The University of British Columbia | Okanagan

School of Engineering

OKANAGAN

ENGR 451 Microelectronics II

Lab 5: Monostable Multivibrator Circuits

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Introduction and Objectives

In the previous lab, we designed a comparator stage that produced the output $v_{o,3}$, show as V_{in} in the figure below. This output was a square wave, reading high when the detected PPG signal rose above the desired high threshold value until it dropped below the desired low threshold value. In this lab, our goal was to use this digital high or low signal from the output of the comparator to trigger an LED to flash for a desired on-time. This was achieved by the addition of the edge detection circuit, monostable multivibrator, and LED driver circuit pictured in Figure 1.

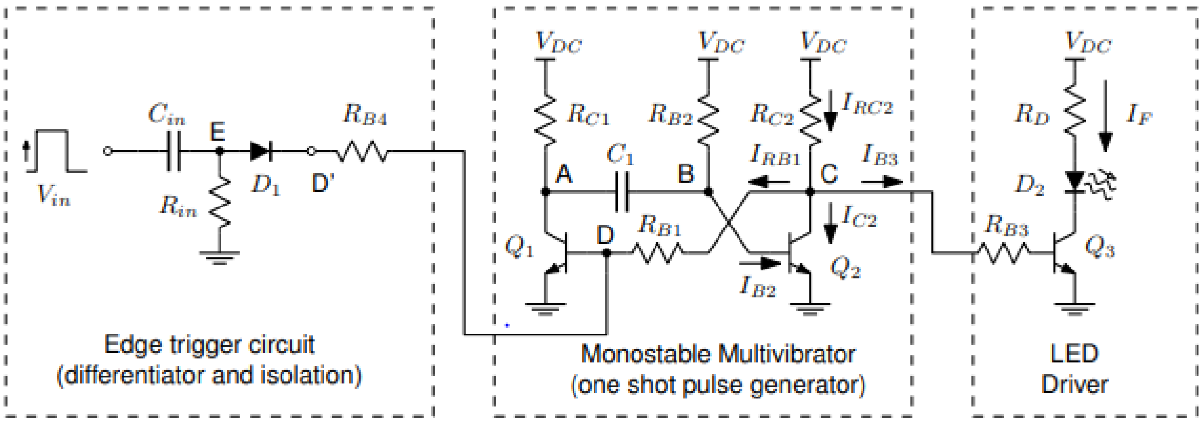

Figure 1. Monostable multivibrator circuits stage.

A brief overview of the operation of the circuitry above is as follows: the edge trigger circuit passes positive pulse voltages when the input comparator signal V_{in} has a rising edge. This triggers the transistor Q_1 to turn on, which in turn causes the transistor Q_2 to turn off. This causes node C to go from $V_{CE,sat}$ ~= 0.1V to a relative high voltage since it is no longer fixed by Q_2. This allows transistor Q_3 to turn on and Q_1 to stay on as node C is at a high enough voltage to forward bias their base-emitter junctions. Furthermore, when Q_2 turns off, the capacitor C_1 is initially nearly charged to the full supply voltage (V_{AB} ~= V_{DC}) since node B was held at ~0.7V by Q_2 being on and no current could flow through R_{C1}. When Q_1 turns on, the capacitor maintains the same voltage across it of approximately V_{DC}, meaning that node B has a negative potential since node A has a potential of $V_{CE,sat}$ = 0.1V. The capacitor then begins to discharge, or charge with the opposite polarity. Eventually, node B reaches a high enough voltage to turn transistor Q_2 back on (this occurs at roughly 0.7V). This causes the voltage at node C to go low again (back to $V_{CE,sat}$ ~=0.1V). At a high level, this analysis shows that when a rising edge occurs in the comparator signal V_{in}, the LED driver transistor Q_3 will turn on and allow the LED to emit light for the period of time that it takes the capacitor C_1 to discharge to the point where the voltage at node B becomes high enough to turn transistor Q_2 back on. This period of time is related to the RC time constant given by C_1 and R_{B2}.

Design

The purpose of this stage is to visualize our PPG signal in the form of a pulsing LED. For every pulse, we would like the LED to be on for a certain length of time. To achieve this, we cannot simply use the comparator signal from the previous stage. Instead, we must detect edges on the comparator signal, then whenever an edge is detected, we operate a monostable multivibrator to switch on for a certain time which then drives a LED as the output of our heart rate monitor.

This stage hence can be designed as three independent stages: an edge trigger circuit, a monostable multivibrator, and a LED driver.

Edge Trigger Circuit

The purpose of the LED is to pulse once per PPG signal. For each PPG signal, we can see that the previous stages generate one comparator pulse. By using an AC coupling capacitor, we can detect changes in the comparators stage. The signal at the node just after the AC coupling capacitor is shown below.

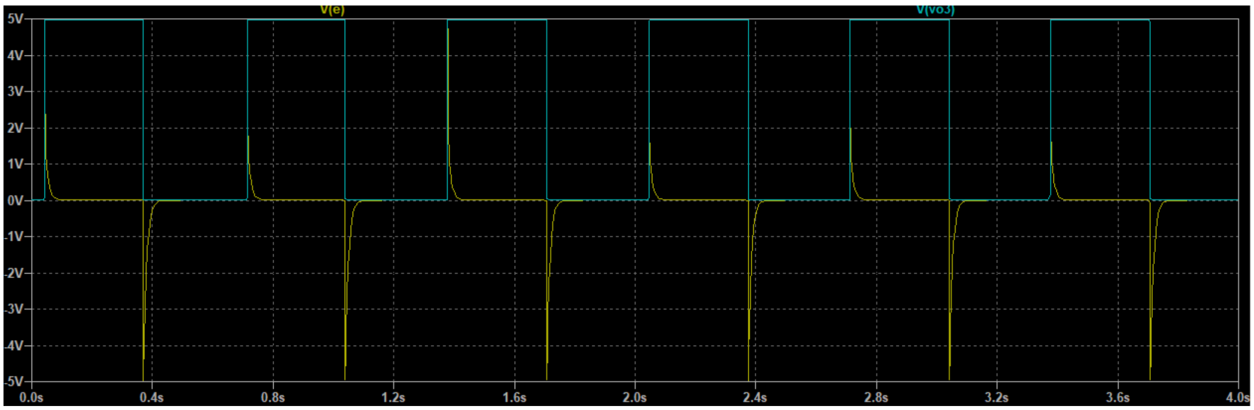

Figure 2. Signal of comparator output and after AC coupling capacitor.

As we can see from the above, the signal past the capacitor shows a pulse whenever the comparator output changes states, on positive (rising) and negative (falling) edges. We would like to only generate one pulse per PPG signal; hence we should eliminate the detection on the negative edges. To achieve this, we may use a diode to only allow forward voltage and eliminate, most of, the negative edge signal. Tying the node to ground through a resistor and adding another current limiting resistor towards the output of this stage, we get.

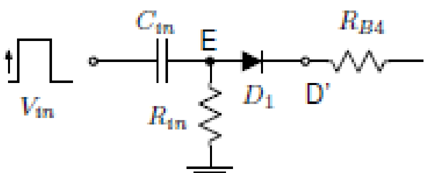

Figure 3. Edge Trigger Circuit.

As the components available for this circuit has already been given as the following, this concludes the design of our edge detection circuit.

Table 1. Edge detection circuit list of components.

C_{in}	$1\ \mu F$
R_{in}	$10\ k\Omega$
R_{B4}	$2\ k\Omega$
D_1	$1N4148\ Diode$

A simulation of the input/output of the edge detection circuit is shown below.

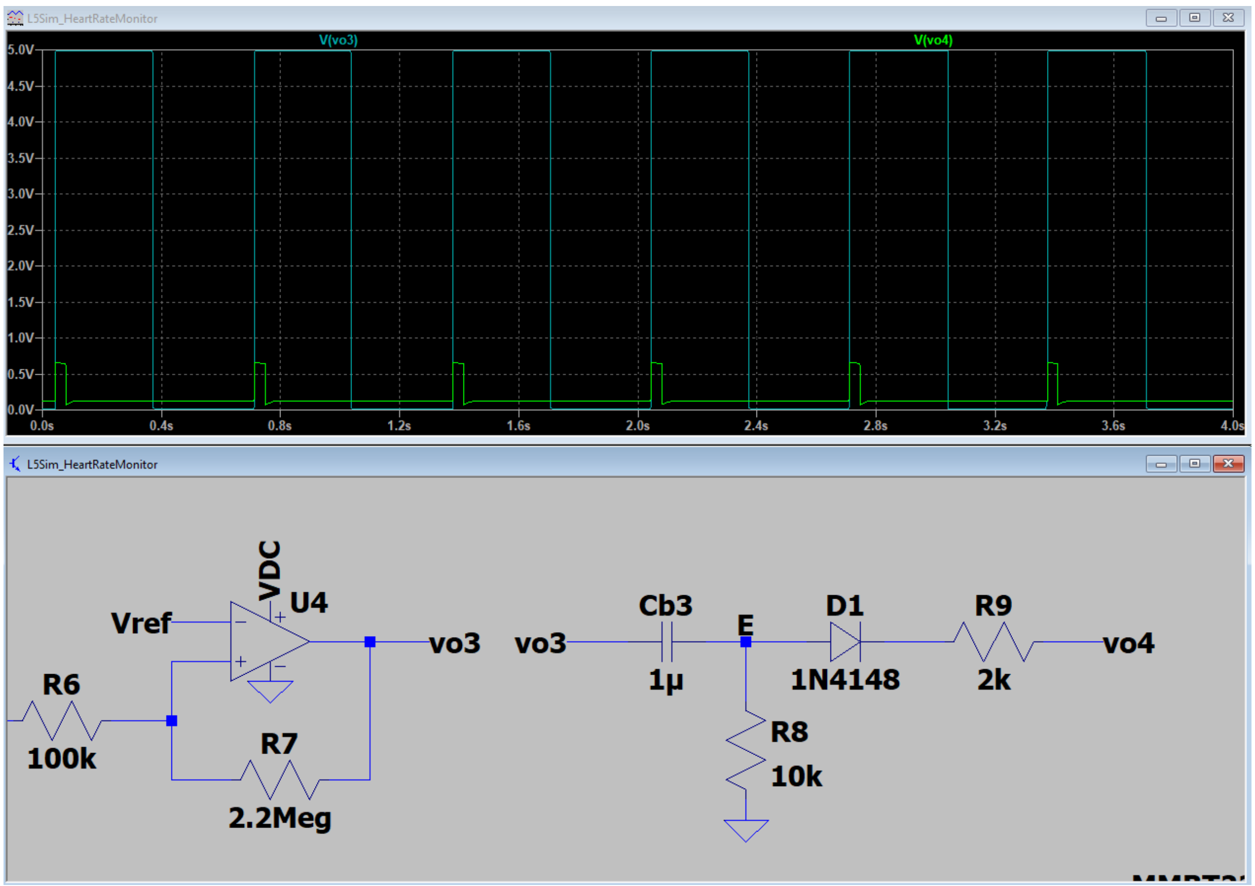

Figure 4. Simulation of edge detection circuit.

Monostable Multivibrator

From the output of the edge detection circuit, we would like to control the time the LED pulses for each edge detected. To accomplish this, here we use a monostable vibrator.

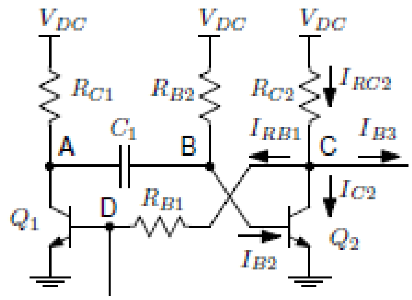

Figure 5. Monostable Multivibrator Circuit

A monostable multivibrator has only one stable state. When the above circuit has no input at node D, we can analyze it's DC OP (operating point). At the DC OP, node D is tied to ground through the input, hence the transistor Q_1 is not on. Since Q_1 is not on, and capacitor C_1 is an open circuit at DC, the base current I_{B2} turns Q_2 on and a current I_{C2} passes through Q_2. At node C, we can assume that the currents I_{RB1} and I_{B3} are small enough to be negligible as we implement current limiting resistors between both the LED driver and edge detection circuit from the monostable vibrator. With the above, we may now design the bias conditions for Q_2. We can first decide on a desired current I_{C2}. For a I_{C2} of $10\ mA$, from the specification sheet of the PN2222A transistors, we can see that $\beta = 35{\sim}75$ for a range of temperatures, $V_{CE,sat} \approx 0.3V$, and $V_{BE,sat} \approx 0.6V$. If we were to assume a reasonable $\beta = 50$, $V_{C,sat} = 0.3V$, and $V_{BE,sat} = 0.6V$, we have everything to find R_{C2} and R_{B2}.

$$R_{C2} = \frac{V_{DC} - V_{CE,sat}}{I_{RC2}}$$

Since we assumed and will design with the goal of $I_{RC2} \approx I_{C2}$

$$R_{C2} \approx \frac{5V - 0.3V}{10\ mA} = 470\ \Omega$$

And

$$I_{C2} = \beta I_{B2}$$

$$I_{B2} = \frac{I_{C2}}{\beta} = \frac{10\ mA}{50} = 0.2\ mA$$

Then

$$R_{B2} = \frac{V_{DC} - V_{BE,sat}}{I_{B2}} = \frac{5V - 0.6V}{0.2\ mA} = 22\ k\Omega$$

Since Q_1 and Q_2 are simply mirrored when on, we can use the same bias conditions. Hence

$$R_{B1} = R_{B2} = 22\ k\Omega$$

$$R_{C1} = R_{C2} = 470\ \Omega$$

With the above designed, there only remains the value of C_1. This capacitor defines the transient response of this circuit. When an input is detected at node D, Q_1 switches on, voltage at node A, V_A, drops to the $V_{CE,sat}$ of Q_1, since there originally exists a voltage across the capacitor $V_{AB} > 0$, this consequently drives the voltage at node B, V_B, down by the drop at V_A. For the duration that $V_B < 0.7V$, Q_1 will be on and Q_2 will be off. Since the recovery of node B is tied to the charging of C_1 through R_{B2}, the on time is determined by the RC time constant $\tau = R_{B2}C_1$. Using the expression derived from a general single time constant RC circuit analysis[1]

$$\begin{aligned} T_{on} &= \tau \ln\left[\frac{2V_{DC} - \left(V_{CE,sat} + V_{BE,on}\right)}{V_{DC} - V_{BE,on}}\right] \\ &= \tau \ln\left[\frac{2 \times 5V - (0.3V + 0.6V)}{5V - 0.6V}\right] \\ &= \tau(0.7267) \\ &= R_{B2}C_1(0.7267) \end{aligned}$$

Then

$$C_1 = \frac{T_{on}}{0.7267 \times R_{B2}}$$

$$C_1 = \frac{T_{on}}{15986.74\Omega}$$

Since the frequency of a PPG signal should be around 1.2 Hz, a pulse should last

$$\frac{1}{1.2Hz} = 0.84\ s$$

We need to choose an T_{on} that is under this value since the LED should be off by the time the next PPG signal comes around. We should also choose a value that causes the LED pulse to be visible and comfortable. For the $T_{on} = 30ms$ we chose,

$$C_1 = \frac{30ms}{15986.74\Omega} = 1.88\ \mu F$$

From the list of available components, we should select values close enough to the design and verify them in a simulation.

Table 2. Monostable multivibrator list of components.

R_{B1}, R_{B2}	$22\ k\Omega$
R_{C1}, R_{C2}	$470\ \Omega$
C_1	$2.2\ \mu F$
Q_1, Q_2	$PN2222A$

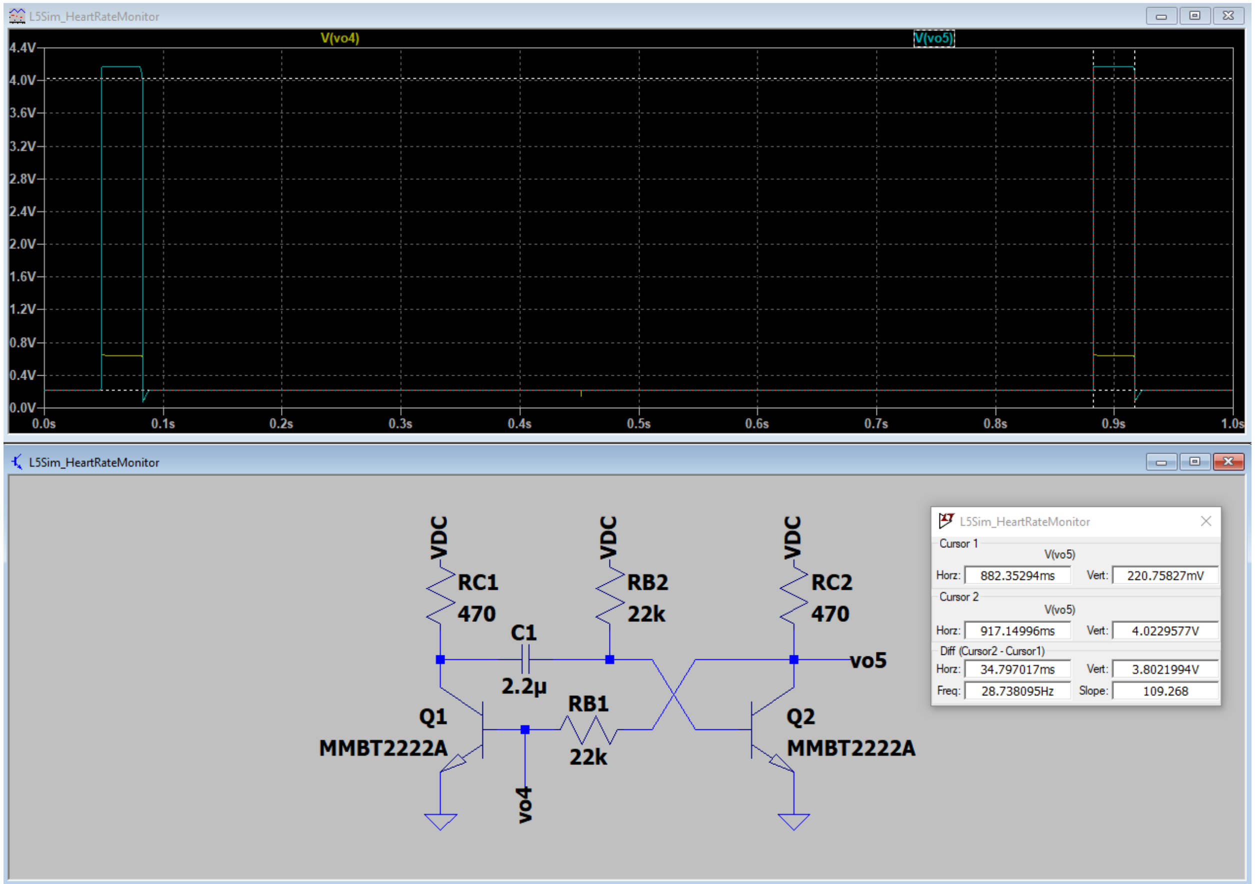

Figure 6. Simulation of monostable multivibrator w/ selected components.

From the above figure, we can see that node C is high for 34.8 ms which is approximately what we designed for.

LED Driver

The purpose of the LED driver circuit is to switch an LED on/off with the output of the monostable multi vibrator. To do this, we can use the same BJT and current limiting resistor, not forgetting an input current limiting resistor to account for the assumption previously made at node C. As the main purpose is to drive the LED, we desire a specific current. Referring to the specification sheets of the MV3450 Diode, the forward voltage is typically $20mA$ and its forward voltage typically $2.2V$. With these values, we can calculate for the current limiting resistor.

$$R_D = \frac{V_{DC} - V_f - V_{CE,sat}}{I_f}$$

$$= \frac{5V - 2.2V - 0.3V}{20mA}$$

$$= 125\ \Omega$$

Since the closest available resistor is 100Ω, we selected it. Using a 2.2 $k\Omega$ resistor as the input current limiting resistor, the list of components is

Table 3. LED driver list of components.

R_D	$100\ \Omega$
D_2	$MV3450\ Diode$
Q_3	$PN2222A$
R_{B3}	$2.2\ k\Omega$

With all components selected, the simulation of the above stages is shown below.

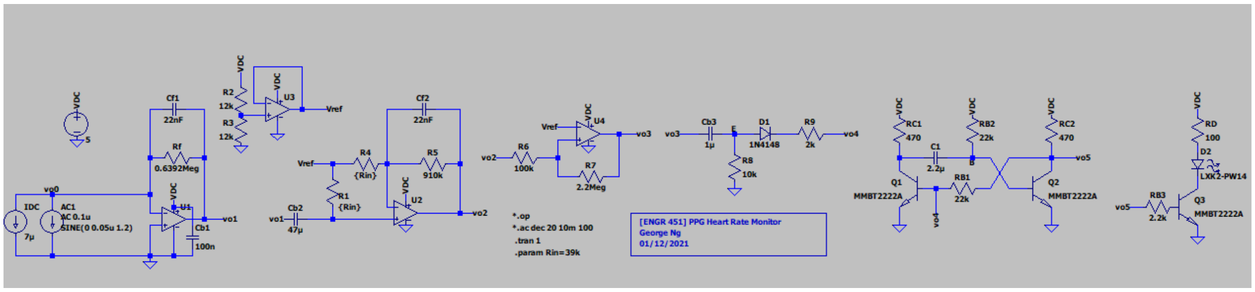

Figure 7. Heart rate monitor circuit simulation.

Figure 8. Heart rate monitor last stage simulation results.

Experiment Procedure and Setup

Since no changes to the previous stages are made, with the above design and lists of components, we can build our last few stages in the heart rate monitor circuit. Since the above stages can be built independently, we should build while testing their functionality one at a time in the order that they were designed.

To complete this lab, to construct and test our circuit, we followed these steps:

1. Setup 5V DC power source and connect the positive lead to the positive rail V_{DC} and the negative to the ground rail V_{SS} of the breadboard.
2. Check for proper operation of stage 1, 2, and 3 by connecting one probe of the oscilloscope and digital multimeter (DMM) to $v_{0,1}$ as well as another probe to $v_{0,3}$. The probe at $v_{0,1}$ should not be moved through the experiment to observe the raw signal bypassing the long delay between stages.
    a. The DMM should be in DC voltage mode to monitor for railing in stage 1.
    b. The oscilloscope probes should both be set to $1X$ and $500ms/div$ horizontal resolution.
        i. The probe connected $v_{0,1}$ should be set to a vertical resolution of $20mV/div$
        ii. The probe connected $v_{0,3}$ should be set to a vertical resolution of $2V/div$
3. Construct the edge detection circuit. Confirm by looking for the output signal simulated in the design section.
    a. Move prove $v_{0,3}$ to the output to achieve this.
4. Construct the monostable vibrator and probe node C with the oscilloscope probe at the output of the edge detection circuit. Confirm its on time by examining the time at which node C is high. This is equivalent to time that the LED driver is on for.
5. Construct the LED driver. We can confirm its operation by simply observing the LED once a signal is present at node C.
6. Adjust the value of C_1 if a different on time is desired.

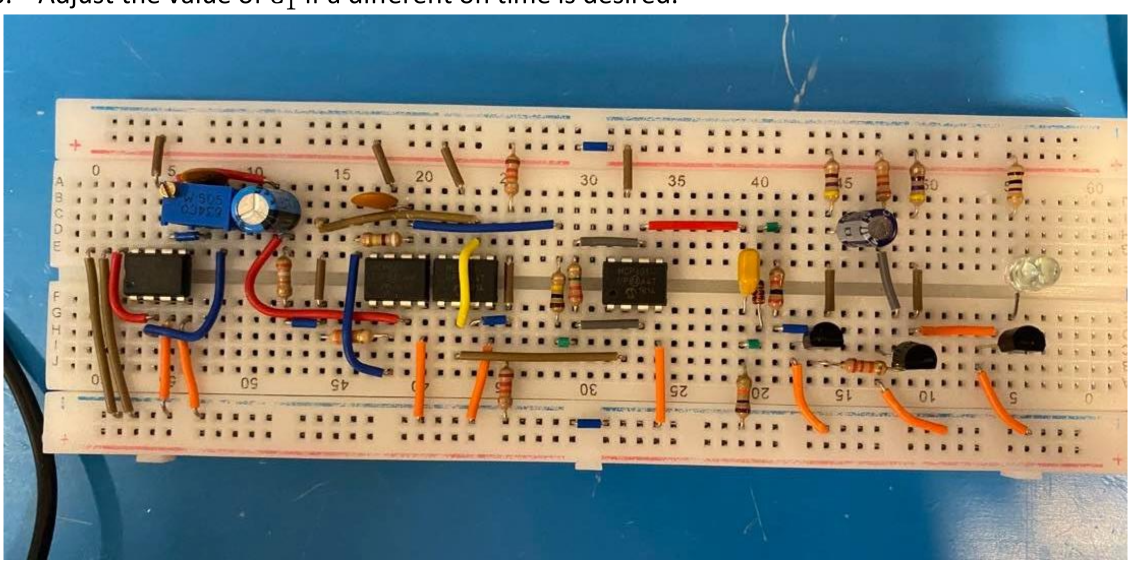

Figure 9. Assembled heart rate monitor circuit.

Data

Note that all the waveforms in this section were taken with the oscilloscope set to AC coupling. Unfortunately, this is how we mistakenly collected data and there is no further lab time before this report is due to capture new waveforms with the oscilloscope set to DC coupling. The discrepancies between these waveforms and their DC counterparts will be discussed with respect to each waveform.

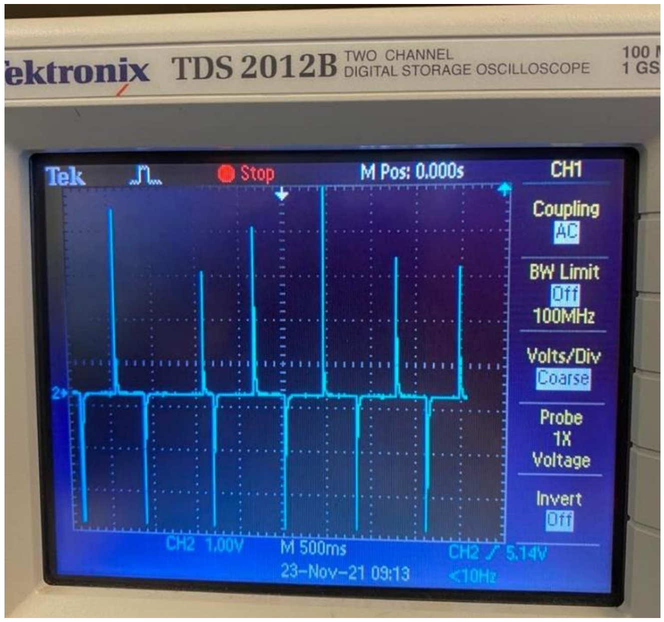

Figure 10. AC coupling waveform at node E.

In Figure 10 above, we see the waveform of the voltage at the node labeled E in Figure 1. This is actually similar to the expected DC coupling waveforms, since there is a DC blocking capacitor C_{in} directly before node E. We see negative pulses when the comparator signal has a falling edge, and positive pulses when the comparator signal has a rising edge.

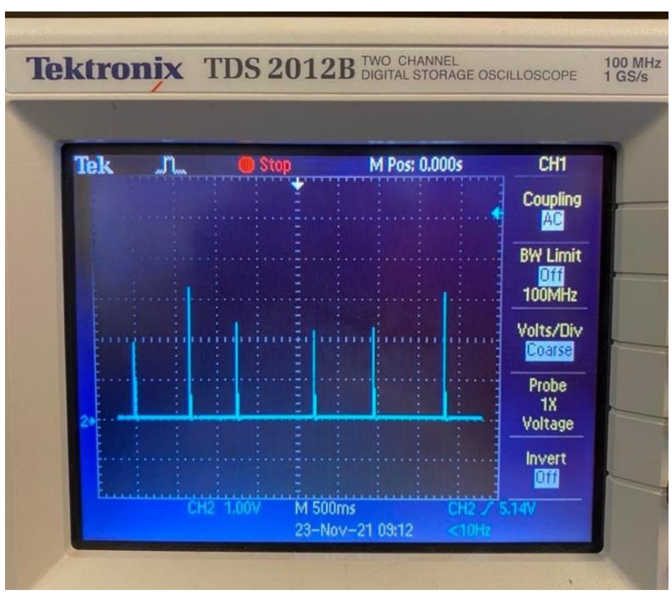

Figure 11. AC coupling waveform at node D.

In Figure 11 above, we see the AC coupling waveform at node D’. This waveform is again similar to the expected DC coupling waveform, as is it just the positive pulses from node E. Only the positive pulses from node E reach node D’ since there is a diode separating the two nodes.

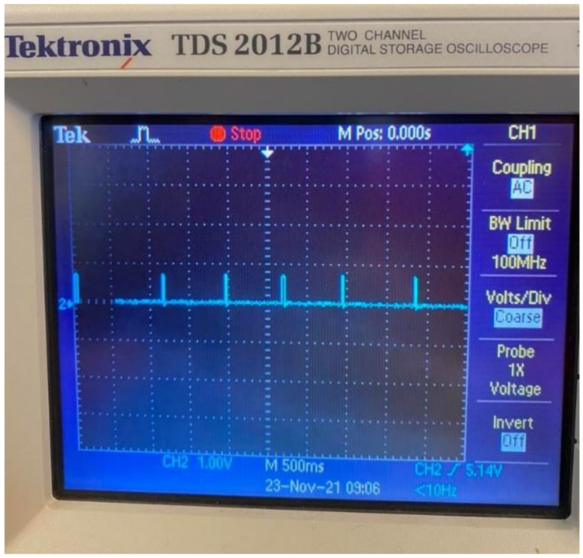

Figure 12. AC coupling waveform at node C.

In Figure 12 above, we see the AC coupling waveform at node C. This waveform is different from what we would expect to see in DC coupling mode. As it is, we see positive square pulses separated by approximately the same time intervals as the positive pulses we saw at node D’. This is because node C jumps instantaneously to a “high” voltage (high enough to turn on Q_1 and Q_3) from a “low” voltage ($V_{CE,sat}$ ~= 0.1V) each time a positive pulse comes through node D’. Then, node C falls instantaneously from the “high” voltage to a “low” voltage when node B reaches a high enough voltage to turn Q_2 back on, consequently turning Q_1 and Q_3 off. It’s difficult to tell from the plot above since the horizontal axis is set to 500ms/div, but the square pulses have a duration of approximately 30ms, as designed.

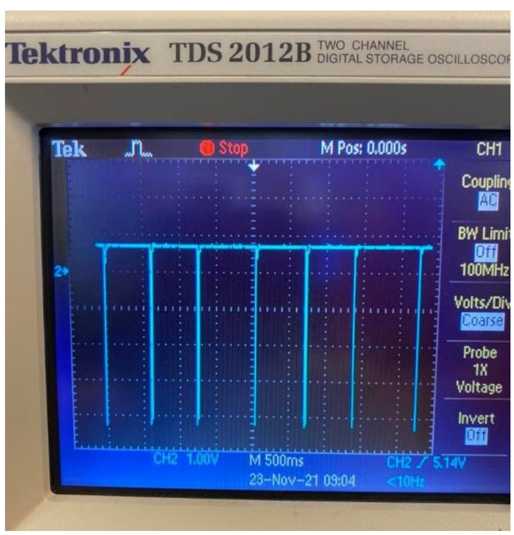

Figure 13. AC coupling waveform at node B.

In Figure 13 above, we see the AC coupling waveform at node B. Here we see negative pulses separated by approximately the same time interval as the positive pulses at node D'. These negative pulses occur when the voltage at node B drops instantaneously to maintain the capacitor voltage when Q_1 turns on and Q_2 turns off. This happens when a positive pulses comes through node D', which explains the synchronization of the two waveforms. We then see a continuous and less abrupt rise back up to ~0.7V = V_{BE}, as the capacitor C_1 discharges. When the voltage at node B reaches 0.7V, Q_2 turns back on and the voltage at node C goes low again, turning off transistors Q_1 and Q_3.

Results and Discussion

We were successful in designing an edge trigger, monostable multivibrator, and LED driver circuit to flash an LED for a designed time T_{ON} when a rising edge was detected in our comparator signal. From analyzing video footage in slow motion, we were able to determine that our LED flashed on for approximately 30ms, which is very close to the designed value of 35.7ms. As discussed in the Data subsection, the waveforms we captured aligned with our expectations from calculations and simulations.

Initially, we opted for a smaller capacitor, but this resulted in a lower RC time constant, which left our LED on for such a short duration that it was almost imperceptible. To remedy this, we increased the size of capacitor C_1 nearly threefold, which caused the LED to stay on for a noticeable duration.

We had little difficulty assembling this stage of our heart-rate monitor, though we did struggle to grasp the operating principle behind the monostable multivibrator as our lab section occurred directly after the lecture where the concept was introduced. As discussed in the Data subsection, we also failed to capture waveforms in DC coupling mode, and our horizontal time step was a little large, but this made little difference in our analysis.

After completing this final stage, we opted to solder all our components onto a printed circuit board (PCB), so that we could take our heart-rate monitor home. This process involved quite a few debugging stages and required us to be very methodical in our approach. We moved the heart-rate monitor from the breadboard to PCB stage-by-stage and verified the operation of each stage along the way. One issue that we ran into was that the PCB's designated ground and high rails were in the opposite orientation to our breadboard, which led to some confusion and mis-soldered joints. However, after stepping through our debugging process, we were able to catch our error and re-solder appropriately.

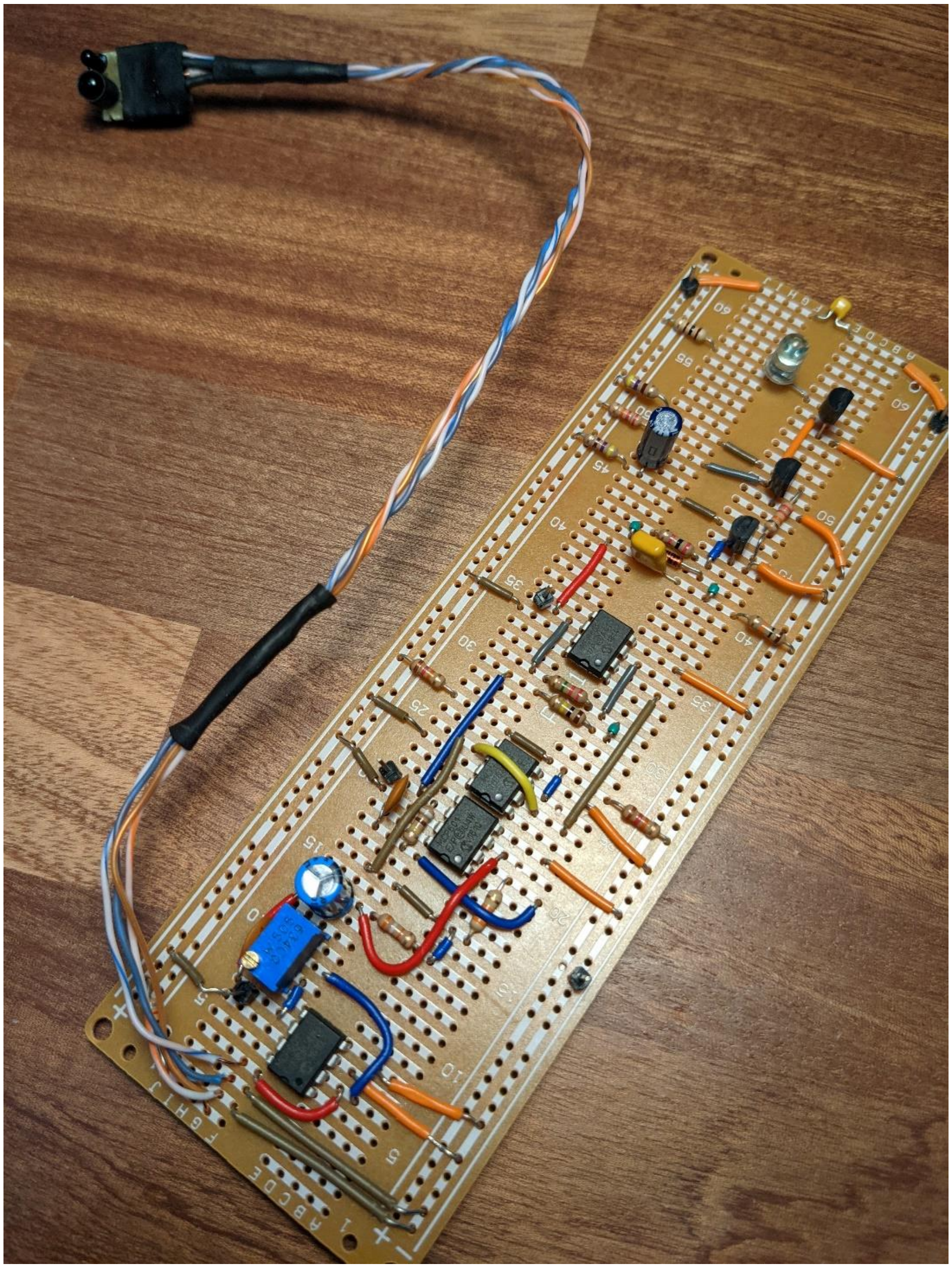

Figure 14. Soldered heart rate monitor.

Conclusion

This lab required us to utilize our knowledge of BJT operational states and the monostable multivibrator to design the fourth and final stage of our heart-rate monitor. We now have a circuit that reads a PPG signal via infrared, amplifies it, filters it, digitizes it, and uses the digital signal to flash an LED in sync with a detected pulse. The optional next step in our design would be to move all the components to a PCB and solder them to have a ready-made heart-rate monitor. As mentioned above, we actually took this step and we now have a working heart-rate monitor soldered to a PCB. A few potential sources of error in this lab include unaccounted-for resistive and reactive losses in the non-ideal components used in this circuit design, inaccurately labeled components, and IR interference from outside sources. Any of these could lead to mild discrepancies between calculated and measured values and may explain differences between our results, our calculated expectations, and the results of others performing the same experiment.

References

[1] T. Johnson, "Lab 5: Monostable Multivibrator Circuits," 2021.