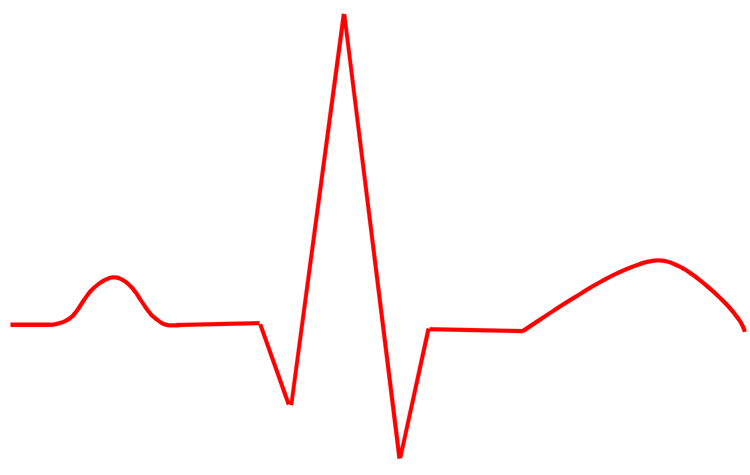
engineeringworldhealth

ECG Simulator

Laboratory Activities Handbook



Contents

Objective

Electrocardiography (ECG) is a standard non-invasive technique for diagnostic and research of human hearts. An electrocardiograph records the cardiac electrical waveform over a period of time. The performance of ECG monitors can be affected by many factors, such as electromagnetic noise, power fluctuations, lack of circuit grounding, measurement cables contact, electrodes attachment and circuit failures.[1] The easiest way to check whether the ECG equipment is working properly is through an Electrocardiogram Simulator. The Engineering World Health (EWH) ECG Simulator kit is able to generate Einthoven's triangle signals (see Appendix 0 and 0) through contacts that correspond to the Left Arm (LA), Right Arm (RA) and Left Leg (LL).

The purpose of building the ECG Simulator kit is to teach engineering students the characteristics of a cardiac electrical signal and to explain the basic principles of analog and digital electronic circuits. The laboratory addresses theoretical principles that can be observed through simulations with Multisim software and measurement. Before using this document, the board should be assembled, following the "ECG Simulator Assembly Instructions."

ECG Simulator Overview

Figure 1 shows a schematic diagram of the ECG Simulator kit. The circuit has a digital block, formed by two frequency dividers (integrated circuits IC1 and IC2) and the analog output network, which shapes the heart electrical signal. The switch S2 selects the cardiac rate, which can be either 1 Hz or 2 Hz (60 bpm/120 bpm).

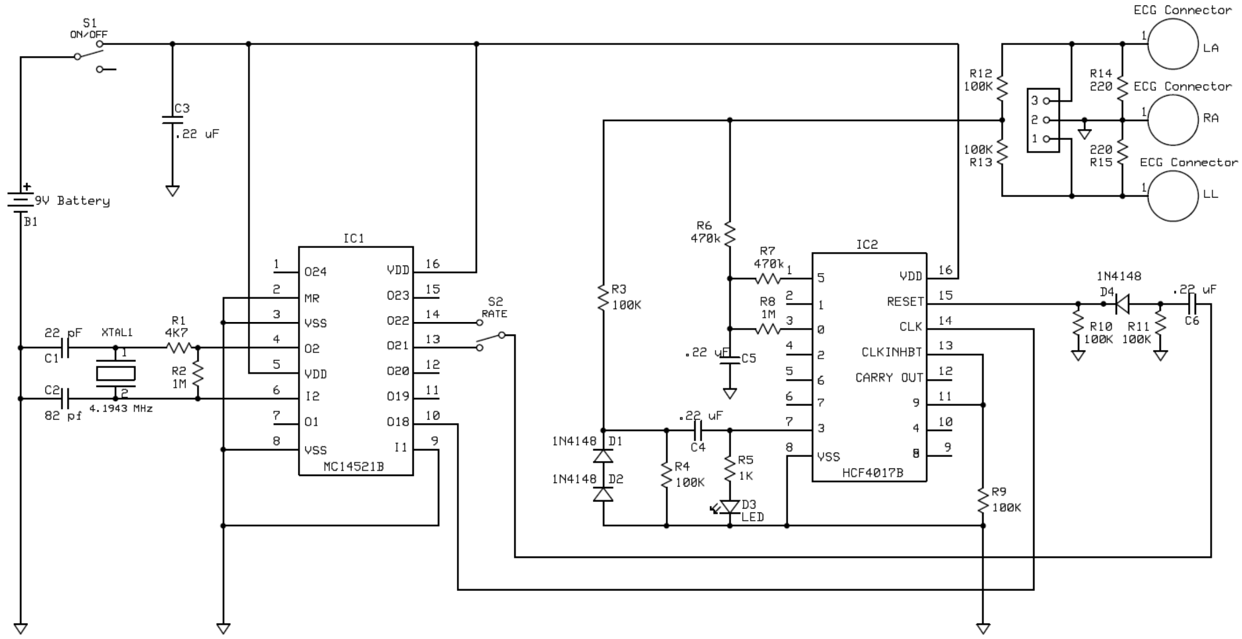


Figure 1 – ECG Simulator electronic schematic diagram.

Oscillator and Frequency Divider

The first digital block in Figure 2 corresponds to an oscillator and a 24 bits counter (IC1 - MC14521B).

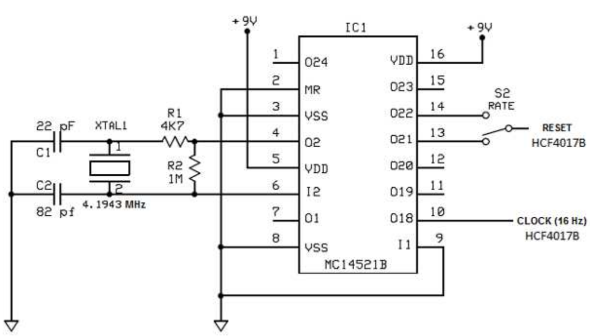
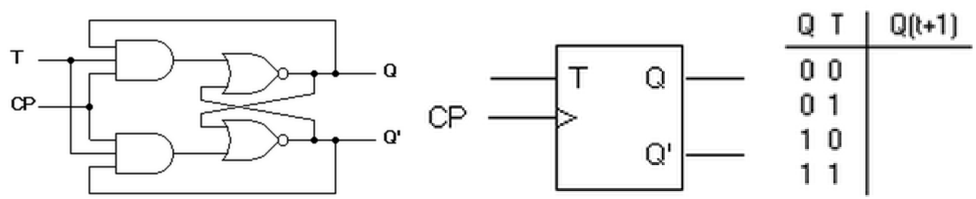


Figure 2 – First frequency dividers stage formed by the MC14521B IC and the oscillator components.

The Oscillator and Frequency Divider chip can generate its own clock in the inputs O2 and I2. The 4.1943 MHz crystal oscillating frequency is suggested by the manufacturer in datasheet[2].

1. The MC14521B has a chain of 24 toggle (T) flip–flops. Observe the flip–flop internal connections in Figure 3 (a) and fill the transition table in Figure 3 (c):[3]



(a) (b) (c)

Figure 3 – Toggle flip-flop Logic diagram (a), graphical symbol (b) and transition table (c).[3]

2. Figure 4 shows the last 7 outputs from the MC14521B IC.

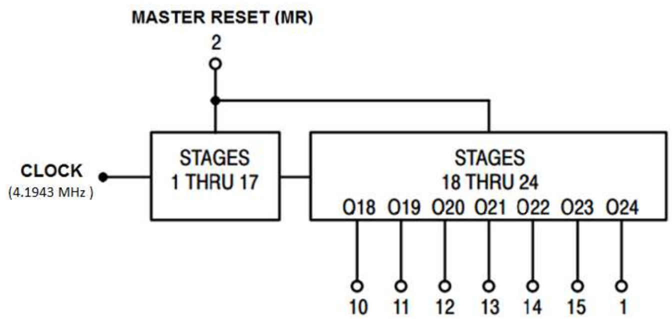


Figure 4 - MC14521B block diagram.[2]

What is the maximum value that this circuit can count?

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3. For an input clock of 4.1943 MHz, calculate the frequencies in Table 1 for the pin 10, 13 and 14 from Figure 4.

Table 1 - MC14521B output frequencies for a 4.1943 MHz input clock. O21 and O22 signals are used to select the heart rate, depending of the position from the S2 switch.

Output	Pin	Frequency (Hz)	Period (s)
O18	10		
O21	13		
O22	14		

Reset Circuit

4. The outputs O21 or O22 from the IC1 are used to reset IC2, therefore, restarting the ECG waveform. What is the expected heart rate (bpm)?

   ____

Use the capacitor charging formula from an RC circuit in Equation 1 to calculate the signals in the points A and B from Figure 5:

$$V_C = (V_1 - V_0)e^{\frac{-t}{(R*C)}} \qquad (1)$$

where:

- V_1 is the final charging voltage, (V)
- V_0 is the initial charging voltage, (V)
- R is the resistance value, (Ω)
- C is the capacitance value, (F)

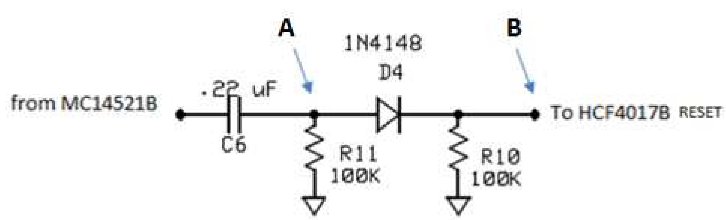

Figure 5 – IC2 reset circuit.

5. Using the Equation 1, calculate and draw in

Voltage Resolution: _______________
Time Resolution: _________________

(c) Waveform in point A if O22 is the input signal

Voltage Resolution: _______________
Time Resolution: _________________

(d) Waveform in point B if O22 is the input signal

6. Figure 6 the waveforms in points A and B from Figure 5 for the signals from the outputs O21 or O22 of IC1 (MC14521B).

Voltage Resolution: _______________
Time Resolution: _________________

(a) Waveform in point A if O21 is the input signal

Voltage Resolution: _______________
Time Resolution: _________________

(b) Waveform in point B if O21 is the input signal

Voltage Resolution: _______________
Time Resolution: _________________

(c) Waveform in point A if O22 is the input signal

Voltage Resolution: _______________
Time Resolution: _________________

(d) Waveform in point B if O22 is the input signal

Figure 6 – Reset waveforms from IC1's (MC14521B) outputs in points A and B.

7. What is the reason to use the diode D4 in the reset circuit?

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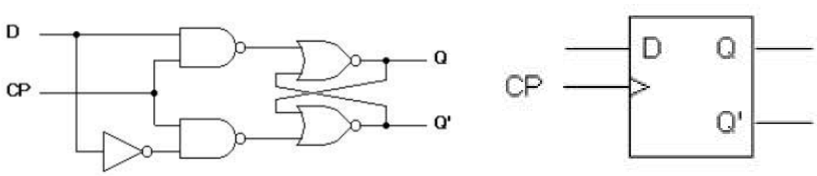
Ring Counter

The HCF4017B uses Data (D) flip–flops logic, shown in Figure 7 (a) and (b).

8. Observe the flip–flop internal connections and complete the transition table in Figure 7 (c):[3]



Q D	Q(t+1)
0 0	
0 1	
1 0	
1 1	

(a) (b) (c)

Figure 7 – Data flip-flop Logic diagram (a), graphical symbol (b), and transition table (c).

The HCF4017B has a similar patter as the chain of 10 Data (D) flip–flops in Figure 8.

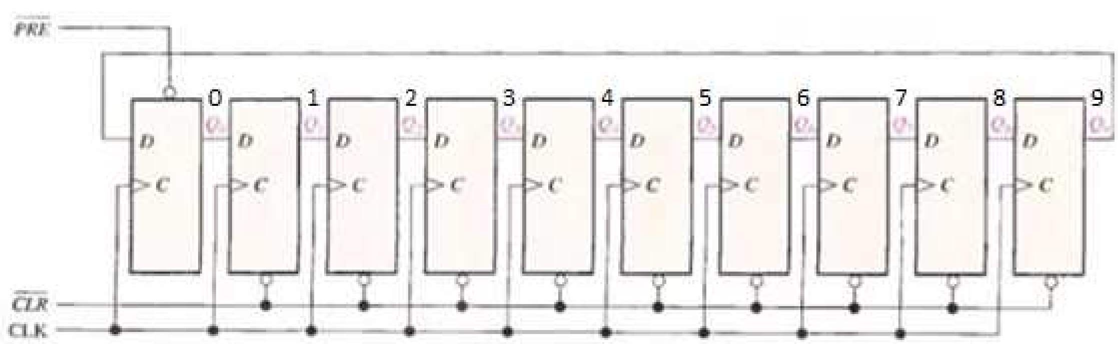


Figure 8 – HCF4017B counting equivalent circuit.

9. Supposing that the initial/reset state of Figure 8 has the signal 9 (Q9) in logic high (9 V) and the remaining outputs are down (0 V), complete the Timing diagram in Figure 9.

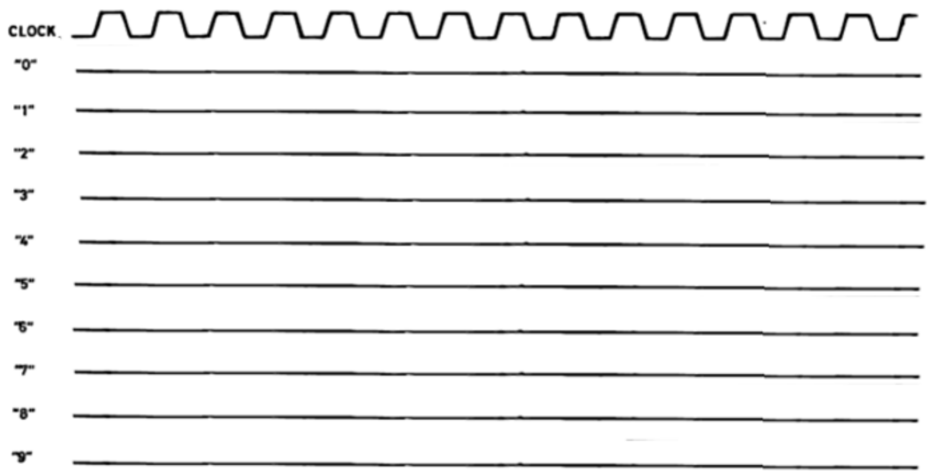


Figure 9 - Timing diagram of the HCF4017B counter output signals.

Output Signal Conditioning

The third stage in the simulator corresponds to a network of resistors that sums their current to shape the ECG wave. Since the HCF4017B has CMOS technology, whenever the logic level is zero, one can consider the outputs as open, which allow the analysis of each circuit branch separately. Only the P, R, S and T sections are generated.

P Wave Circuit

Figure 10 shows the circuit responsible for the P wave

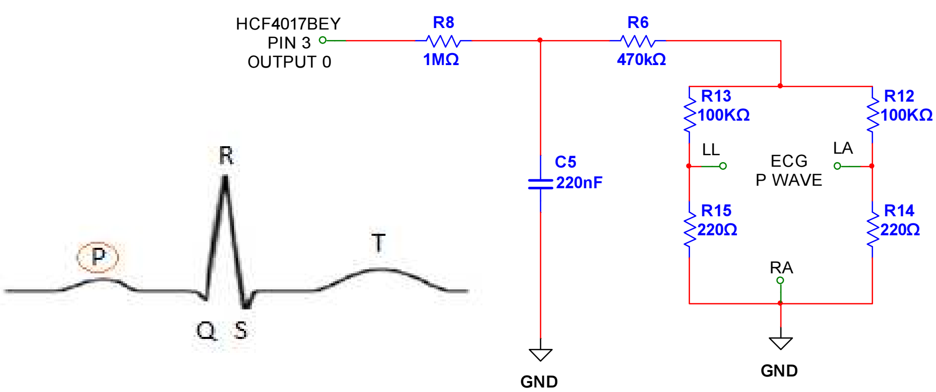


Figure 10 – P wave output circuit.

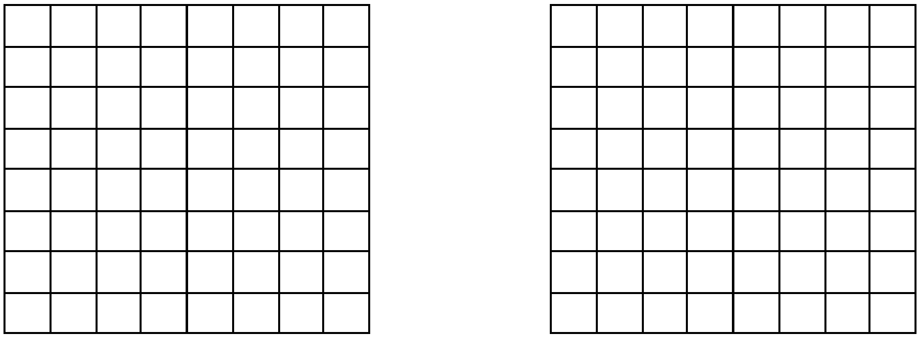
10. Remove the capacitor C5 from the circuit in Figure 10 and use Thévenin's Theorem to calculate and draw in Figure 11 the equivalent voltage and resistance during the capacitor charge.

Figure 11 – Thévenin's equivalent circuit for the charge for the capacitor C5 during the P wave.

11. Supposing that the pin 3 (output 0) from the HCF4017B opens when the logic is "0", draw in Figure 12 the capacitor C5 discharge circuit for the P wave.

Figure 12 – Capacitor C5 discharge circuit during the P wave.

12. Using the frequency that was found for the HCF4017BEY pin 3, use Equation 1 to calculate and draw in Figure 13 the signal in the points LL and LA in relation to the ground GND (RA) during the P waveform.



Voltage Resolution: ________________
Time Resolution: __________________

(a) Voltage in capacitor C5

Voltage Resolution: ________________
Time Resolution: __________________

(b) LL and LA output signals

Figure 13 – P wave circuit signals.

R and S Wave Circuit

Figure 14 shows the circuit that supplies the R and S wave segment.

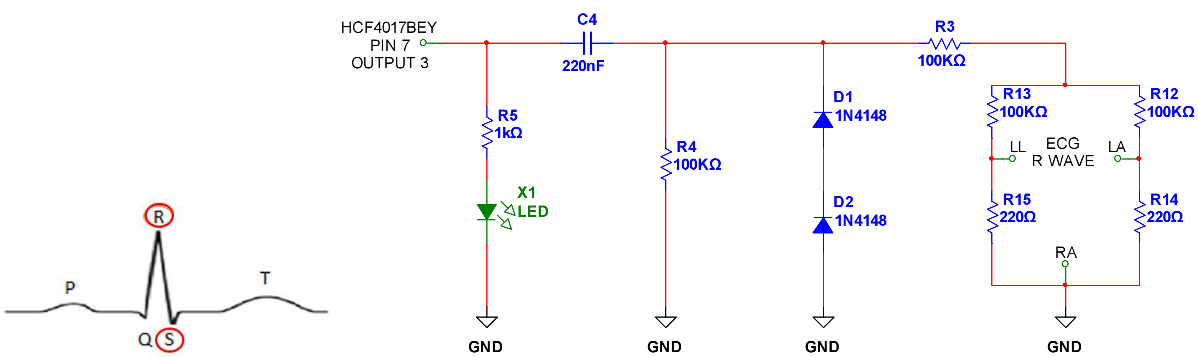


Figure 14 – R, S wave output circuit.

13. What is the reason to use the LED X1 in the circuit of Figure 14?

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14. Draw in Figure 15 the simplified circuit for the capacitor charging, considering that pin 7 (output 3) is in logic “1” (9 V).

Figure 15 – Simplified circuit for the charge of the capacitor C4 during the P wave.

15. Supposing that pin 7 (output 3) from the HCF4017B chip opens when the logic is “0”, draw the capacitor C4 discharge circuit in Figure 16. This signal will be the S segment of the ECG signal.

Figure 16 – Capacitor C4 discharge circuit during the S wave.

16. What is the reason to use the diodes D1 and D2 in the circuit of Figure 14?

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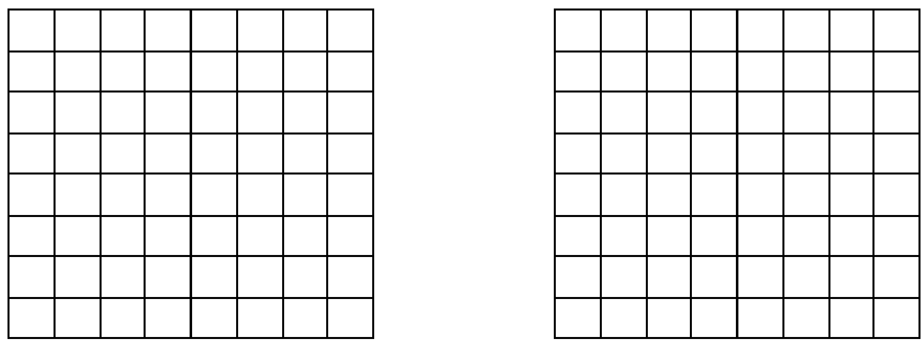
17. Using the frequency found for the HCF4017BEY pin 7, use Equation 1 to calculate and draw in Figure 17 the signal in the points LL and LA in relation to the ground GND (RA) during the R and S waveform.



Voltage Resolution: _______________
Time Resolution: _________________

Voltage Resolution: _______________
Time Resolution: _________________

(a) Voltage in capacitor C4 (b) LL and LA output signals

Figure 17 – R and S wave circuit signals.

T Wave Circuit

The last component of the ECG signal is the T wave. The circuit that shapes this signal (Figure 18) is almost the same as the P wave, except that in pin 1, the series resistance value decreases from 1 MΩ to 470 kΩ.

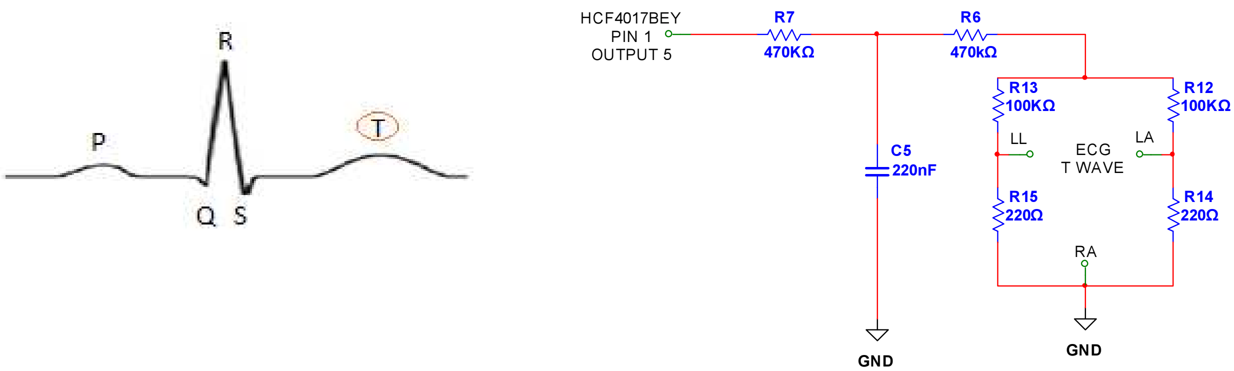


Figure 18 – T wave output circuit.

18. If the resistance value decreases, what should happened with the charging time and the amplitude of the T signal compared to the P phase?

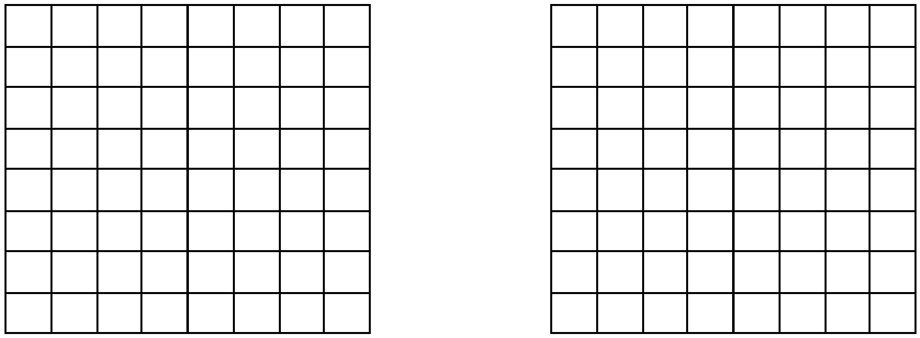
19. Use Thévenin's Theorem to calculate the equivalent voltage and resistance during the capacitor charge when the pin 1 (output 5) is in logic "1". Draw this circuit in Figure 19.

Figure 19 – Thévenin's equivalent circuit for the charge for the capacitor C5 during the T wave.

20. Supposing that pin 1 (output 5) from the HCF4017B chip opens when the logic is "0", draw in Figure 20 the capacitor C5 discharge circuit for the T wave.

Figure 20 – Capacitor C5 discharge circuit during the T wave.

21. Using the frequency found for the HCF4017BEY pin 3, use Equation 1 to calculate and draw in Figure 21 the signal in the points LL and LA in relation to the ground GND (RA) during the T waveform.



Voltage Resolution: ________________
Time Resolution: __________________

Voltage Resolution: ________________
Time Resolution: __________________

(a) Voltage in capacitor C5

(b) LL and LA output signals

Figure 21 – T wave circuit signals.

Final Waveform

22. Using the waves from Figure 13, Figure 17 and Figure 21 draw in Figure 22 the final ECG signal expected in the outputs LA and LL in relation to RA.

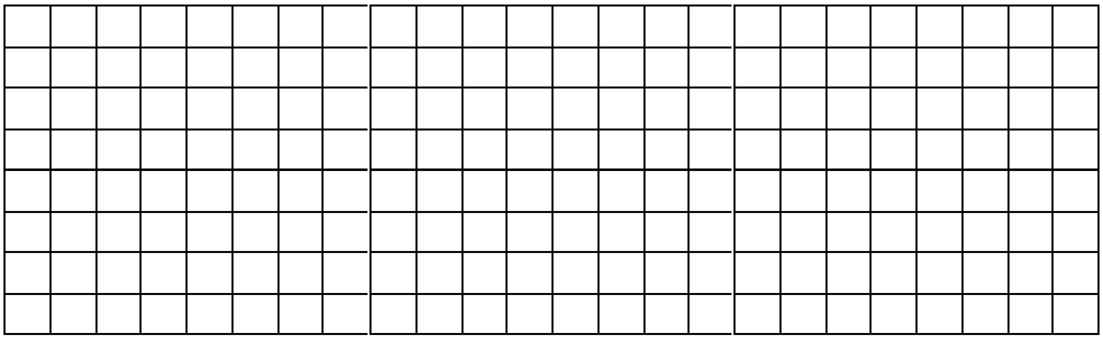


Figure 22 – ECG simulator final waveform.

References

1. Webster, J. G. *Medical Instrumentation Application and Design [Hardcover]*. 720 (Wiley; 4 edition, 2009).

2. ON Semiconductors. MC14521B, 24 - Stage Frequency Divider. (2013). at <http://www.onsemi.com/pub_link/Collateral/MC14521B-D.PDF>

3. Mano, M. M. *Digital design*. 492 (Prentice-Hall, 1984).

4. Dorf, R. C. & Svoboda, J. A. *Introduction to Electric Circuits*. 886 (John Wiley & Sons, 2010).

5. STMicroelectronics. HCF4017B - Decade counter with 10 decoded outputs. (2001). at <http://www.st.com/st-web-ui/static/active/en/resource/technical/document/datasheet/CD00000366.pdf>

Appendix

Basic Heart Anatomy

The cardiovascular system is responsible for circulating blood throughout the body to supply the tissues with oxygen and nutrients. The heart is the muscle responsible for pumping blood to and through the vessels. It is divided into four chambers: right atrium, right ventricle, left atrium, and left ventricle, as seen in Figure 23. There are valves between each atrium and ventricle and in the ventricle output to prevent backward flow. The average adult cardiac rate is 60 beats per minute; however, this rate increases to 120 in the case of infants. The heart contraction stimulus is caused by an electrical signal that initiates at the Sinoatrial (SA) node, located at the top of the right atrium.

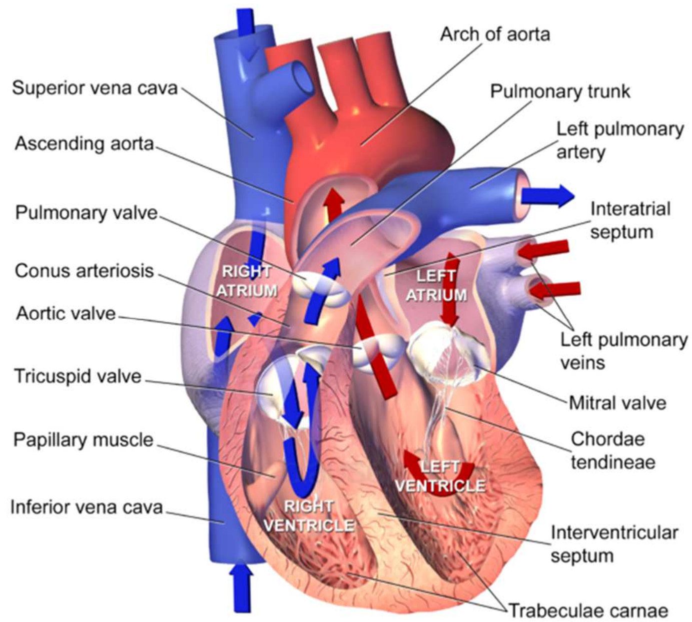


Figure 23 – Sectional anatomy of the heart (Blausen Medical Communications via Wikimedia Commons)..

Principles of Electrocardiography

The small electrical signal (mV) produced in the heart can be measured through a device called an electrocardiogram (ECG). This instrument allows the physician to know the rate and regularity of heartbeats, as well as the size and position of the chambers, the presence of any damage to the heart, and the effects of cardiac drugs or devices. A basic ECG requires at least three connections, which form Einthoven's triangle in Figure 24.

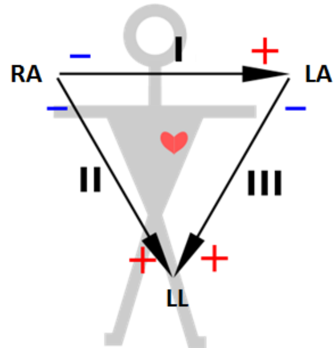


Figure 24 – Einthoven's triangle. Signal I corresponds to the traditional ECG waveform (Kychot via Wikimedia Commons).

Signal I shows the voltage between the (positive) left arm (LA) electrode and the right arm (RA) electrode:

I = LA - RA

Signal II shows the voltage between the (positive) left leg (LL) electrode and the right arm (RA) electrode:

II = LL - RA

Signal III shows the voltage between the (positive) left leg (LL) electrode and the left arm (LA) electrode:

III = LL – LA

The electronic component used for ECG measurement is called an instrumentation amplifier. It has a high gain (multiplies many times the original signal) and requires very low input currents. Inside of this amplifier, there are differential blocks, such as in Figure 25. These circuits are able to measure signals I, II and III directly from the patient's leads.

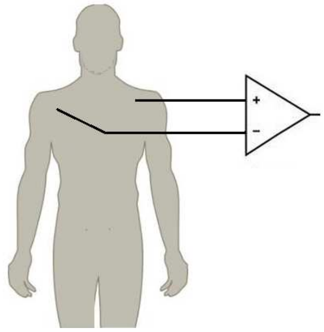


Figure 25 – The ECG measurement circuit uses a differential amplifier to subtract the voltages between the right and left arm (BotMultichill via Wikimedia Commons).

Figure 26 shows a standard ECG signal (II) divided into five parts: P-QRS-T. The P wave represents atrial depolarization, and the QRS represents ventricular depolarization. The T wave reflects the phase of rapid repolarization of the ventricles.

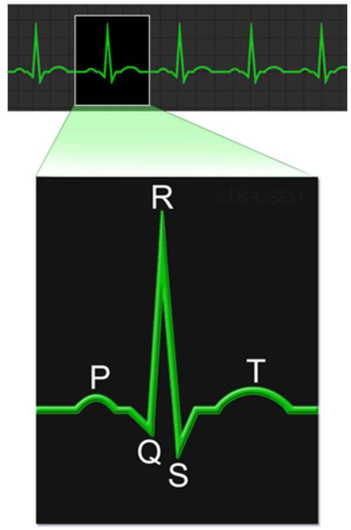


Figure 26 – Normal heart beat electrocardiogram wave signal (Blausen Medical Communications via Wikimedia Commons).

Parts List

The EWH ECG Simulator package should contain the Printed Circuit Board (PCB) and the components listed in Table 2. Do not remove them from the package until you read the "Assembling Instructions" document. If mixed, some parts cannot be identified without test instruments.

Table 2 – ECG Simulator Kit part list.

Description	Value	Quantity	Schematic ID
Resistor	4700 Ohm (4K7)	1	R1
Resistor	1,000,000 Ohm (1M)	2	R2, R8
Resistor	100, 000 Ohm (100K)	7	R3, R4, R9, R10, R11, R12, R13
Resistor	1,000 Ohm (1K)	1	R5
Resistor	470,000 Ohm (470K)	2	R6, R7
Resistor	220 Ohms	2	R14, R15
Capacitor	22 Pico farad (22 pf)	1	C1
Capacitor	82 Pico farad (82 pf)	1	C2
Capacitor	220 Nano farad	4	C3, C4, C5, C6

	(.22 uf)		
Diode	1N4148	3	D1, D2, D4
LED	3 mm red	1	D3
Integrated Circuit	4521	1	IC1
Integrated Circuit	4017	1	IC2
Crystal	4.1943 MHz	1	XTAL1
ECG Connectors Sew-on Snaps	N/A	3	ECG Connectors (LA, RA, LL)
ECG Connector Header Contact	N/A	1	N/A
Switches	N/A	2	S1, S2
Battery Connector	N/A	1	N/A
PCB Rubber Feet	N/A	4	N/A
Printed Circuit Board	N/A	1	N/A