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_{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

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

- 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:

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

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 $V_{C1}(t)$ simultaneously. Sketch and label the waveforms. Explain the difference between the voltage waveform $V_{C1}(t)$ 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 $V_{C1}(t)$ 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.

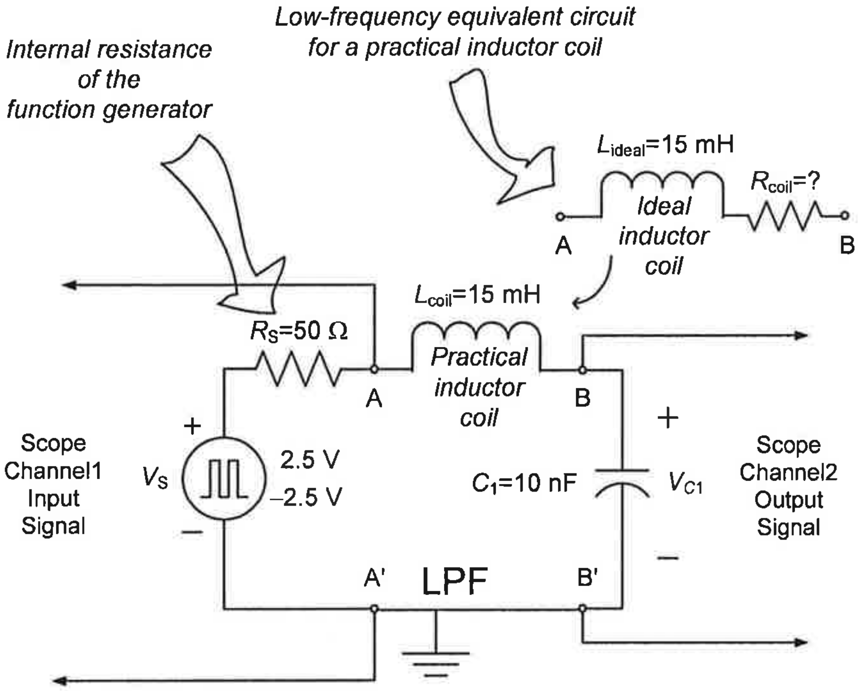


Figure 4. Second-order series *RLC* circuit.

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

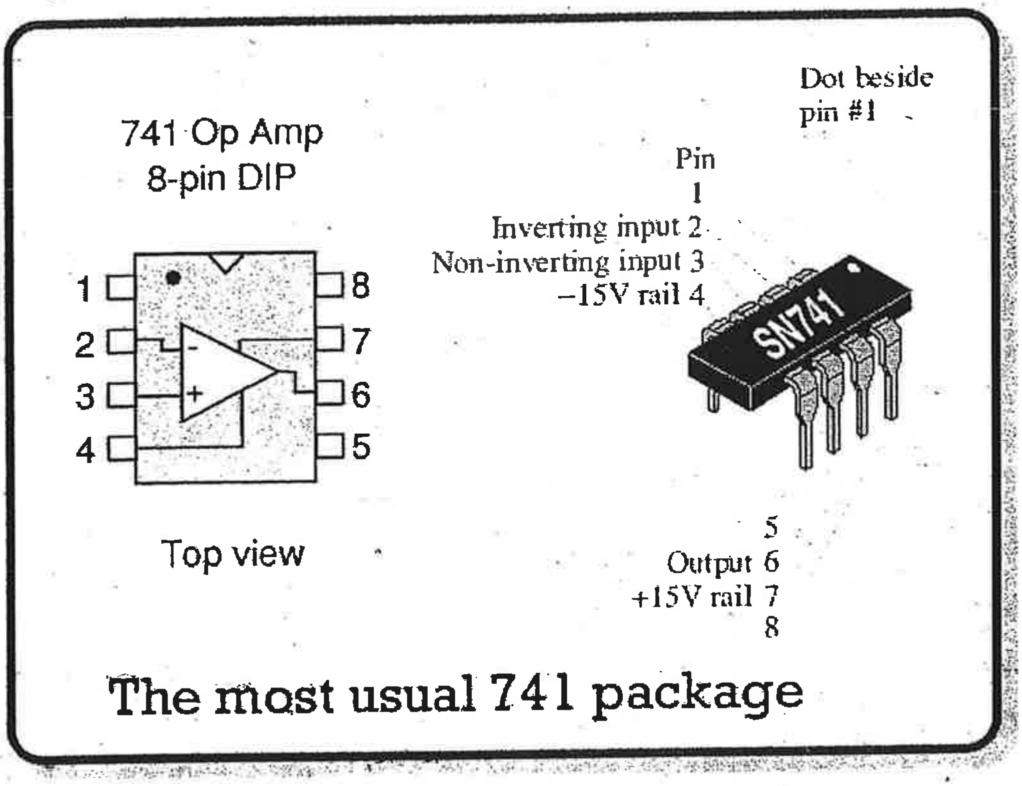
In this section, discuss the various aspects of Experiment # 8 and state some conclusions. In your write-up, you should at least address the following questions:

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.

Appendix A—Experiment # 6—The Op Amp & IC Amplifier

Although transistor amplifiers made with 'discrete' components (i.e. individually packaged) are still used for some special purposes like high-quality 'Hi-Fi', most modern signal processing systems use Integrated Circuits (ICs). The one of the oldest, most commonly used – and cheapest! – IC *Operational Amplifiers* is the SN741. This experiment uses a 741 as a simple audio-frequency amplifier.

741 Op Amps come in a variety of packages. One of the most common is an 8-pin Dual-In-Line (DIL) or Dual In-line Plastic (DIP) package of the kind shown below



The most usual 741 package

The 741 has *two* signal inputs – called 'inverting' and 'non-inverting'. It also must be powered using two voltage lines that provide ±15V.

For this experiment, build the circuit shown in figure 7. As with earlier circuits, make your circuit look similar to the one in the photographs. Click on the picture of a camera if you want to see the photos.

Remember to label your circuit and hand it in with your results. You should be able to work out which pin to connect to what by comparing this diagram with those for the 741's package and the wires shown in the photos. If not sure, ask a demonstrator.

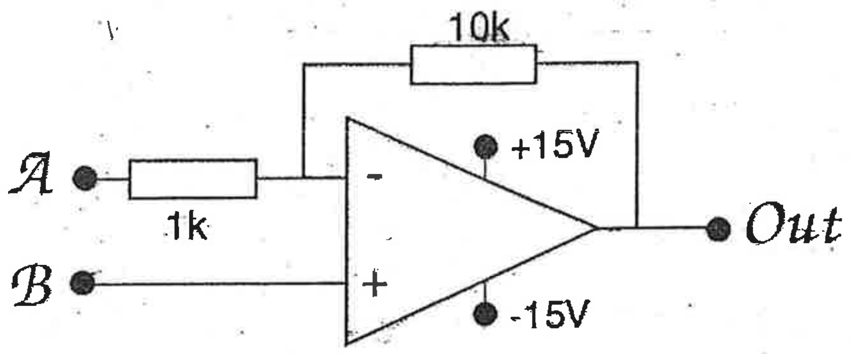
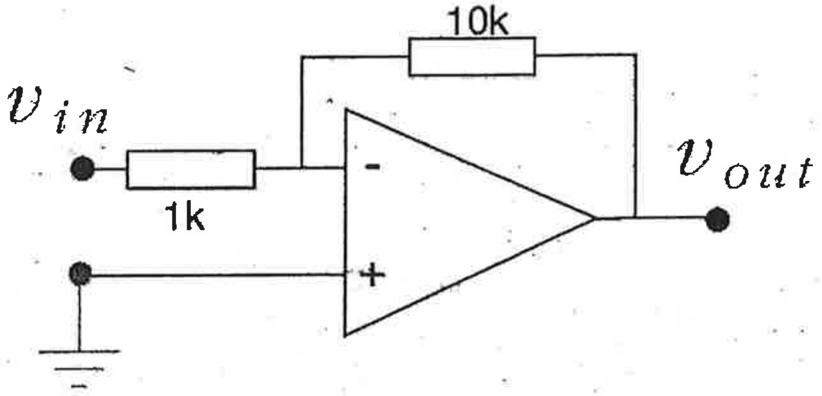


Diagram 7 Basic '×10' Op Amp

The circuit shown in diagram 7 can be used as either an 'inverting' or a 'non-inverting' voltage amplifier depending on how you apply an input signal. This is because the Op Amp has the property that its output depends on the *difference* in the voltages applied to the *pair* of pins, 2 & 3. First, use it as an inverting amplifier by connecting it as shown below.



'Inverting' Op Amp

The earth symbol shows where we connect 0V (earth) from the power supply. We also connect the earth leads (outer wires of the co-axial cables) to this point. The live input lead is connected to the inverting input resistor (shown as 'A' in figure 7).

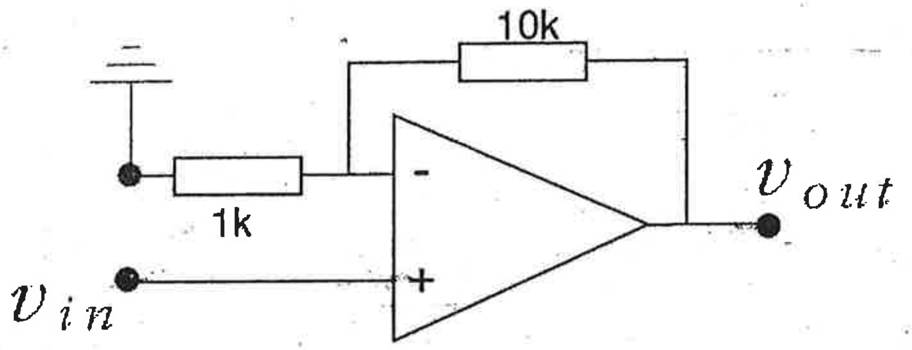
? Measure the voltage gain, v_{out} / v_{in}, of the inverting Op Amp, using sinewaves at 10Hz, 1kHz, 10kHz, and 100kHz. What value does this gain have at most frequencies?

Remember to check and see if the output is inverted, if so the gain value should be *negative*. Also, as usual when making gain measurements, make sure the output isn't distorted – clipped or bent in any way. If it seems distorted, reduce the amplitude of the signal until the output looks like a sinewave.

? You should find that the gain is fairly uniform at low frequencies, but tends to fall away at high frequencies. At what frequency does the gain fall to 70% of its low-frequency value?

? What is the peak to peak voltage of the largest output the amplifier can produce at low frequency (e.g. 300 Hz)? Say why you think the output is limited to the value.

Now change the connections to your Op-Amp so that the 'live' input and the earth connections have been swapped over. Your circuit should now be a non-inverting amplifier as shown below. Repeat the same gain measurements as before and note your results.



'Non-inverting' Op Amp

! You should find that both the sign and the value of the gain of the two types of amplifier differ. Say why you think this is the case. (If unsure, ask a demonstrator.)

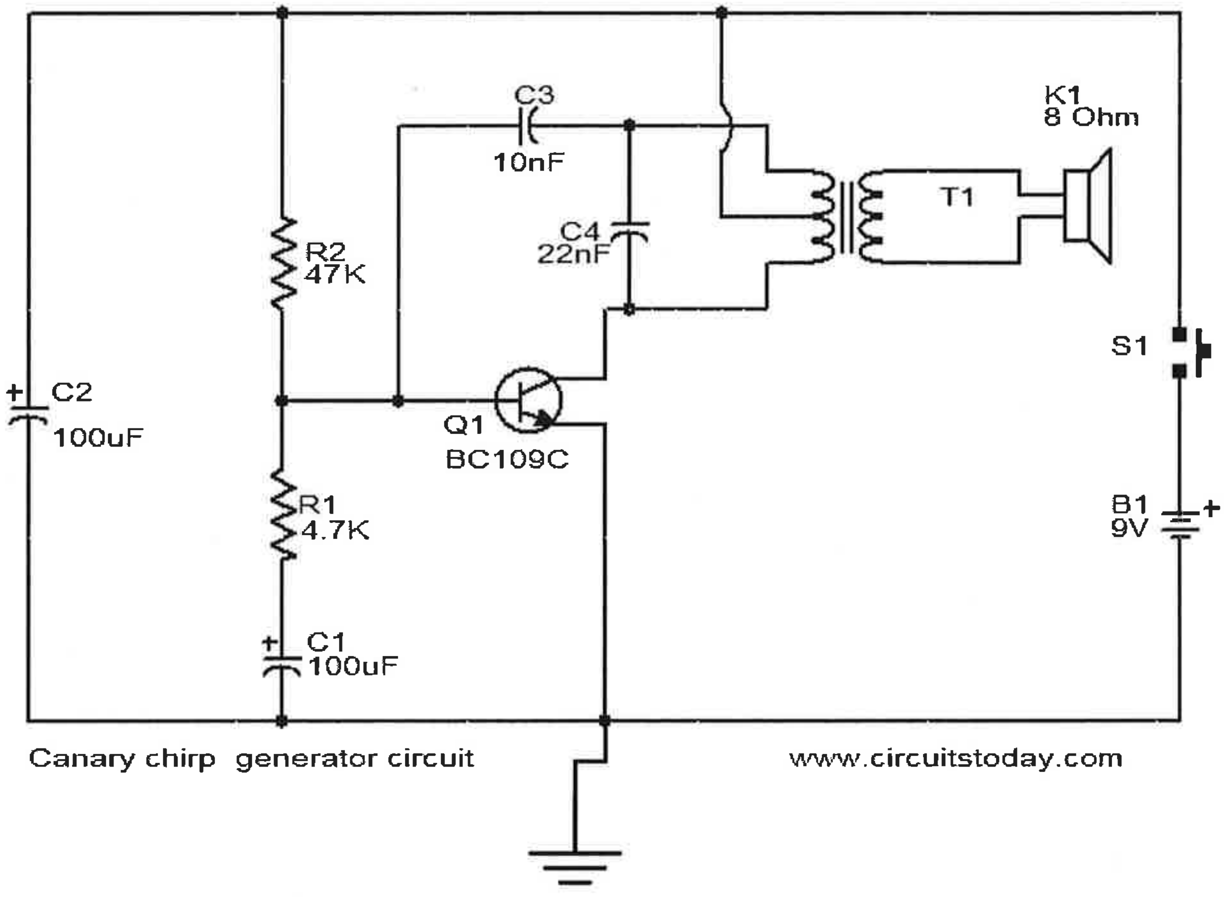
Say what change you would make to the circuit you have built if you wanted to increase the voltage gain of the inverting amplifier to −22.

Lab

Content and pages maintained by: Jim Lesurf (jcgl@st-and.ac.uk)
using TechWriter and HTMLEdit on a RISCOS machine.
University of St. Andrews, St Andrews, Fife KY16 9SS, Scotland.

Appendix B—Fun Project # 1
Canary Chirping Generator Circuit

Description. This is a simple electronic alarm circuit that imitates the chirping of a canary. The circuit is nothing but a Hartley oscillator with few more passive components added. As the capacitor C1 charges through the resistor R1 and the transistor Q1 is driven to cut off. This makes the oscillations to stop. As the capacitor discharges through the Resistor R1 and base emitter junction of the transistor the oscillation start again. Actually the R1 and C1 are the components that make the characteristic chirping sound.

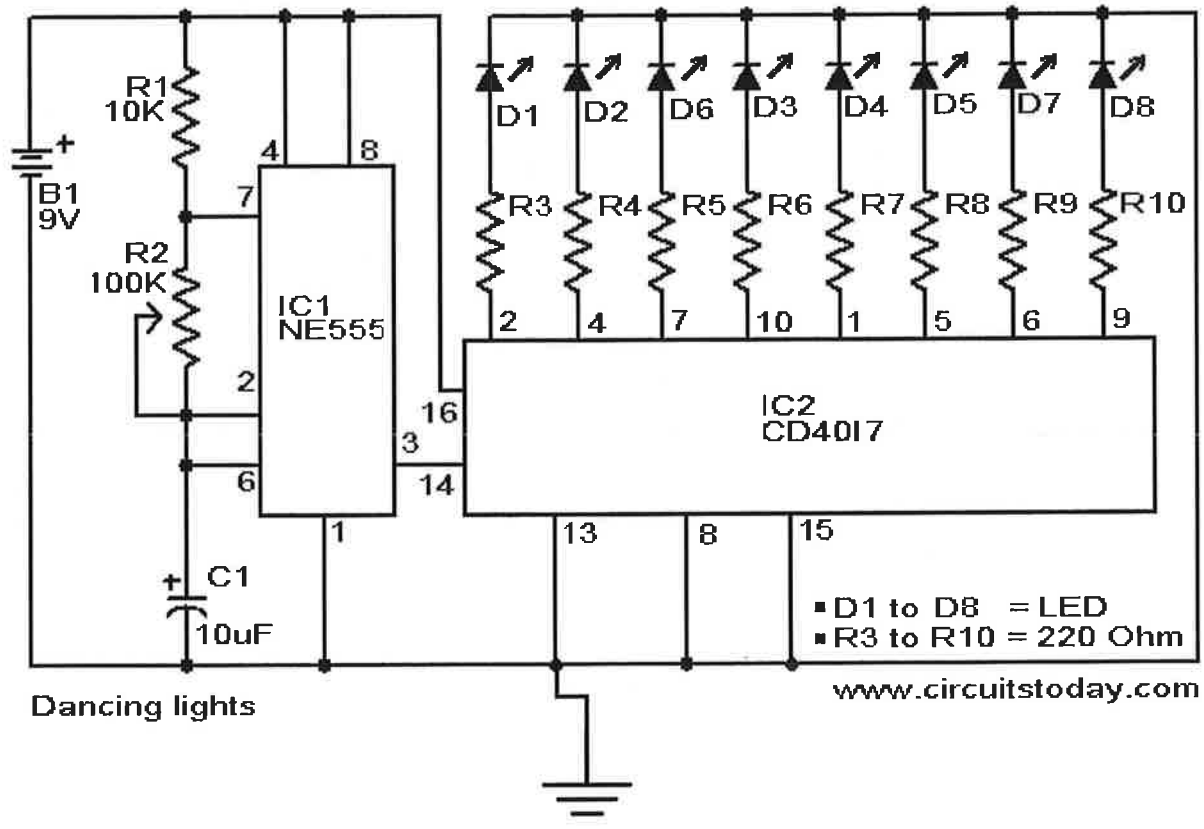


Notes.

- Assemble the circuit on a general purpose PCB.
- The circuit can be powered from a 9V PP3 battery.
- The transformer T1 can be an audio output transformer like LT700.
- If LT700 is not available, try the audio output transformer used on you old transistor radio board.
- The speaker can be an 8 ohm tweeter.
- Switch S1 can be a push button switch.
- The chirping sound can be altered by changing the value of R1 and C1.

Appendix C—Fun Project # 2—Dancing Lights

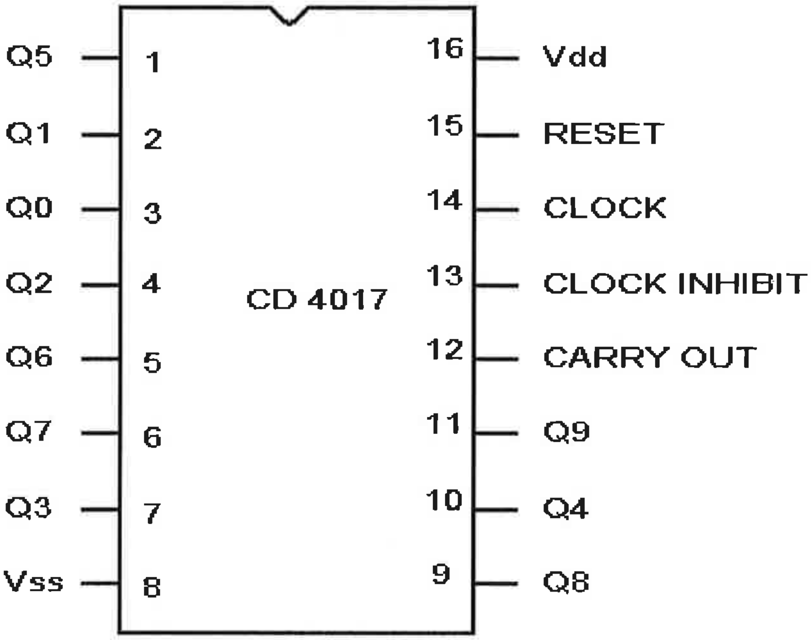
Description. Here is a simple dancing light circuit based on NE555 (IC1) & CD4017 (IC2) . The IC1 is wired as an astable multivibrator to provide the clock pulses for the CD4017. For each clock pulse receiving at the clock input (pin14) of IC CD4017, the outputs Q0 to Q9 (refer pin diagram of CD 4017) becomes high one by one alternatively. The LEDs connected to these pins glow in the same fashion to give a dancing effect. The speed of the dancing LEDs depends on the frequency of the clock pulses generated by the IC1.



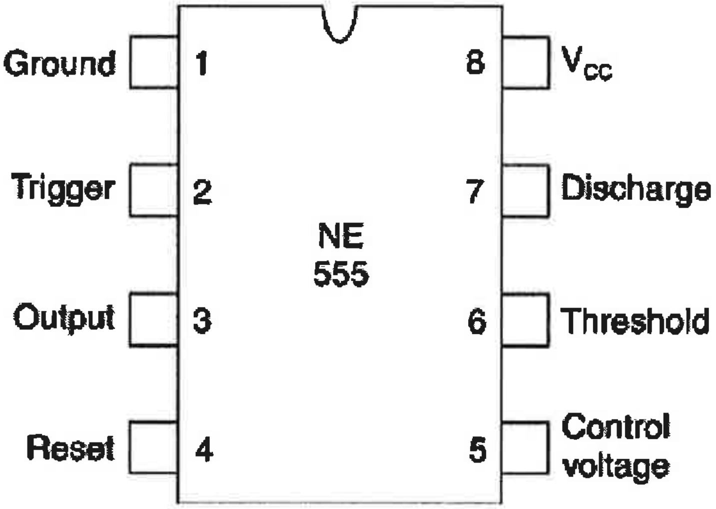
Dancing lights

Notes.

- Assemble the circuit on a good quality PCB or common board.
- The ICs must be mounted on holders.
- The speed of the dancing LEDs can be adjusted by varying POT R2.
- The capacitor C1 must be rated 15V.
- Using different color LEDs could produce a better visual effect.



CD 4017 Pin configuration



NE 555 Pin configuration

Appendix D—Fun Project # 3—Heart Rate Sensor

Use the following pages attached for this fun project

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

Prelab for Laboratory Project 5: Operational amplifier

1. Read the laboratory syllabus *BEFORE* coming to laboratory and answer questions that follow.

2. How many connections do you need for each operational amplifier—*op-amp*? What is the purpose of each of these connections?

3. What power supply is needed in order to power the present amplifier?

Note: This laboratory considers a realistic amplifier circuit. The accuracy of the circuit assembly is the key to the project completion.

Introduction

In this laboratory project you will familiarize with two basic operational amplifier (*op-amp*) circuits. The laboratory involves the construction and testing of two op-amp circuit configurations:

i. non-inverting operational amplifier;
ii. a high-gain amplifier stage including the non-inverting amplifier and the comparator amplifier.

The second circuit is rather complex. It will require the careful block-by-block building procedure.

Furthermore, you will continue working with the digital oscilloscope in this laboratory.

Setting up The Dual-Polarity Power Supply

The dual-polarity power supply – also discussed in class – is shown in Fig. I1. The reason for connecting two single-polarity power supplies (batteries) into the dual-polarity power supply is a desire to have COMMON (or NEUTRAL for AC circuits) port.

The COMMON port is a virtual ground for the circuit. Furthermore, the common port allows us to obtain simultaneously positive and negative voltages in the different parts of the circuit. The last circumstance is important for many electronic devices. Therefore, starting from this point, we will use the dual-polarity power supply.

The laboratory power supply unit (GPS 3303 or similar) has two adjustable single-polarity power supplies: CH1 and CH2. The two power supplies can be converted into one dual-polarity power supply with a +9V terminal, a -9V terminal, and a COMMON terminal, that you will set up.

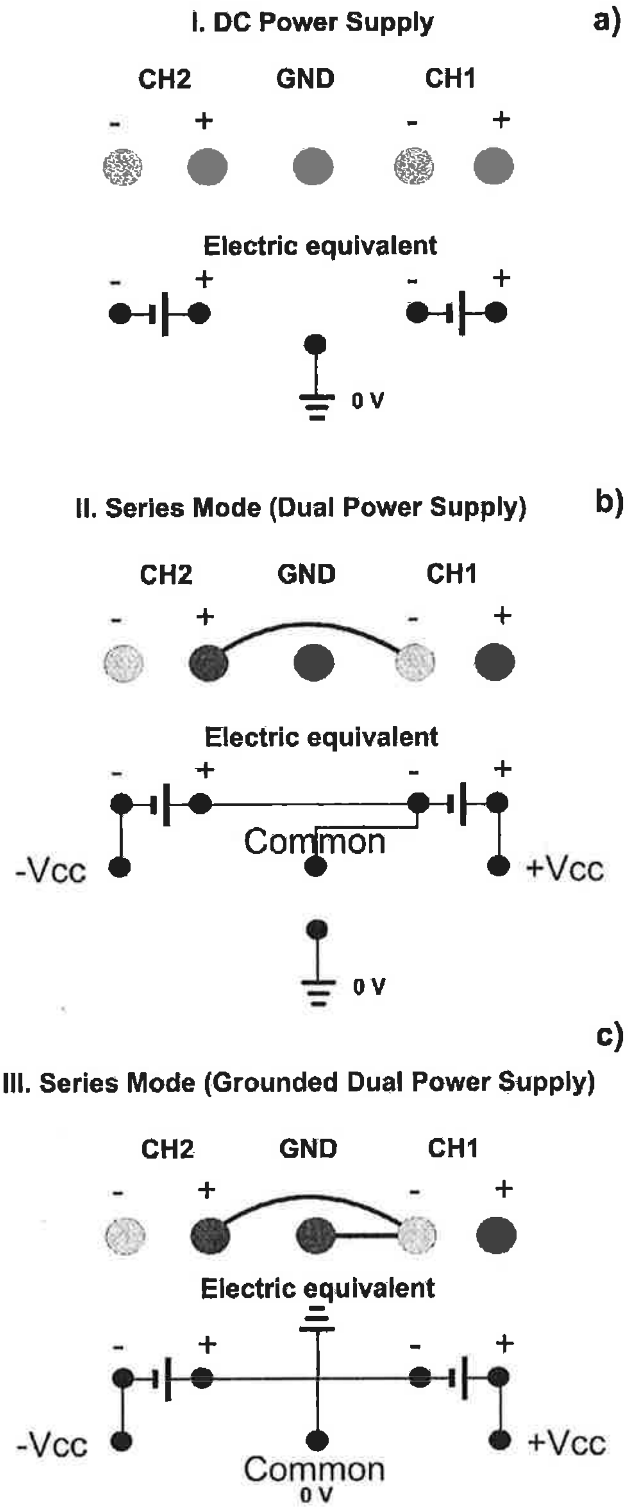


Fig.I1. Setting up the dual-polarity power supply.

To do this:
1. Make sure the output of the power supply is off (button on the left is off).

   i. Make sure both CURRENT knobs (CH1 and CH2) are adjusted to maximum current of 0.25A.

   ii. Adjust the VOLTAGE knobs (CH1 and CH2) until you obtain a reading of 9 V each. Turn off the power supply until it is needed. Then, you have two choices:

      a. Physically connect the "plus" of power supply CH2 to the "minus" of power supply CH1 using a <u>jumper wire</u> as shown in Fig. I1b. Make sure that the TRACKING indicator in the middle of the power supply unit is set up as "independent".

      b. Do not use any jumper wires but set up the TRACKING indicator in the middle of the power supply in "<u>series</u>" mode. This operation will introduce a jumper wire internally, without the need of an external connection.

   The second method should clearly be preferred. The first method should only be used if automatic series tracking is not available, i.e. for custom battery power supplies.

2. Connect the power supply to the red and blue power buses of the protoboard using red and black cables:

   - The red cable is connected between the + of power supply CH1 (+9V) and the a red power bus of the board.

   - The black cable is connected to the - of power supply CH2 (-9V) and the blue power bus on the board's opposite side.

   -Yet another red or black cable is connected to the COMMON port (ether – of CH1 or + of CH2) and corresponds to 0V. It is connected to one of two the remaining buses of the board. Both remaining buses are to be interconnected by a jumper wire. They will correspond to the COMMON port.

Thus, there should be three active protoboard buses: +9V, -9V, and COMMON. Note that GROUND and COMMON typically have different symbols. The

COMMON port could (and should in many cases) be grounded as shown in Fig. I1c.
Record the connection schematic in your notes.

Part I Amplifier Circuit and Measurements

1. Amplifier IC

In this laboratory exercise, you will employ the *integrated circuit* – IC – that is implemented in the dual in-line package – DIP. The dual operational amplifier LM1458N that you are using is one of these integrated circuits.

The dual operational amplifier LM1458 was originally manufactured by National Semiconductors Corporation. Then it has been sold to another group of companies (STMicroelectronics), which is indicated by change in abbreviation.

Yet another large manufacturer of general-purpose integrated circuits is Analog Devices, Inc. with headquarters in Norwood, MA. Each of the semiconductor companies has its own abbreviation, e.g. **LM** for an amplifier manufactured by National Semiconductor or **AD** for an amplifier manufactured by Analog Devices, or **MC** for STMicroelectronics. The part number is given by the numerical code that is imprinted on the top of the package.

After this short introduction, we need to do something real. Let's start with positioning a DIP (dual-in-line package) IC into the protoboard. Remove the dual op-amp LM1458N from your laboratory kit, and insert it into the protoboard somewhere near the center of the board, bridging the groove that runs along the entire length of the board. Make sure that the little legs of the DIP are lined-up with the protoboard holes and then apply pressure to push it into place. Any loose pin connection may result in malfunctioning the entire chip.

2. Power connection

Now, use short jumper wires to connect pin 4 of the IC to the -9 V supply bus and pin 8 of the IC to the +9 V supply bus – see Fig. 1. Your IC is ready to function! Power is now supplied to the two op-amps in the DIP (or it will supplied later when the power supply will be turned on) that are ready to behave like the op-amps we have started to study in class. Remember, though, that the output voltage that an op-amp can provide is **limited** by the supply voltages applied (the so called "rails") and that the maximum output current that the op-amp can source is also **limited** to its so called "short-circuit current" capability.

Fig. 1 shows the connection diagram for the LM1458N dual op-amp IC. Note the U-shaped curve on the center of the left side of this diagram. The U-shaped curve is used to denote the small notch—or dimple—on one end of the DIP. This notch is your key to the pin numbers of the IC. If you hold the diagram next to your protoboard so that the U is on the same end as the notch of the DIP, the pins shown in the diagram are the corresponding pins of the IC.

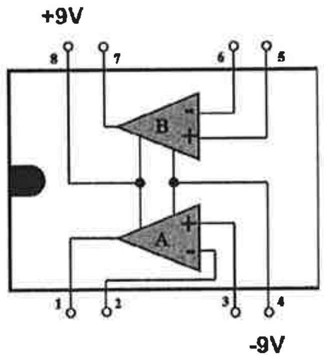


Fig. 1. Top view of the dual op-amp IC package containing two individual amplifiers. Note power connections (pins 4 and 8).

In the schematic diagrams that follows, the pin numbers of connections you should use will be marked next to the op-amp symbols in the circuit. If you follow the pin numbers suggested in the diagram, you will find that the TA will be more readily able to assist you with any troubleshooting problems.

Note that Fig. 1 is given mostly for our convenience. As a matter of fact one should be able to read the pin layout diagram from the original company's datasheet. The first page of the LM1458N datasheet is attached to the handout – see Appendix A. Alternatively, try to go to Google search and type "LM1458", or "LM1458 datasheet", or etc. You will find the datasheet immediately.

3. Non-inverting amplifier

3.1 Circuit

The circuit for testing the non-inverting amplifier configuration is shown in Fig. 2. It includes two separate parts:

- BLOCK I is the voltage divider with two resistors and a potentiometer. The output of the voltage divider (variable voltage) is pin 2 of the potentiometer.
- BLOCK II is the non-inverting amplifier with a negative feedback loop.

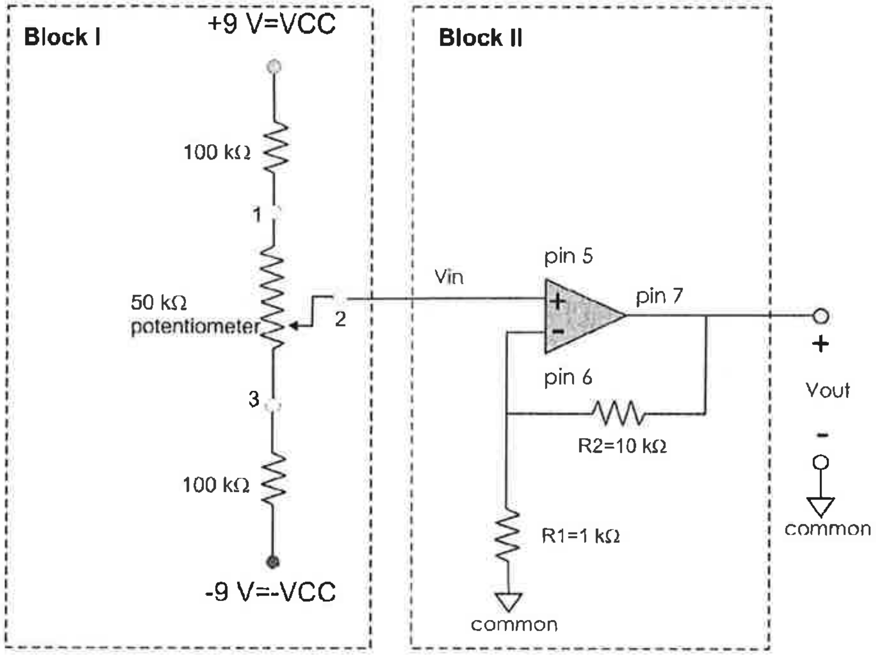


Fig. 2. Experimental non-inverting op-amp circuit.

3.2 Voltage divider (BLOCK I)

With regard to power connections, connect the positive terminal of the dual voltage supply to the red bus on the board, connect the negative terminal to the blue bus of the board on its *opposite* side, and finally tighten the remaining two buses with a jumper wire as one common ground.

Build the voltage divider from Fig. 2 on the protoboard, leaving room around the op-amp. Turn the power on. This circuit must be familiar to us.

Using the DMM, measure voltage variation at pin 2 of the potentiometer with respect to COMMON.

1. Record the minimum and maximum voltage values.
2. Do these values agree with the corresponding theoretical estimate for the present voltage divider?
3. What are possible sources of the error?

Now turn the power supply off but still keep the DMM connected at pin 2 of the potentiometer.

3.3 Non-inverting amplifier (BLOCK II)

Build the amplifier feedback loop as shown in Fig. 2 on the right. The feedback loop includes two fixed resistors – R_1= 1 kΩ and R_2= 10 kΩ. The gain A of this type of amplifier is determined by the characteristic equation derived in class:

$$A = \frac{v_{\mathrm{out}}}{v_{\mathrm{in}}} = 1 + \frac{R_2}{R_1} = 1 + \frac{10000}{1000} = 11 \tag{1}$$

Eq. (1) means that the gain is approximately 11, i.e. the output voltage, v_{out}, is 11 times the input voltage v_{in}. The exact value of 11 (or 20, 50, 1,0000) cannot be achieved since the resistors you are using have the 5%-tolerance.

The variable voltage at pin 2 of the potentiometer will be the input voltage to the amplifier, v_{in}. Now connect pin 2 of the potentiometer to the amplifier's input pin 5.

In a real world, the voltage v_{in} often corresponds to the sensor voltage. The sensor may be rather different: a capacitive accelerometer, an induction sensor, a thermocouple, etc. The sensor voltage is typically small.

Turn the power supply on. Adjust the input voltage to the amplifier v_{in} to approximately 500 mV using the DMM. Accuracy of ± 5 mV is enough since the resolution of the carbon potentiometer is rather low.

3.4 Testing the amplifier. Oscilloscope

You will need to test the output voltage v_{out} of the amplifier (at pin 7) using the oscilloscope. The output voltage is always measured vs. COMMON port. The input voltage is still measured using the DMM.

With the power supply on connect CH1 of the oscilloscope to the amplifier output (pin 7, v_{out}). Connect the alligator clip of the probe to COMMON of the circuit.

TDS2004B Four-Channel Oscilloscope

Turn the whole unit on and, after that, push AUTOSET button. CH1 menu should appear. If this is not the case, push the yellow button CH1 menu.
Setup (CH1, default):

Coupling	DC
BW limit	OFF
Volts/Div	Coarse
Probe	10x
Invert	Off

- CH1 voltage resolution 2.00V/division (rotate the resolution dial of CH1)

- CH1 time resolution 5.00ms/division (rotate the resolution dial SEC/DIV on the right if necessary)

Now, you should be able to see the DC voltage on the screen. You should see a signal line on the screen at approximately 5.3 - 5.7 V. To be able to accurately measure its value, push MEASURE button on top of oscilloscope menu and use MEAN measure option in order to measure the mean voltage. This measurement should give you at least three significant voltage digits.

Note that the oscilloscope voltage measurements are significantly MORE accurate than the rough voltage indicated, for example, by the INSTEK power supply. If you cannot obtain the proper oscilloscope reading ask TA for help.

3.5 Amplifier gain measurements

Adjust the potentiometer and use the DMM voltmeter in order to obtain input voltages, v_{in}, from the first row of Table 1 that follows. Accuracy of ± 10 mV in measured values of v_{in} vs. suggested values of v_{in} is sufficient since the resolution of the carbon potentiometer is rather low.

1. Measure the output voltage of the amplifier for each obtained value of the input voltage and fill in second and third rows of Table 1. You might want to change the oscilloscope resolution (VOLTS/DIV) to obtain better accuracy.

2. Plot the output voltage of the amplifier (the *y*-axis) as a function of the input voltage (the *x*-axis) to scale in the lab notebook. Simultaneously, plot the function $v_{\mathrm{out}} = 11 v_{\mathrm{in}}$.

3. Are two lines close to each other?
4. How can you explain the disagreement at large absolute values of the input voltage?

Table 1. Input/output voltages.

v_{in} (suggested)	50 mV	100 mV	200 mV	400 mV	600 mV	800 mV	950 mV
v_{in} (measured)							
v_{out} (measured)							

v_{in} (suggested)	-50 mV	-100 mV	-200 mV	-400 mV	-600 mV	-800 mV	-950 mV
v_{in} (measured)							
v_{out} (measured)							

Turn the power supply off but do not disassemble the circuit.

5. Estimate the gain tolerance (±X%) of the non-inverting amplifier in Fig. 3 assuming that the tolerance is determined by the errors in the resistor values. You have 5%-tolerance resistors.
6. Are the measured values in Table 1 (for the absolute values of the input voltage less than or equal to 600 mV) are within the estimated tolerance limit?

Take a short break. The journey is about to begin.

Part II High-Gain Amplifier Stage

In this part of the laboratory you will built a more practical and more realistic amplifier circuit. This is a simple yet accurate hearth 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. 1KΩ instead of 1 MΩ);
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 hearth 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.

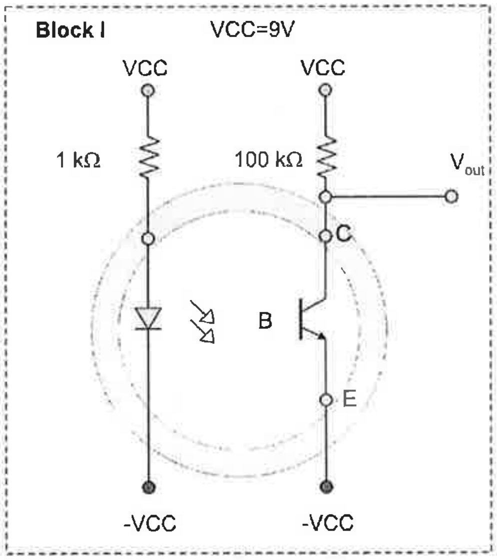


Fig. 3. Block I of the circuit - a sensor (top view). The blue LED is on the left.

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.

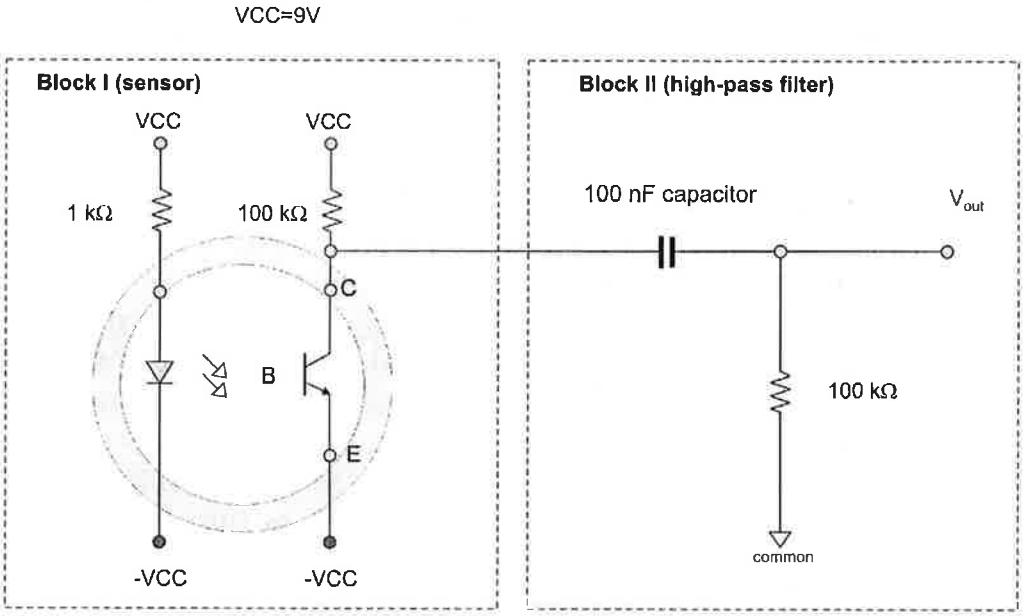


Fig. 4. Block II - a high-pass filter.

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 filer, 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.

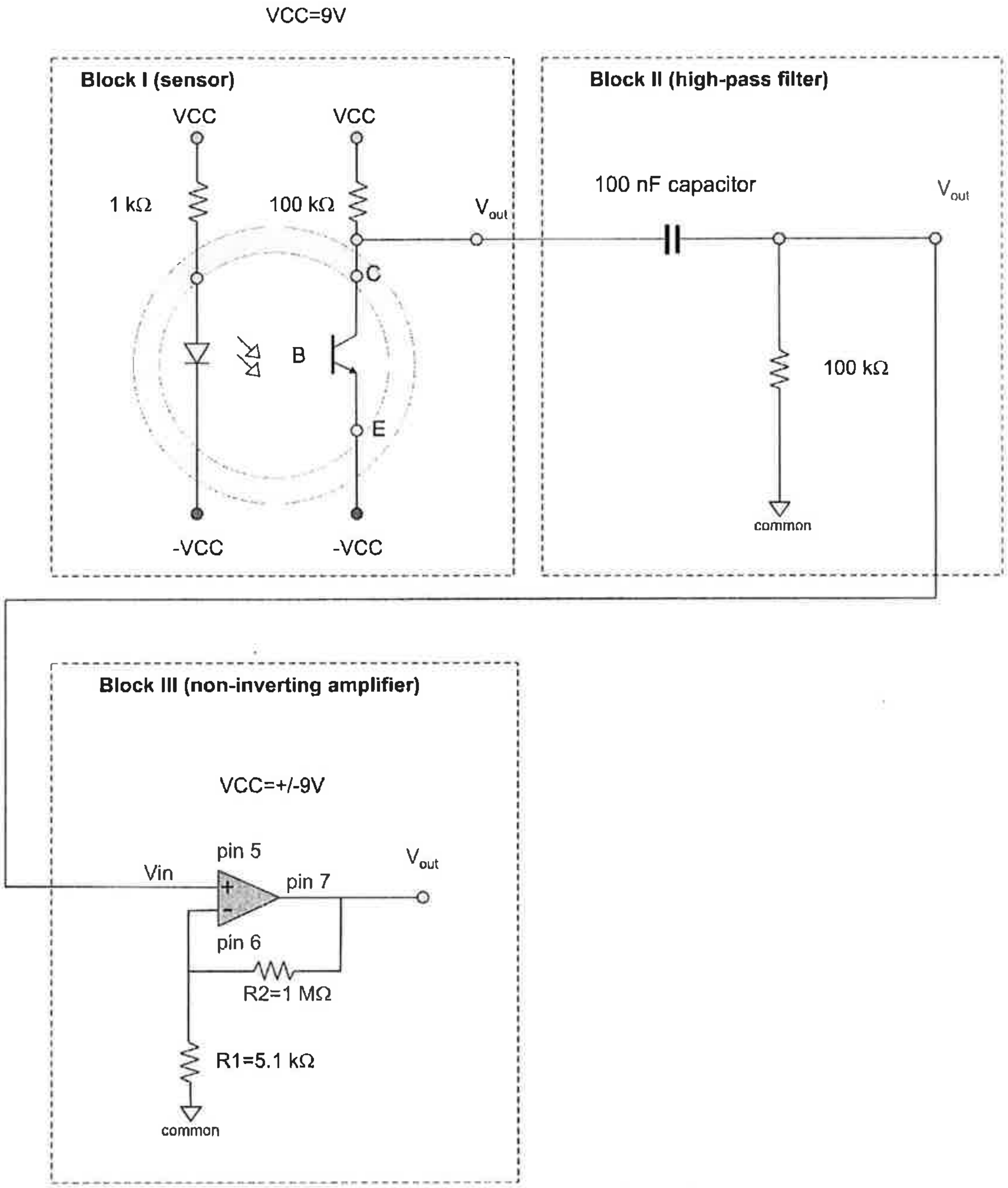


Fig. 5. Block III - a high-gain non-inverting amplifier stage.

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.

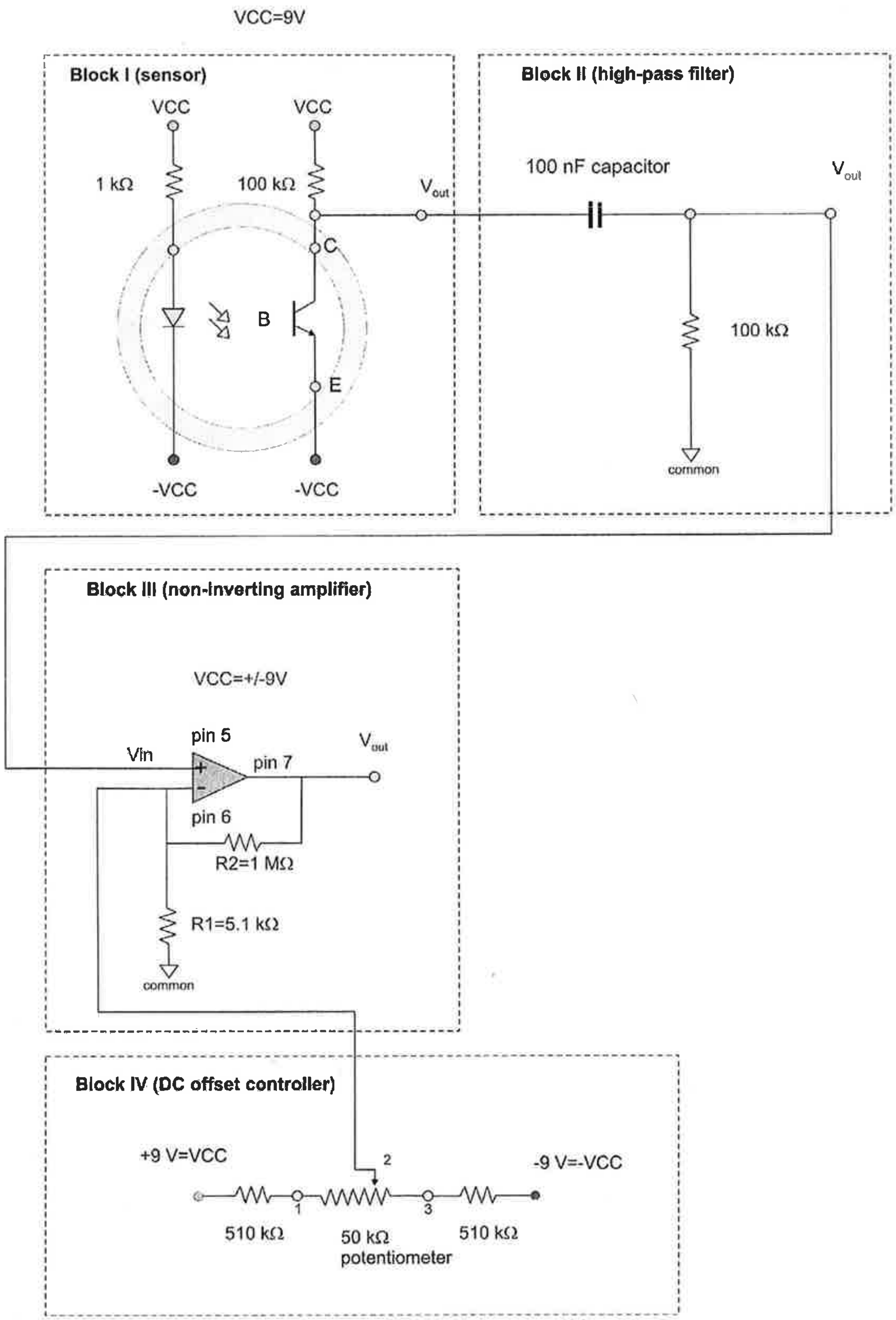


Fig. 6. Block IV - Controlling the DC offset of the amplifier.

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.

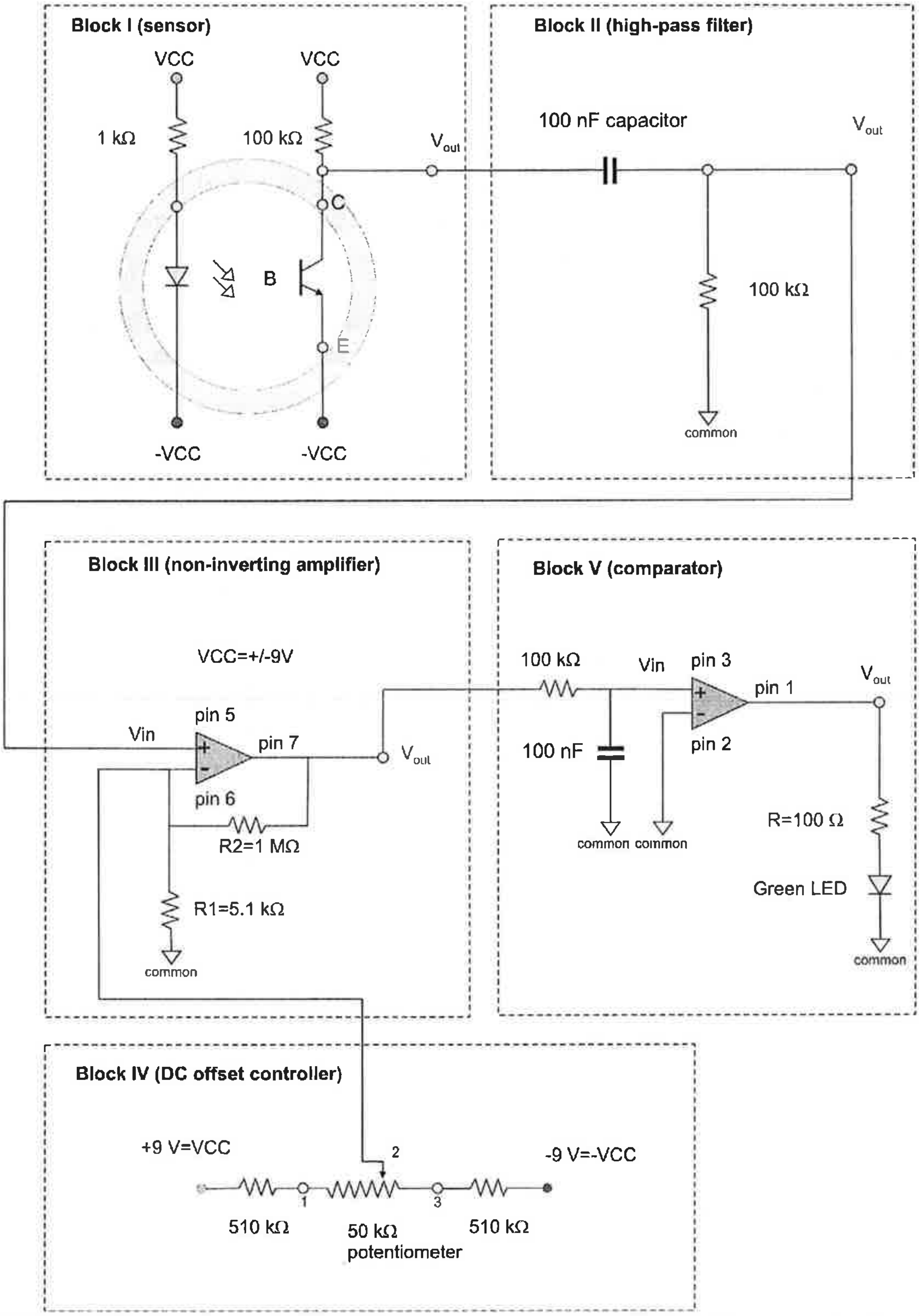


Fig. 7 Block V - the second amplifier stage - the comparator. The sensor circuit is complete.

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 ±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.

Laboratory parts list:
One 100 Ω resistor
One 1 kΩ resistor
One 5.1 kΩ resistor
One 10 kΩ resistor
Three 100 kΩ resistors
Two 510 kΩ resistors
One 1 MΩ resistor
50 kΩ potentiometer
LM1458 IC
Two 100 nF capacitors
Green LED
IR sensor

Grading criteria - present laboratory

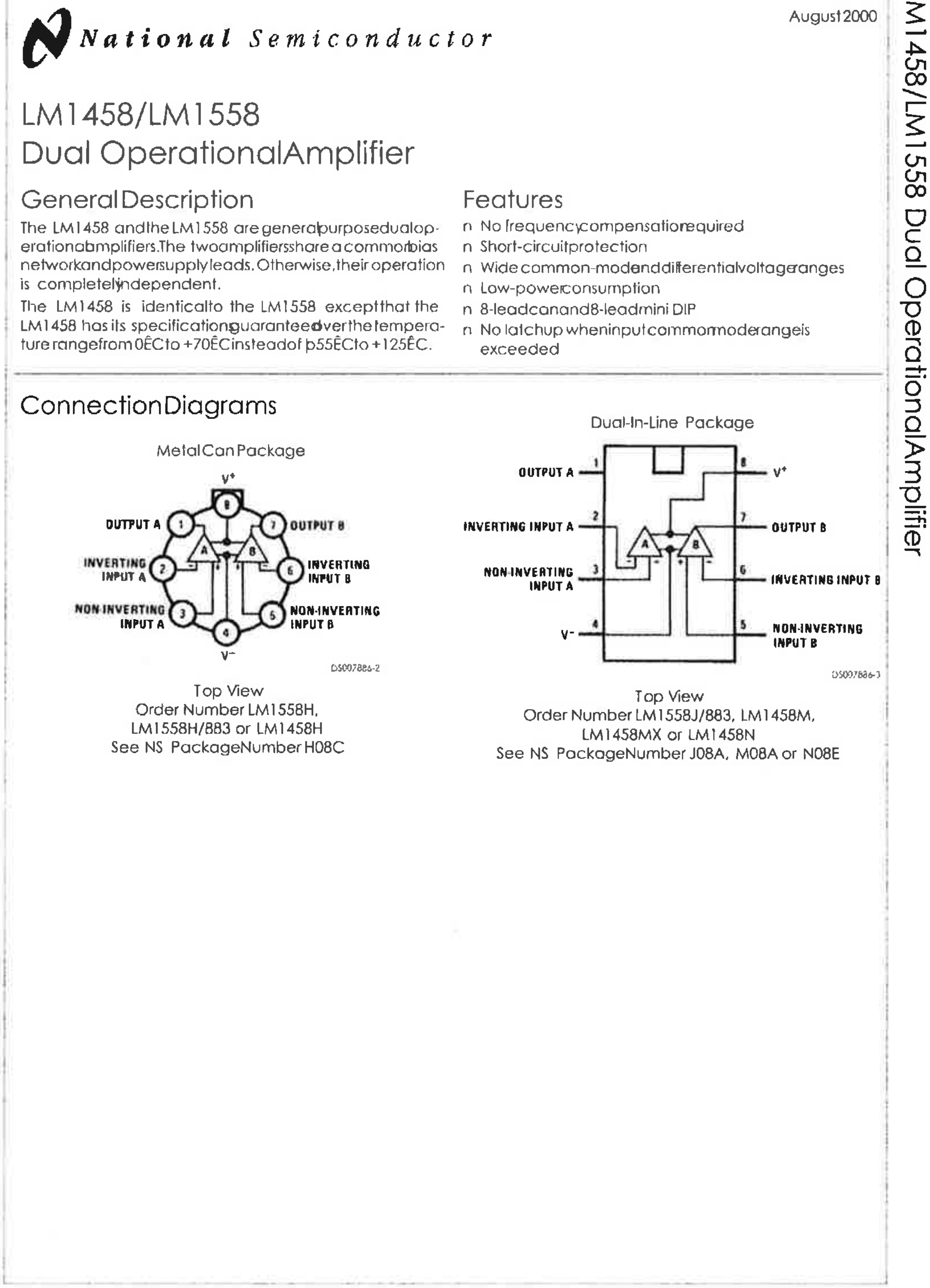
Grading is out of 100 points.

- Format (5 points)
  - Date
  - Time
  - Name & Partner's name (or N/A)
  - Bench number
  - Section headings
  - Organization
- All schematic(s) (25 points)
- Data & Results

Part I:	Measurements/tables/plots/questions	(25 points)
Part II:	Measurements/working circuit	(25 points)
Part III	Question 1	(2.5 points)
	Question 2	(2.5 points)
	Question 3	(2.5 points)
	Question 4	(2.5 points)
	Question 5	(6.0 points)
	Question 6	(2.0 points)
	Question 7	(1.0 point)
	Question 8	(1.0 point)

In general – If we can't read it, you don't get credit for it. Please be **NEAT**!

Appendix A
LM1458 Datasheet (first page only)



National Semiconductor

August 2000

LM1458/LM1558 Dual Operational Amplifier

LM1458/LM1558
Dual Operational Amplifier

General Description

The LM1458 and the LM1558 are general purpose dual operational amplifiers. The two amplifiers share a common bias network and power supply leads. Otherwise, their operation is completely independent.

The LM1458 is identical to the LM1558 except that the LM1458 has its specifications guaranteed over the temperature range from 0ÊC to +70ÊC instead of þ55ÊC to +125ÊC.

Features

- No frequency compensation required
- Short-circuit protection
- Wide common-mode and differential voltage ranges
- Low-power consumption
- 8-lead can and 8-lead mini DIP
- No latch up when input common mode range is exceeded

Connection Diagrams

Metal Can Package

Top View
Order Number LM1558H, LM1558H/883 or LM1458H
See NS Package Number H08C

Dual-In-Line Package

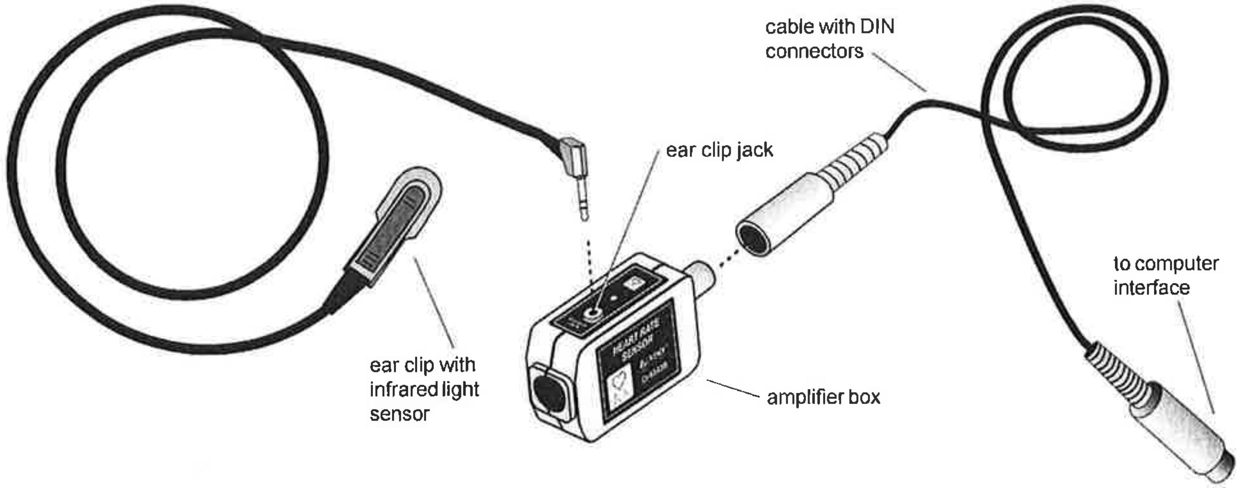
Top View
Order Number LM1558J/883, LM1458M, LM1458MX or LM1458N
See NS Package Number J08A, M08A or N08E

Appendix B
Heart Rate Sensor From Pasco Scientific

Instruction Sheet
for the PASCO
Model CI-6543B

012-06752A
04/98
$1.00

HEART RATE SENSOR



Introduction

The PASCO CI-6543B Heart Rate Sensor works with a PASCO *Science Workshop*® computer interface to monitor a person's heart rate. Unlike an electrocardiograph (EKG), which monitors the electrical signal of the heart, the Heart Rate Sensor monitors the flow of blood through a part of the body, such as an ear lobe, by shining a light through it and monitoring the change in intensity. As the heart beats and forces blood through the blood vessels in the ear lobe, the light transmittance through the ear lobe changes.

The sensor consists of a Heart Rate Sensor amplifier box, a cable with DIN connectors for connecting to a PASCO computer interface, and an ear clip. The ear clip can be attached to a part of the body such as an earlobe, a fingertip, toe, or the web of skin between the thumb and index finger. The sensor shines an infrared light through the earlobe and measures the change in light that is transmitted. The light source is a small infrared light–emitting diode.

EQUIPMENT INCLUDED

- Heart Rate Sensor Amplifier Box
- cable with ear clip
- 6-foot cable with DIN connectors

ADDITIONAL EQUIPMENT REQUIRED

- computer (PC or Macintosh)
- *Science Workshop*® computer interface
- *Science Workshop*® software version 2.2. or higher

Note: This instruction sheet was written assuming that the user has a basic familiarity with *Science Workshop* and has access to the *User's Guide for Science Workshop*. Users can gain basic skills by working through the tutorial within *Science Workshop*. Another useful resource is the *Quick Reference Card for Science Workshop*.

PASCO® scientific
10101 Foothills Blvd. • Roseville, CA 95747-7100
Phone (916) 786-3800 • FAX (916) 786-8905 • www.pasco.com
better
ways to
teach science

Operation

Setting up the Equipment

1. Connect the Heart Rate Sensor amplifier box to analog channel A, B, or C of the *Science Workshop* computer interface box using the cable with the DIN connectors (Figure 1). Alternatively, the amplifier box can be plugged directly into the analog channel jack.

2. Connect the ear clip to the ear clip jack on the Heart Rate Sensor amplifier box.

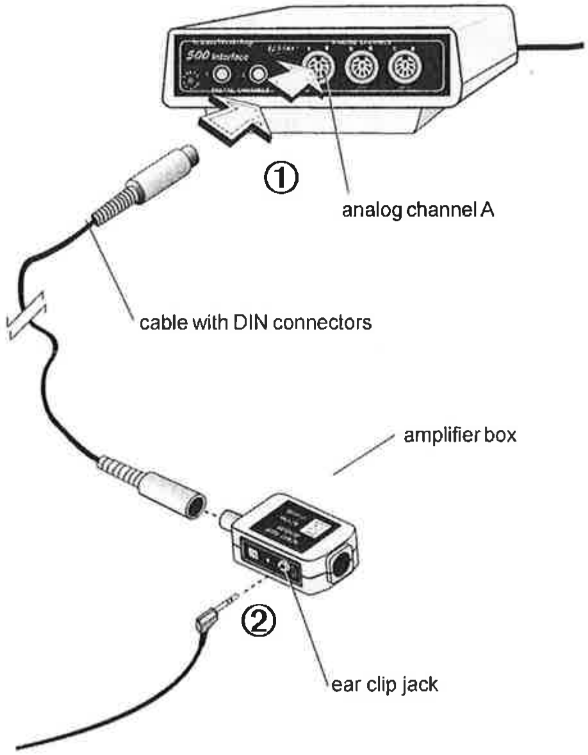


Figure 1
Connecting the amplifier box to the interface box and connecting the ear clip cable to the amplifier box

Setting up Science Workshop

1. Start *Science Workshop.*

2. In the Experiment Setup window, drag the icon for the analog plug to the icon for the channel you are using, and select Heart Rate Sensor from the pop-up menu. Click **OK**.

3. Click the **Sampling Options . . .** button, and adjust the sampling rate to 50 Hz by moving the slider under **Periodic Samples**. Click **OK**.*3.* Open a Graph display that plots Heart Rate (beats/minute) vs. Time, by dragging the icon for the Graph display to the Heart Rate Sensor icon, and selecting Heart Rate (b/m). Click **Display**.

4. Open a Digits display that displays Heart Rate (beats/minute) by dragging the icon for the Digits display to the Heart Rate Sensor icon, and selecting Heart Rate (b/m). Click **Display**.

5. Adjust the Digits display to show three digits to the left of the decimal and none to the right by double-clicking the Digits display and typing **3** in the **Digits Left** box and **0** in the **Digits Right** box. Click **OK**.

6. Clip the ear clip to your earlobe and adjust so it is firmly attached. Sit or stand quietly to avoid disturbing the ear clip (Figure 2).

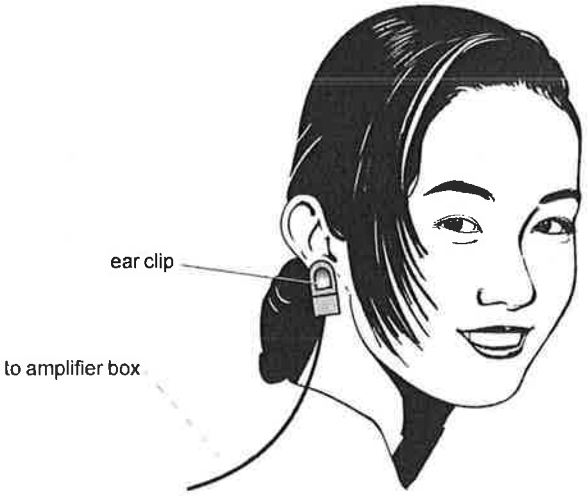


Figure 2
Correct placement of the ear clip

7. Begin monitoring your heart rate by clicking the **MON** button on the Experiment Setup window, choosing **Monitor** from the Experiment menu, or using the keyboard shortcut: ALT + M (Windows), ⌘ + M (Macintosh). Click the **STOP** button to stop monitoring.

8. If the Heart Rate Sensor appears to be working properly, you can begin recording data. However, if the pattern appears jumpy rather than smooth, reposition the ear clip until you see a smooth heart rate pattern as in Figure 3. If problems persist, consult the *Troubleshooting* section.

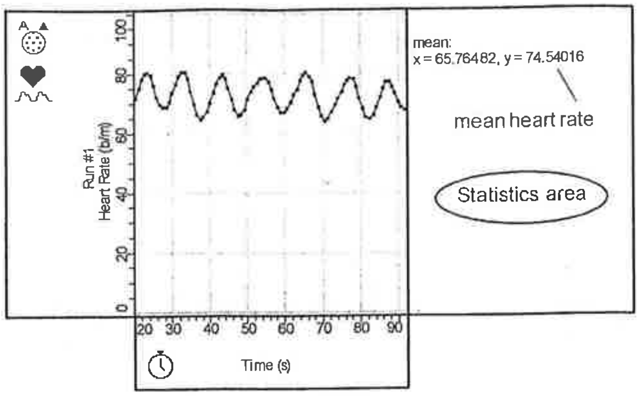


Figure 3
Typical plot of Heart Rate (b/m) vs. Time (as shown on the Graph display)

Recording and Analyzing Heart Rate Data

1. Begin recording your heart rate by clicking the **REC** button on the Experiment Setup window, choosing **Record** from the Experiment menu, or using the keyboard shortcut: ALT + R (Windows), ⌘ + R (Macintosh).
2. Record your heart rate for 60 seconds, and then stop recording by clicking the **STOP** button on the Experiment Setup window, choosing **Stop** from the Experiment menu, or using the keyboard shortcut: ALT + . (Windows), ⌘ + . (Macintosh).
3. Click the **Statistics** button on the Graph display to open the Statistics area of the Graph display.
4. Click the **Statistics Menu** button and select **Mean** from the statistics menu. (The value for the *y* axis is your average heart rate.)

Note: You may be surprised to note that your heart rate varies over time on the Heart Rate vs. Time Graph display. For example, although your average resting heart rate over a period of 10 seconds may be 70 b/m, your heart rate that is determined moment to moment by the Heart Rate Sensor may vary from 60 b/m to 80 b/m. The amount of variation in heart rate differs among people and under different circumstances.

To calculate your average heart rate that corresponds to the heart rate you would measure by counting your pulse over a period of 10 seconds, drag a box over a 10-second segment of recorded heart rate data on the Graph display and note the mean *y*-axis value in the statistics area.

For additional information about the natural variability of resting heart rate, see Saini, M. W., et. al., "Correlation of heart rate variability with clinical and angiographic variables and late mortality after coronary angiography," *American Journal of Cardiology* 62: 714–717 (1988).

Displaying Voltage Data

1. To display the voltage recorded or being monitored by the Heart Rate Sensor, click the **Plot Input Menu** button on the Graph Display, and select **Analog A ➤ Voltage,** or open a new Graph display and select **Voltage** in the **Choose calculations to display** menu. (This voltage corresponds to the variation in light intensity transmitted through the body that results from the pulsating flow of blood through the tissues.)
2. Change the *x*-axis scale to span a period of 3 or 4 seconds by clicking in the *x*-axis area and changing the values in the dialog boxes. (The plotted voltage will look similar to that in Figure 4.)

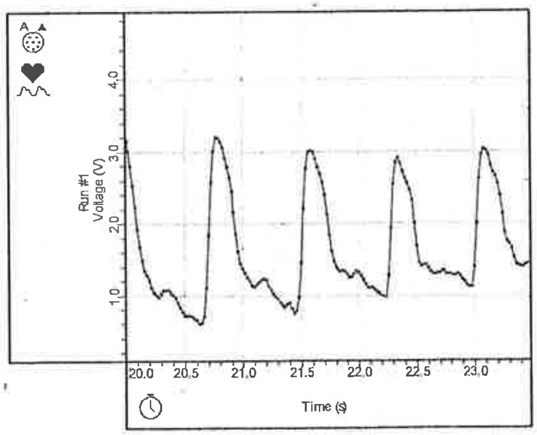


Figure 4
Typical plot of Voltage vs. Time (as shown on the Graph display)

Suggested Activities

1. Record your heart rate at rest and after vigorous exercise. Compare your mean heart rate under these two conditions.
2. Determine your recovery time by recording your heart rate after vigorous exercise until your heart rate returns to the resting rate, and then note the time required.
3. Assume a meditative state and record your heart rate. Next record your heart rate while you have a heated discussion with someone. (Try to keep your head still during data recording.) Compare the pattern of variability in your heart rate under these two circumstances. (Hint: change the scale of the *y*-axis of the Graph display to a minimum of 50 b/m and a maximum of 110 b/m by clicking in the y-axis area and changing the values in the dialog boxes.)
4. Use two Heart Rate Sensors, connected to analog channels A and B, with the clips fastened to two separate parts of the body (such as ear and finger), to compare the timing of the pulse of blood from the heart in various parts of the body. Set up a Graph display with plots of Voltage vs. Time for analog channels A and B by clicking the **Add-A-Plot** button on the Voltage vs. Time Graph display and selecting **Analog B ➤ Voltage.**

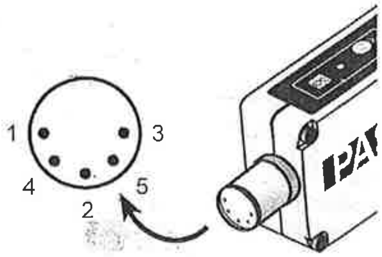
Troubleshooting

If the system is not functioning properly, try the following:

- Adjust the position of the clip. Try moving the clip to a different part of your ear lobe or perhaps try the tip of one of your fingers or the web of skin between your thumb and index finger.
- Hold still while using the Heart Rate Sensor. If you want to study how exercise affects your heart rate, move around and then stop briefly to get a pulse reading.
- Be patient when using the Heart Rate Sensor. When you move the ear clip, it takes a few seconds for the signal to adjust to the new conditions.
- Let the person being tested sit down, rather than stand up.
- If you are in a room with bright overhead lighting, block some of this light from the clip. Otherwise, it may pick up the flickering of the artificial light, which distorts the signal. Try holding your hand to block the light from the clip.

DIN Connector Specifications

1: analog output (+), 0 to 5 V
2: analog output (-), signal ground
3: (no connection)
4: + 5 V DC power
5: power ground



Limited Warranty

PASCO scientific warrants the product to be free from defects in materials and workmanship for a period of one year from the date of shipment to the customer. PASCO will repair or replace, at its option, any part of the product which is deemed to be defective in material or workmanship. The warranty does not cover damage to the product caused by abuse or improper use. Determination of whether a product failure is the result of a manufacturing defect or improper use by the customer shall be made solely by PASCO scientific. Responsibility for the return of equipment for warranty repair belongs to the customer. Equipment must be properly packed to prevent damage and shipped postage or freight prepaid. (Damage caused by improper packing of the equipment for return shipment will not be covered by the warranty.) Shipping costs for returning the equipment after repair will be paid by PASCO scientific.

Address: PASCO scientific
10101 Foothills Blvd.
Roseville, CA 95747-7100

Phone: (916) 786-3800
FAX: (916) 786-8905
email: techsupp@pasco.com
web: www.pasco.com