Crystal Clear Electronics

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15 - PWM or Pulse-Width Modulation

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In a previous chapter we have learned about the NE555 integrated circuit and the astable circuit. In this chapter we will talk about a similar circuit shown on the schematic below.

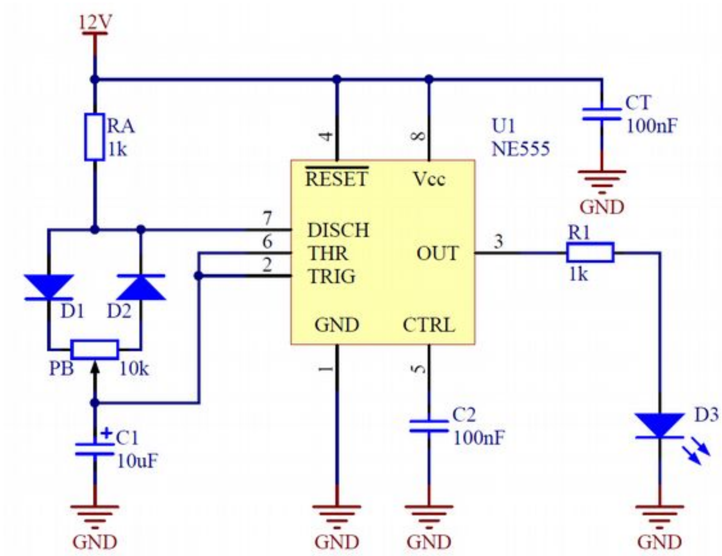
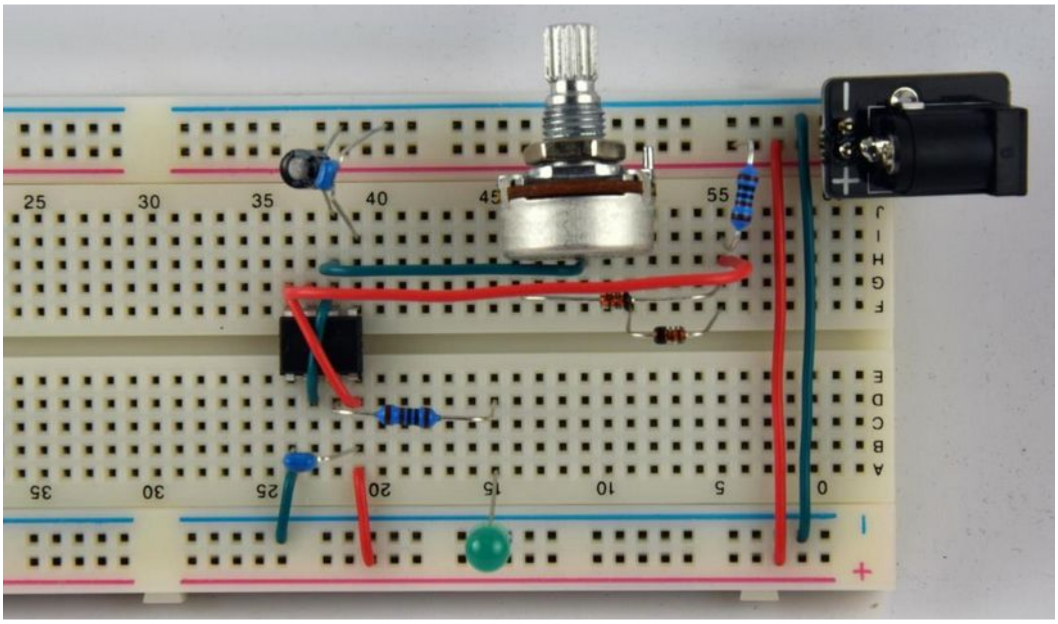


Figure 1 – Changing the brightness of a LED with NE555

Connect the components on a breadboard shown in the figure below:



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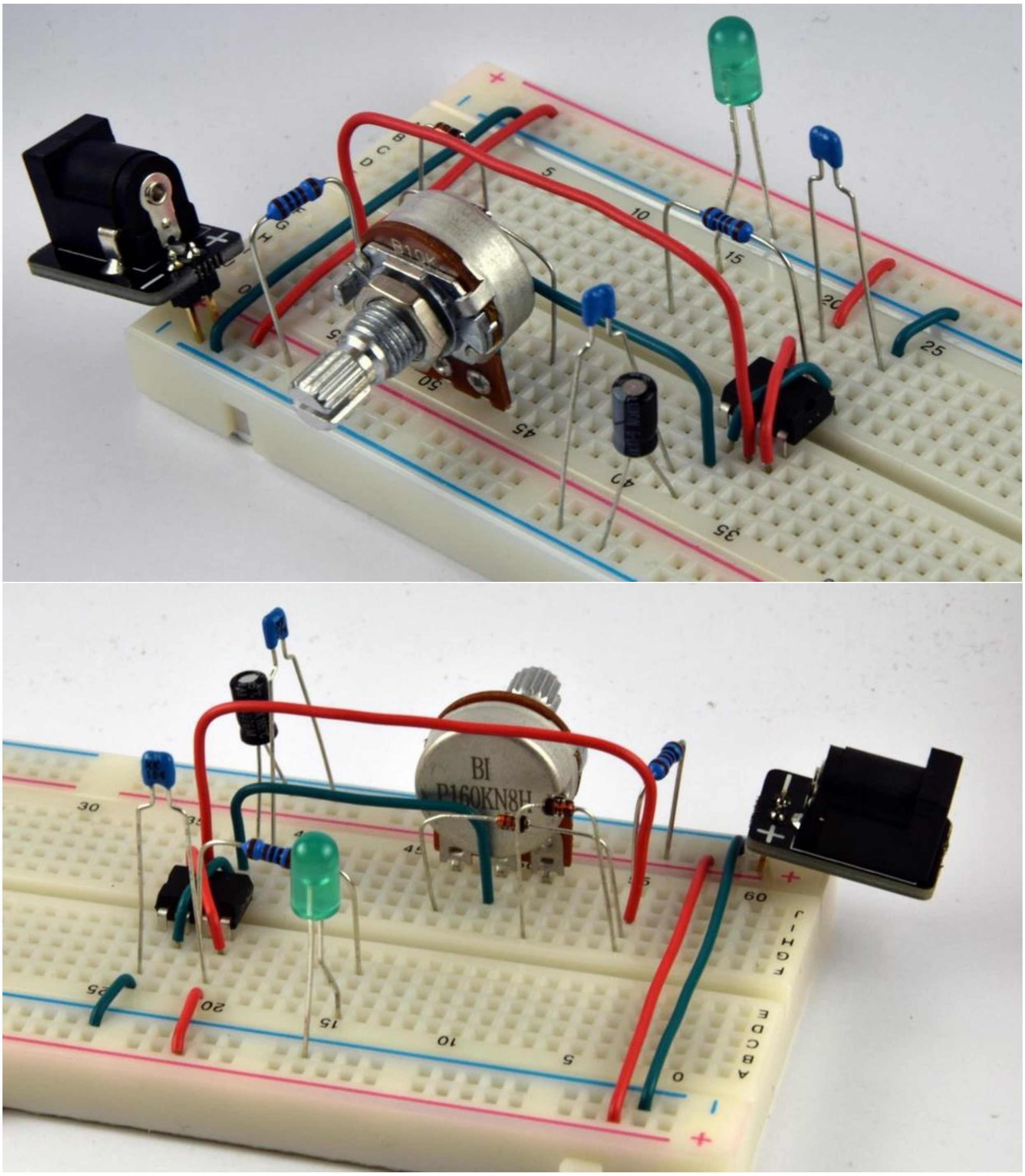

Figure 2 - The assembled circuit

When trying out the circuit you can see that if you adjust the potentiometer P_B the brightness of the LED changes. By following this chapter of the curriculum, you will learn why we have solved a very simple task using so many components and learn a very important and widespread control method as well.

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WHAT IS THIS CIRCUIT GOOD FOR?

First, check the output of the NE555 (3rd pin)! If we had an oscilloscope, we would measure signals similar to the ones on Figure 4.

Oscilloscope

An oscilloscope is an electronic test instrument that can examine how a voltage changes over time and display the waveform graphically.

Figure 3 – Oscilloscope
Author: Xato [Public domain]
https://commons.wikimedia.org/wiki/File:Oscilloscope_sine_square.jpg

The horizontal axis on the screen represents time and the vertical axis shows the voltage. The picture above shows a two-channel oscilloscope, that can measure two voltages at the same time. One of the inputs (the waveform on the top) is a triangle-wave, while the other input (the waveform on the bottom) is a square wave. You can also see that an oscilloscope is a pretty complex instrument, and they are expensive too.

If the potentiometer P_B is adjusted during measurement we can see an either increasing or decreasing duty cycle, while the frequency stays constant. The duty cycle is the ratio of “on time” and “off time” of the wave.

In Figure 4, all three signals are square waves with a frequency of 11 Hz, differing only in the duty cycle. The first waveform has a duty cycle of 30%, which means that 30% of the time the supply voltage appears on the output, while in the remaining 70% the output is 0 V (GND). This ratio is 50-50 in the second case, and 80-20 in the third.

Changing the duty cycle of a fixed-frequency signal according to an input value is called pulse-width modulation (PWM), or pulse-duration modulation (PDM).

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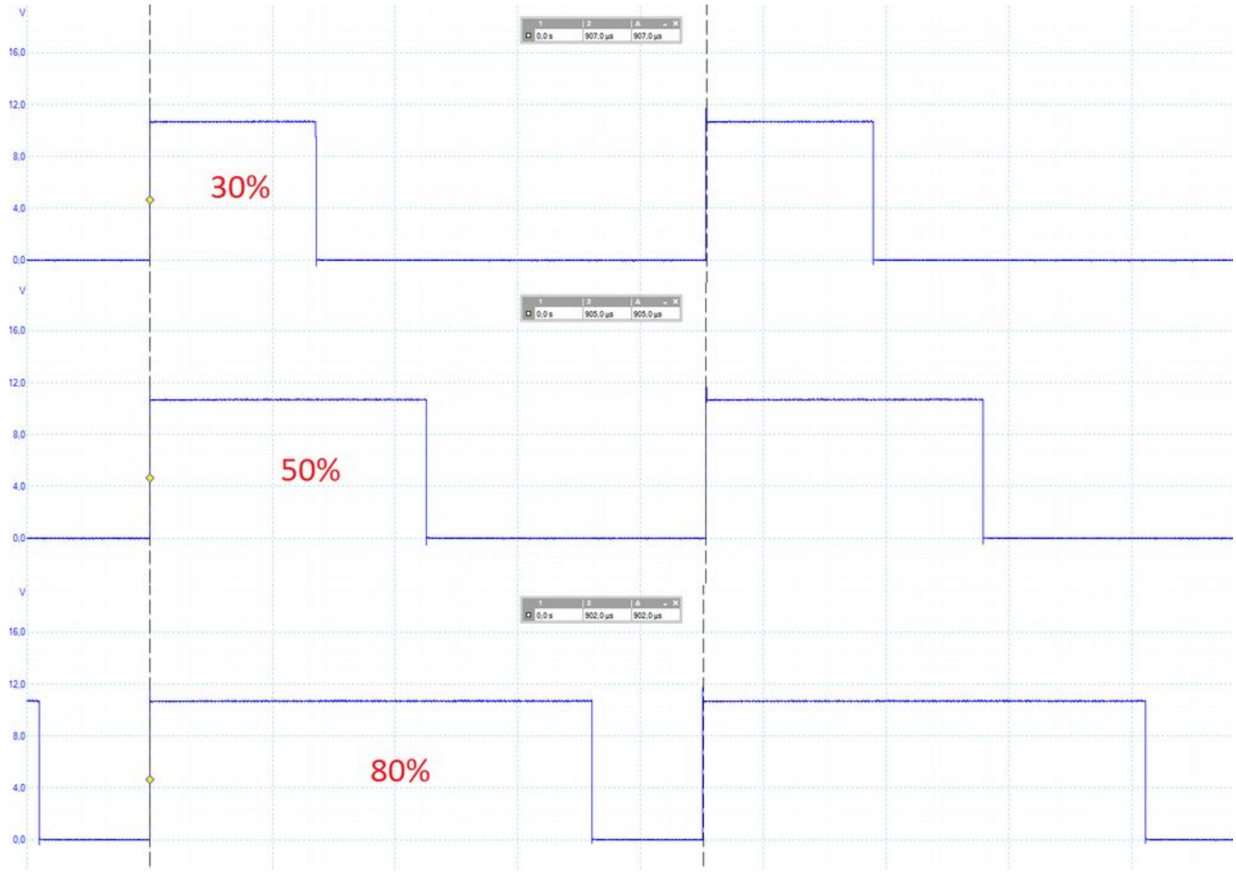

Figure 4 – PWM signals with different duty cycle

What Is It Good For, What Can PWM Be Used For?

Before understanding how the circuit introduced in the beginning, we must talk about PWM. To understand it easier, take a look at a simple example. Connect the output to an RC circuit, which is a resistor and a capacitor in series (also called RC filter). In the next example we are using a $R_1 = 330\ \Omega$ resistor and a $C_3 = 10\mu F$ capacitor.

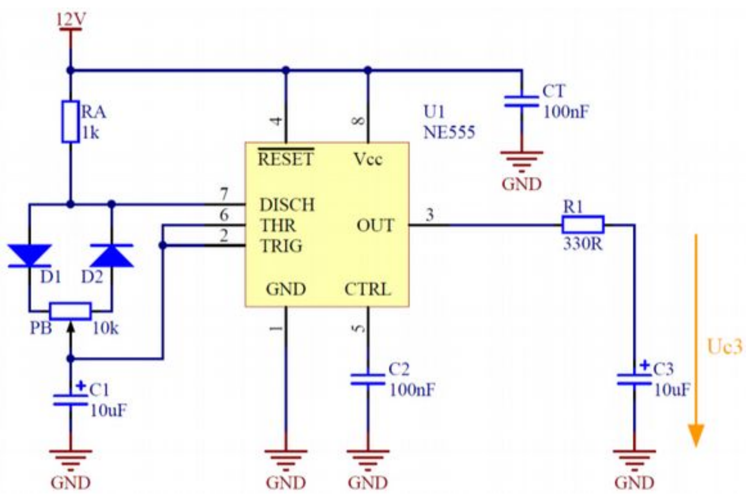

Figure 5 – PWM circuit, with and RC filter on the output

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If you would view the voltage on the capacitor of the RC filter with an oscilloscope, you could see the capacitor charge and discharge (Figure 6). Perhaps you can remember from physics class that the voltage U_{C3} is an exponential function of time. But we don't have to go into this much into detail now, and it will be understandable without it.

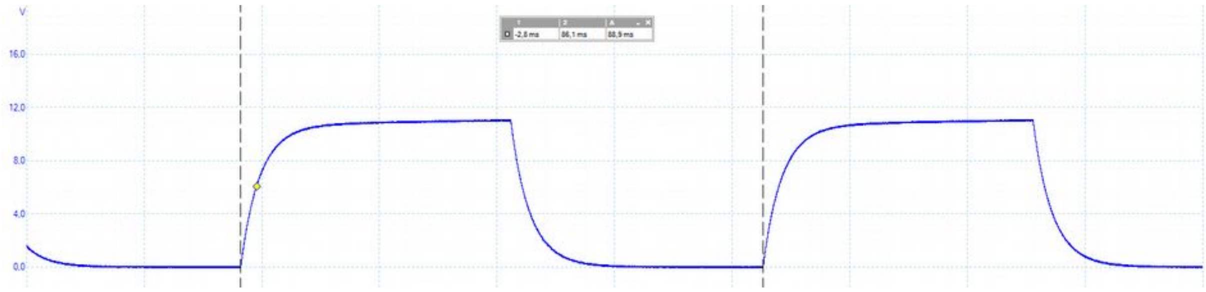

Figure 6 – Voltage on capacitor C3 with a 11 Hz square wave with 50% duty cycle

If the capacitor C_1 is replaced with a 100 nF one, the output signal frequency changes to 1.1kHz. Figure 7 illustrates the difference that makes it understandable why we did it.

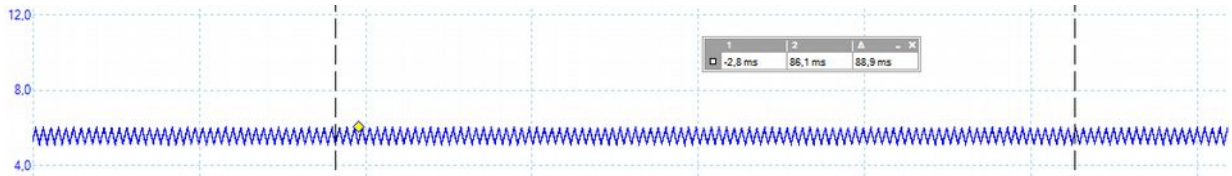

Figure 7 – Voltage on capacitor C3 with a 1.1 kHz square wave with 50% duty cycle

In the first case (11 Hz signal) the capacitor has time to fully charge to the supply voltage and then to completely discharge, but in the second case (1.1 kHz signal) it does not have time, it fluctuates between 5-6 V with an almost 50 % PWM duty cycle. If we increase the frequency further, this fluctuation will become smaller, approaching a steady analog signal. Increase the output frequency to 110 kHz! To do this, the value of C_1 capacitor must be replaced with a 1 nF capacitor!

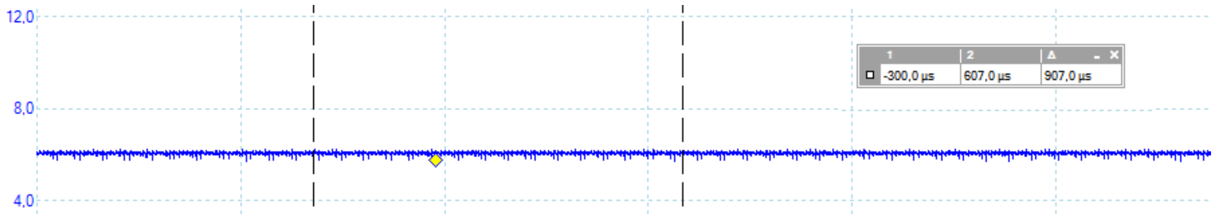

Figure 7 – Voltage on capacitor C3 with a 110 kHz square wave with 50% duty cycle

As this signal is very close to a constant analogue signal, you can take out your multimeter and measure the signal for yourself. Connect the multimeter to two terminals of the capacitor C_3 with a voltage measurement setting. If you adjust the potentiometer you can see the measured output voltage change accordingly. We know that adjusting the potentiometer adjusts the duty cycle of the output signal. The RC filter averages the output and produces a near-constant voltage. For example, if the duty cycle is 20%, then the output signal will be “on” 20% of the time, and “off” 80% of the time. This is averaged out to a constant voltage that is 20% of the supply voltage. In our case with a 12 V supply voltage, that averages out to a constant 2.4 V on the output.

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You should know about the multimeter that this meter is averaging too, otherwise you would not be able to read the fast-changing numerical values from the display. So, in the previous two examples, you would get the same averaged value with the multimeter too, but that would not be the real signal, because the multimeter would hide the fast changes in the time domain.

This simple example illustrates that we can control analogue systems with a high frequency digital signal. Here, the signal we want to control is the U_{C3} voltage on the capacitor.

Replace the output capacitor with an LED. The resistor will be current limiter series resistor for the LED, but we want the LED current to be 10 mA, so replace the R_1 resistor to 1 kΩ ($\frac{12\ [V]-2.2[V]}{1[k\Omega]} = 9.8[mA]$). Is this circuit familiar? This is our initial example.

This circuit utilizes the inability of the human eye to perceive fast changes. The LED is turned on an off very fast, but our eyes will average this blinking and turn it into a perceived brightness level. Therefore, we can control the brightness of an LED with the duty cycle of the signal. If you are curious about the blinking, replace the C_1 capacitor to a higher value (e.g. 100-1000 µF)!

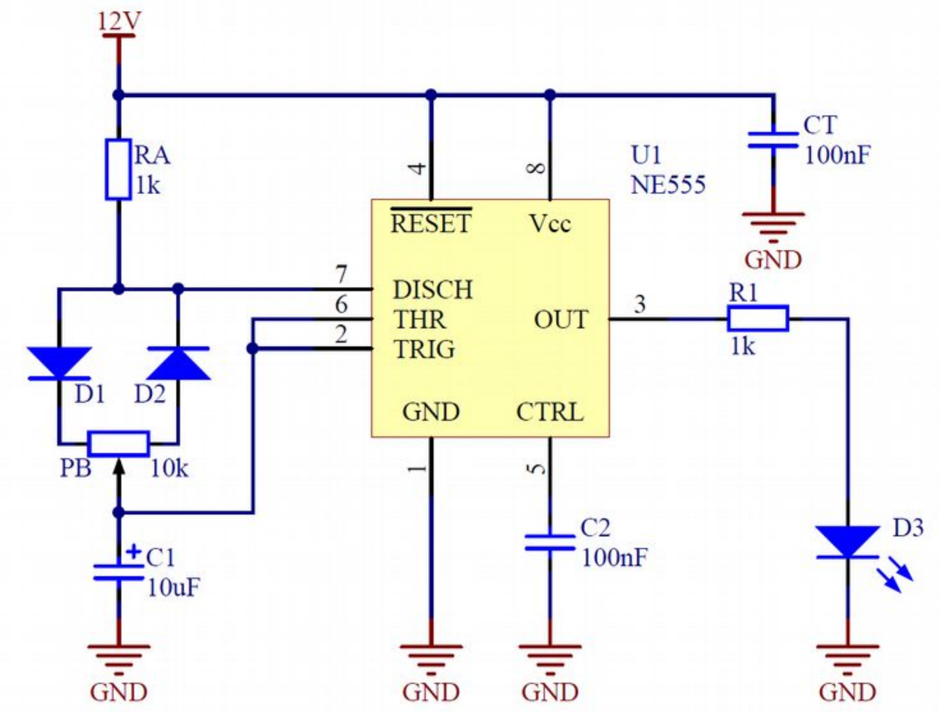

Figure 9 – PWM circuit with an LED on the output

It is much more spectacular to control a DC motor with our circuit. Fans used in computers are powered by 12 V DC motors, which are appropriate for us. Of course, you can use any other DC motor, just make sure that the maximum allowable voltage of the motor is higher than the supply voltage!

We may need more modifications, depending on the current consumption of your motor. The maximum output current of the 555 IC is 200mA, so fans with less current consumption can be connected directly to the IC output. It would not be able to drive a motor or fan, which has a higher current consumption, because it would overload the IC and it would break. Therefore, we need to connect our motor through a FET (Figure 10).

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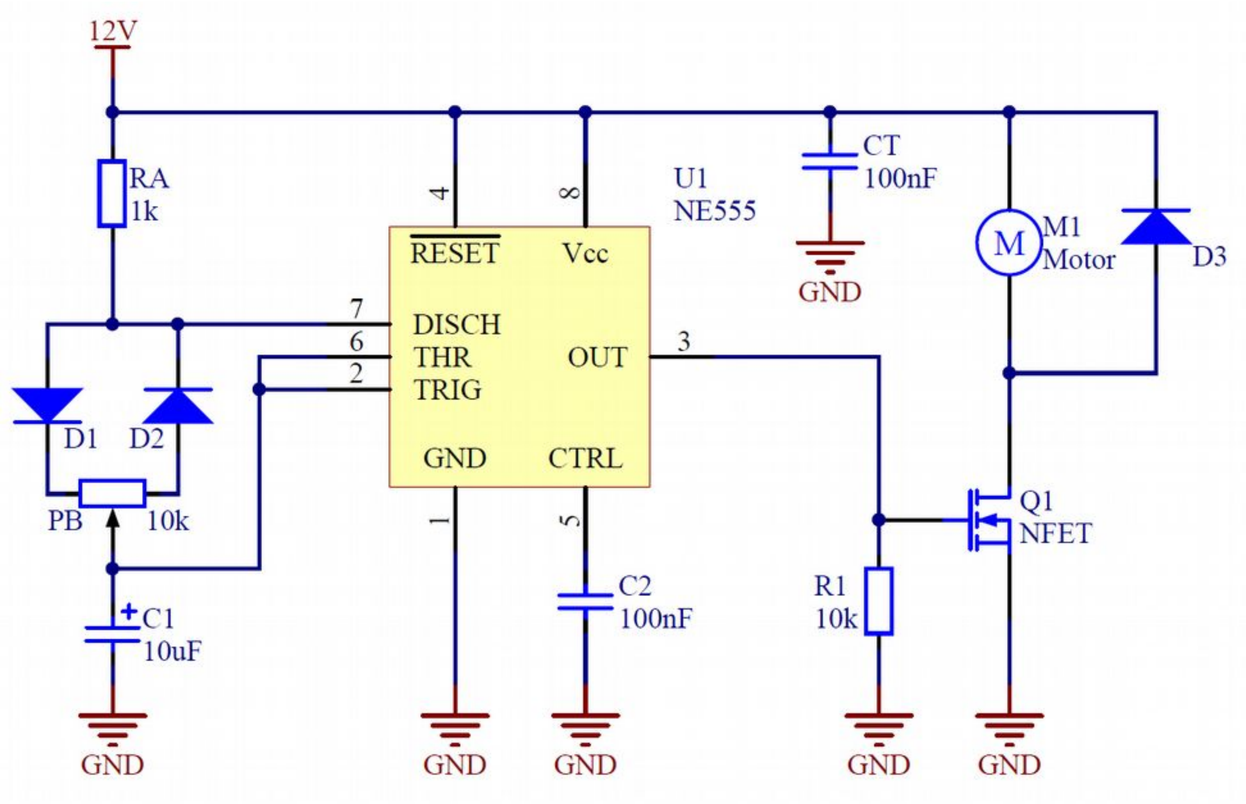

Figure 10 – PWM circuit with a fan on the output

We have to talk about the diode D_3. Inductive components such as coils, electric motors, or relays should be fitted with a protection diode because if the current on them is suddenly interrupted, the voltage can suddenly rise. In our example when the Q1 FET is switched off the current flowing through the motor is interrupted. Because the motor has inductive windings inside and current of an inductor cannot suddenly jump, a voltage spike would be induced at the point between the FET and the motor. This high voltage can be high enough (even in the kV range) to exceed the maximum voltage rating of the FET, destroying it. To eliminate this problem a protection diode is connected antiparallel with the motor, so when the FET is switched off, the current has a path to flow through the protection diode, and no voltage spike occurs. Also, the diode does not allow the voltage on the drain of the MOSFET to rise above the supply voltage.

Induced voltage

The induced voltage always tries to maintain the existing magnetic field.

When the current increases on the motor, there is an induced voltage due to the self-inductance of the motor, which has an opposite polarity, which decreases the current and hinders the creation of a magnetic field.

When the current decreases on the motor, the same induced voltage has an opposite polarity yet again, which tries to keep the current flowing and hinders the destruction of the magnetic field.

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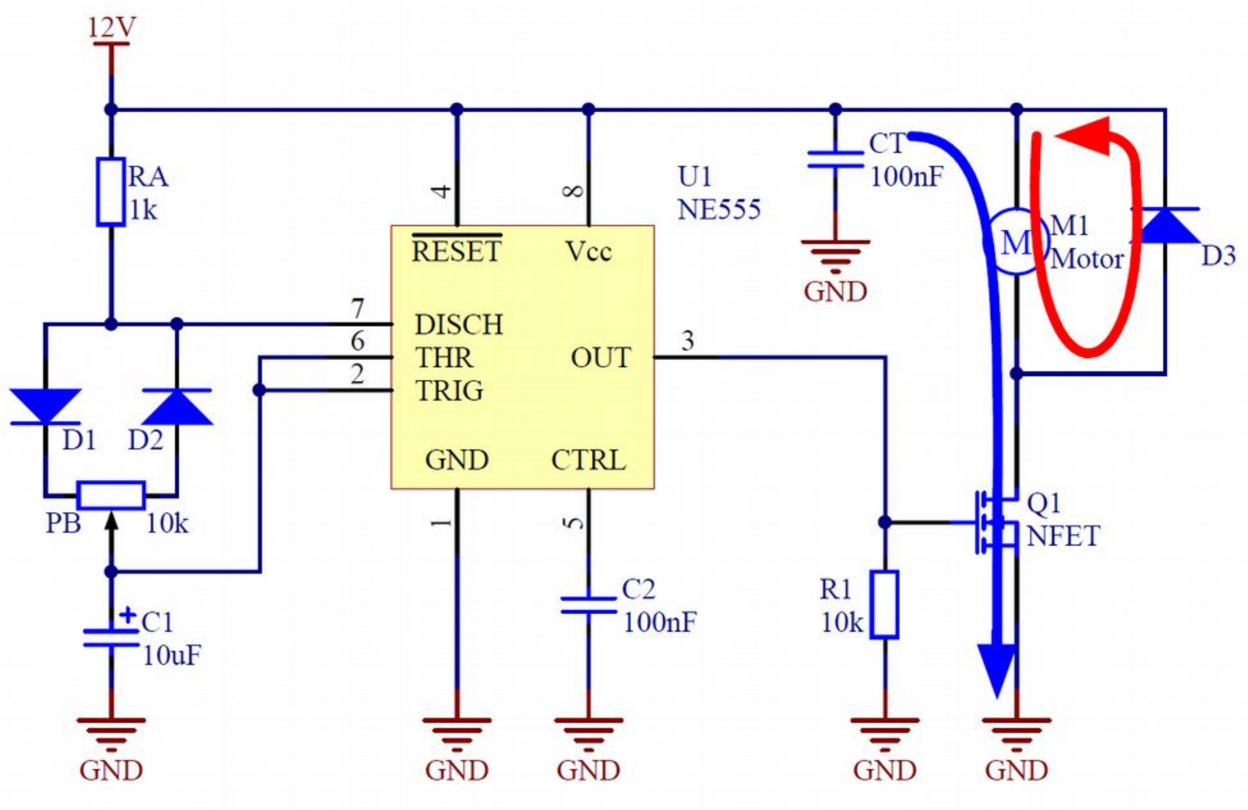

Figure 11 – Current flow paths when the Q1 FET is on (blue arrow), and off (red arrow)

We can see from the above that the highest current on the diode is the same as the highest current on the motor, therefore we should choose a suitable diode that can withstand the maximum current of the motor stated in its datasheet. This way you can avoid damaging the diode. Now we can talk about how our circuit works after we have discussed PWM.

How Does Our Circuit Work?

As a starting point remember the astable circuit with an NE555 (Figure 12, left side). In that circuit we have seen that the capacitor C_1 is charged through the resistors R_A and R_B, but it is only discharged through the resistor R_B. The NE555 IC outputs a high signal for t_H time, and a low signal for t_L time. These can be calculated using the following equations:

$$t_H = 0.693 \cdot (R_A + R_B) \cdot C_1$$

$$t_L = 0.693 \cdot (R_B) \cdot C_1$$

$$t_{period} = t_H + t_L = 0.693 \cdot (R_A + 2 \cdot R_B) \cdot C_1$$

$$f = \frac{1}{t_{period}} = \frac{1.44}{(R_A + 2 \cdot R_B) \cdot C_1}$$

There is only one difference between the astable circuit and the PWM circuit, the R_B resistance is replaced by a P_B potentiometer and 2 diodes. (In Figure 12 these are marked with green).

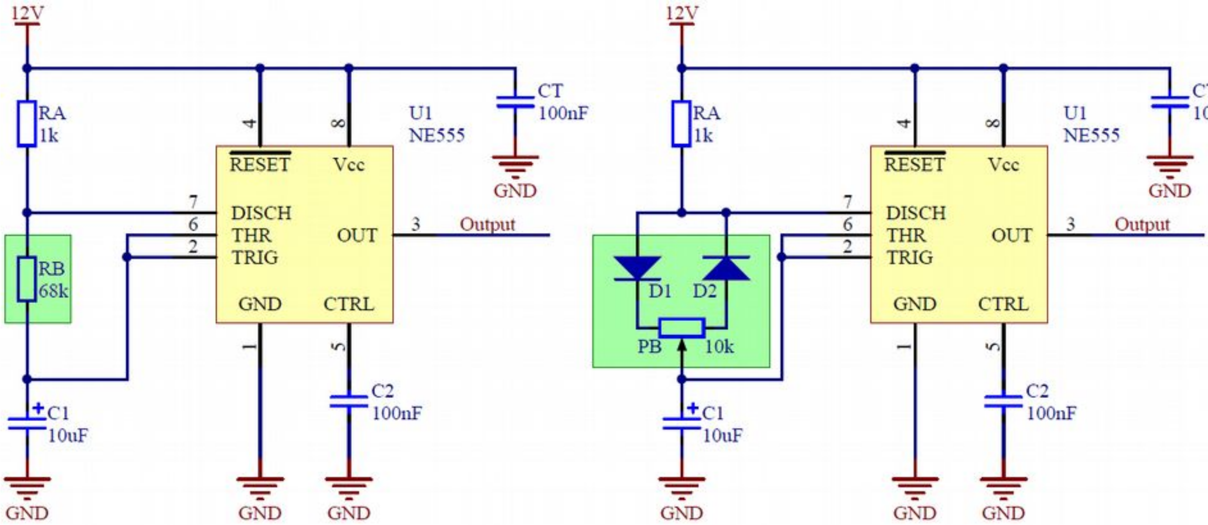

Figure 12 – The difference between the astable circuit and the PWM circuit

The potentiometer P_B can also be interpreted as two pieces of resistors (P_{B1}, P_{B2}) which ratio can be set by adjusting the potentiometer, but their sum is constant. The diodes are required to separate the charge and discharge of the capacitor C_1 (Figure 13).

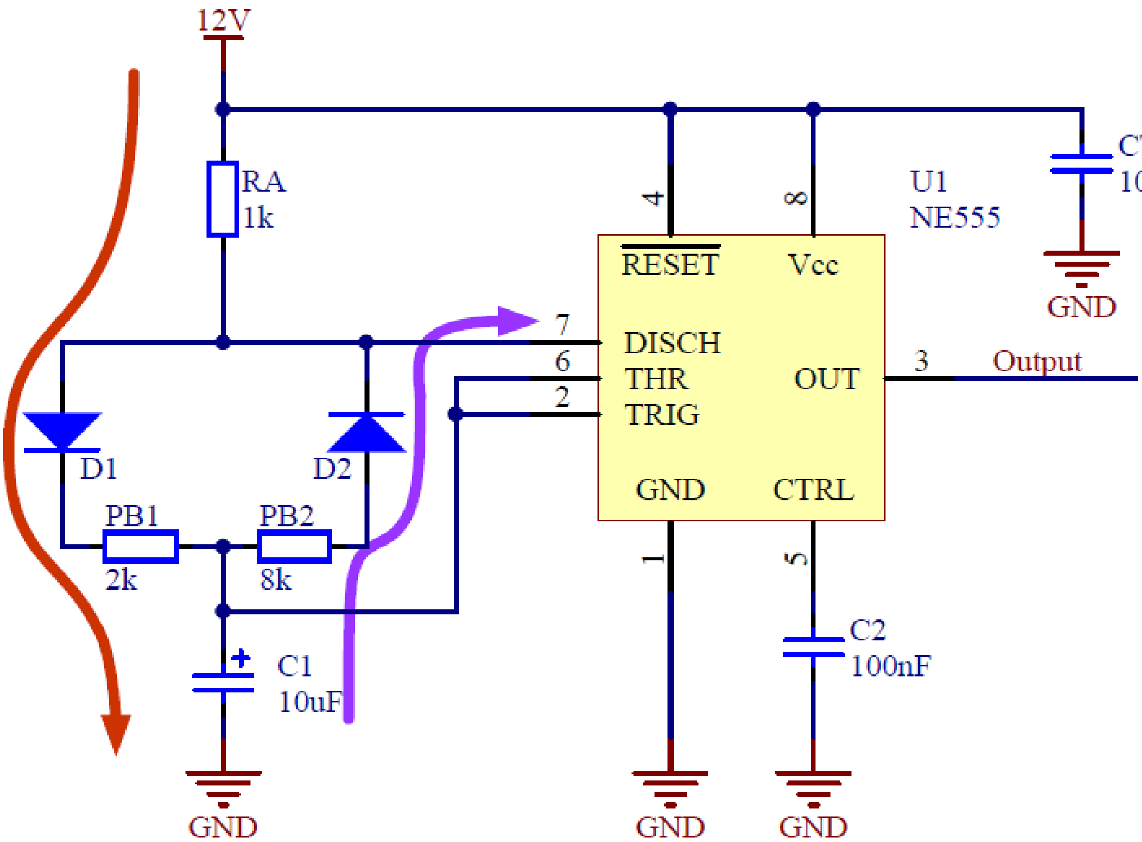

Figure 13 – The way of current when the capacitor C_1 is charging, and discharging

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So, the capacitor C_1 is charged through the resistors R_A and P_{B1}, but is discharged through the resistor P_{B2}. If we look at the on and off time formulas again, we can explain why our circuit implements the generation of the PWM signal:

$$t_H = 0.693 \cdot (R_A + P_{B_1}) \cdot C_1$$

$$t_L = 0.693 \cdot (P_{B_2}) \cdot C_1$$

$$t_{period} = t_H + t_L = 0.693 \cdot (R_A + P_{B_1} + P_{B_2}) \cdot C_1 = 0.693 \cdot (R_A + P_B) \cdot C_1$$

$$f = \frac{1.44}{(R_A + P_B) \cdot C_1}$$

From this we can see that the signal frequency will not change when adjusting potentiometer, since the values of R_A and P_B are also constant ($P_B = P_{B1} + P_{B2}$). Only the ratio of P_{B1} to P_{B2} will change, which will determine the duty cycle.

$$duty\ cycle = \frac{t_H}{t_{period}} = 1 - \frac{P_{B_2}}{R_A + P_B}$$

Outputting zero

The equations also show why we can't reach with a duty cycle of 0% with this circuit. As recommended by the datasheet of the 555 IC,R_A should not be less than 1 kΩ because a too high current would flow through the DISCH. transistor within the 555 IC, which would cause unnecessary heat or damage. So we turn the potentiometer in the direction of $P_{B2} = P_B$ in vain, because we will not have 0% duty cycle since

$$\frac{P_{B2}}{R_A + P_B} \neq 1.$$

Hopefully, this chapter of the curriculum and the completion of the tasks helped you to better understand what exactly PWM is. In the next section, you will find even more exciting examples, where the PWM will be produced with the help of a microcontroller.

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