does not flow through the capacitor that is open circuit at DC). At the same time, it lets the AC signal to come through. Build this circuit on the protoboard: start with the left side of the board and allocate no more than ¼ of total protoboard space for it.

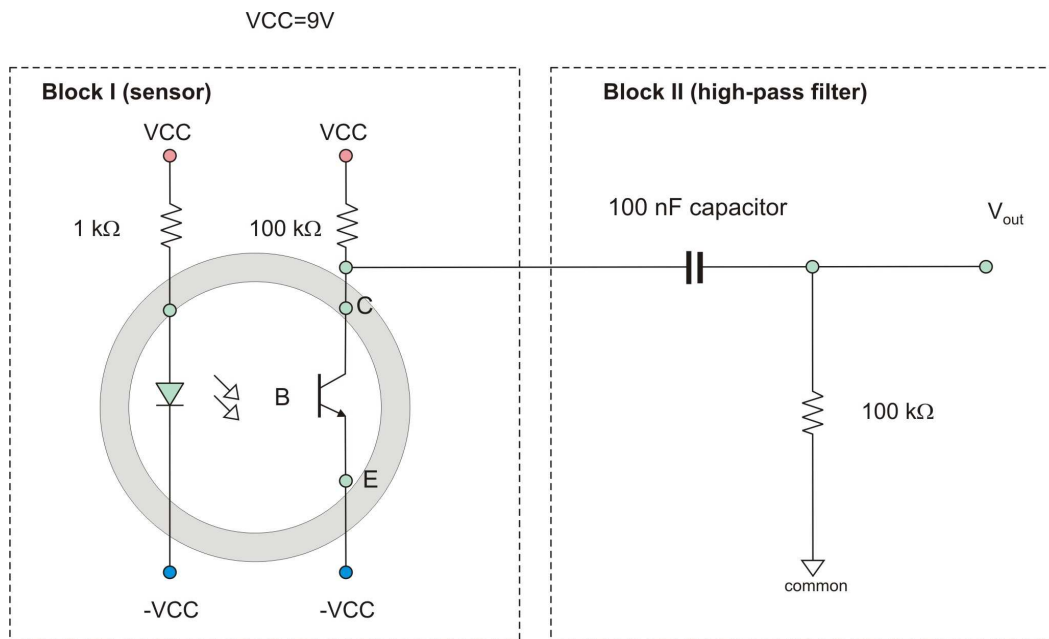


Fig. 4. Block II - a high-pass filter.

The present capacitor (the tantalum capacitor) is not the electrolytic one: the polarity does not matter. The high-pass filter in this circuit has only one function: it eliminates a DC voltage offset from the voltage V_{out} . Only a pure AC signal ideally passes through it.

Turn power supply on. With CH 1 of the oscilloscope measure the output voltage versus the common port after the second block. Use 50mV per division (the y-axis) and **500 ms per division** (the x-axis) resolution settings. When the finger is in the PVC tube, the reading voltage should be close to zero. It should have small but usually visible noisy beats corresponding to the heart rate. If this is not the case, ask TA for help. *Once Block II is tested turn the power supply off.*

4. Amplification

After the sensor output is conditioned with the high-pass filter, we should amplify it. To do so, a non-inverting amplifier shown in Fig. 5 is employed. Please build the corresponding block (Block III).

Turn the power supply on. With CH 1 of the oscilloscope we still measure the input voltage to the amplifier (output voltage of Block II) versus the common port. Use 50mV per division (the y-axis) and 500 ms per division (the x-axis) resolution settings. With CH 2 of the oscilloscope we now measure the output voltage to the amplifier (output voltage of Block III) versus the common port. Use 1V per division (the y-axis) and 500 ms per division (the x-axis) resolution settings for CH 2. The strong amplification of the input voltage signal should be observed. If this is not the case, ask TA for help. *Once the circuit block is tested turn the power supply off.*

5. A potential problem with the high-gain amplifier

A potential problem with the high-gain amplifier in Fig. 5 is the *input offset voltage*. This voltage appears internally, even if the input voltage to terminals + and - is exactly zero Volts. It is an internal property of the real amplifier chip. For LM1458, the input offset voltage may have any value between ± 1 mV and ± 6 mV. The offset voltage is also amplified, along with useful signal. If the amplifier has a high gain, the corresponding DC offset at the output may be quite large.

This DC offset voltage at the output (with no finger in the sensor) should be observed in the previous experiment and should be recorded in your notes (an approximate value is fine).

To solve this problem we introduce one more circuit block (Block IV) shown in Fig. 6.

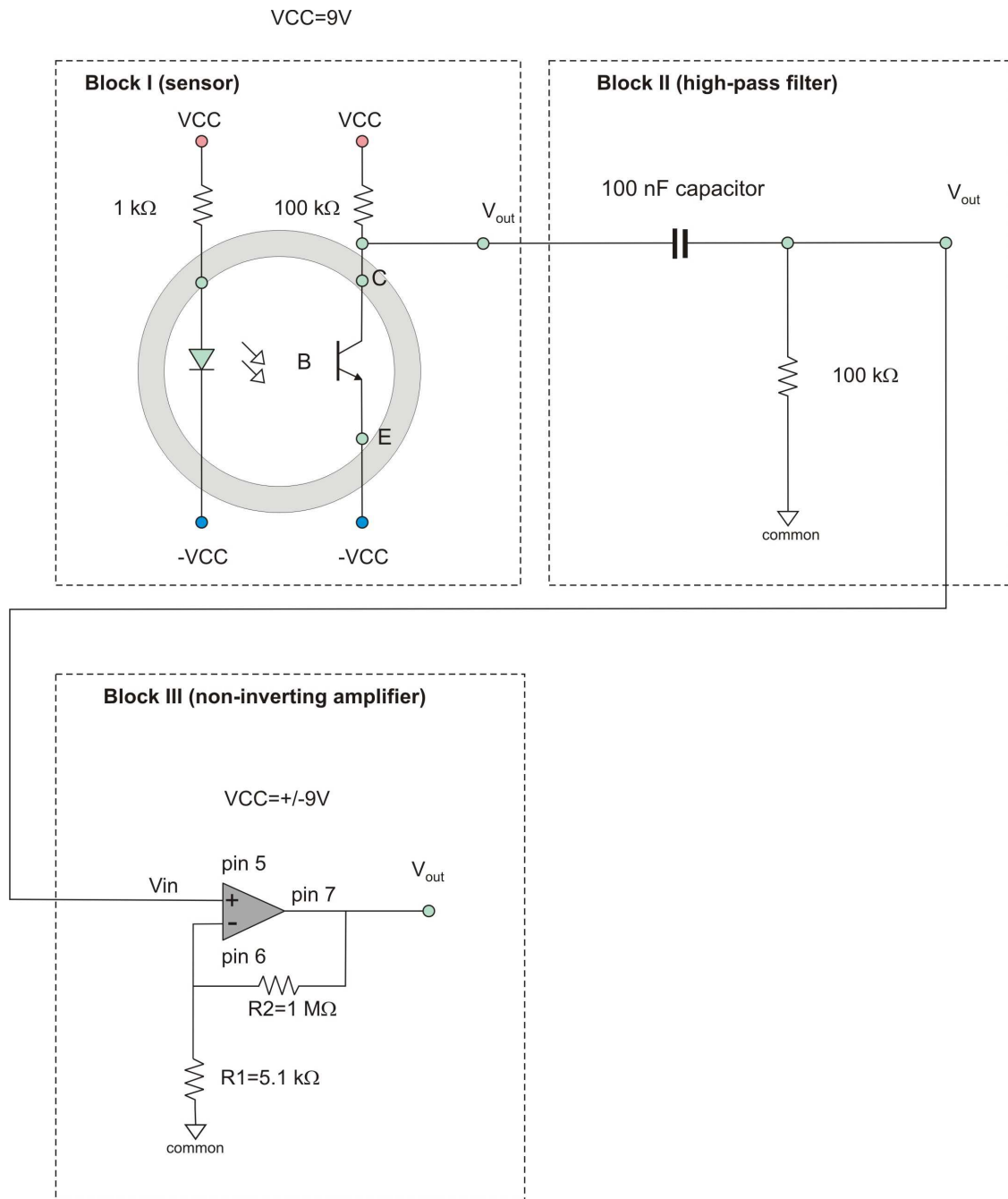


Fig. 5. Block III - a high-gain non-inverting amplifier stage.

This block slightly adjusts the voltage at the negative input terminal and thus eliminates the DC offset voltage of the chip. Plus, it allows us to introduce a desired offset. Please add the block shown in Fig. 6. Turn power supply on. With the finger in the sensor, use CH 2 of the oscilloscope adjust the potentiometer in order to have the zero output voltage level approximately at the half height of the beats. In that way, the noisy voltage between the beats should be primarily negative.

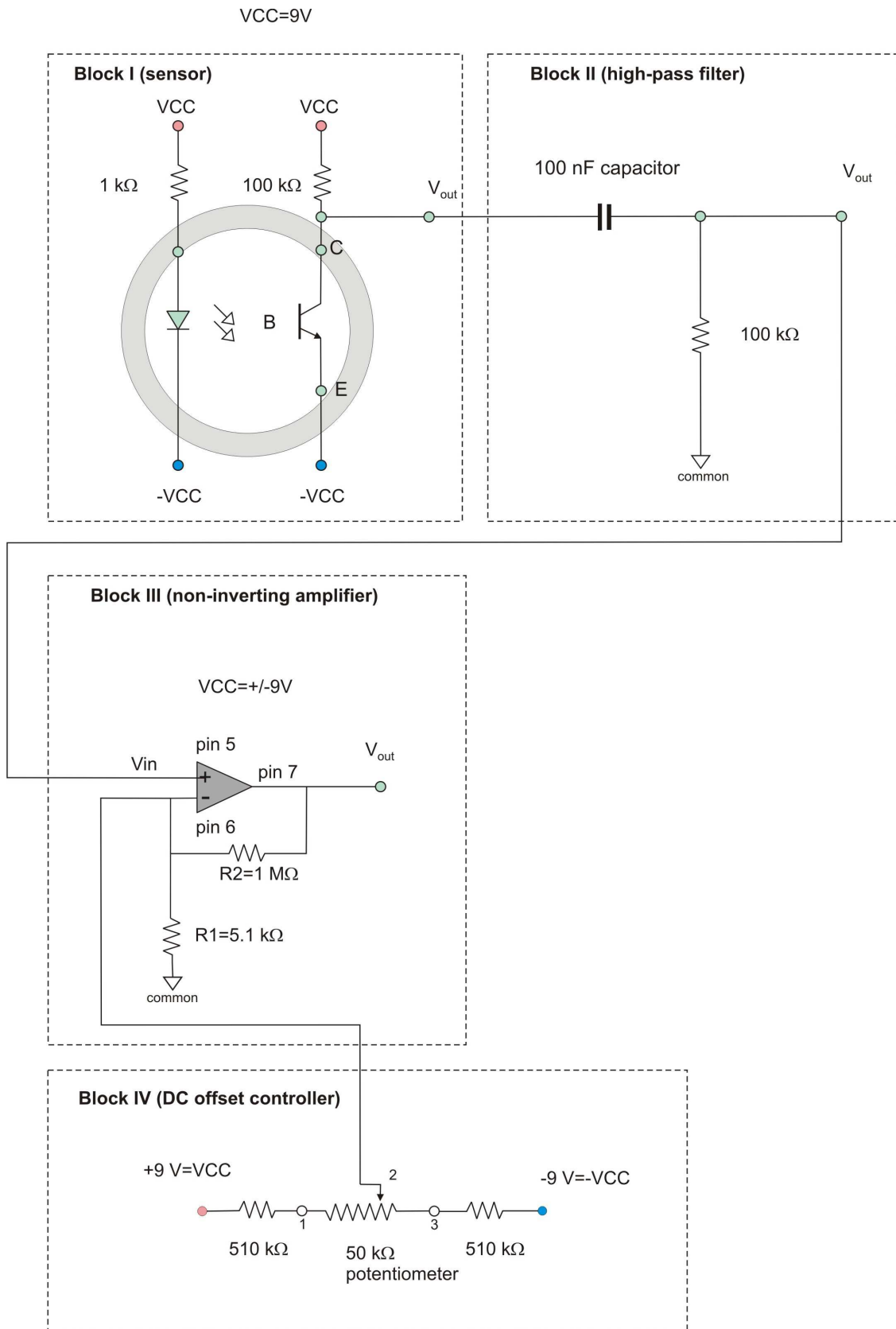


Fig. 6. Block IV - Controlling the DC offset of the amplifier.

6. The complete circuit

The complete circuit is shown in Fig. 7 that follows. It includes a new amplifier stage - the *comparator amplifier*. This amplifier does not have a feedback loop. The comparator amplifier is a convenient tool for creating rectangular pulses at the output. It may only be in two states: on or off. When the input voltage to its plus terminal is negative, the output is close to the negative rail of the power supply. When it is positive, no matter how small or large it is, the amplifier's output approaches the upper rail voltage.

The comparator is used to turn on the light indicator when the output pulse beat is above zero Volts and turn it off otherwise. In other words, it helps us to "digitize" the signal.

The RC block in front of the comparator (on the left side of Block V) in Fig. 7 is the so called *low-pass filter* to be studied in class. This filter is optional but quite useful: it removes high-frequency components (spikes) from the signal prior to comparator. Without this filter, the comparator might respond to a high-frequency noise at a frequency that is much higher than the heart rate.

Please add Block V shown in Fig. 7. Turn the power supply on. With the finger in the PVC tube, the LED should blink precisely in tact with your heart rate. If this is not the case, try to hold the finger in the same position and slightly adjust the potentiometer.

1. Reconnect CH 1 of the oscilloscope to the output of the non-inverting amplifier. Use 100mV per division (the y-axis) and 500 ms per division (the x-axis) resolution settings.
2. Reconnect CH 2 of the oscilloscope to the output of the comparator and observe the digitized output voltage waveform on the screen. Use 2V (or 5V) per division (the y-axis) and 500 ms per division (the x-axis) resolution settings for CH 2.
3. Using LabView please plot the comparator output voltage over the period of 10 seconds, separately for you and your partner. Attach both plots to the laboratory report. Who has a higher heart rate - you or your partner?

Demonstrate the operating circuit to the TA and obtain his/her signature. Do not disassemble the circuit without answering the final questions.

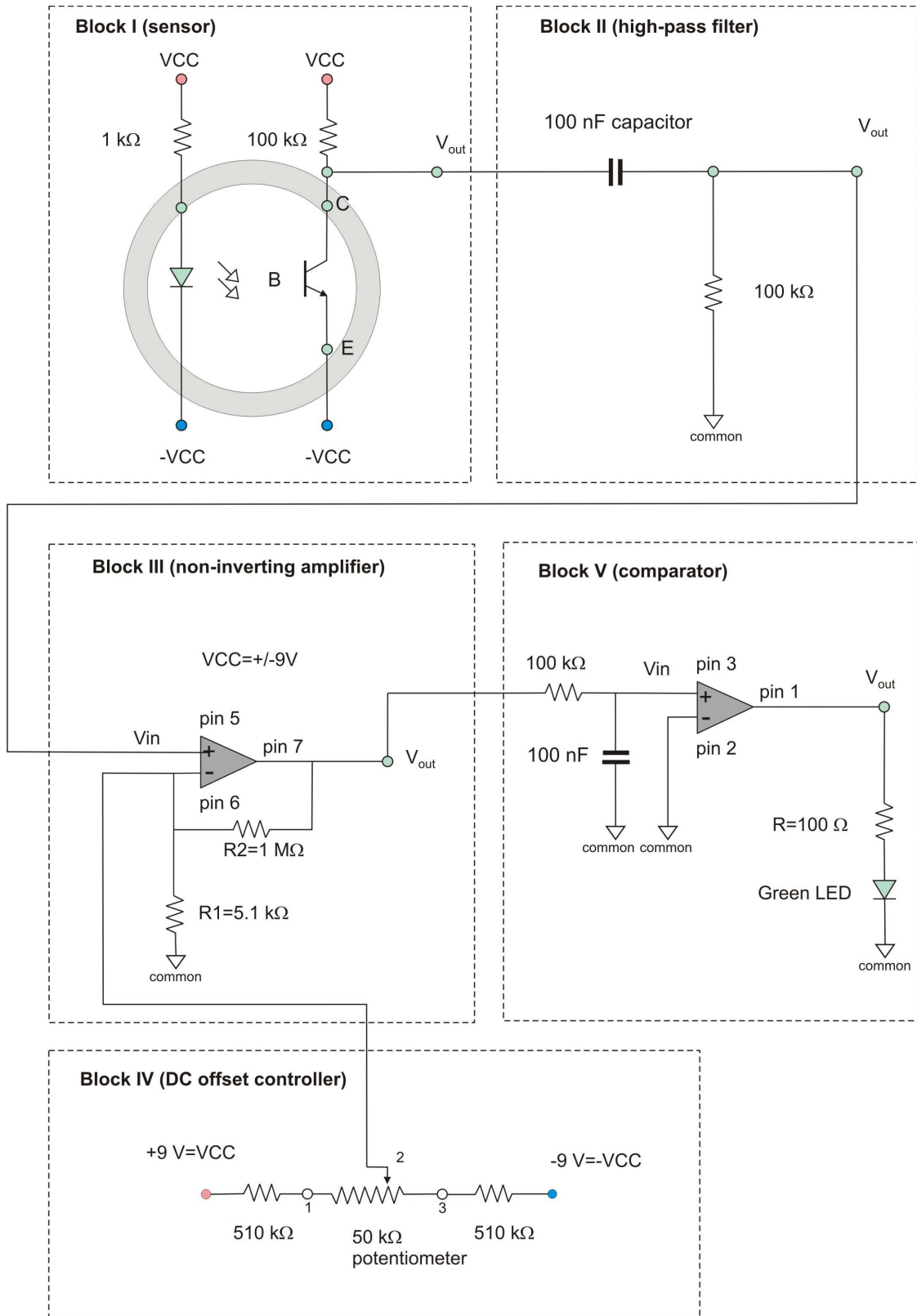


Fig. 7 Block V - the second amplifier stage - the comparator. The sensor circuit is complete.

NOTE: General way of tuning the circuit without the oscilloscope (if necessary):

1. Put the finger in the PVC tube and hold it in the same position;
2. Using the potentiometer, adjust to the maximum reading when the LED is on during the largest period of time;
3. By slowly rotating the potentiometer knob in the opposite direction achieve the state when the LED blinks synchronously with the heart rate.

Part III Questions

1. Why the sensor output voltage in Fig. 3 is high when the finger is in the sensor and why is it low otherwise?
2. Why do we need the high-pass filter in the heart-rate sensor circuit from Fig. 7. Do you think the circuit without the filter will still function? *Hint:* short out the filter and observe the circuit operation.
3. What is the gain of the first amplifier stage (Block III) in Fig. 7?
4. What is the gain of the second amplifier stage (Block V) in Fig. 7?
5. The input voltage to the comparator amplifier is a sinusoidal function with the amplitude of 1V. The amplifier rails are at $\pm 10V$. Assuming the ideal amplifier please plot the input and output voltages to scale over one period.
6. All electronic parts for the present laboratory cost about \$6.50 total. A very similar in operation heart rate sensor from Pasco Scientific (<http://www.pasco.com/>) costs \$80.00. It is listed in Appendix B. What do you think we are paying for?
7. Could you think of some possible applications of the present sensor concept?
8. This question is worth only one point of the laboratory grade. Please do not attempt this question if your time is limited. With the help of the present circuit and the built-in LabView signal processing tools, could you please try to precisely measure the heart rate for you and your partner? Consider the time duration of 30 sec as the base sampling window.