5

Timers and Oscillators

This lab continues our exploration of basic transistor switching circuits to include timing circuits and oscillators. We will explore some simple multivibrator circuits using discrete transistors, comparators, and finally circuits that use the popular 555 timer chip. We will use the latter to create a simple fan speed controller using a variable duty-cycle driver.

Pre-lab Preparation

Before Coming to the Lab

Read through the lab experiment to familiarize yourself with the components and assembly sequence. Before coming to the lab, each group should obtain a parts kit from the ECE Shop.

Parts List

The ECE2 lab is stocked with resistors so do not be alarmed if you kits does not include the resistors listed below. Some of these parts may also have been provided in an earlier kit.

Laboratory #5	
Timers and Oscillators	
Qty	**Description**
1	2N7000 NMOS
4	2N3904 NPN BJT
1	2N3906 PNP BJT
2	LM393 Comparator
2	LM555CM
4	LED, Red diffused, 5mm (T1 3/4) 20mA
4	0.1uF capacitor (low-volt. ceramic)
4	10uF capacitor (electrolytic, 25V, radial)
2	100uF capacitor (electrolytic, 25V, radial)
8	330-Ohm 1/4 Watt resistor
4	1-KOhm 1/4 Watt resistor
2	2.2-KOhm 1/4 Watt resistor
3	4.7-KOhm 1/4 Watt resistor
6	10-KOhm 1/4 Watt resistor
2	22-KOhm 1/4 Watt resistor
3	33-KOhm 1/4 Watt resistor
8	100-KOhm 1/4 Watt resistor
4	PC Mount Tactile push-buitton switch (PB1)
2	10k trimpot

Background information

Suggested background reading:

- Hands-on Electronics, Chapter 9
- http://en.wikipedia.org/wiki/Multivibrator
- Phillips Application Note AN170, "NE555 and NE556 Applications" (posted on course web site).

Duty Cycle

In this lab we will work with rectangular pulse waveforms, for which the term "duty cycle" comes up frequently. For such waveforms, the duty cycle is defined as the ratio of pulse duration to pulse period. For example, consider the waveform shown in Figure 5-1:
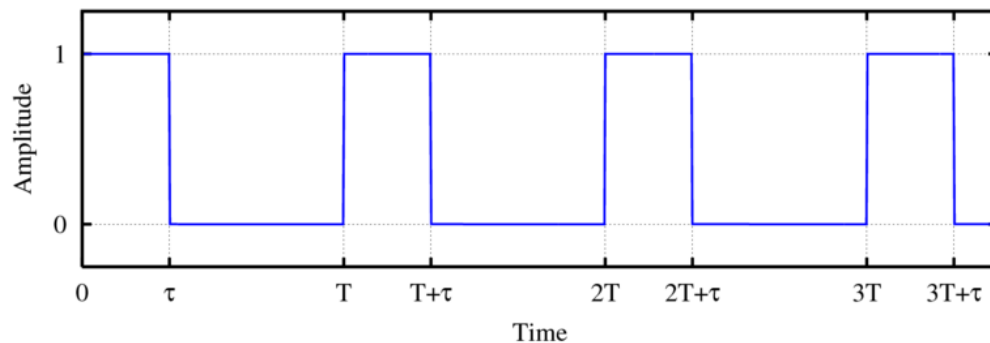

Figure 5-1 – Rectangular waveform for duty cycle definition

The pulse duration is τ; this is how long the pulse remains high (amplitude=1 in the figure).The pulse period is T; this is the duration of one complete cycle, and is just the inverse of the frequency in Hz ($f = 1/T$). So the duty cycle in this case would be

$$D = \frac{\tau}{T} \tag{5.1}$$

Clearly $0 \le D \le 1$, which we usually express as a percentage. So, for example, a 50% duty cycle is one where $D = 0.5$, or $\tau = 0.5T$.

In-Lab Procedure

5.1 Discrete Multivibrator Circuits

A multivibrator is a circuit used to implement a variety of simple two-state systems such as oscillators, timers and flip-flops. There are three types of multivibrator circuit:

- *Astable*, in which the circuit is not stable in either state, and continuously oscillates from one state to the other.

- *Monostable*, in which one of the states is stable, but the other is not. The circuit will flip into the unstable state for a determined period, but will eventually return to the stable state. Such a circuit is useful for creating a timing period of fixed duration in response to some external event. This circuit is also known as a one shot. A common application is in eliminating switch bounce.

- *Bistable*, in which the circuit will remain in either state indefinitely. The circuit can be flipped from one state to the other by an external event or trigger. Such a circuit is important as the fundamental building block of a register or memory device. This circuit is also known as a flip-flop. A similar circuit is a Schmitt trigger.

In this section we will build a simple version of each type using discrete transistors. In practice, it is more common to use dedicated ICs such as the 555 Timer that we will discuss later, but discrete transistor circuits are a good place to start from a pedagogical standpoint.

Manual One-Shot Timer

There are many circuit applications that require a response to some event in a fixed time interval. For example, in a home security system, the alarm is usually disabled for a fixed time period (1-2 minutes) to give the homeowner time to enter a security code; once that interval has elapsed without the code being entered, the alarm will sound. How would you implement a 1 minute time delay before the alarm is triggered?

In analog circuits, such timing functions are often implemented with the help of RC circuits. The well-defined RC time-constant gives a predictable and easily controllable delay that can be adjusted over a wide range.
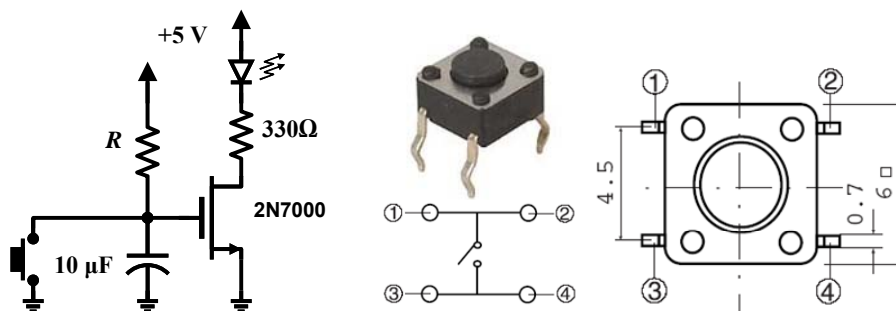

Figure 5-2 – (a) A simple "one-shot" using a MOSFET.   (b) Tactile momentary-on switch.

Consider the circuit shown in Figure 5-2a.   Here the 10µF capacitor and resistor R form a timing circuit. When the switch is pressed it temporarily shorts out the capacitor and turns off the transistor, cutting off the current flow to the LED. When the switch is released, the capacitor begins to charge through the resistor R.   When the capacitor voltage reaches the

FET's gate threshold voltage, the transistor will turn on and the LED will illuminate again. The "off" duration of the LED is approximately the RC time constant of the gate bias circuit.

☐ Build the circuit in Figure 5-2a using a 2N7000. The pin assignments for the tactile switch are shown in Figure 5-2b; press these firmly into the protoboards. Choose a resistor value to give a time constant on the order of 1-2 seconds, and verify that the circuit keeps the LED off for approximately this time period after the button is pressed.

☐ Can you think of a way to reverse the operation, so that pushing the button turns the LED *on* for a brief period instead of off?

The circuit you just built is a crude form of a monostable multivibrator or "one-shot". The circuit has two possible states: either the transistor is on or off. The state with the transistor conducting and the LED illuminated is the only *stable* state. Pressing the switch puts the circuit temporarily the other state, but this is *unstable* and the circuit eventually returns to its stable state.
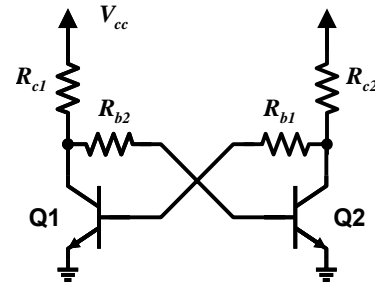

Figure 5-3 – Bistable circuit.

Bistable-Multivibrator or "Flip-Flop"

In contrast to the circuit you just built, the cross-coupled transistor circuit of Figure 5-3 has *two* stable states. Can you see why? Let's say transistor Q1 is "on"; that would mean the base of Q2 is effectively grounded, so Q2 would be off, and thus the base of Q1 would be connected to V_{cc} through the series combination of resistors R_{c2} and R_{b1}, consistent with our initial assumption that Q1 was on. So, one stable state can be summarized as "Q1 on, Q2 off". By similar arguments we can show that "Q1 off, Q2 on" is also a stable state.

Which state will the circuit be in when we power-up the circuit? It is impossible to predict: small differences in the components will cause one to turn on before the other.

To be useful, then, we need a way of toggling the circuit between the two states. One way is shown in Figure 5-4 using pushbutton switches (these could also be implemented as electronic switches with a couple of transistors).
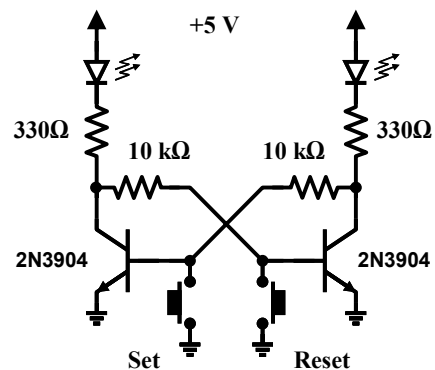

Figure 5-4 – Bistable Set-Reset "flip-flop".

☐ Construct the circuit of Figure 5-4. Record your observations.

This bistable circuit is an example of a set-reset, or SR flip-flop. Flip-flops find many uses in digital systems, but the SR type is rarely used for reasons we will learn later.

Another Monostable-Multivibrator or "One-Shot"

Look back at the monostable circuit that you first built. There is another way to implement this circuit (Figure 5-5) that combines some elements of the two circuits you just built using a transistor to help discharge the capacitor. Here the stable state is "Q1 off" and "Q2 on". The base of Q2 is biased through resistor R, so when Q2 is on, the right side of capacitor *C* is at

around 0.7V DC; the base of Q1 is grounded through Q2, hence Q1 is off and the left side of the capacitor is at around 5V DC.

Now, throwing the switch turns off Q2, allowing Q1 to turn on. At the instant this happens the left side of the capacitor is grounded through Q1. The capacitor will discharge quickly through the switch and Q1, and begins to charge in the opposite polarity through resistor R. Eventually it will charge enough to switch Q2 back on, thus returning to the stable state, so the RC time constant again controls the duration of the one-shot interval. However, since the capacitor voltage only needs to reach 0.7V, this circuit will change states more quickly than our earlier FET-based monostable. Consequently we needed to use a larger capacitor here for a similar pulse duration.
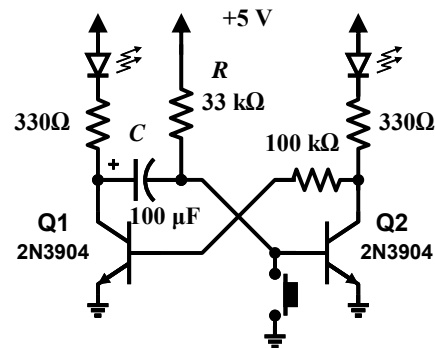
Figure 5-5 – Monostable multivibrator.

☐ Build the Figure 5-5 and record your observations.
☐ There is a subtlety here relating to the choice of resistor R. Try replacing R with a 100kΩ resistor and watch what happens (be patient). Can you explain this behavior?

Please note that the operation of this circuit is by no means immediately obvious, so tip your hat to the (unknown) inventor! For now, just make sure you understand how the circuit works before continuing.

BJT-based Astable Multivibrator

There is a clever way to make the monostable circuit trigger itself periodically, shown in Figure 5-6: we just need to replace the switch by another RC circuit, much as we did in going from the flip-flop to the monostable. This is called an *astable multivibrator* because neither of the two states are stable; the circuit just periodically switches back and forth between each state.
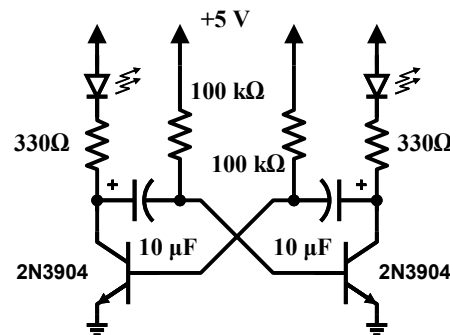
Figure 5-6 – Astable Multivibrator

☐ Modify your last monostable circuit to build the astable multivibrator in Figure 5-6. Record your observations.
☐ Modify the circuit to oscillate at a 100 Hz rate. Note that the waveforms measured at the collector terminals of each device are essentially square waves, which you can observe on the oscilloscope; how might you control the duty cycle of this oscillator?

This kind of oscillator using cross-coupled transistors is the basis of many IC-based oscillator circuits, and similar principles are at work in the oscillators we will construct later in this lab.

5.2 Relaxation Oscillator with Variable Duty Cycle

In many of the circuits you just built, the voltage across a timing capacitor is used to trigger a change in the circuit somewhere. This triggering event occurs when the capacitor voltage equals the turn-on voltage of the transistor. So the choice of transistor largely determines the threshold for switching.

In some cases it is desirable to have a greater degree of control over the threshold voltage for the triggering event, and that is where comparators come in. In this section we will construct a simple comparator-based oscillator circuit and show how it can be used to generate a rectangular waveform with a variable duty cycle.
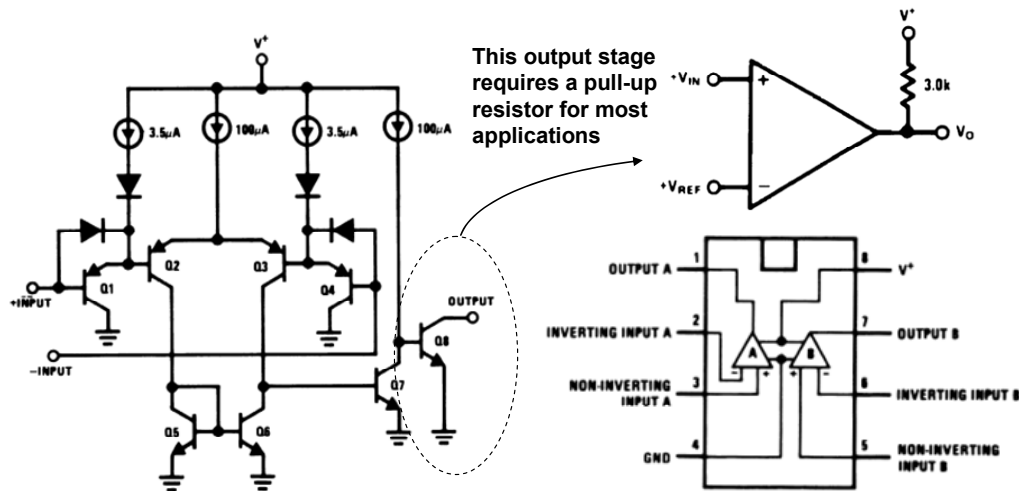

Figure 5-7 – Schematic for the LM393 dual comparator (from data sheet) and pinout. This type of comparator requires a pull-up resistor at the output.

You first experimented with comparators in an ECE 2A lab, so you probably remember the basic function. Briefly: comparators are similar to op-amps, but are designed to produce an output that can switch rapidly between two states (often the output voltage swings between the supply rails) based on the polarity of the differential input.

Figure 5-7 shows the internal schematic and pin-out of the comparator IC we will use in this lab. It is a commonly-used and inexpensive dual-comparator chip, the LM393 (note that there is also a modern pin-for-pin substitute called the TLC393 that is functionally equivalent but draws a twentieth of the power). The schematic may look complicated, but if you focus on the output stage, notice that it is simply a common-emitter BJT switch with an open collector. You should be very comfortable with this kind of output stage by now! Since there is no internal pull-up resistor, we must provide one as shown in Figure 5-7 for all our circuits if we want the output voltage to switch between the supply rails.

Schmitt Trigger

In a comparator, the threshold for switching is just set by the reference voltage applied to one of the inputs. This is a nice feature compared with our previous circuits, but there is an even more useful variation on the basic comparator circuit that uses positive feedback. This is shown in Figure 5-8, and is called a Schmitt trigger. There are of course discrete transistor-based implementations, but many modern circuits will either use a comparator as shown, or a dedicated Schmitt-trigger IC that implements this function.

The key feature of the Schmitt trigger is that the threshold for toggling the output state depends on the output state itself (!).   If the output is low, it takes an input voltage *substantially greater* than the reference ($V_{in} > V_{ref} + \Delta V$) to make the output voltage go high. Conversely if the output is high, the input voltage must drop *substantially below* the reference ($V_{in} < V_{ref} - \Delta V$) in order to cause the output to switch back to the low state. Devices or circuits with this behavior are said to possess *hysteresis* in their transfer chracteristics. The etymology of this word comes from the Greek *hysterein* "to be late" and *hysteros* "later".   Hysteresis is effectively a kind of memory effect, since the outcome is determined by the prior state of the device.
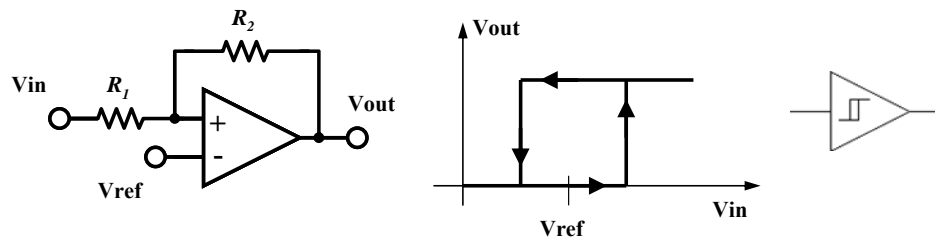

Figure 5-8 – Schmitt trigger using a comparator, transfer characteristic, and circuit symbol.

In the Schmitt trigger of Figure 5-8, the amount of voltage ΔV that is required above and below the reference is set by the feedback resistors.

☐   Derive expressions for the two tripping points on the hysteresis curve of the Schmitt trigger for the circuit in Figure 5-8.

You do not have to build this circuit. We will use a variant of it in the larger circuit in the next section Note that we left off the pull-up resistor in Figure 5-8 for clarity; if you *were* to build this using an LM393 or equivalent, you would need this, plus some reference voltage.

Relaxation Oscillator Circuit

The relaxation oscillator uses an RC time constant circuit and a Schmitt trigger to create an astable multivibrator. The basic circuit for a bipolar power-supply is shown in Figure 5-9a. In fact you built one of these in the ECE2A lab this year! When the output is low ($-V_s$), the capacitor voltage V_- begins to decrease until it hits the reference set by resistors R_1 and R_2, which form a voltage divider with the output. When this happens, the output switches high, and the capacitor voltage increases until it hits the new reference.
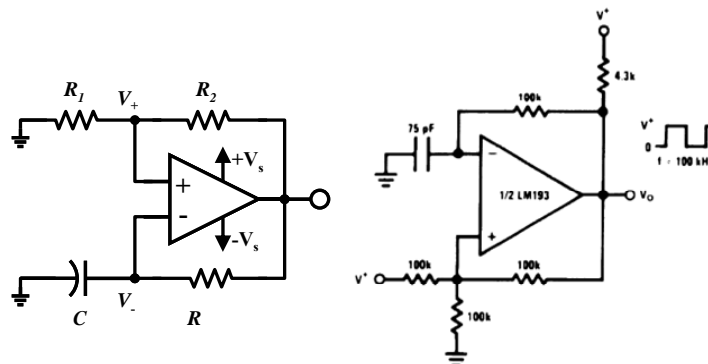

Figure 5-9 – (a) Classic relaxation oscillator; (b) An implementation using the LM393.

The LM393 implementation in Figure 5-9b is slightly more complicated, simply because it operates from a single supply voltage, and requires the extra pull-up resistor. We will use this variant in our variable duty-cycle design below.

Variable Duty-Cycle Oscillator

We are now ready to understand and build the circuit in Figure 5-10. You will recognize the first stage as a relaxation oscillator of the type shown in Figure 5-9b.   Here we have chosen component values to create an oscillator frequency in the range of 200-400Hz. The second stage is a basic vanilla-flavored comparator circuit, with a reference voltage set by a trimpot.

☐ First build the oscillator stage in Figure 5-10, and observe the waveforms on the two ports labeled Va and Vb. Can you understand the operation now?

☐ Now add in the output comparator stage and observe the waveform at the port labeled PWMout. You should be able to vary the duty cycle of this circuit by varying the trimpot.

The technique used here to generate a variable duty cycle—driving a comparator with a triangular-ish waveform and varying the reference voltage—is one of the most common methods and is widely used in a variety of switching applications. It is a simple example of a "pulse-width modulator", a circuit that generates a variable pulse width in response to some modulating signal, which is this case is provided by the trimpot.
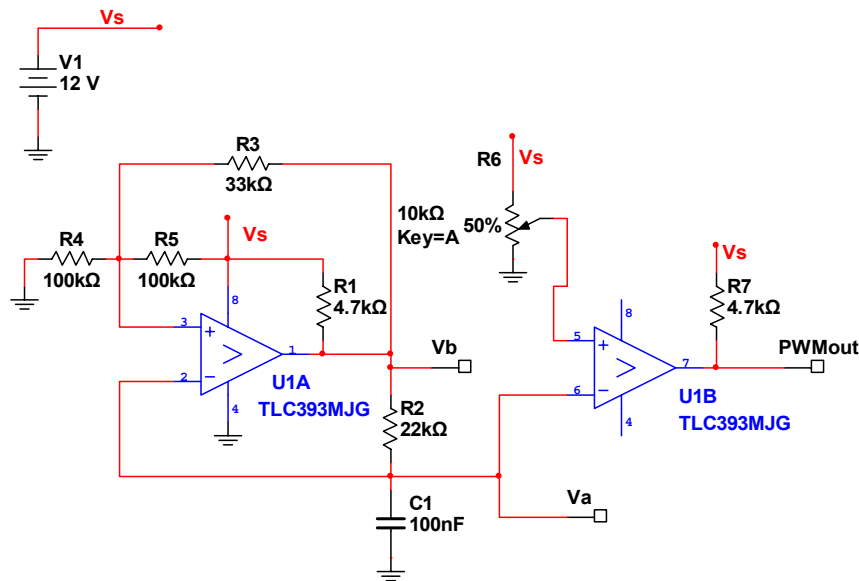

Figure 5-10 – Variable Duty-Cycle Oscillator.

Note: the schematic in Figure 5-10 is from a Multisim file that is posted on the website. Our lab circuits are now approaching a level of complexity that makes the simulation programs useful for preliminary testing and schematic generation.

5.3 The 555 Timer IC

When engineers find themselves building the same circuits over and over again, the local neighborhood IC foundry will often be called on to design a dedicated integrated circuit that implements those fundamental building blocks in order to save time, space, and money. That is the *raison d'etre* of the 555 timer chip: it collects together many of the key functional circuit blocks that people always use when making multivibrator and timing circuits.
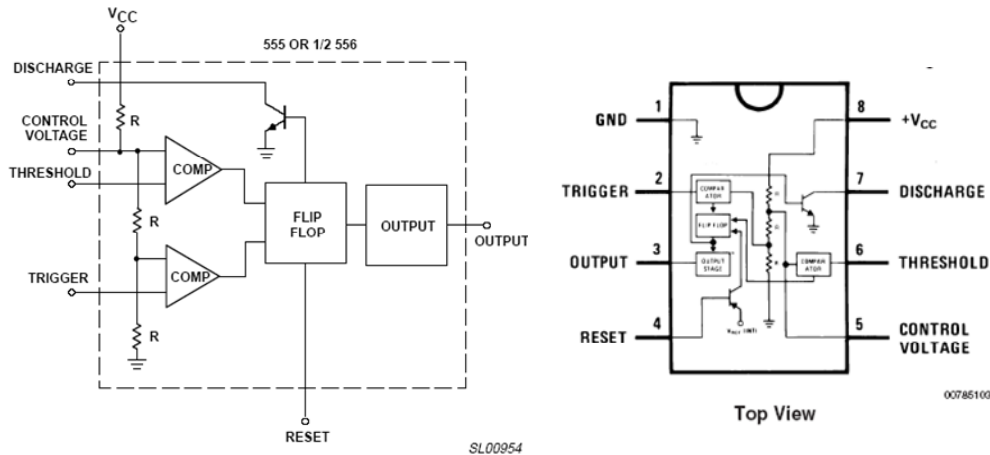

Figure 5-11 – (a) Block diagram of the 555 timer, and (b) pinout of the LM555 (from LM 555 data sheet and Phillips Application Note AN170).

The block diagram and pinout of the 555 are shown in Figure 5-11. It is a very old chip (circa 1972!) but has proven to be quite useful, and over the years many engineers have thought up clever uses for it that were never imagined by the original designers. In fact, entire books have been written on the many uses of this circuit, so we will content ourselves with a couple of basic configurations on our way to implementing a 555-based fan speed controller.

Astable Multivibrator

The 555 datasheet and Application Note AN170 are the best sources of information on the various circuits. A common astable configuration is shown in Figure 5-12. The timing capacitor C is charged through two resistors, R1 and R2. These components control the duty cycle of the output (see data sheet for formulae). Here we have chosen values to give an oscillation frequency in the 200-400Hz range using a 0.1uF capacitor. Note the other capacitor (Cf, connected to the control pin) is just a termination that is recommended by the manufacturer when the pin is not being used (see AN170).

□ Build the circuit in Figure 5-12. Observe and record the output waveform. Is the frequency and duty cycle consistent with predictions from the formulae in the datasheet?
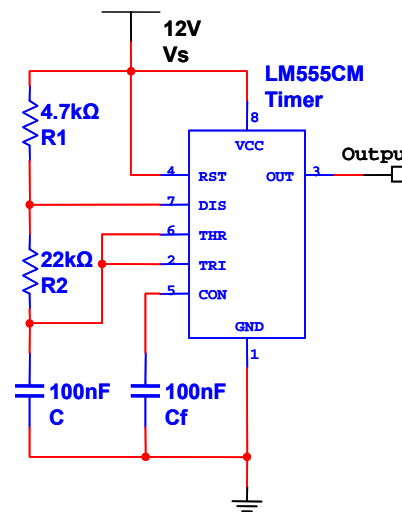

Figure 5-12 – Astable 555 configuration

Linear Ramp Generator

You may recall in the previous lab that we were able to create a linear time dependence in the voltage across the capacitor (instead of an exponential time dependence) by charging the capacitor through a constant current source, implemented with a transistor. We can do the same thing with the timing capacitor on the 555 to create a linear ramp waveform. Figure 5-13 shows how this can be done.
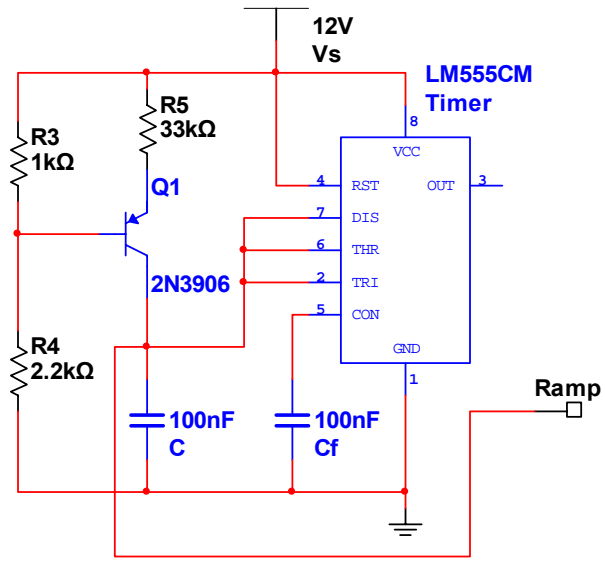
□ Construct the circuit in Figure 5-13. At this point it is advisable to clear some space on your protoboard and assemble this circuit on the leftmost side. We

Figure 5-13 – Linear ramp astable using the constant-current charging technique.

will add more components moving to the right, and some of these circuits will be used again in subsequent labs.

□ Observe and record the output waveform for the linear ramp astable.

Fan/Motor Speed Control

By adding a comparator to the ramp generator we can create a very nice variable duty-cycle pulse generator, much like we did in the previous section. We will use this for a speed controller for our little DC brushless fan.
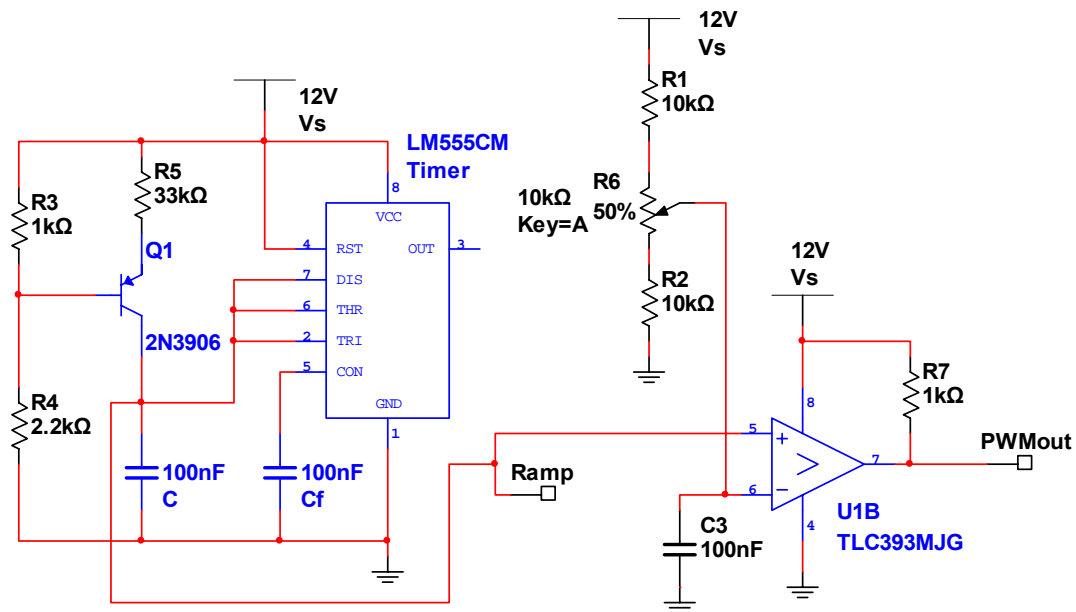
Figure 5-14 – Improved 555-based PWM controller

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□ Construct the circuit in Figure 5-14. Note that the comparator stage is identical to that used in Figure 5-10, except for the pull-up resistor. More on that later

□ Observe and record the output waveform for this circuit. You should be able to control the duty cycle over the full range of 0-100%. If for some reasons you are not able to do this, observe the minimum and maximum voltages on the ramp signal from the 555, and adjust the values of R1 and R2 accordingly.

□ Lastly, add the DC fan and driver stage from lab 4 (repeated here in Figure 5-15). You should mount the fan on the protoboard using a piece of double-sided sticky foam in your kit. Mount the fan vertically at least an inch (8-9 holes) away from the edges normal to the fan blade (in the direction of air-flow). We are going to use this circuit in the final lab of the course and add a few components in this space.

□ Verify that you can vary the speed of the fan over a very wide range with this circuit.
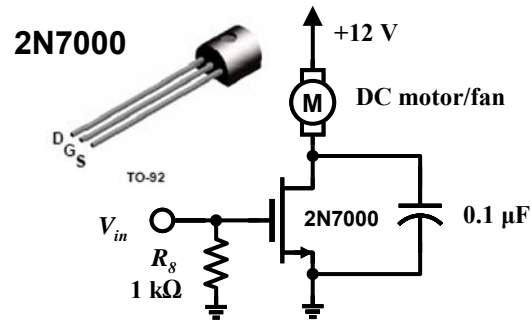

Figure 5-15 – Fan driver stage from Lab 4

Note the 1k resistor R8; together with pull-up resistor R7 in Figure 5-14 forms a simple voltage divider that biases the gate at ~6V in the high-state of the comparator.

Congratulations!
You have now completed Lab 5