Worcester Polytechnic Institute
Department of Electrical and Computer Engineering

Heartbeat Monitor

An Introductory Lab to the Fascinating World of Electrical & Computer Engineering

1.0 PURPOSE

The purpose of this laboratory investigation is to build a heart pulse monitor capable of displaying a *photoplethysmogram* (*PPG*)[1] on an oscilloscope as well as blinking an LED in synchronization with a person's heart rate.

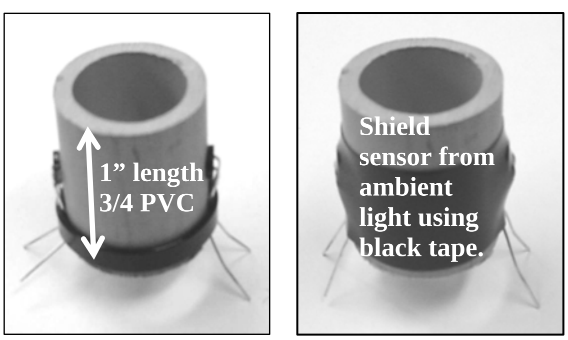
Upon completion of this lab you should be able to:

- Understand how to detect blood pressure changes using an infrared LED and phototransistor sensor.
- Amplify a small sensor signal using an operational amplifier circuit.
- Filter out unwanted electrical interference in a biological signal using low-pass and high-pass filters.
- Display a changing blood pressure signal (plethysmogram) on a standard oscilloscope.
- Use a comparator circuit to threshold detect a changing voltage and pulse an LED.

2.0 MATERIALS

- ECE Lab Kit (See Appendix for Schematic and Parts List)
- Dual DC Power Supply
- DMM
- Oscilloscope

Infrared Sensor Module (below)
- IR-LED (Digikey 751-1202-ND)
- Phototransistor (Digikey 160-1301-ND)



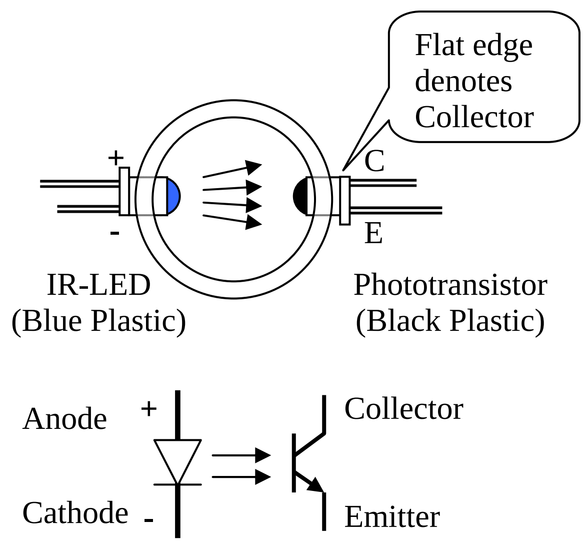


Figure 2-1: IR Sensor Module (infrared LED and matching phototransistor)

[1] A *photoplethysmogram* is a graph of blood pressure changes obtained by shining light on some part of the human body.

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3.0 BACKGROUND

A person's heartbeat can be detected by monitoring blood pressure changes within the human body. As the heart muscle contracts, blood pressure goes up and as it relaxes, blood pressure goes down. One clever method of monitoring blood pressure is to shine light through an appendage of the body and to measure the amount of light reaching a sensor. The amount of light striking the sensor is inversely proportional to the blood volume within the appendage. In this way, blood pressure changes can be converted to an electrical signal and displayed on an oscilloscope. Such a graph is known as a *photoplethysmogram or PPG.*

In addition, the best spectrum of light to use for this application is *infrared*, since human blood absorbs these wavelengths quite readily. Therefore, for this experiment an *infrared light emitting diode* (IR LED) with a wavelength of 940nm has been chosen along with a matching *phototransistor sensor*.

4.0 BLOCK DIAGRAM

Figure 4-1 shows the *Block Diagram* of the Heartbeat Monitor. The system consists of an infrared (IR) LED, a phototransistor sensor, both high and low-pass filters, as well as an amplifier, comparator and output LED. An oscilloscope is included to display the signal.

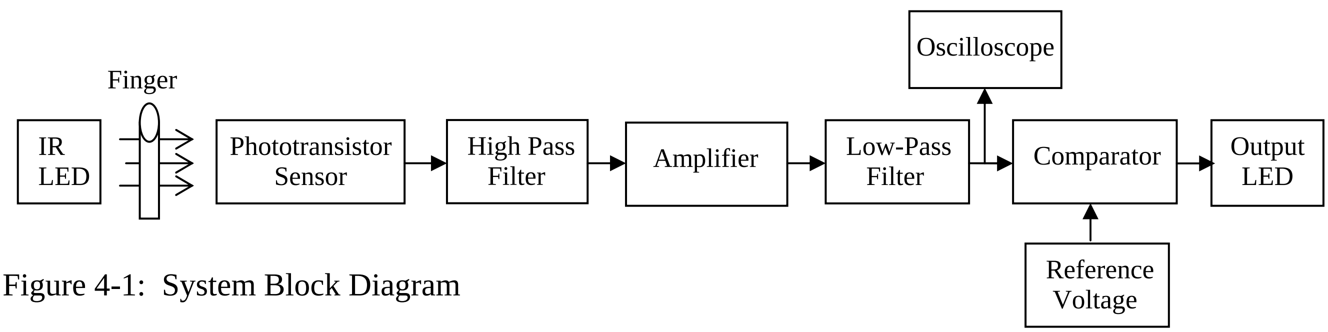

Figure 4-1: System Block Diagram

5.0 SYSTEM OPERATION

Initially, the IR-LED is used to illuminate a person's finger with infrared light. The light intensity is then modulated by blood pressure changes within the finger before striking the phototransistor. The sensor then converts the changing light intensity into a proportional voltage containing two components – a large DC offset corresponding to the average light intensity as well as a small varying signal caused by changing blood pressure.

The voltage signal is then passed through a high-pass filter to remove the DC component and then amplified. Low-pass filtering is then applied to remove any high frequency noise before displaying the signal on an oscilloscope. Finally, the signal is compared to a reference voltage using a voltage comparator, and an output LED is illuminated if the signal is greater than the desired threshold, indicating a heartbeat.

6.0 SCHEMATIC

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Figure 6-1 shows the *schematic* of the Heartbeat Monitor with the circuitry for each block of the system. A ***DC Level Adjust*** has been added to provide a means of adjusting the average DC level of the output. All resistance values are in Ohms.

NOTE: Be sure to use bypass capacitors on your breadboard to provide additional power supply filtering locally, near the circuit.

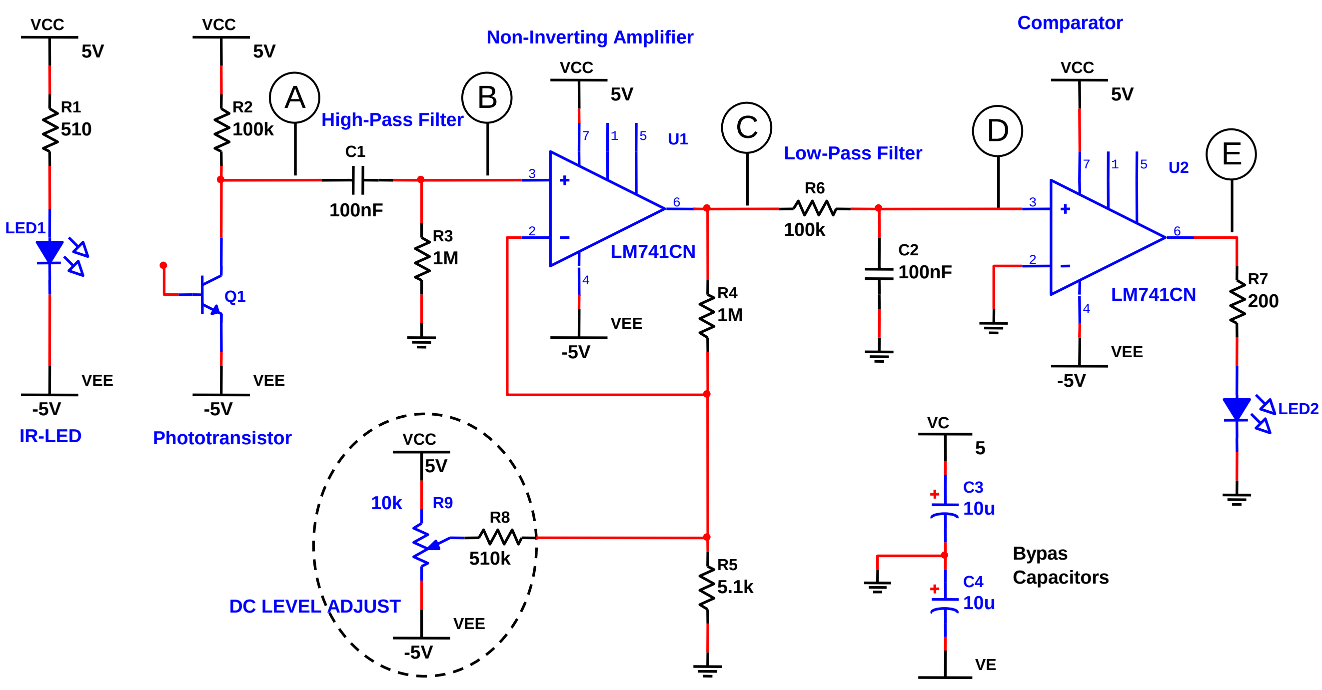

Figure 6-1: Schematic

7.0 LAB PROCEDURE

During this lab procedure, build and test each functional block individually before proceeding to the next stage. Use the oscilloscope to check each stage for proper ***DC bias*** as well as for proper ***signal processing***. In this manner, the amount of time spent troubleshooting the circuit can be minimized.

7.1 Power Supply – Set up the DC power supply as follows:

Dual Supply:	+/– 5V
Current Limit:	100mA per supply (as a safety precaution)

NOTE: Be sure to TURN OFF the power supply before building each successive stage of the circuit.

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7.2 IR-LED and Phototransistor Module:

(1) Build: **(Power OFF Reminder)**
Hook up the IR-LED as shown in the schematic. Be sure to connect R1 in series with the LED to limit the current to approximately 20mA. Since infrared light is invisible to the naked eye, you will not be able to see the operation of the LED, directly.

(2) Test: **(Power ON Reminder)**
If available, try viewing the IR-LED through a cell phone camera. Most digital cameras are sensitive to infrared, so you should be able to see the LED through the camera![2]

7.3 Phototransistor Amplifier:

The purpose of the phototransistor is to convert the incident infrared light into a proportional electrical current. This current is then converted into a voltage signal by passing it through resistor R2.

(1) Build: **(Power OFF)**
Connect the phototransistor as shown in the schematic. Be sure to connect the collector terminal to the 100k load resistor and the emitter terminal to the negative supply.

NOTE: The phototransistor used in this lab is in a package similar to an LED. Be sure to check the specification sheet for proper terminal locations.

(2) Check DC Bias: **(Power ON)**
Use the oscilloscope to verify proper DC bias of the phototransistor circuit. Set up the oscilloscope to the following settings:

Display:	Channel 1
Coupling:	DC Coupling
Amplitude:	2V / division
Time Base:	250msec / division
Triggering:	Channel 1

With the IR-LED turned on, connect the scope probe to the collector of the phototransistor **(point A)** in the circuit. Also be sure to connect the ground reference.

Verify that the collector voltage at the output of the phototransistor is –5V, as shown in Figure 7-1.

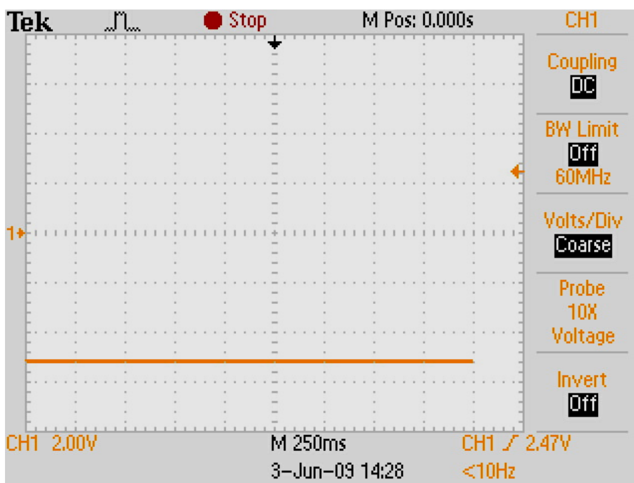

Figure 7-1

[2] The author discovered this feature when a person inadvertently waved a TV remote in front of his video camera.

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(3) Check Signal:
Now insert your finger into the sensor module between the IR-LED and the phototransistor and lightly press your finger against the LED. Verify that the collector voltage **(point A)** increases to a value between 0 and +4V, as shown in Figure 7-2.

NOTE: At this point, the voltage signal contains both a DC bias and a small ac ripple which is the actual blood pressure signal that needs to be amplified!

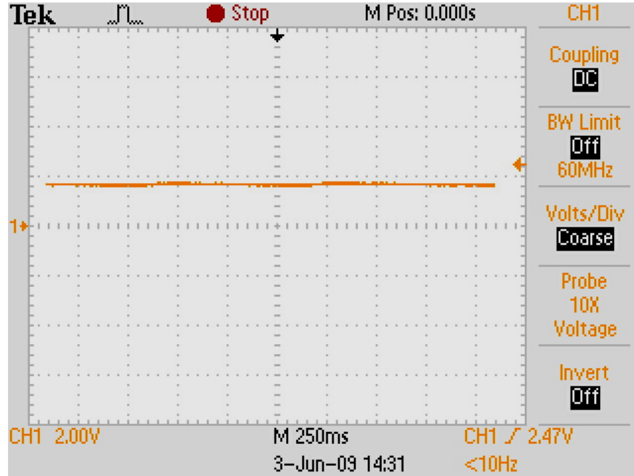

Figure 7-2

(4) Check Signal (zoom in)::
To view the signal more clearly, select AC Coupling to strip the DC bias from the signal and change the vertical sensitivity to 20mV/division, to zoom in.

Display:	Channel 1
Coupling:	**AC Coupling**
Amplitude:	**20mV / division**
Time Base :	250msec / division
Triggering:	Channel 1

Place your finger into the sensor module and lightly press against the IR LED to illuminate your finger with infrared light.

If the sensor is working properly, you should see a varying signal similar to Figure 7-3. If the signal is moving around too much, rest your hand against the table to minimize movement.

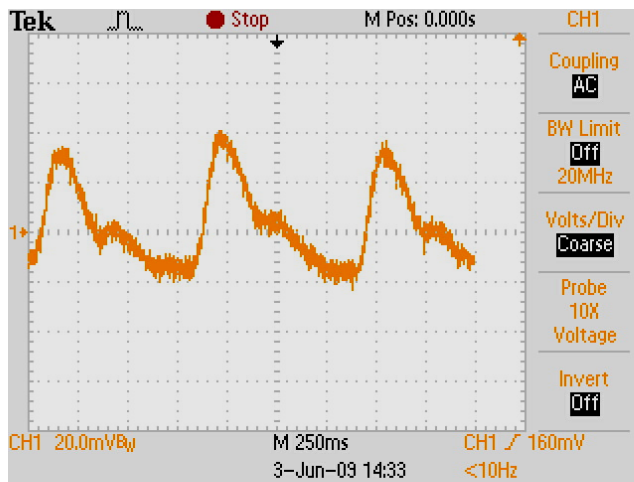

Figure 7-3

(5) Record Waveforms:
Sketch all resulting waveforms in your notebook. Record the peak-to-peak amplitude and period of the signal, as well as any other interesting features worth noting. How do they compare to the given figures?

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7.4 High-Pass Filter:

The voltage signal at the output (collector) of the phototransistor contains a large DC offset due to the average infrared light level incident on the sensor. In order to strip away this DC offset, a simple first order high-pass filter comprised of capacitor C1 and resistor R3, is used. This filter has a cut-off frequency of approximately 1.59 Hz.

(1) Build: **(Power OFF)**
Connect the high-pass filter as shown in the schematic.

(2) Check Signal: **(Power ON)**
Set the scope back to DC Coupling.

Display:	Channel 1
Coupling:	**DC Coupling**
Amplitude:	20mV / division
Time Base :	250msec / division
Triggering:	Channel 1

Connect the probe to the output of the high-pass filter **(point B)** and insert your finger into the sensor. You should see the same signal as before, BUT with a different DC bias.

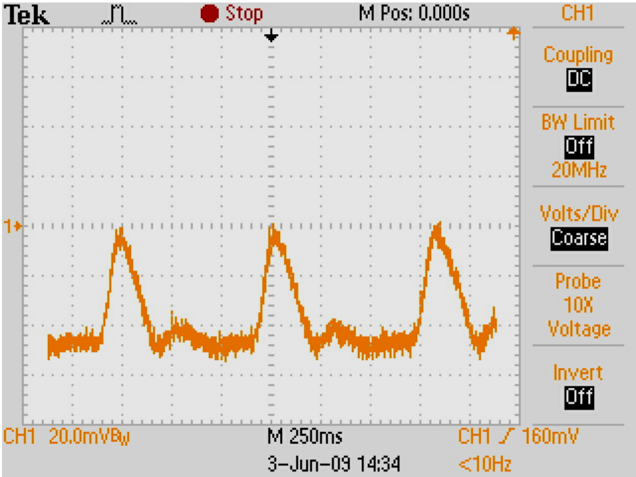

Figure 7-4

NOTE: The DC bias should be 0V if the high-pass filter is not connected to the input of the amplifier stage. Otherwise, you may see a DC offset due to the input offset of the op-amp, as shown in Figure 7-4.

(3) Record Waveform:
Record this waveform in your notebook and be sure to note key features of the graph including shape, amplitude, period, DC offset, noise level, etc. How does it compare to the given figure?

7.5 Non-Inverting Amplifier (Gain of 200):

The amplifier stage is comprised of operational amplifier U1 and resistors R4 and R5. The amplifier circuit is configured as a non-inverting amplifier with a gain of approximately 200 (ie: Av = 1 + R4/R5). Resistor R8 and potentiometer R9 provide a means for adjusting the DC level of the output and can compensate for any DC offset at the output of the amplifier.

(1) Build: **(Power OFF)**
Connect the amplifier stage as shown in the schematic, as well as the DC level-adjust circuitry.

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(2) Check Signal: **(Power ON)**
Change the vertical sensitivity of the scope to 2V/division to view the amplified signal.

Display:	Channel 1
Coupling:	DC Coupling
Amplitude:	**2V / division**
Time Base :	250msec / division
Triggering:	Channel 1

Connect the probe to the output of the amplifier **(point C)** and adjust R9 for an average DC voltage of -1V.

Place your finger into the sensor as before. If your circuit is working properly, you should see an amplified signal similar to Figure 7-5.

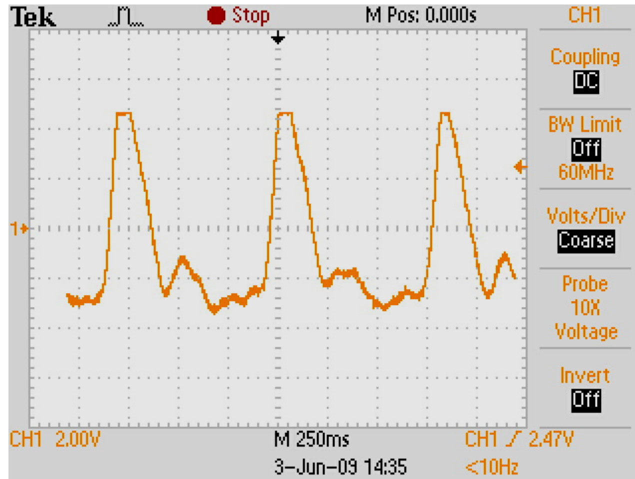

Figure 7-5

NOTE: You may notice some distortion due to "clipping" which occurs if the output tries to exceed the power supply rails. Adjust the DC Bias to reduce or prevent clipping.

(3) Record Waveform: Record this waveform in your notebook, as before.

7.6 Low-Pass Filter:

The amplified signal contains some high frequency noise or *fuzz*[3] which can be reduced using a low-pass filter. Resistor R6 and capacitor C2 form a simple first order RC filter with a cut-off frequency of 15.9Hz.

(1) Build: **(Power OFF)**
Connect the low-pass filter as shown in the schematic.

(2) Check Signal: **(Power ON)**
Place your finger in the sensor and measure the output of the filter **(point D).** Verify that the signal is the same size and shape as before, but with the noise reduced.

(3) Record Waveform:
Record and note the reduction in noise.

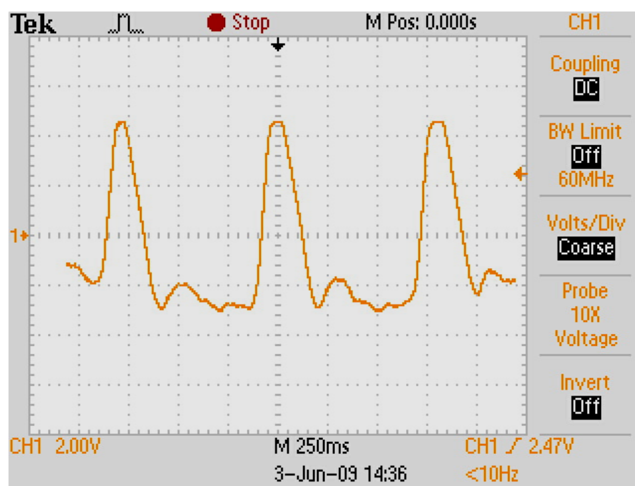

Figure 7-6

[3] Or more correctly, thermally generated Gaussian white noise, due to the random motion of electrons in the circuit.

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7.7 Voltage Comparator:

Op-amp U2 is used as a voltage comparator to compare the signal voltage to a reference of 0V. If the input voltage is greater than 0V, the output of the comparator will saturate to the positive supply rail and if the input signal is less than 0V, the output will swing to the negative supply rail. Typically, the saturation voltages will not be exactly equal to the supply voltages since there are internal voltage drops within the comparator.

***(1) Build:* (Power OFF)**
Connect the comparator circuit as shown in the schematic.

***(2) Check Signal:* (Power ON)**
Place your finger in the sensor and measure the output of the comparator **(point E).**

NOTE: The output of the comparator should be a square wave signal swinging between (or close to) the voltage supply rails.

(3) Record Waveform:
Record this waveform and note the saturation voltages. How do they compare to the supplies?

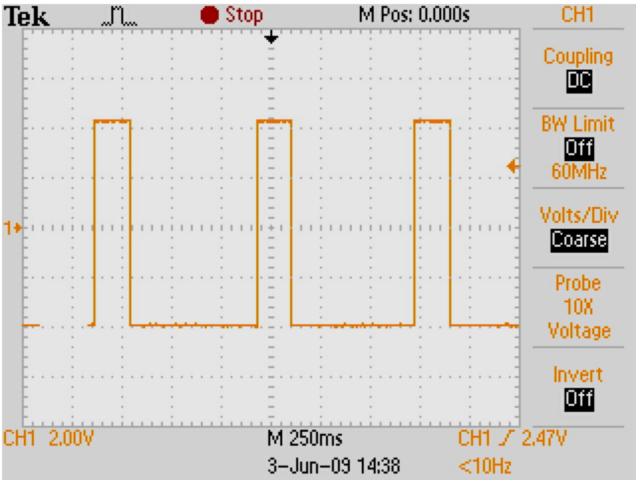

Figure 7-7

7.8 Output LED:

LED2 is used to indicate the output of the circuit. Resistor R7 limits the current in the LED to approximately 15mA.

***(1) Build:* (Power OFF)**
Connect LED2 and resistor R7 to the output of the comparator. Be sure to observe the LED polarity. If connected properly, the LED should remain off when the sensor module is empty.

***(2) Test Functionality:* (Power ON)**
Now place your finger in the circuit, rest your hand against the table. If you have followed this procedure and tested each stage, the circuit should work properly.

(3) Record Results:
Using this circuit, determine your heartbeat in beats-per-minute (bpm). A healthy person should have a heartbeat of around 60 bpm. Lower is better.

Congratulations! You have built your first piece of electronic medical equipment!

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8.0 SYSTEM LEVEL DISCUSSION:

This lab highlights one technique for monitoring blood pressure and displaying a photoplethysmogram (PPG) on an oscilloscope. It also indicates how to use a voltage comparator to determine when to flash an LED, in synchronization with a person's heartbeat.

In general, sensors of many types are often used to convert a variety of physical phenomena into electrical signals. These signals are often small and obscured by electrical noise. Therefore the process of amplifying, filtering and comparing must be used to extract the signals and make them large enough to view on an oscilloscope, or to do something useful like turning on an LED. The process used in this lab is indicative of this approach.

In addition, this lab introduces a method for prototyping circuits by building and testing each stage before proceeding to the next. This methodical approach is time-tested and will save you countless hours in lab when building or troubleshooting electronic systems.

Learn to be disciplined in prototyping your circuits or you will be very frustrated and discouraged when your circuits do not work!

9.0 FINAL NOTE:

The approach taken in this lab is primarily *qualitative*, in that you were given a design and simply asked to build it and get it to work in order to appreciate understanding the problem from a system level.

As you progress through your Electrical and Computer Engineering education, however, you will have to become the designer by remembering these techniques and applying them to new problems. Of course, this will require *quantitative* analysis, which is the primary skill that engineers are valued for.

Welcome to ECE!

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Appendix: