



Class #6: Experiment The 555-Timer & Pulse Width Modulation

Purpose: In this experiment we look at the 555-timer, a device that uses digital devices and other electronic switching elements to generate pulses.

Background: Before doing this experiment, students should be able to

- Analyze simple circuits consisting of combinations of resistors.
- Do a transient (time dependent) simulation of circuits using LTspice
- Build simple circuits consisting of combinations of resistors on protoboards and measure input and output voltages vs. time.

Learning Outcomes: Students will be able to

- Characterize the operation of a 555 Timer in Astable Multivibrator configuration both experimentally and using SPICE simulation.

Equipment Required:

- **Analog Discovery** (with Waveforms Software)
- **Voltmeter** (DMM or Analog Discovery)
- **Oscilloscope** (Analog Discovery)
- **Function Generator** (Analog Discovery)
- +5V (+Vcc) Power Supply (Analog Discovery, be sure to use V+ and Ground ***and not V-***)
- 555-Timer IC

Pre-Lab

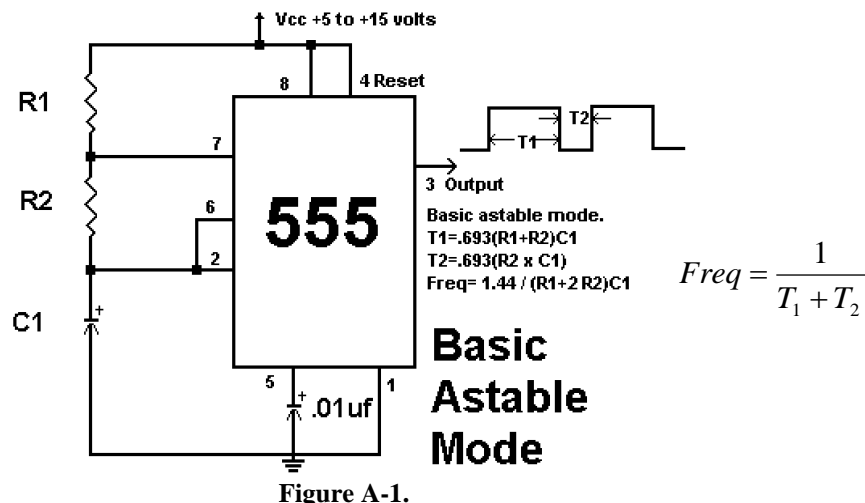
Required Reading: Before beginning the lab, at least one team member must read over and be generally acquainted with this document and the other materials listed for this class.

Hand-Drawn Circuit Diagrams: Before beginning the lab, hand-drawn circuit diagrams must be prepared for all circuits either to be analyzed using SPICE or physically built and characterized using your Analog Discovery board.

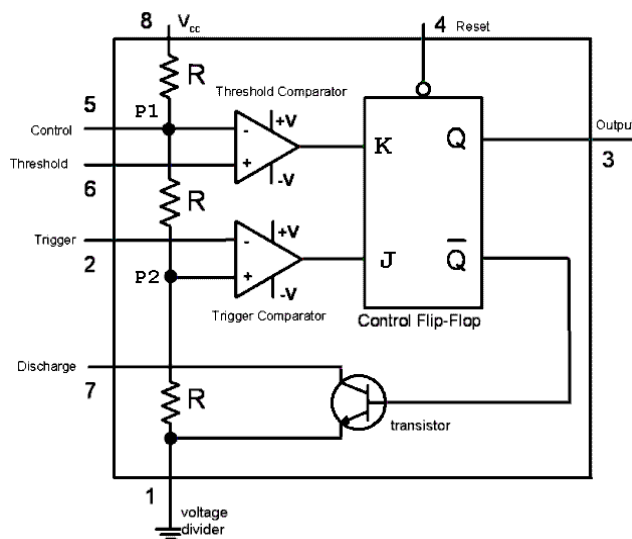
Part A – The 555-Timer

Background

The 555-Timer: The 555-timer is a chip that allows us to create a variety of useful digital and analog signals. Much like the op-amp, it can be used to perform different functions depending upon what circuit you place it into. The 555-timer can be used to generate digital pulses. When it is wired as a “one-shot” (also called mono-stable mode), it generates a single, clean, digital pulse at the output, when it experiences a (possibly noisy) pulse at the input. This is useful when de-bouncing a mechanical switch or in the famous ‘Clapper’ circuit. In this experiment, we are concerned with the 555-timer when it is wired in astable mode. This is also called an astable multivibrator. In this mode, the 555-timer circuit creates a stream of regular pulses. The wiring diagram for the 555-timer in astable mode is shown in Figure A-1.



Inside the 555-Timer: In order to understand how the 555-timer can create this regular stream of pulses, we need to look inside and see how it functions. As you can see in Figure A-2, the inside of the device contains many of the components we have not yet studied. We will, as one of our goals in this class is to understand the functioning of this clever device. In this experiment, we will focus on what the 555 IC does rather than on how it does it.



First note that there is a **voltage divider** along the left side of the diagram. This divides a DC source voltage at V_{cc} into three equal voltages. Therefore, P1 is equal to $(2/3)V_{cc}$ and P2 is equal to $(1/3)V_{cc}$. The voltage divider is the only part of the 555 that we have discussed so far. The other devices inside the 555 will be mentioned now, but only focus on what their job is, not on how they do it. Next to the voltage divider, there are two comparators. The Threshold Comparator compares the voltage at pin 6 (the Threshold) to the voltage at P1. The Trigger Comparator compares the voltage at pin 2 (the Trigger) to the voltage at P2. The outputs of these two comparators are used to control a flip flop. The output of the flip flop is attached to the 555-timer chip's pin 3 (Output). The 555-timer chip has one more feature, a transistor switch. This switch will be off when the Output pin is high and the signal at pin 7 (Discharge) will not be influenced by the switch. When the Output pin 3 is low, however, the transistor switch is closed. This forces the Discharge pin to ground. The key take-away point is that pin 7 will either be floating (not connected to anything) or will be connected to ground. This is controlled by the transistor acting as a switch. How this is used is discussed in the next paragraph.

The 555-Timer in Astable mode: When we wire the 555-timer in astable mode, we create a circuit that generates a string of pulses with the same period and duty cycle. The nature of these pulses is determined by the values of the R1, R2, and C1

located outside of the timer in the diagram for the Basic Astable Mode on the previous page. We have seen that when current flows through a series combination of a resistor R and a capacitor C, that the circuit responds with a characteristic time constant $\tau = RC$. The on-time for each pulse is determined by how fast the capacitor C1 charges when the transistor switch is open and the output of the timer chip at pin 3 is high. In this case, the capacitor is attached to the source voltage through the resistors R1 and R2. The charging time constant is $\tau_{\text{charge}} = C1(R1+R2)$. When the capacitor has charged up to $(2/3)V_{CC}$, the Threshold Comparator tells the flip flop to switch, the output goes low and the transistor switch closes. The off-time for each pulse is determined by how fast the capacitor discharges to ground through the transistor. The discharge path is through R2 to pin 7 to ground, so the discharging rate is $\tau_{\text{discharge}} = C1(R2)$. When the capacitor has discharged down to $(1/3)V_{CC}$, the Trigger Comparator tells the flip flop to switch again, the output goes high, the transistor opens, and the capacitor is no longer attached to ground at pin 7. The capacitor begins to charge again and the cycle repeats.

By selecting just the right values for the resistors and capacitors in this circuit, we can make the voltage at pin 3 (the OUTPUT) go from zero to V_{CC} at whatever rate we desire. We can also control the percentage of time that the output will be on relative to the length of an entire cycle. The equations that govern this behavior are:

$$T_{ON} = 0.693(R1 + R2)C1 \quad T_{OFF} = 0.693(R2)C1 \quad f = \frac{1}{T_{ON} + T_{OFF}} = \frac{1.44}{(R1 + 2R2)C1}$$

Pulse width modulation: One of the most important things we can use 555-timers for is to control and drive a large variety of systems with pulse width modulation. The power of pulse width modulation comes from its simplicity. Rather than controlling the flow of some liquid by carefully opening a valve part way, you can alternately open and close the valve fully in such a manner that the average open time produces the same effect as a partially open valve. In effect, the rate of flow is controlled by the duty cycle of the controlling voltage. It is much easier to fully open or close a valve than to precisely open it part way. One can also apply power to a motor in this manner to control the speed of rotation or to an LED to control light level. The key goal of this modulation process is to achieve a desired average value for some process. The range of possibilities is shown in Figure A-3 where A has a high duty cycle (fast) and C a low duty cycle (slow).

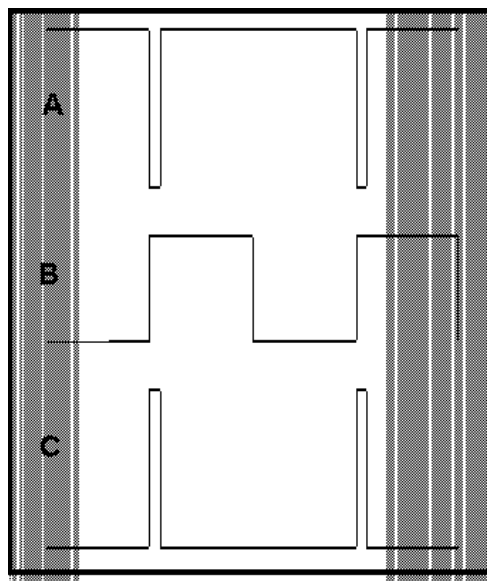


Figure A-3.

Experiment

Simulation of a 555-timer circuit

In this part of the experiment, we will use LTspice IV to demonstrate the operation of the 555-timer chip in astable mode.

- Draw the circuit in Figure A-4 in LTspice.

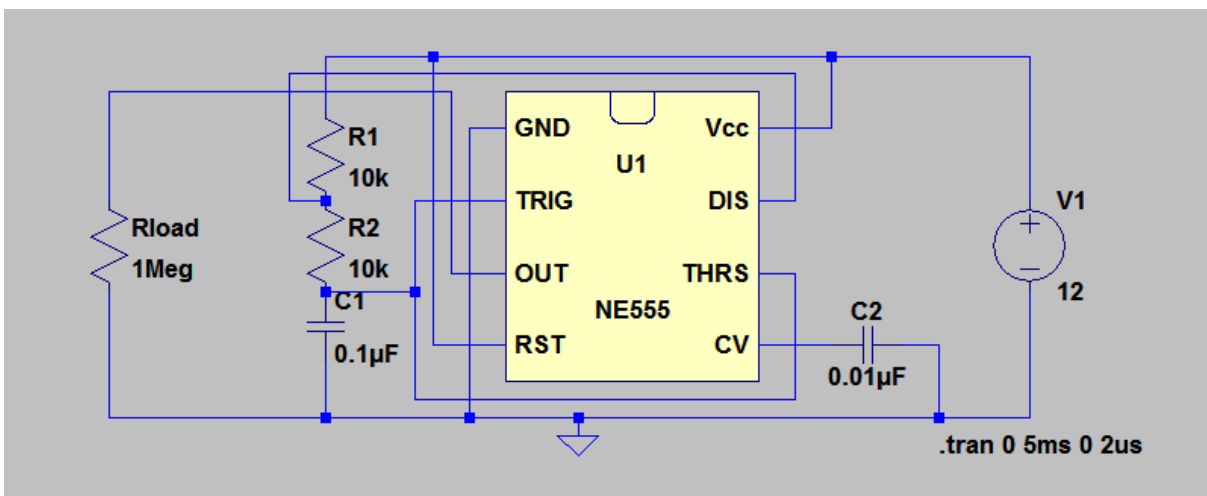


Figure A-4.

- Run the simulation.
 - Perform a transient analysis in increments of 2µs up to 5ms.
 - Plot the threshold/trigger, discharge and output voltages. The trigger voltage is pin 2 and the threshold voltage is pin 6. (They are tied together by the external circuit.) The discharge voltage is pin 7, and the output is taken at pin 3.
 - Include a copy of the plot and your circuit in your report.
 - Verify that the timer output changes according to the rules listed for the 555-timer in astable mode. Use the plot to find the time period that the output is ON and the time period that the output is OFF. *Note: Do not use the first cycle of pulses produced by the timer circuit. It takes one cycle to settle in to its steady-state condition.* One of these times should be equal to $0.693(R1+R2)C1$ while the other should be equal to $0.693(R2)C1$. Which is which? What is the total period of this output? To be able to read the times more easily, use the cursors. To open a cursor, use your mouse to click on the name of the output voltage at the top of the screen. To add a second cursor (to read both ends of a time period simultaneously), click on the voltage name again. The locations of the cursors will be displayed in the cursor window. (See Figure A-5) When your mouse nears the location of a cursor on the screen, its number will appear. Then you can move it wherever you wish.
 - Which of the three signals on your plot corresponds to the charging and discharging of the capacitor, C1? To what voltage does it charge each time? To what voltage does it discharge? What is the rate of charge? Is the rate of discharge the same?

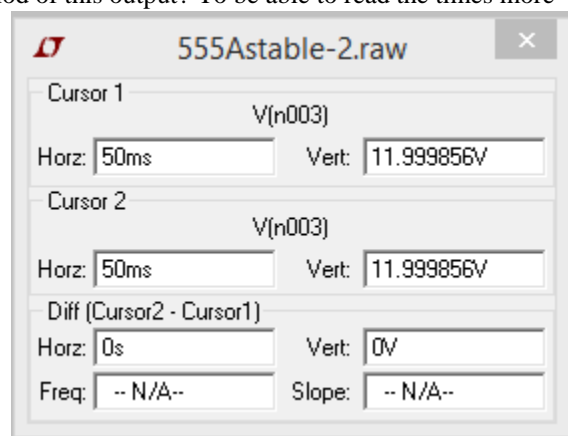


Figure A-5

- Determine the average voltage of the signal.
 - Change the end time for the transient analysis to 100ms.
 - Display only the output voltage (pin 3) on your plot.
 - Rerun the simulation.
 - Hold down the Ctrl key and click on the name of the voltage trace again. This time a new window will appear that shows the average of the signal for the time period displayed in the plot.
 - Copy the plot generated for the output voltage and label it with its duty cycle and average output voltage. Show your annotated plot and live simulation to a TA or instructor, explain why your results make sense and then have them sign here. _____(TA/Inst)

- Find a larger and smaller average voltage for your circuit
 - Find an expression for the duty cycle of an astable 555-timer circuit using the equations given. Consider what relative values of R1 and R2 would produce the highest duty cycle and what relative values of R1 and R2 would produce the smallest duty cycle.
 - Now, using any combination for 3kΩ, 10kΩ or 30kΩ resistors (only one of each value) for R1 and R2, find the combination of two resistors which results in the largest average voltage and the combination of two resistors which results in the smallest average voltage.
 - Copy the plot for each of these two cases, write the values for R1 and R2 you used on each plot. Also have LTspice tell you the average output voltage, using the method described above, and add the average voltage to your plots. Include these two plots in your report.
 - Verify in each case that the pulses produced by the multivibrator circuit obey the design rules. If the simulation does not work, the design rules are probably violated.

Build the 555-timer circuit on your protoboard

In this part of the experiment, we will build the astable multivibrator and then see how it can be modified to produce slower and faster output pulses. We will observe the output pulses with a LED.

- Wire the astable multivibrator shown in Figure A-6 on your protoboard. Use the =5V DC output from the Analog Discovery board for V_{CC}. Use any color LED. It does not have to be red. Please pay close attention to the 555 Timer Chip pinouts, which are described in both the video and PowerPoint slides for this class. *Note: If you do not have components that match the ones in the circuit exactly, use the closest value. For example, for the 330Ω resistor, use the 470Ω in your kit.*

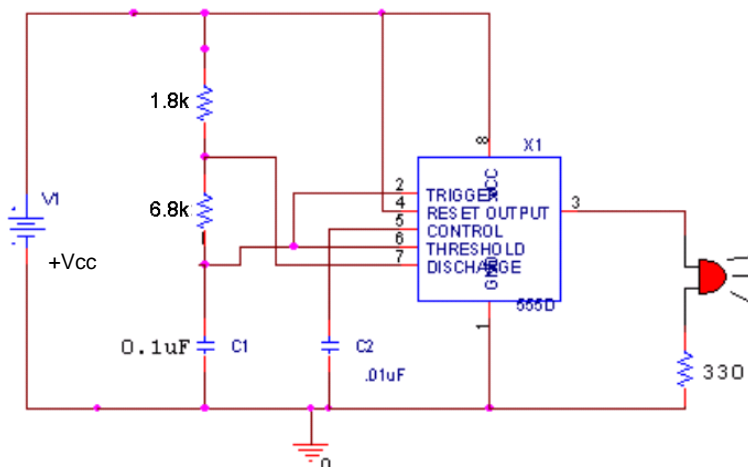


Figure A-6.

- Record your results.
 - You will not be able to see the LED flash because the period of your circuit is too fast.
 - Take an Analog Discovery picture of your output. (That is, measure the output voltage with Channel 1)
 - Copy this plot and include it in your report.
 - What is the period of your output signal? What are the off-time and on-time? Use the equations to calculate what these values should be. How do they compare?
- Slow down the pulses so that you can observe them with the LED. ***Do not change components with power applied to the circuit. Turn power off before you make the changes and then turn it back on.***
 - Keeping the resistors R1 and R2 the same, determine a new value for C1 such that the period of the timer will be around 1 second.
 - Replace C1 in your circuit and observe the LED. Does it flash once a second?
 - What is your on-time and off-time now? How are these related to the on- and off-times of the original circuit? Why does this relationship hold? _____(TA/Inst)

Part B – Pulse Width Modulation

Background

For background, read the Wikipedia entry on Pulse Width Modulation. https://en.wikipedia.org/wiki/Pulse-width_modulation. Also, the Sparkfun tutorial: <https://learn.sparkfun.com/tutorials/pulse-width-modulation> and the information from All About Circuits: <http://www.allaboutcircuits.com/textbook/semiconductors/chpt-11/pulse-width-modulation/>. Do not expect to understand everything. Rather, focus on the main idea ... that duty cycle translates to signal average.

Experiment

Pulse Width Modulation with Analog Discovery

- Disconnect the 330Ω resistor (or 470Ω if that is what you are using) and the LED from the 555 Timer circuit and connect them to the first Analog Discovery function generator (AWG1) and ground. Measure the input voltage with Channel 1 of the scope. It is not necessary to measure across the LED in this experiment. W1 and 1+ are connected to the left end of the resistor and GND and 1- are connected to the bottom end of the LED. The circuit is shown in Figure B-1.
- Set up the function generator so that it produces a train of square pulses at a frequency of 1Hz, with maximum voltage = 3V and minimum voltage = 0V. That is, the pulses are only positive. The function generator window should look like the one in Figure B-2 below.

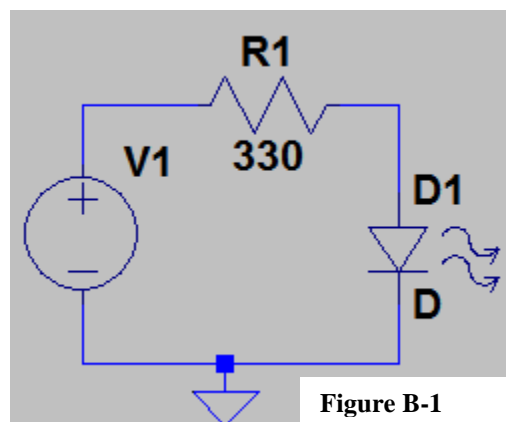


Figure B-1

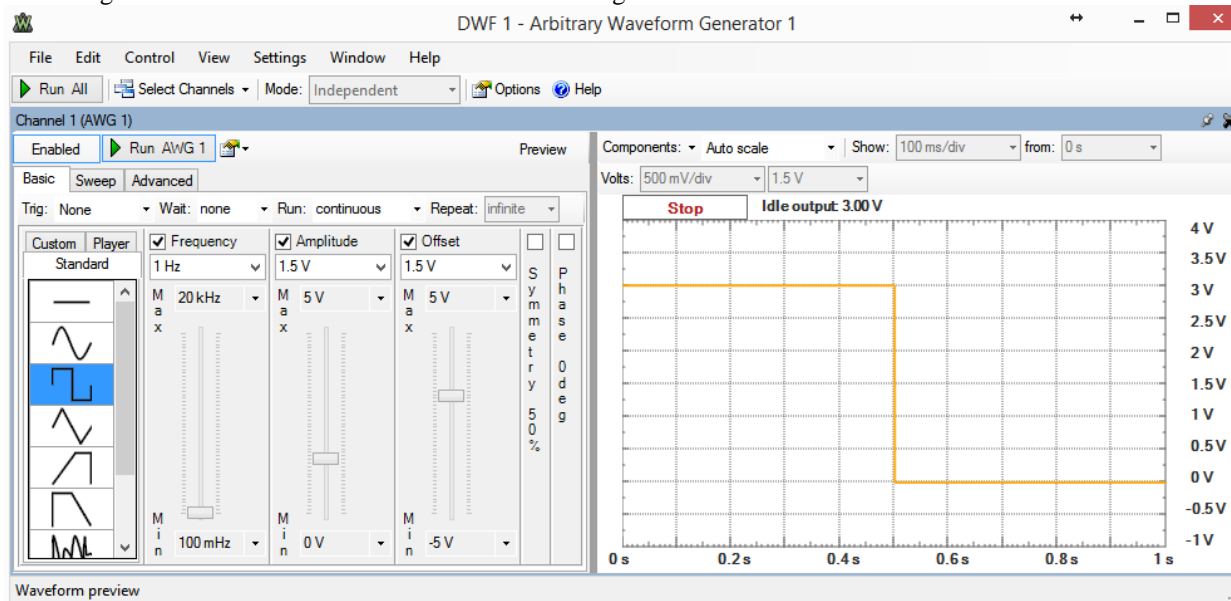


Figure B-2

- Turn on the function generator and describe what you see as you observe the LED.
- Next, check the box above the word ‘Symmetry.’ This will allow us to vary the duty cycle. Vary the duty cycle throughout its range from 0% to 100% and describe what you observe.
- Set the duty cycle back to 50%. Turn off the function generator. Now adjust the frequency to 200Hz (see Figure B-3 below). Describe what you see now. Again vary the duty cycle from 0% to 100% in steps of 10% and describe what you see. While you are varying the duty cycle, measure the voltage that is being produced by the function generator using a DC Voltmeter (the cheap \$3 meter from Harbor Freight will work just fine. Record the measurement for each duty cycle. _____(TA/Inst)

- Finally, at 50% duty cycle, reduce the frequency of the square pulses until you can see the LED flash. Observe the LED both directly and to the side using your peripheral vision. Record the value of the highest frequency that you are able to sense flashing looking in both directions. Are they the same? How does this frequency relate to the refresh rate of video displays?

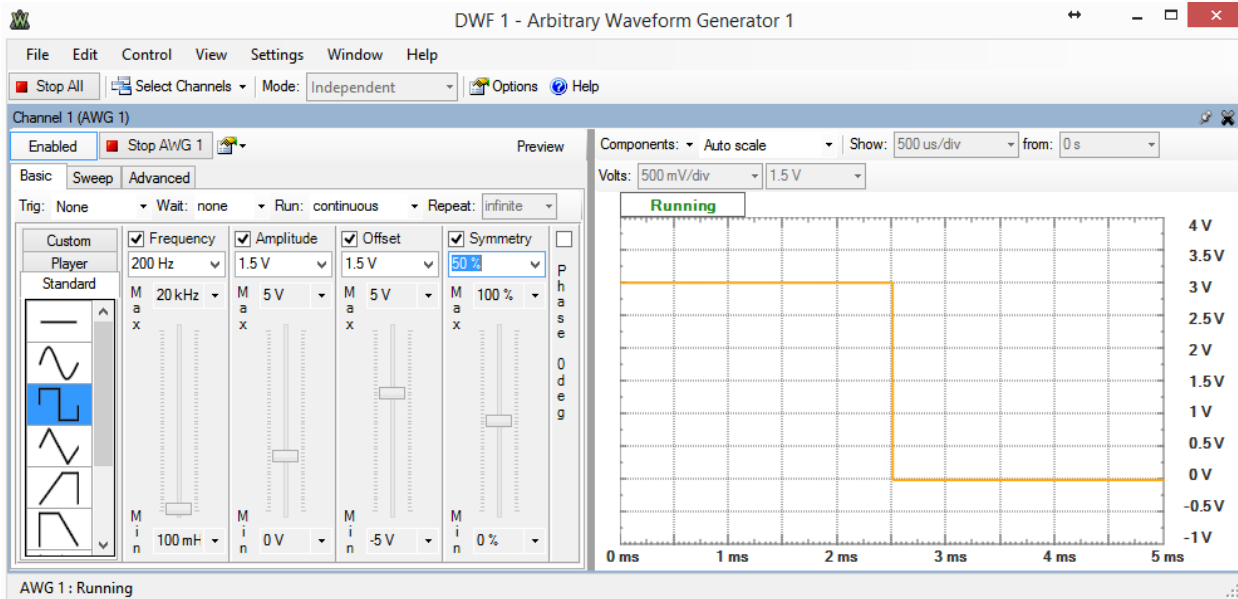


Figure B-3