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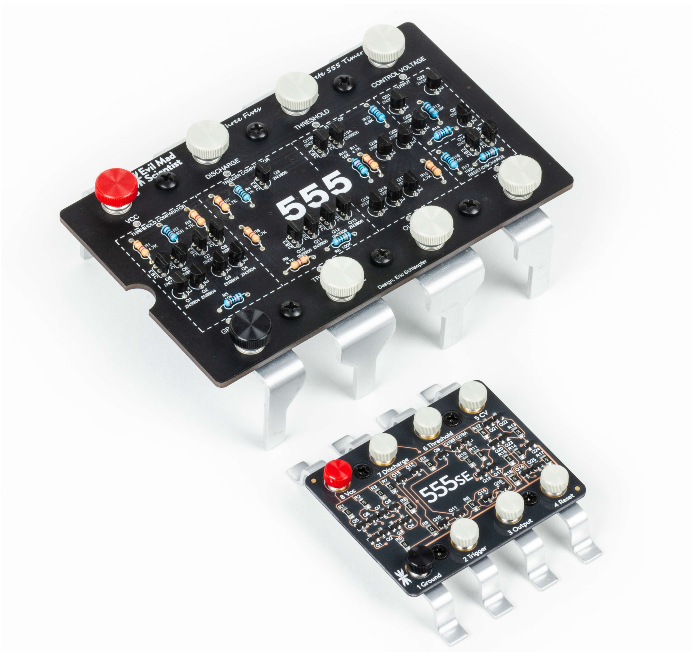
Educational Supplement



The 555 Timer: Principles of Operation

What's inside a 555 timer chip, and how does it work?

Supplementary documentation for the "Three Fives" and 555SE Discrete 555 Timer Kits

The 555 timer is one of the most iconic and popular integrated circuits of all time. It was designed in 1970 by Hans R. Camenzind for the Signetics Corporation. Today – half a century later – it is still an immensely popular circuit building block. By some estimates, over a billion 555 timer circuits are built every year.

The 555 was the first commercially available integrated circuit of its type and found immediate and widespread use as a circuit "clock" oscillator and timing delay generator. The original Signetics NE555 datasheet described the function of the chip as follows:

> *"The NE/SE 555 monolithic timing circuit is a highly stable controller capable of producing accurate time delays, or oscillation. Additional terminals are provided for triggering or resetting if desired. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. For a stable operation as an oscillator, the free running frequency and the duty cycle are both accurately controlled with two external resistors and one capacitor. The circuit may be triggered and reset on falling waveforms, and the output structure can source or sink up to 200 mA or drive TTL circuits."*

Since its release, the chip has had a loyal following as a building block for all manner of custom circuitry and as an introductory electronics teaching tool – inspiring several books about the 555 alone.

Throughout the years there have been a great many derivatives and descendants of the original 555 – low power and low voltage types, dual and quad-555 chips, ultra-tiny surface mount versions, and countless implementations of the 555 circuit itself.

Amongst these derivatives are our Three Fives and 555SE kits: both discrete implementations of the "equivalent circuit" from the NE555 datasheet, built up using resistors and individual '3904 and '3906 transistors. These are, so to speak, "dis-integrated circuits," containing essentially the same components that you might find on the die of a 555 IC.

As with the integrated circuit version of the 555, you can build working timer and oscillator circuits out of the discrete version, and hook up with solder connections (or, being large, even alligator chips) to monitor what happens at the pins. However, unlike with the chip version, it's also easy to insert your own probes *inside* the circuit, to monitor what happens at any point inside what might otherwise just be a black box.

This ability to peek inside the circuit makes these kits a unique educational tool. In what follows, we'll work through the circuit diagram, discuss the theory of operation of the 555 timer IC, and present some opportunities for further exploration.

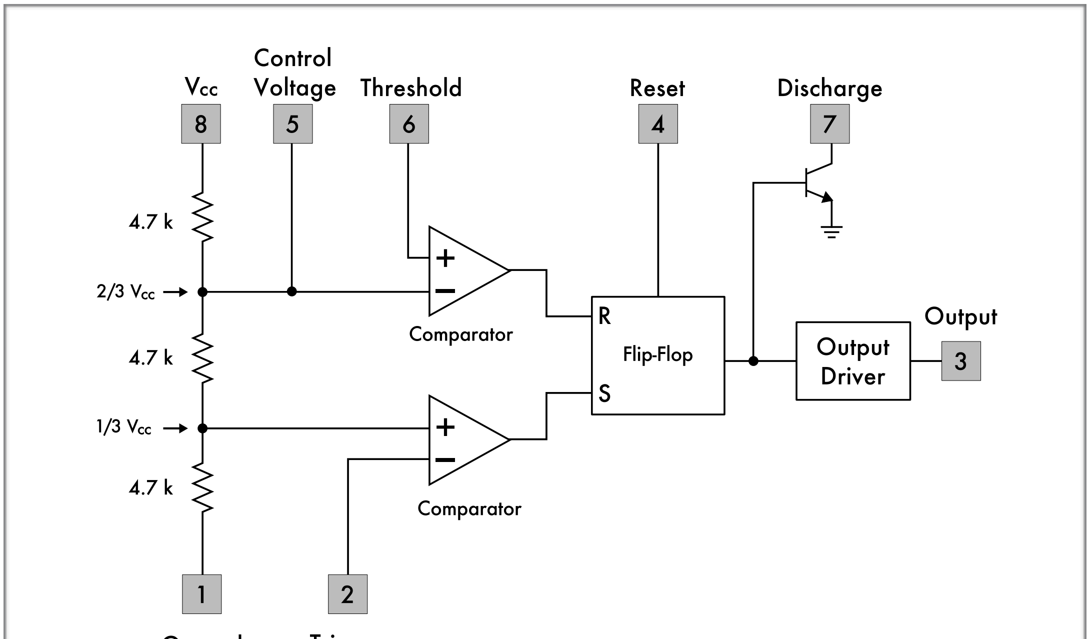


Figure 1: The 555 Block Diagram

The High-Level Overview

Let's begin by looking at the 555's block diagram, Figure 1. Here, we simplify the many individual components of the 555 into a much smaller set of functional blocks.

In this view, the 555 is a relatively straightforward circuit that is at its core composed of these three basic elements:

- A *voltage divider*,
- Two *voltage comparators*, and
- A *flip-flop* logic gate

(Besides these, there is also a power amplifier, or "output driver," that supplies output current, and a separate driver for the Discharge pin.)

You may be familiar with the core elements, but let's go through them anyway:

The voltage divider:
The voltage divider consists of three 4.7 k resistors connected between V_{cc} (pin 8)† and ground (pin 1). Since the three resistors are in series and of equal value, the voltage ⅓ of the way up the resistor chain from ground (as measured at the point between the lower two resistors) is ⅓ V_{cc}. Similarly, the voltage between the upper two resistors is ⅔ V_{cc}.

The comparators:
A comparator is a circuit element that compares two analog input voltages at its (+) and (–) input terminals. It produces an output voltage that is logical-high (or "true") if the voltage at the (+) input is higher than that at the (–) input, and low (or "false") otherwise.

The two comparators in the 555 circuit test the input signals from the Trigger (pin 2) and Threshold (pin 6) inputs against the reference voltages from the voltage divider, ⅓ V_{cc} and ⅔ V_{cc}, respectively.

Thus, when the voltage on the Trigger pin is below ⅓ V_{cc}, the output of the lower "Trigger" comparator is high, and when it is above ⅓ V_{cc}, the output is low. Similarly, the output of the upper "Threshold" comparator is only high when the voltage on the Threshold pin is above ⅔ V_{cc}.

The flip-flop:
Generally speaking, a flip-flop is a circuit element that changes output state (logical low or high) depending on the values of its inputs, but *also* upon its previous output state. Effectively, it is a digital logic gate with a built-in one-bit memory cell.

The type of flip-flop gate in the 555 has two main inputs, called "S" (or Set) and "R" (or Reset). Those inputs are driven by the outputs of the two comparators. When the Trigger pin falls below ⅓ V_{cc}, the "S" input goes high. That causes the flip-flop output to go high. It will then stay high even if the trigger pin later rises above ⅓ V_{cc}. The "R" input has the opposite effect: When the Threshold pin voltage rises above ⅔ V_{cc}, "R" goes high, causing the flip-flop output to go low, and stay low even if the Threshold voltage later falls below ⅔ V_{cc}.

When both the "S" and "R" inputs are low, the flip-flop output remains in whichever state it had been in whether it was high or low.

There is also a separate Reset input (pin 4), which causes the flip-flop to reset to its low output state when it is pulled low.

† The name "V_{cc}" means "the positive power supply input to the 555." In this case, a DC voltage in the range of 4 to 18 V.

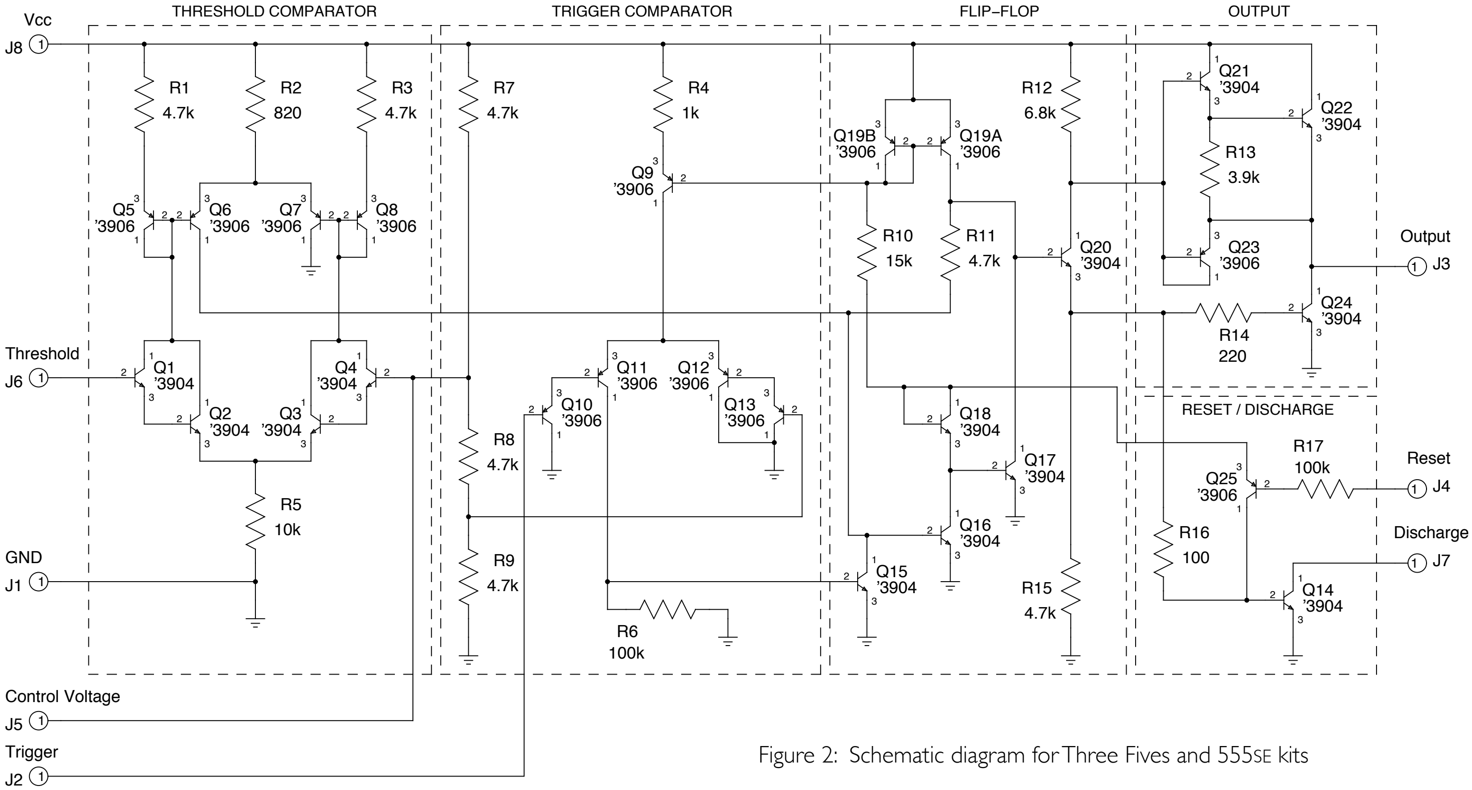


Figure 2: Schematic diagram for Three Fives and 555SE kits

Other pins:
There is an open-collector discharge pin. Normally it floats (high impedance), but when the flip-flop output is low, it goes low also. It is useful for discharging external timing capacitors.

A control voltage (CV) pin connects to the reference input of the threshold pin (normally ⅔ V_{cc}). This is a good analog signal input for PWM (pulse-width modulation) circuits.

The Overall Schematic

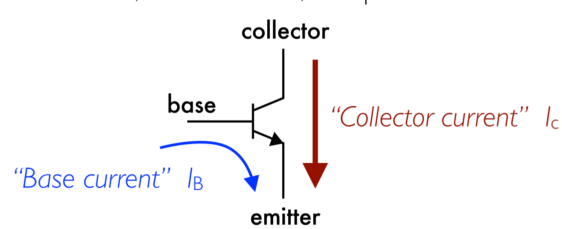
The detailed schematic for the Three Fives and 555SE circuit boards is shown in Figure 2. As we walk through the details of the different blocks that make up the circuit, it will help to keep this overall diagram nearby.

The schematic is roughly divided into the same blocks as the block diagram, but please note that the divisions are only approximate. For example, the resistive voltage divider (which you will recall from the block diagram) consists of resistors R7, R8, and R9. In figure 2, those three components appear inside the "Trigger Comparator" block, even though (as you may recall from the block diagram) the voltage divider is not actually part of that comparator.

You may notice – from this schematic or the parts included with the kit – that the electronic components in the circuit consist solely of resistors and transistors. We'll briefly review these two components before we dive into the heart of the circuit diagram.

Review: Resistors
The defining property of resistors is that they are circuit elements that follow Ohm's law, which is $V = I \times R$, where V is the voltage across the resistor, I is the current through the resistor, and R is the value of the resistor (measured in ohms). For example, if a 4.7 kΩ resistor has current of 1 mA through it, then the voltage difference between its two sides is 4.7 V.

Review: Transistors
While there are many types of transistors, the ones in this circuit are bipolar transistors, in which a small current controls a larger one, to act as an amplifier or switch. There are two flavors of these, NPN and PNP; we'll pick NPN to look at first:



NPN Transistor

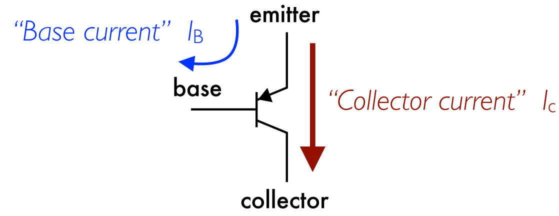
The three terminals of an NPN bipolar transistor are named "base," "collector," and "emitter." The base and emitter pins comprise a diode, indicated by the little arrow on its schematic symbol. A diode is a unidirectional circuit element, so under normal circumstances, current can only be made to flow from the base to the emitter, and not from the emitter to the base.

Aside: An NPN transistor also has a *second* internal diode, which conducts (only) from the base to the collector. In most use cases, a circuit that uses this kind of transistor is designed to always keep (or "bias") the collector at a higher voltage than the base, so that the base-collector diode does not conduct current. So long as this bias is maintained, we can usually ignore the presence of the second diode.

An important detail is that there is a small voltage loss across a diode, usually about 0.7 V. This means that (a) when current is flowing from the base to the emitter, the voltage at the emitter pin is usually about 0.7 V below that at the base (b) current does not begin to flow from the base to the emitter until the voltage of the base is about 0.7 V above that of the emitter. This typical voltage difference of 0.7 V is usually referred to as a "diode drop."

Finally, there is the matter of switching and amplification. When current flows from the base to emitter, that current ("base current," symbol I_B) is said to "switch on" the transistor: it allows current to flow from the collector to the emitter. The maximum amount of current that can flow from the collector to the emitter is given (to good approximation) by $I_C = h \times I_B$, where I_C is the "collector current" (the current flowing from the collector to the emitter) and h is a gain factor that depends on the particular transistor. If h has a value of, say, 30, then the transistor acts as an amplifier where a small change in I_B causes a change 30 times larger in I_C.

The other flavor of transistor – PNP – works almost exactly the same way. Its schematic symbol is similar with the major



PNP Transistor

change that the little arrow is pointing in. (Mnemonics! PNP: **P**ointing i**N** **P**lease, NPN: **N**ot **P**ointing i**N**.) In a PNP, the emitter and base form a diode where current can only flow one way, but this time only *from emitter to base* (again, in the direction of the arrow). And, when current flows through that diode, it allows a current $I_C = h \times I_B$ to flow from the emitter to collector.

The particular components that we are using are type 2N3904 or MMBT3904 for our NPN transistors and 2N3906 or MMBT3906 for our PNP transistors. These are some of the most common and well known types of bipolar transistors.

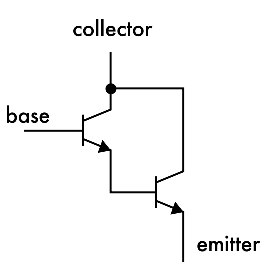
The Threshold Comparator

The first block on the schematic diagram is the "threshold" comparator, which looks at the voltage on the threshold pin and compares it to a reference voltage of ⅔ of V_{cc}, which comes from the voltage divider (again, R7, R8, and R9). Notice that the control voltage (CV) pin taps directly into this reference voltage so it can be modified externally.

There are two main parts to the comparator circuit: The input differential amplifier and the second stage differential amplifier (with current mirrors).

Darlington Pairs

One of the first things to notice is that some of the transistors (e.g., Q1 and Q2) are hooked up together in what is known as the Darlington configuration:



In the Darlington configuration, the emitter of one transistor is connected to the base of another. This effectively makes one new "super transistor" out of the two, since it is the amplified current out of the first collector that serves as the base current for the second transistor. If the gain of a single transistor were 30, then the effective gain of the Darlington pair would be 30 × 30 = 900.

This huge improvement in gain is not without cost. Since there are two transistors, there are also two diode drops to be overcome; the Darlington pair will not begin to turn on until its base is at least 1.4 V above the emitter.

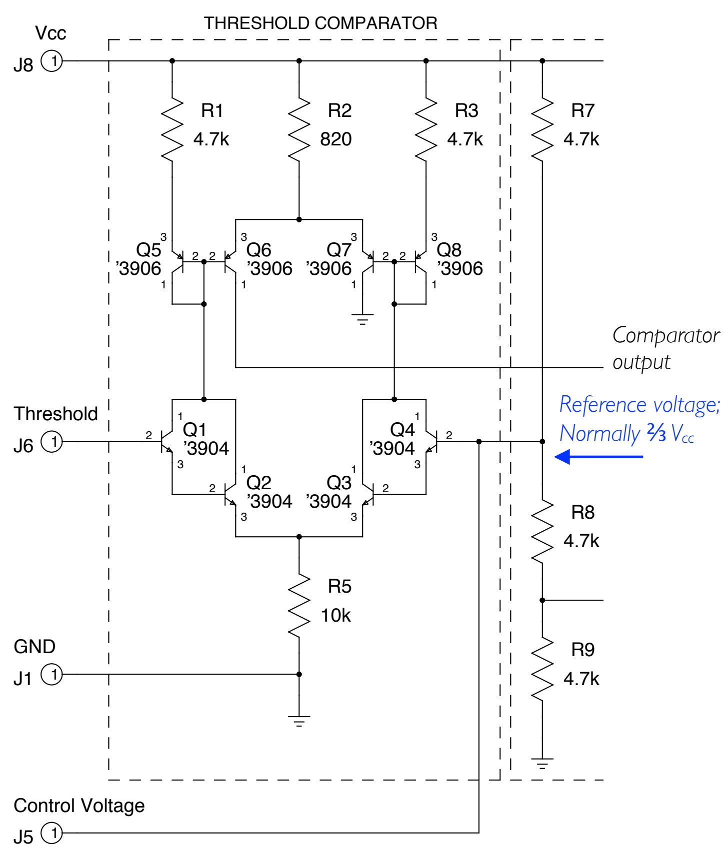


Figure 3: Threshold Comparator

Differential Amplifier

Two Darlington pairs, Q1/Q2 and Q3/Q4 form a differential amplifier. Using the Darlington pairs (with their high gain) reduces the current drawn from the comparator inputs.

The differential amplifier itself acts a little like a seesaw: when the voltage on the threshold input is higher than the voltage on the reference input (⅔ of V_{cc}), the current flow in the circuit comes mainly from the left side through Q1 and Q2. (remember that the circuit is symmetrical). When the threshold voltage falls below the reference voltage, the circuit changes state and the majority of the current flows through Q3 and Q4.

We can help illustrate the main idea with a simplified differential amplifier:

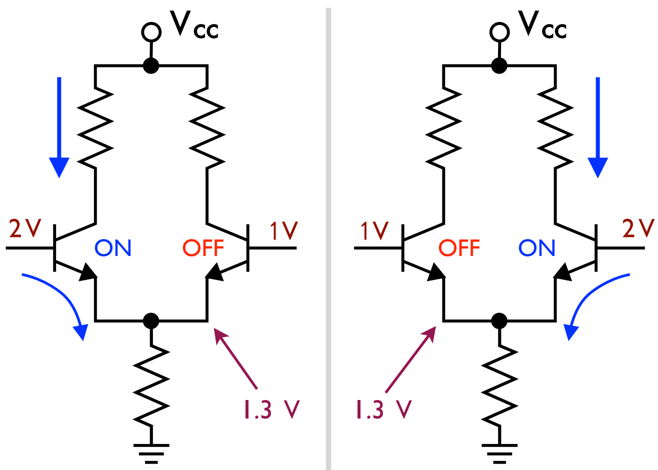


Figure 4: Simplified differential amplifier

In the case on the left, the inputs to the amplifier are 2 V (left input) and 1 V (right input). Since the left input is higher, the left transistor turns on more strongly, pulling more current through its collector. The voltage at the emitter saturates to 1.4 V (2 V, less one diode drop), turning off the other transistor (since the emitter voltage is higher than the base voltage).

If the inputs change to the case on the right, when the inputs are 1 V (left input) and 2 V (right input), the opposite happens, and the current flows down the right hand of the circuit.

In these two cases what you should notice is that current is always flowing but the *branch* of the circuit (left or right) that it flows through depends upon the values of the input voltages.

A valid question at this point is "If this is a differential amplifier, how is a difference actually being amplified?" The answer is that the difference between the input voltages controls an amplified current that flows through one of the two resistors near the top of the diagram. Ohm's law tells us that the voltage drop across those "load" resistors depends on the current through them, and thus the amplified difference could be read out below the resistors (i.e., as the voltage difference between the collectors of the two transistors).

Let us now return back to the main circuit. Regardless of which set of transistors conduct the current through the differential amplifier, the current always travels through R5 to ground.

Because of the Darlington pairs, the voltage drop from each input to the top of R5 is two diode drops. For proper operation, at least one of the inputs must be at least 1.4 V above ground (the minimum "common mode" input voltage). Since the other comparator input connects to ⅔ of V_{cc}, this condition is satisfied. This is why typical 555 timer datasheets specify a limited voltage range for the Control Voltage (CV) input.

The maximum common mode range (how high both inputs can be at the same time) extends close to V_{cc}. However, if you bring the voltage on either input too high, you could forward bias the base-collector junction† of Q1 or Q4 and the current flowing in that side of the comparator will quickly drop to zero. This manifests as "comparator inversion" where the output flips to the wrong state.

Current mirrors

Before we get to Q5, Q6, Q7, and Q8 at the top of the threshold comparator block, we must digress for a moment to describe a circuit block called a "current mirror" that appears repeatedly both in this section and elsewhere in our overall schematic.

A current mirror is called that because it "copies" a current through one circuit element to a current through another element. Let's first examine a relatively simple example of a current mirror. Look at how Q19A and Q19B are wired up:

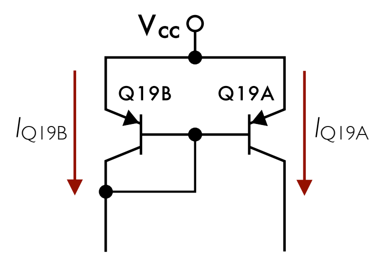


Figure 5: Q19A/Q19B Current Mirror

Notice that transistor Q19B is connected "as a diode," with its base short-circuited to its collector. Even so, it allows current to pass through its collector.

Since their emitters and bases are wired together, both Q19A and Q19B have the same base-emitter voltage. Symmetry then dictates that the same amount of current should flow from the emitter to the base of each transistor. Accordingly, both transistors permit the same amount of current to pass through their collectors. If current I_{Q19B} is sourced from the collector of Q19B, the same amount of current will flow through the collector of Q19A: $I_{Q19A} = I_{Q19B}$. In this sense, the current through the collector of Q19A "mirrors" that of Q19B.

† Remember that the base-collector of the NPN transistor also forms a diode. This is a case where that actually becomes important; If the base voltage were to become higher than the collector voltage, then that diode could begin to conduct.

Second Stage Differential Amplifier
The outputs of the first differential amplifier in the threshold comparator feed into a second differential amplifier formed by transistors Q5, Q6, Q7, and Q8, with resistors R1, R2, and R3.

This differential amplifier looks different for a couple of reasons. First, it is "upside down" when compared to the one that we looked at earlier. And second, its input stages are current mirror circuits. However, it works using the same principle: it amplifies the signal coming from the first differential amplifier and increases the overall gain.

One current mirror is formed by Q5, Q6, R1, and R2. Another is formed by Q7, Q8, R2, and R3. Transistors Q6 and Q7 do double duty – they are part of the current mirror circuit but, working with R2, also act as a differential amplifier. The collector of Q6 is the output of the amplifier and gets routed to the flip-flop block. Q7's collector goes to ground and is not used but it could be considered the "inverted" output.

In essence this part of the circuit is actually three circuits superimposed on each other: Two current mirrors mashed up with a differential amplifier.

Questions and Experiments I

1. Measure the resistance of the CV (control voltage) pin to the V_{cc} pin. You can try this out with a real 555 timer. If you can find one, try this experiment with a CMOS 555 timer, like the TLC555 or the LMC555.

2. Measure the voltage across R5. How much current flows in the comparator? Does it change when you adjust the voltage on the threshold input? What happens if you force the CV pin and the threshold input below about 1V?

3. Measure the current flowing into the threshold input. Connect a variable power supply to the threshold input and wire an ammeter in series so you can measure the current for various input voltages.

4. Short the base and emitter connections of Q1. Repeat for Q4. Can you describe what effect that change should have on the circuit? Now measure the input current on the threshold pin. How does this affect the behavior of a 555 circuit such as an oscillator?

5. What happens to the voltage across R2 as the comparator changes state?

6. Measure the offset voltage. Try putting a voltmeter across the input terminals (threshold and control voltage), and record the voltage right as the comparator changes state. This directly affects the timing accuracy of the chip since it will cause the comparator to trip slightly too late every time.

7. Given an unlabeled bipolar transistor and a multimeter, how would you figure out whether it's a PNP or NPN type, and which pin is which?

8. Download the datasheet for the NPN transistors (2N3904 or MMBT3904) that are used in the kit. What value of transistor gain should you actually expect? Can you measure it somewhere in the circuit? What does it say about the "diode drop" voltage? Can you measure a typical diode drop in the circuit?

Trigger Comparator

The trigger comparator works like the first (lower) part of the threshold comparator except it is upside down and uses PNP transistors in a slightly different arrangement. The reason they are upside down is to ensure that the common mode input voltage range extends all the way to zero. This is important because the reference voltage terminal comes from ⅓ V_{cc} from R7, R8, and R9. The two inputs to the differential amplifier are that ⅓ V_{cc} reference and the input from the Trigger pin.

Two pairs of transistors (Q12/Q13 and Q11/Q10) are configured into Darlington pairs. They conduct directly to ground, and a bias current (i.e., one that keeps current flowing through the transistors in the correct direction) comes from Q9, which acts as a constant current source. The output current from Q11 serves as the output of the comparator and is routed to the flip-flop block.

Current mirrors, again
Q9 sources current by being part of a "current mirror" formed with Q19A and Q19B, two transistors in the flip-flop block that we discussed earlier when talking about current mirrors.

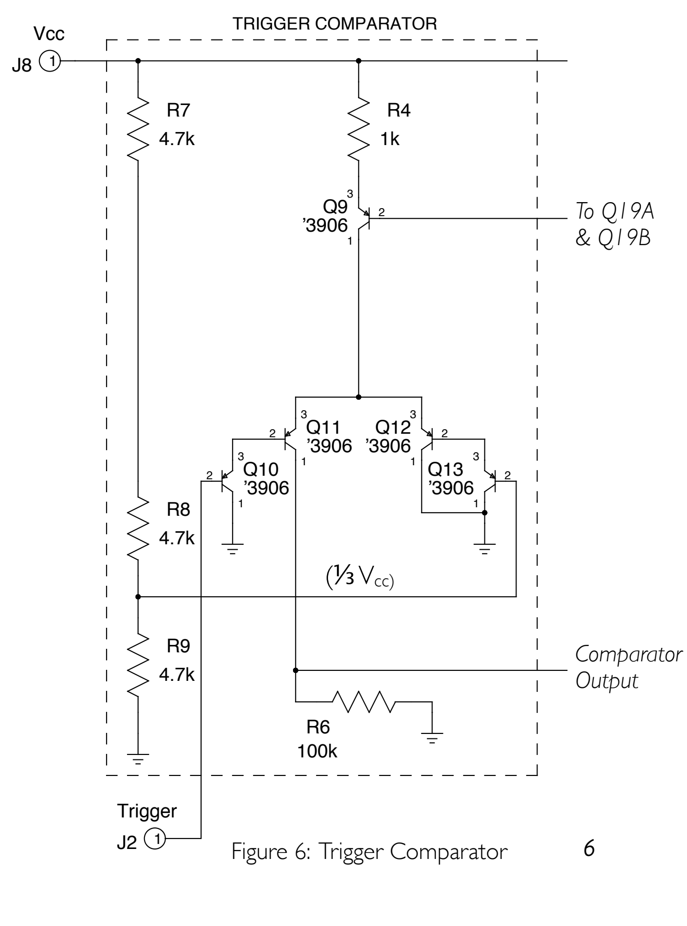
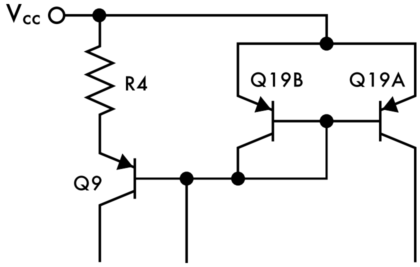


Figure 6: Trigger Comparator

How does Q9 fit into all of this?



Current mirrors can be constructed with multiple "output" transistors, and Q9 is an additional output transistor that – in parallel with Q19A – tracks changes in the current through Q19B.

However, unlike Q19A, the current through Q9 is not a direct copy but instead is divided by a fixed ratio determined by R4. Because R4 is in series with the emitter, this circuit is called a Widlar current source (invented by Bob Widlar, the legendary IC designer who invented IC op amps, regulators, and basic building block circuits like bandgap voltage references).

Finally, why does this comparator only have a single differential amplifier and not two? The Widlar current source is an "active" load (compared with the "passive" resistor load found in the threshold comparator) and this increases the gain of the amplifier, making a second stage unnecessary.

Aside 1: It is worth noting that in the original 555 timer integrated circuit, there is only a single Q19, not two. This is one of a few differences between the discrete version and the original IC.

The single Q19 on the integrated circuit is a rather strange beast called a dual collector PNP transistor – A transistor with two collectors. IC designers used them because all you had to do was take a regular lateral PNP transistor and split the collector into two halves, giving two transistors for the price of one (with roughly equal currents from both collectors). However, for a kit, two mirrored discrete PNP transistors are an excellent substitute, and that is why we have Q19A and Q19B. Their presence also provides a superb example of a simple current mirror, which helps lead into the role of Q9.

Aside 2: Please see additional references in the last section ("Further Reading") for links to additional information about current mirrors and sources. We have glossed over some interesting details for the sake of brevity and clarity.

The Flip Flop

There is a lot of analog subtlety in this block. It is known as a *bistable circuit* because it has two stable states. To simplify the analysis, we will look at the block in its two possible states: where the output pin is either on or off.

Bias current for this block comes from the current mirror pair Q19A/Q19B. R10 sets the current through Q19B and consequently, through mirrors Q19A and Q9. (Recall that Q9 is the transistor that provides the constant current source for the trigger comparator.)

The actual output of the flip-flop gate is the voltage at the collector of Q17, indicated in Figure 7. The three elements to the right of that point, (R12, Q20, and R15 in the overall schematic, Figure 2) are part of the output driver and are not shown here.

Case: Output Pin On (Q17 on, Q16 off)
The voltage at Q18's emitter is about a diode drop above ground. The current from Q18 flows entirely through the base of Q17 to ground, keeping the transistor on. R11 then acts as a pulldown, keeping the base of Q16 low and that transistor switched off. Since Q17 is turned on, the flip-flop output is low. The output pin itself is high because there is another inverter in the output stage between the flip flop output and the output pin.

To switch the flip-flop to the off state, the threshold comparator output has to turn on and source current into the base of Q16. If there is enough current there to overcome R11, then Q16 turns on, pulling the base of Q17 low, which turns off Q17, which changes the flip-flop output to the high state (for which the state of the output pin is low).

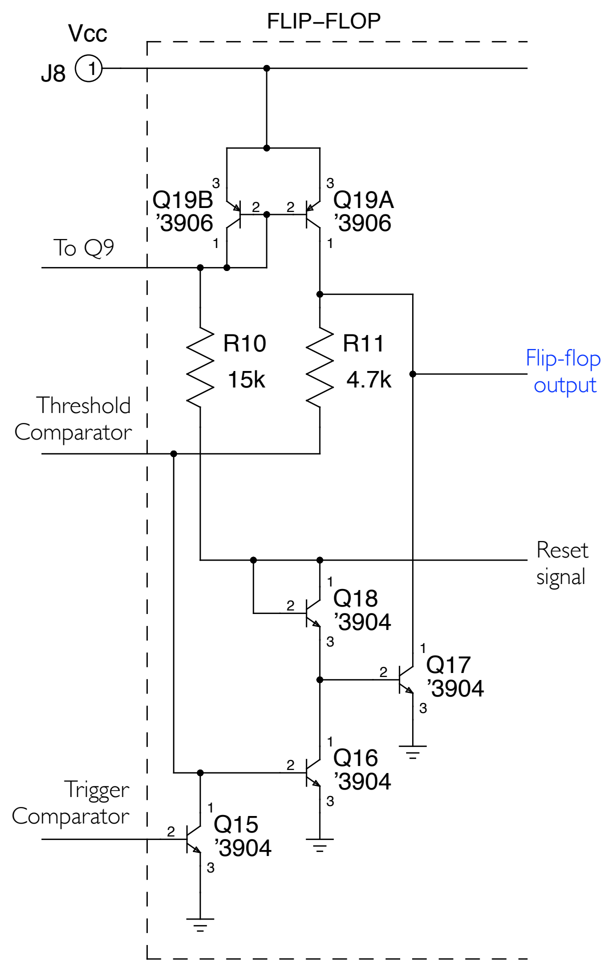


Figure 7: Flip Flop Block

Another way to switch states is by using the reset circuit. If the reset input pin goes low, it turns on Q25 which pulls the collector of Q18 low and robs the base current from Q17, which turns off Q17. The base-emitter drop across Q25 is "cancelled out" by the base-emitter drop of Q18 (a diode-connected transistor).

Case: Output Pin Off (Q17 off, Q16 on)
In this case, the current from Q18 flows entirely through Q16 to ground. Q17 has no base current so it is off. R11 is pulled high through Q19A, providing current to the base of Q16, turning it on. Since Q17 is off, the output of the flip-flop is high.

To change from this state to the on state, trigger comparator output has to turn on. This switches on Q15 and yanks the base of Q16 low, turning it off and changing state.

Questions and Experiments II

1. Without using the threshold, trigger, or reset inputs, how can you probe the circuit and change the state of the flip flop?
2. In the High-Level Overview section, we described the behavior of the flip-flop in terms of its "R" and "S" inputs and its output state. Test the circuit as you change R and S to see if it behaves the way that we've described it.
3. Compare the current flowing in Q19B with the current in Q19A. Also compare it with the current in Q9. You will have to desolder one transistor lead to wire an ammeter in series.
4. Does the current flowing in R10 change when VCC changes? (You can measure the voltage across R10, and use Ohm's law to calculate the current.)
5. Build a simple oscillator circuit. Now change R10. How does it affect the operation of the circuit? (You can clip a resistor in parallel to R10 to reduce its value without clipping wires or desoldering.)
6. The circuit has an available Reset pin for the flip-flop, but there is not a corresponding *Set* input pin. How would you add one?

Output Stage

Q20 takes the raw output of the flip-flop gate and creates a buffered (non-inverted) version and an inverted version of the signal. It will also help to analyze the circuit in two states.

Case: Output Pin On (Q20 off, Q21/Q22 on, Q24 off)
The output from the flip-flop is low. Q20 therefore has no base current and is turned off. Q21 and Q22 form a Darlington pair configured as a voltage follower. They try to follow the voltage on the base of Q21, which is pulled to V_{cc} through R12. The output voltage in this state is V_{cc} minus two diode drops. Q24 and Q14 are kept on the off state by R15.

Case: Output Pin Off (Q20 on, Q21/Q22 off, Q24 on)
The flip-flop output drives current into the base of Q20, turning it on. Current from Q20 turns on Q24 and Q14. R16 and R14 split the current from Q20 so that both of these transistors can be driven from one output. Q14 pulls the discharge pin low, and Q24 pulls the output pin low.

Since Q20 is on, Q21 and Q22 are off. The voltage at the base of Q21 is about one diode drop above ground; no current flows because it takes two diode drops to begin to turn on the Darlington transistor pair.

A Quick Note About Q23
Q23 is yet another diode-connected transistor. It provides a little more current capability to the output stage when it is driving low. If the voltage on the output rises enough to forward bias Q23 (that is, if the emitter goes at least one diode drop above the base), the resulting current flows into Q24's base and makes it work a little harder.

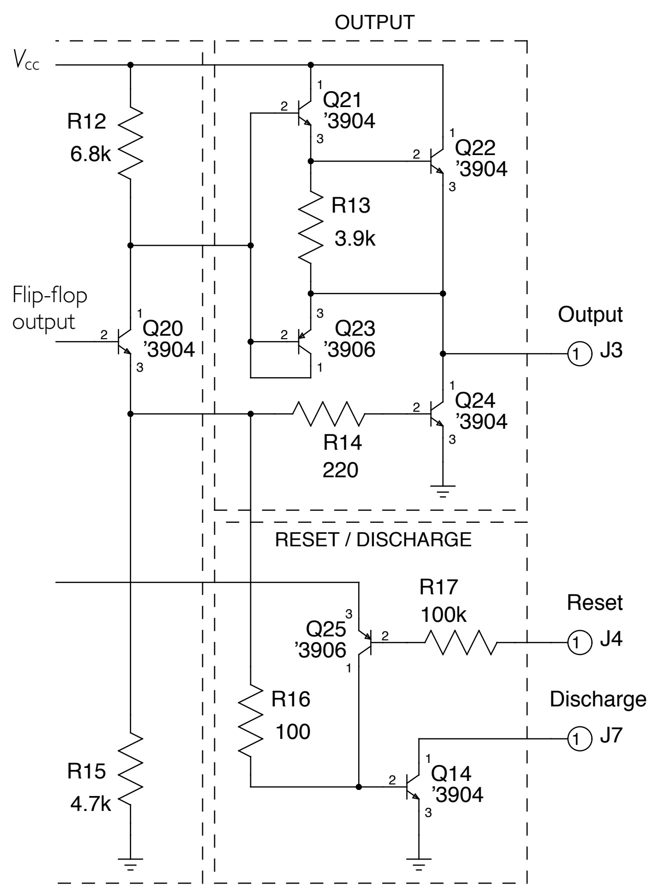


Figure 8: Output, Reset, Discharge

Reset Input

Pulling the reset pin low turns on Q25. This steals current from the flip flop, putting it into the on state (for which the output pin is low), and uses that current to switch on Q14 and Q24, which drive the output pin and the discharge pin low.

Resistor R17 is not in the original 555 timer integrated circuit. It has been added to help protect the reverse biased junction of Q25. In the kit, Q25 is a '3906 transistor, which has a maximum reverse bias voltage on the base-emitter junction of only 6V, whereas the original 555 could handle 18 V. Therefore, when the Reset pin is tied high and the V_{cc} is high enough, it is possible to exceed this breakdown voltage, and R17 prevents damage by limiting the current. (The first version of the Three Fives kit did not include this resistor, and so required an external 100 k resistor to be added when the reset pin needed to be connected to a voltage above 6 V.)

Questions and Experiments III

1. Try shorting R14. Does this change the function of the discharge or output pins? Try again, but short R16 this time instead.
2. Compare the base voltage of Q21 with the output voltage. Now change the flip-flop to the other state. If you have an oscilloscope, make an oscillator circuit and probe these two nodes.
3. The original 555 IC did not include resistor R17, and yet was usable at voltages above 6 V without an external resistor on the Reset pin. How is that possible? Can you find a different transistor (to replace the '3906) that would make it so that R17 was not needed?
4. What is the maximum speed of the 555? How would you increase it?
5. What components could you add to make the 555 comically slow? Add a few (buffered) LEDs and maybe you could build a human-watchable 555 timer.
6. Can you fix the output buffer's shoot-through current problem?
7. What limits the circuit's maximum operating voltage? How about the minimum? How could you change those limits?
8. The original 555 does not bring the reference input to the trigger comparator out to a pin, unlike the threshold comparator's CV pin. With the discrete version, you have access to connect anything you want to the trigger comparator's hidden input! What sort of circuit can you dream up that uses this feature?
9. How could you rework the threshold comparator to use an active load (like the trigger comparator) instead of a second stage differential amplifier?

FURTHER READING

1. Main documentation page for the Three Fives and 555SE kits: http://wiki.evilmadscientist.com/555
2. Main product pages for the kits. The Three Fives kit: https://emsl.us/652 The 555SE Kit: https://emsl.us/922
3. Original Signetics 555 datasheet (scan): https://cdn.evilmadscientist.com/wiki/555/555_556Signetics.pdf
4. Modern TI NE555 datasheet: http://www.ti.com/lit/ds/symlink/se555.pdf
5. An interview with Hans Camenzind: http://www.semiconductormuseum.com/Transistors/LectureHall/Camenzind/Camenzind_Index.htm
6. Tube Time, the web site of Eric Schlaepfer, Designer of the Three Fives and 555SE circuit boards: http://tubetime.us
7. Forrest M. Mims III, *Engineer's Mini-Notebook: 555 Timer IC Circuits,* Radio Shack Catalog No. 276-5010, 1984.
8. Article about Bob Widlar at hackaday.com: http://hackaday.com/2014/04/08/heroes-of-hardware-revolution-bob-widlar/
9. Introduction to open collector circuits, at Evil Mad Scientist Laboratories: http://www.evilmadscientist.com/2012/basics-open-collector-outputs/
10. Over 100 555 timer IC projects at Talking Electronics: http://tinyurl.com/555projects
11. 555 timer teardown: inside the world's most popular IC, on Ken Shirriff's blog: http://www.righto.com/2016/02/555-timer-teardown-inside-worlds-most.html
12. Wikipedia is an excellent resource for learning basic electronics. Some potential topics of interest include:
    http://en.wikipedia.org/wiki/Widlar_current_source http://en.wikipedia.org/wiki/Current_mirror
    http://en.wikipedia.org/wiki/Transistor http://en.wikipedia.org/wiki/555_timer_IC

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