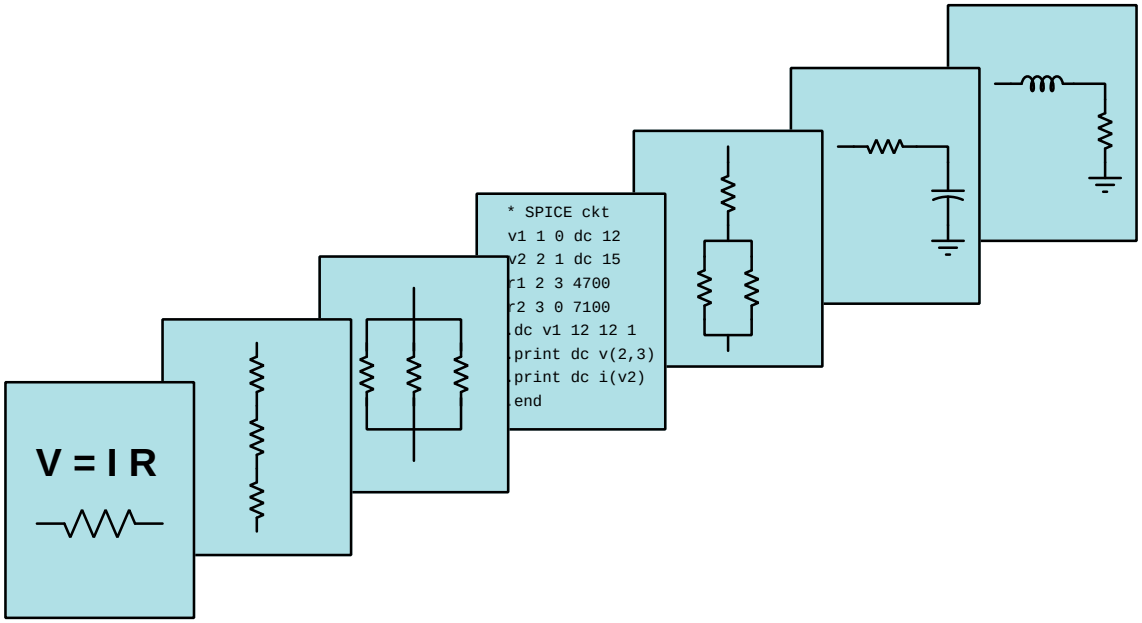
Modular Electronics Learning (ModEL) project



555 Timer Circuits

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Chapter 1

Introduction

The model 555 integrated circuit (IC) timer is a very popular product, used in a wide array of applications. It also serves well as an educational tool, teaching students how to use resistor-capacitor networks to perform practical timing functions. This module is written with the assumption that the 555 timer will be the first integrated circuit students encounter in their study of electronics, immediately following the study of capacitive time constants.

Important concepts related to the operation of the 555 timer IC include **capacitance**, **resistance**, capacitive **relaxation oscillator** circuits, **RC networks**, **inverse exponential** functions, **time constants**, **hysteresis**, **BJT** behavior, **oscillographs**, and **integrated circuits**.

Here are some good questions to ask of yourself while studying this subject:

- What is a relaxation oscillator, and how does one function?
- Why does a capacitor's voltage rise and fall according to an inverse-exponential function in an RC network?
- How does neon lamp behavior differ from other types of lamps (e.g. incandescent, LED)?
- Would a neon lamp-based relaxation oscillator work if the lamp were replaced with an incandescent? How about if it were replaced by an LED?
- How could the frequency of a neon-lamp-based relaxation oscillator be increased or decreased?
- What is an *integrated circuit*?
- Which ways should current flow through the terminals of a bipolar junction transistor?
- Why does the sawtooth waveform from a simple 555 astable circuit have different "rise" and "fall" times?
- What makes some 555 circuits astable and others monostable?
- How could the frequency of a 555-based oscillator be increased or decreased?

Chapter 2

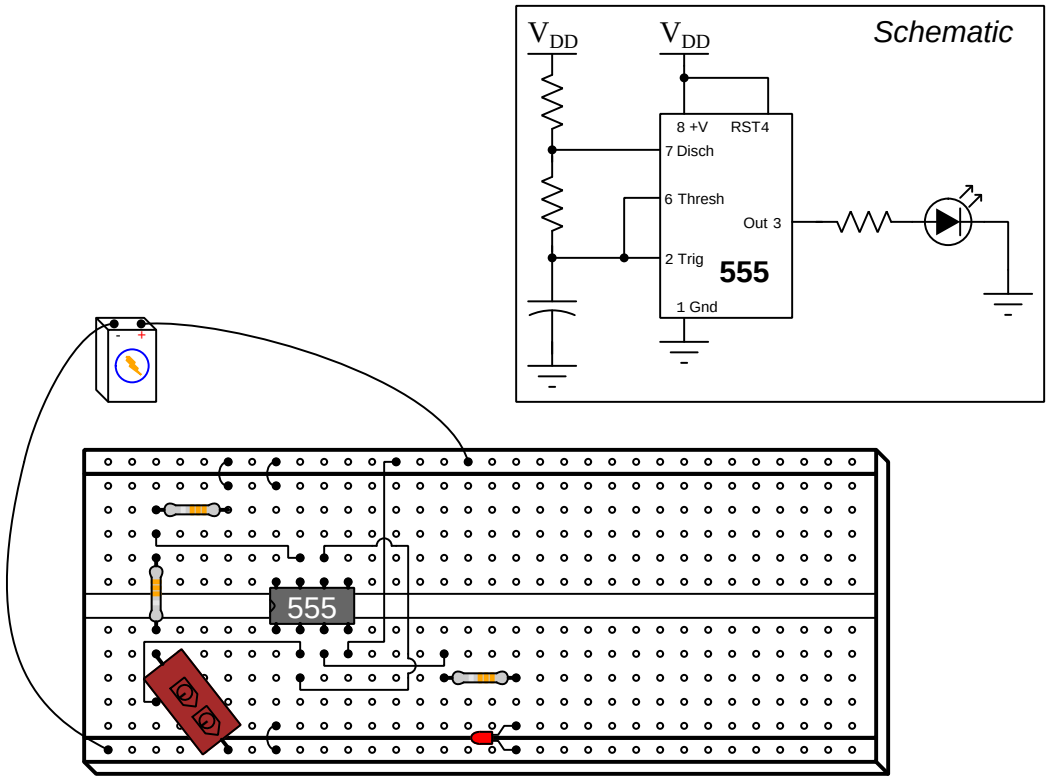
Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: astable 555 oscillator demonstration circuit

This demonstration circuit uses a generic 555 timer IC in a standard "DIP" package:



Research a manufacturer's *datasheet* for this timer IC to see the "pinout" diagram showing which pins on the IC package connect to which of the 555 timer circuit's terminals inside, as well as to identify its acceptable minimum and maximum DC voltage limits so you may select an appropriate power supply voltage. You will need to select appropriate resistor and capacitor values to set a timing frequency you can easily see at the LED, and also a suitable current-limiting resistor for the LED so as not to over- or under-power it.

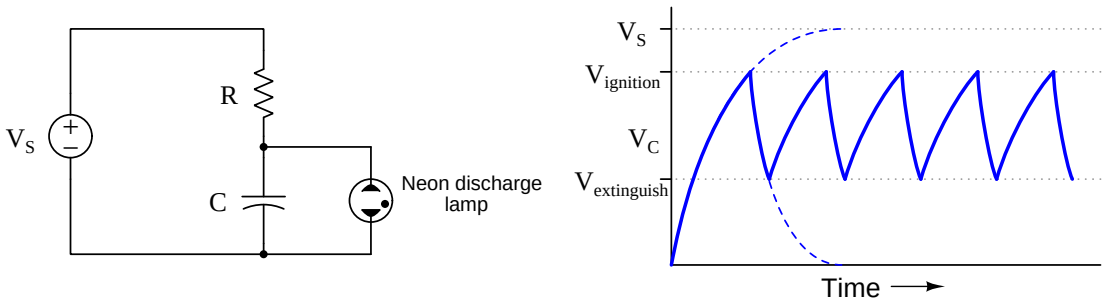
Note: you may find it helpful to connect a *decoupling capacitor* with a value of 1 μF or so between the positive and negative DC power supply "rails" (not shown in the schematic or the pictorial illustration) to stabilize the source voltage. If the DC power source has significant internal resistance, and/or the connecting wires between it and the breadboard are too long, what often happens is that "noise" will appear on the IC's supply voltage (between pins 8 and 1) when the 555 timer switches from "discharge" to "charge" mode, often with detrimental effects on timing accuracy.

Chapter 3

Tutorial

3.1 Relaxation oscillators

A practical category of circuits known as *oscillators* generate pulsing or alternating electrical signals useful for a great many applications. Perhaps the simplest type of oscillator is called a *relaxation oscillator*, based on the time-delayed energizing of a capacitor. A primitive relaxation oscillator is shown here, using a resistor, capacitor, neon discharge lamp (requiring about 70 Volts to produce light), and a DC voltage supply of approximately 100 Volts:



One way to begin analyzing this oscillator circuit is to apply the problem-solving technique of *simplifying the system*. If we were to remove the neon lamp from the circuit, we would be left with just the DC supply, resistor, and capacitor, which of course would result in the capacitor's voltage rising over time to finally equal the supply voltage (approximately 100 Volts). The trajectory of the capacitor's voltage over time is traced by the first curve in the graph (rising asymptotically to supply voltage V_S).

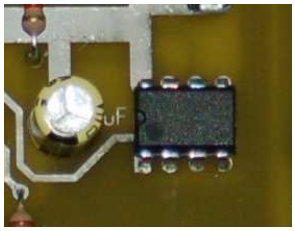
Neon lamps are quite unlike incandescent lamps, in that they conduct zero current unless and until the voltage impressed across their terminals exceeds the "ignition" voltage, which is the amount of voltage necessary to ionize the neon gas and make it electrically conductive. Once ionized, such a lamp will exhibit a relatively low resistance through the ionized gas, and will continue to conduct current until the voltage across its terminals falls to a much lower value (the "extinguishing" voltage) at which point the neon gas returns to a non-ionized state and becomes an electrical insulator once again.

Now that we know how a neon lamp functions with different levels of applied voltage, we may form another simplified circuit to explore its behavior. Imagine letting the capacitor energize to the "ignition" voltage level, then removing the resistor from the circuit and inserting the neon lamp back into the circuit (in parallel with the capacitor). The lamp, of course, would immediately begin conducting current which would cause the capacitor to begin to de-energize, its voltage asymptotically descending toward 0 Volts. The capacitor's voltage would not actually fall all the way to zero, though, because the neon lamp would turn off at its "extinguishing" voltage. At this point the capacitor's voltage would remain at that level with the lamp off, but the second dashed line on the graph shows what the voltage *would* do if somehow the neon lamp were to remain lit all the way to zero.

Putting all these concepts together, we can imagine what would happen with all components connected: beginning at zero volts, the capacitor's voltage rises asymptotically toward supply voltage with current limited by the resistor. Once the capacitor's voltage reaches the ignition level, the neon lamp turns on and provides a low-resistance load for the capacitor to dissipate its stored energy

(even with the resistor still supplying current from the DC source). Once the capacitor's voltage falls down to the extinguishing level, the neon lamp turns off and the capacitor begins absorbing energy again. The result is a "sawtooth" voltage waveform measured across the capacitor. This is the cycle of a relaxation oscillator: a capacitor gradually energizes over time, then "relaxes" as some non-linear component (e.g. the neon lamp) switches to a conductive state to dissipate the capacitor's stored energy, the cycle repeating itself at some lower voltage value.

Relaxation oscillators using neon lamps as the switching element are extremely simple in their design and generally pleasing to behold: the neon lamp emits a bright flash of light with every de-energizing portion of the cycle. Neon discharge lamps are not the only type of switching element we can use to build a relaxation oscillator, though. Modern semiconductor technology allows the construction of transistor-based switching circuits to perform the same function as the neon lamp, but with much greater repeatability and at much lower (and safer) voltage levels. One such semiconductor device is called the *model 555 timer*, which takes the form of an eight-pin *integrated circuit* (IC)[1], as shown in the following photograph. This particular 555 timer[2] has been soldered into a printed circuit board (PCB), to the right of an electrolytic capacitor:

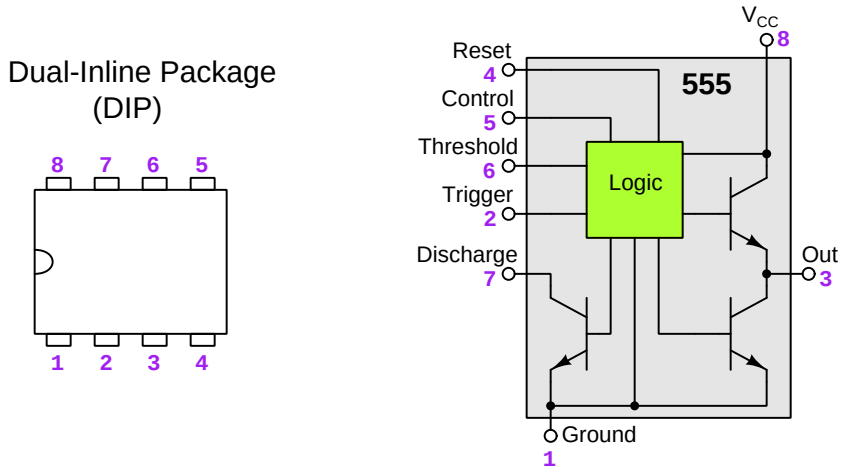


[1] An "integrated circuit" is one where all components are built on a single wafer of semiconducting material, usually purified silicon. This manufacturing technique lends itself very well to mass-production, the goal being to produce electronic circuits of small size having exceptionally consistent performance.

[2] An 8-pin DIP integrated circuit is quite small, approximately 10 millimeters in length and just over 6 millimeters in width. Standard DIP pin spacing is 0.100 inch (2.54 millimeters) between pin centers.

3.2 Internals of a 555 timer IC

The following diagram shows the standard pin numbering of a dual-inline integrated circuit package (DIP) as well as the internal functionality of the model 555 timer IC:

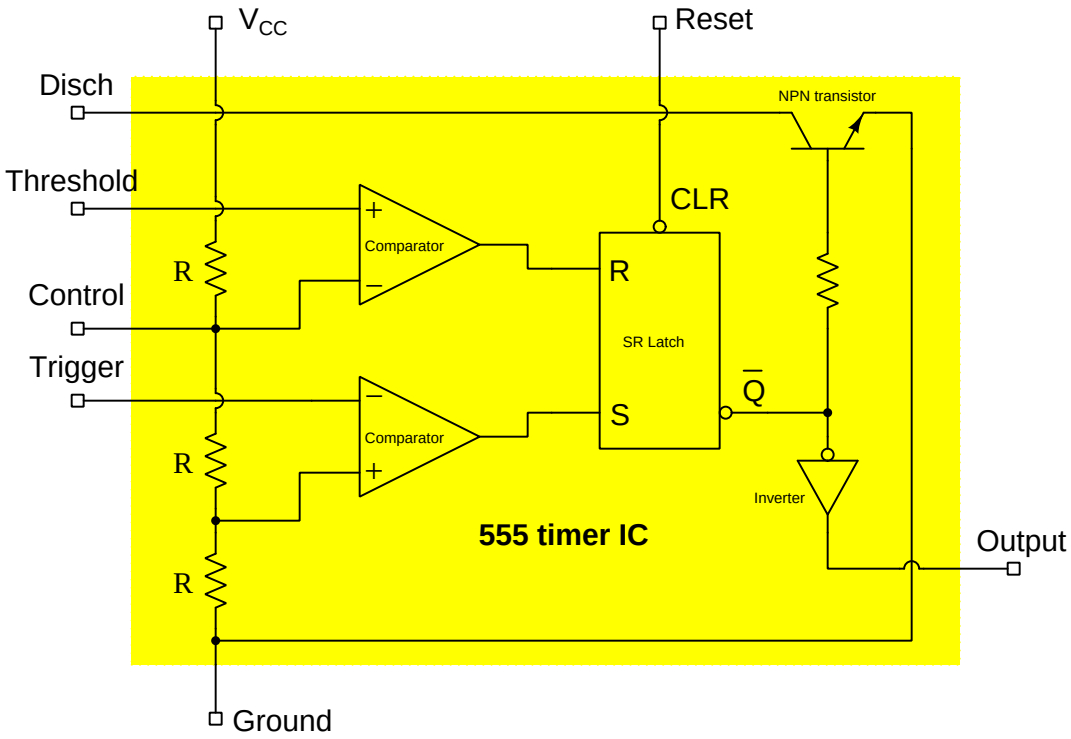


This functional diagram omits much of the complexity internal to the model 555 integrated circuit. The green-colored "logic" section, for example, contains over two dozen transistors and eleven resistors, and serves the purpose of switching the three transistors shown in this simplified diagram fully "on" and fully "off" depending on the voltage levels sensed between the Threshold and Ground pins, and between the Trigger and Ground pins. This "logic" section of the 555 timer's internal circuitry requires DC power to properly function, which is why it connects to the V_{CC}[3] (+) and Ground (−) terminals.

The Threshold, Trigger, and Discharge pins of the 555 timer replace the neon lamp in the simple relaxation oscillator circuit. Whereas the neon lamp switched between conducting and non-conducting states based on voltage impressed across its two terminals, the 555 timer switches between "discharge" and "charge" states (the Discharge transistor on and off, respectively) based on voltage sensed at the Threshold and Trigger terminals with respect to Ground. The 555 timer toggles to the "Charge" state whenever the Trigger terminal senses a voltage less than $\frac{1}{3}$ of V_{CC} (supply voltage), and toggles to the "Discharge" state whenever the Threshold terminal senses a voltage greater than $\frac{2}{3}$ of V_{CC}. Thus, by connecting these three terminals together, and then connecting a capacitor between those common terminals and Ground, the 555 timer stands ready to sense capacitor voltage and switch between charge and discharge states based on the sensed voltage.

[3] The label subscript "CC" in the label V_{CC} refers to the internal configuration of transistors inside the integrated circuit. "CC" simply refers to the power supply pole connected to the "collector" terminals of internal bipolar transistors. Some integrated circuits label one of the DC supply terminals V_{EE} referring to the supply pole directly connected to the "emitter" terminals of bipolar internal transistors. For integrated circuits built with field-effect transistors, the power supply terminals are commonly labeled V_{DD} (to the "drain" terminals) and V_{SS} (to the "source" terminals). These details need not concern the user of any integrated circuit, except for the importance of maintaining proper DC voltage polarity between the supply terminals. IC datasheets will always specify this polarity, regardless of terminal labeling.

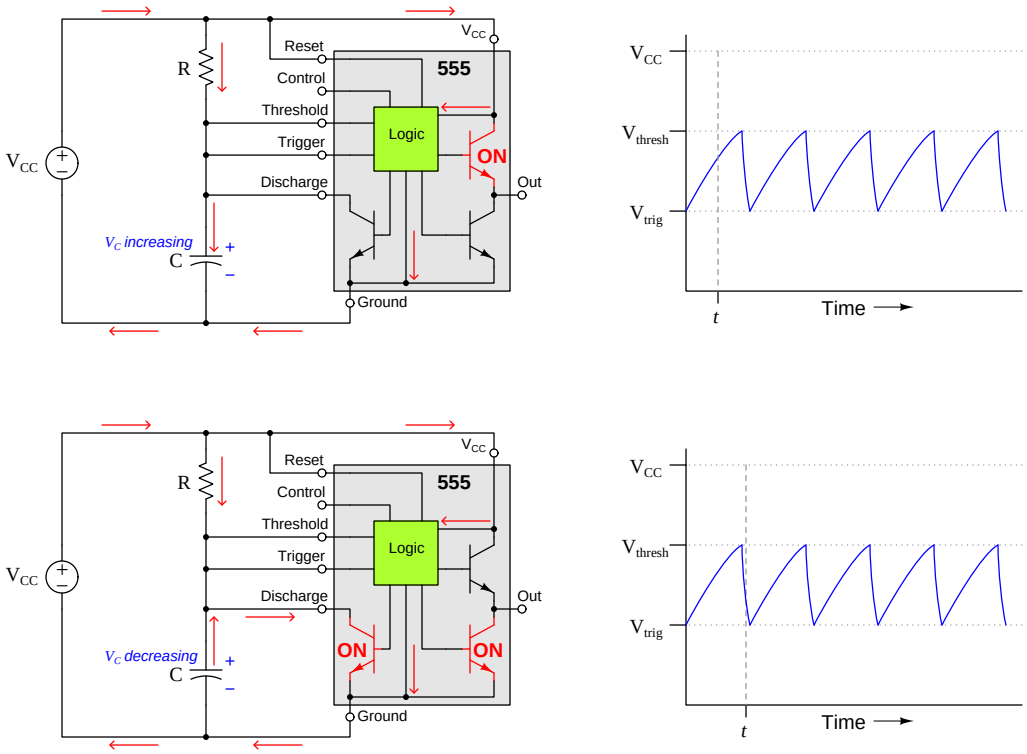
A more detailed view of the 555 timer's internal circuitry is shown in the following illustration:



Here you can see the three equal-valued resistors (R) setting the $\frac{1}{3}V_{CC}$ and $\frac{2}{3}V_{CC}$ Trigger and Threshold voltage reference levels. The two triangular-shaped symbols represent *comparators*, which are specialized subcircuits designed to compare two analog voltage signals and drive their output terminals either "high" (+V potential) or "low" (ground potential) depending on which of the two compared voltages are larger. The *SR latch* is another specialized subcircuit designed to toggle between two states at the command of its "set" (S) and "reset" (R) input terminals.

3.3 Astable 555 operation

Here we see the 555 timer functioning as a relaxation oscillator. A graph showing the capacitor's "sawtooth" voltage waveform over time, with time markers (t) for each state of the 555 timer circuit, demonstrate the operation of this oscillator[4]:



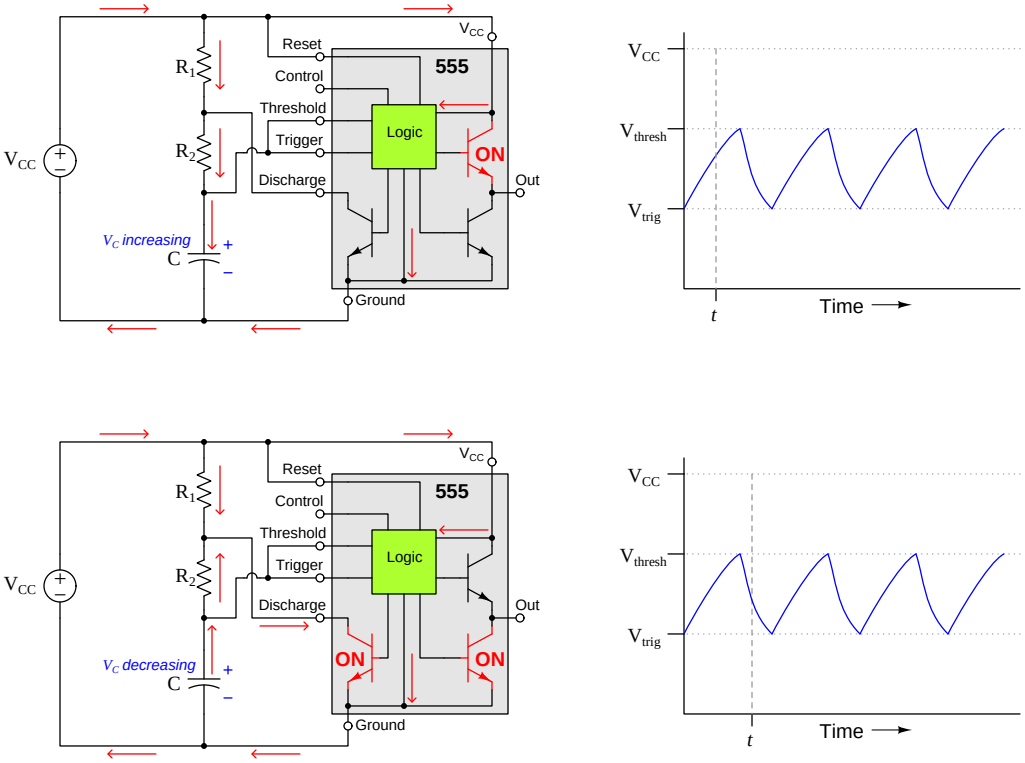
The "charge" portion of this oscillator's cycle lasts for 69.3% of the RC time constant (τ), because this is the length of time required for an inverse exponential function to achieve the half-way[5] point from where it begins (V_{trig}) to its ultimate end-point (V_{CC}). By contrast, the "discharge" period is virtually instantaneous because no resistor is present in the capacitor's discharging circuit, the 555's internal discharge transistor directly shorting the capacitor when activated.

$$t_{charge} = 0.693RC \qquad\qquad t_{discharge} \approx 0$$

[4] An important feature to remember about the 555 is that its `Out` and `Discharge` terminals both assume a "low" state simultaneously because their sinking transistors are activated by the same line within the latching logic circuit. That is to say, a 555's `Out` terminal will go "high" as the capacitor charges up and will go "low" as the capacitor discharges.

[5] With V_{thresh} equal to $\frac{2}{3}$ of V_{CC} and V_{trig} equal to $\frac{1}{3}$ of V_{CC}, V_{thresh} will be exactly half-way between V_{trig} and V_{CC}; likewise, V_{trig} will be half-way between V_{thresh} and zero. Solving for t in the equation $0.5 = e^{-t}$ yields a value of 0.693, which is 69.3% of one time constant, each time constant (τ) in a simple RC circuit equal to R times C. Therefore, $t_{charge} = 0.693RC$ in this astable circuit where V_C oscillates between V_{trig} and V_{thresh}.

Another popular astable 555 timer configuration uses two resistors rather than one:



In this circuit we see a much more gradual discharge period than the previous version, owing to the presence of R_2 in the circuit limiting how quickly the capacitor is able to release its stored energy. The RC time constant (τ) of this circuit during the "charge" period is equal to $(R_1 + R_2)C$ because the capacitor's current must flow through both R_1 and R_2, but the time constant during the "discharge" period is only equal to R_2C because the capacitor's current through the discharge transistor is limited only by R_2. Once again the time duration is equal to 69.3% of τ, the difference between "charging" time and "discharging" time being the two values for τ:

$$t_{charge} = 0.693(R_1 + R_2)C \qquad t_{discharge} = 0.693R_2C$$

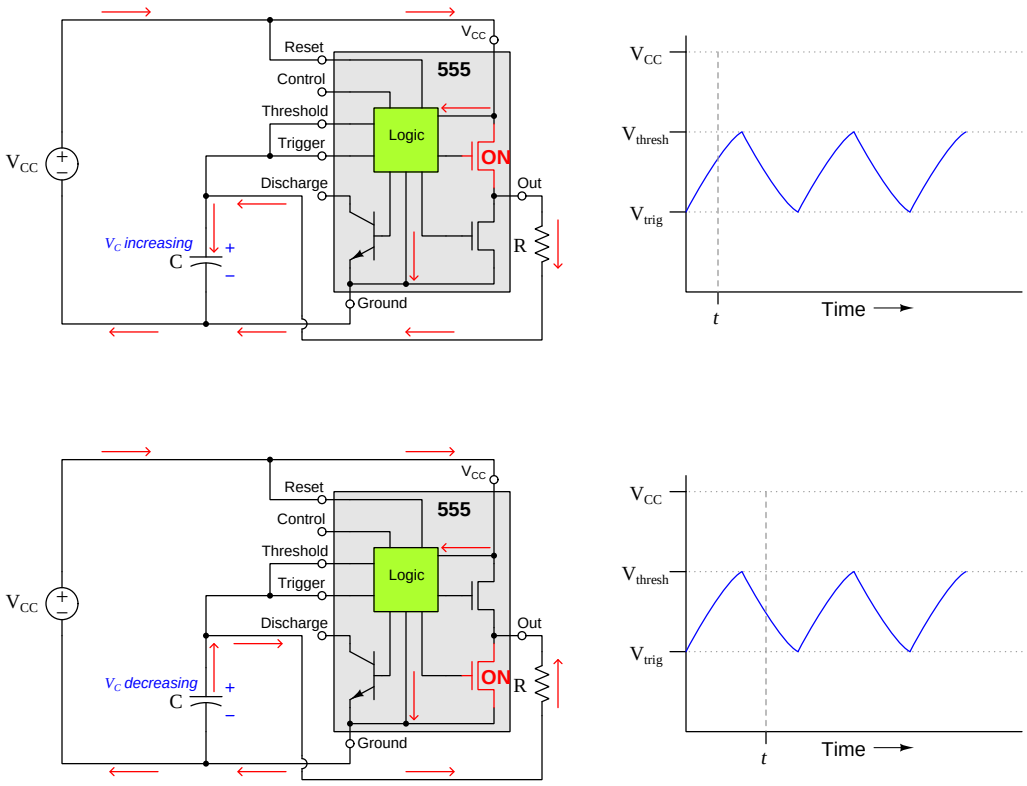
Total time for each complete cycle of the capacitor's voltage is called the *period* of the signal, and is equal to the sum of charge and discharge times:

$$t_{period} = 0.693(R_1 + R_2)C + 0.693R_2C = 0.693(R_1 + 2R_2)C$$

Frequency is the reciprocal of any oscillating signal's period, being the number of complete charge/discharge cycles per second, "cycles per second" being expressed in the unit of *Hertz*:

$$f = \frac{1.44}{(R_1 + 2R_2)C}$$

A less-common but very useful astable 555 timer configuration uses the Output terminal to charge and discharge the capacitor. This circuit only requires one resistor, and results in the charge and discharge times being very nearly equal *if* the particular model of 555 has MOSFET output transistors enabling it to output full supply voltage (V_{CC}) in its "high" output state:



Since both the charge and discharge current paths pass through the same resistor (R) there is no substantial difference between the charging and discharging time delays. This makes the calculations extremely simple:

$$t_{charge} = t_{discharge} = 0.693RC$$

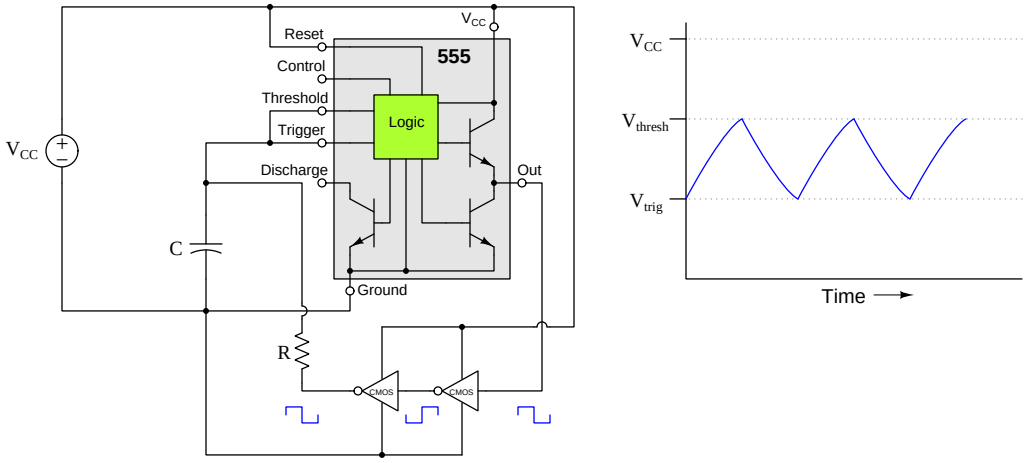
Total period for the cycle is simply the sum of charge and discharge times:

$$t_{period} = t_{charge} + t_{discharge} = (2)(0.693)RC = 1.386RC$$

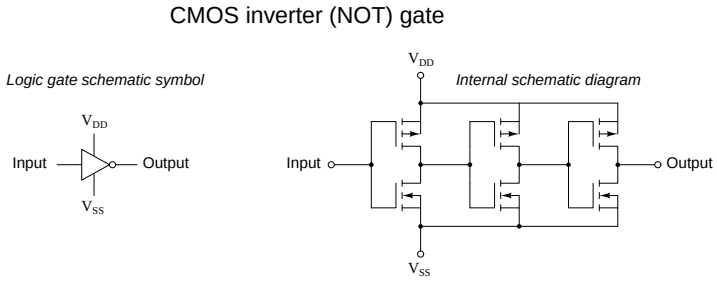
Frequency is of course the reciprocal of this total period:

$$f = \frac{1}{1.386RC} = \frac{0.721}{RC}$$

If this symmetrical oscillation (i.e. equal charge and discharge times) is desired but no 555 timer is available with MOSFET outputs, one may achieve the same effect by using CMOS logic gates to "buffer" the 555 timer's output signal as shown below. In this circuit, the timing capacitor is charged and discharged through the output of the final CMOS inverter logic gate rather than by the 555 timer's output terminal:



CMOS logic gates use complementary P-channel and N-channel MOSFET pairs at their output terminals, and so when the output of a CMOS gate asserts a "high" state its output terminal potential will be very nearly equal to its positive power supply terminal potential because MOSFETs drop very little voltage when "on". Conversely, when the output of a CMOS gate asserts a "low" state its output terminal potential will be very nearly equal to its negative power supply terminal for the same reason. In the following illustration you can see the P-/N-channel MOSFET pairs comprising the internal circuitry of a CMOS inverter logic gate:

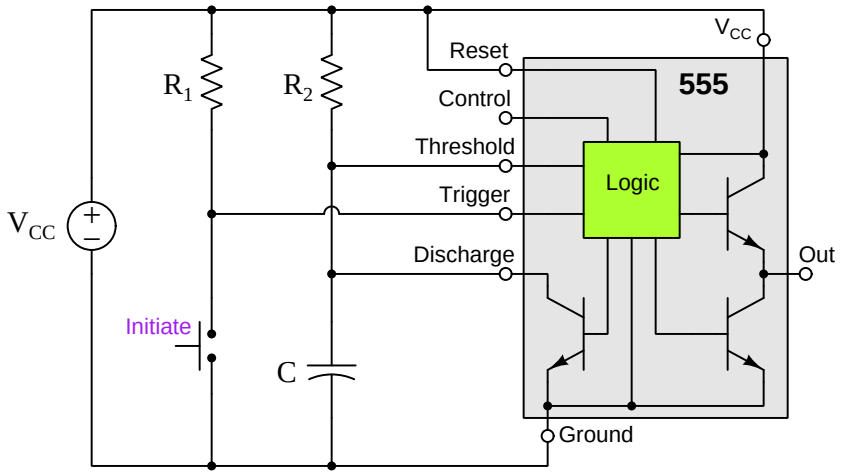


All the 555 timer's output terminal potential needs to do is rise high enough for the first CMOS gate to properly interpret it as a "high" state, and fall low enough that the CMOS gate properly interprets it as a "low" state. Any asymmetry in the 555 timer's "high" versus "low" output states is essentially hidden from the capacitor's view by the CMOS logic gates which are able to drive equally-firm "high" and "low" output states to charge and discharge the timing capacitor symmetrically.

3.4 Monostable 555 operation

Many other configurations of the 555 timer circuit exist. Configurations resulting in continuous oscillations such as the circuit shown above are called *astable*, because they have no stable state but rather switch periodically between two states. Configurations resulting in one stable state and one unstable (temporary) state are called *monostable*, and are used to provide time-delay functions in larger circuits.

A simple monostable circuit configuration is shown here, where the Trigger senses voltage across a normally-open (NO) pushbutton switch rather than sensing voltage across the capacitor as in the astable (oscillator) circuit:

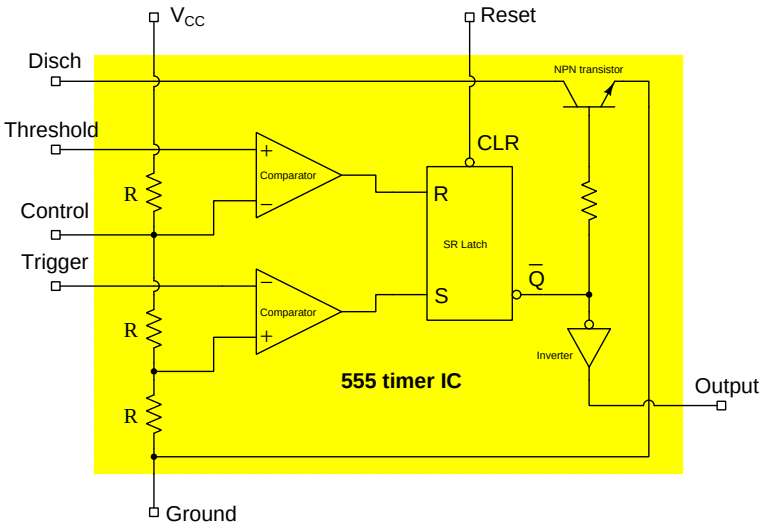


When the switch is unpressed, R_1 conducts negligible current and drops negligible voltage, which means the Trigger input senses a "high" voltage state with reference to ground and the 555 timer refuses to enter the "charge" state, remaining in the "discharge" state which leaves the capacitor voltage at zero (Discharge transistor turned "on") and the Out terminal switched to Ground through the "on" lower-right transistor. As soon as the pushbutton switch is pressed, however, the Trigger input senses zero voltage which is less than $\frac{1}{3}$ V_{CC} and so the 555 timer toggles to the "charge" state, allowing the capacitor voltage to rise and the Out terminal to become connected to the V_{CC} terminal through the "on" upper-right transistor. This "charge" state only lasts as long as it takes for the capacitor's voltage to rise to the Threshold value ($\frac{2}{3}$ of V_{CC}, which requires 109.9% of the time constant τ)[6], at which point the 555 toggles back to the "discharge" state and awaits another closure of the pushbutton switch.

[6] Using the inverse exponential function e^{-t} again, we may solve for the monostable timer's "charge" time by calculating the amount of time necessary for the capacitor's voltage to rise within $\frac{1}{3}$ its ultimate value, since it begins at 0 Volts and is cut off by the 555 timer at $\frac{2}{3}$ V_{CC}, which means the "charge" state lasted until the capacitor's voltage had $\frac{1}{3}$ of the way left to go. Solving for t in the equation $\frac{1}{3} = e^{-t}$ yields a value of 1.099, which is 109.9% of one time constant. Therefore, t_{delay} for this astable circuit is $1.099 R_2 C$.

3.5 Altering trigger and threshold values

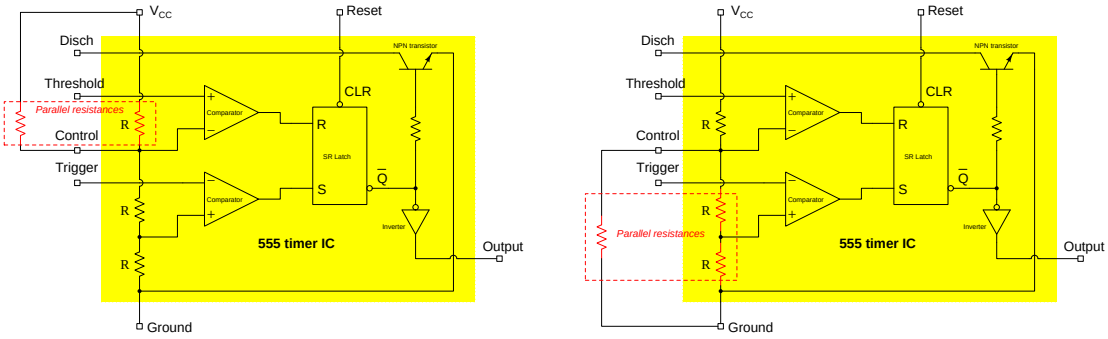
Inside every 555 timer IC is a three-element resistive voltage divider setting the voltage values at which the Trigger and Threshold inputs control the charging and discharging states. With the three resistors shown inside the 555 timer being of equal value, this divides the DC supply voltage into thirds, such that the Threshold input will activate the timer's discharge state when greater than $\frac{2}{3}$ supply voltage, and the Trigger input will activate the charge state when less than $\frac{1}{3}$ supply voltage:



For example, with a supply voltage of 12 Volts, the Threshold activates at 8 Volts and the Trigger at 4 Volts. If configured for astable operation, the capacitor's voltage will follow a sawtooth pattern over time, oscillating between 4 and 8 Volts for a 12 Volt supply. If configured for monostable operation, the capacitor's voltage will rise to 8 Volts before toggling to the discharge state.

Some 555 timer applications may demand different Trigger and Threshold values, though. An example of this is when using the 555 timer expressly for the purpose of generating a voltage waveform across the capacitor with high and low peak values other than $\frac{2}{3}$ and $\frac{1}{3}$ V_{CC}. In order for a 555-based astable circuit to produce a sawtooth waveform peaking at values other than $\frac{2}{3}$ and $\frac{1}{3}$ of V_{CC}, these Threshold and Trigger levels must somehow be modified.

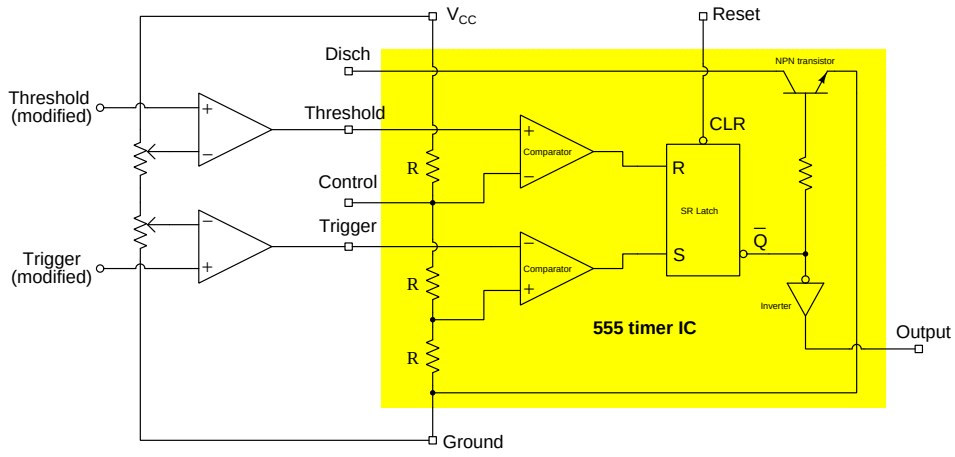
One way to alter the Threshold and Trigger voltage values is to connect a resistor between the Control pin of the 555 timer IC and either Ground or V_{CC}. This places another resistance in parallel with one or more of the 555 timer's internal resistors, thus modifying that resistance within a section of the voltage divider. Connecting a resistor between Control and V_{CC} will effectively reduce the upper resistance value in the three-element voltage divider network to something less than $\frac{1}{3}$ total resistance, thus elevating both the Threshold and Trigger voltage values. Connecting a resistor between Control and Ground similarly depresses both the Threshold and Trigger values. In either case, the Trigger voltage value will still be one-half that of the Threshold voltage value:



Exactly how much external resistance one would need to connect to the Control pin depends on the desired elevation or suppression of Threshold/Trigger voltages as well as on the resistance values internal to the 555 timer which vary by specific model.

The most significant limitation to this technique is that the ratio of Threshold to Trigger voltage values will always be 2:1 because there is no provision on the 555 timer IC to access the node between its two lower resistors.

A more sophisticated strategy involves the use of external comparators[7], allowing for independent adjustment of Threshold and Trigger values:



The purpose of any comparator is to compare two ground-referenced voltage signals and output a discrete (high/low) voltage signal based on which of those two input signals is greater. Here, the two external comparators use potentiometers (or fixed-value resistors if desired) to create *new* Threshold and Trigger voltage levels for the 555 timer to operate with. If the new Threshold's voltage exceeds the voltage established by the upper potentiometer, the upper comparator will output a "high" logic signal which of course is greater than the $\frac{2}{3}$ V_{CC} value needed by the 555's own Threshold pin to initiate the discharge state. If the new Trigger's voltage falls below the voltage established by the lower potentiometer, the lower comparator will output a "low" logic signal which of course is less than the $\frac{1}{3}$ V_{CC} value needed by the 555's own Trigger pin to initiate the charge state. Thus, we are using the 555's original Threshold and Trigger pins as *digital inputs* rather than analog inputs, allowing the external comparators and external voltage-divider network to establish new Threshold and Trigger values for any 555-based application circuit.

A caveat when using external comparators on a 555 timer like this is that you must design your circuit such that the two external comparators never simultaneously activate the Threshold and Trigger pins on the 555 timer (i.e. the Threshold pin being "high" and the Trigger pin being "low" at the same time). Doing so would cause the 555's internal SR latch circuit to enter into an invalid state rather than the customary "charge" or "discharge" states offered by the 555 timer. This is why the two potentiometers in the above schematic diagram are connected in series with each other, so that the upper potentiometer's wiper must necessarily exist at a higher electrical potential than the lower potentiometer's wiper. If the new Threshold and new Trigger terminals are both made electrically common to a capacitor's ungrounded terminal, no capacitor voltage value can ever simultaneously activate the Threshold and Trigger pins on the 555 timer.

[7] As typical in schematic diagrams containing logic gates and/or comparators, the power supply terminal connections on these external comparators have been omitted for simplicity. Comparator ICs are commonly available providing multiple comparators in one integrated-circuit package, in which case only two pins (V_{CC} and Ground) need be connected to the DC power source to energize all comparators offered within that IC.

Chapter 4

Derivations and Technical References

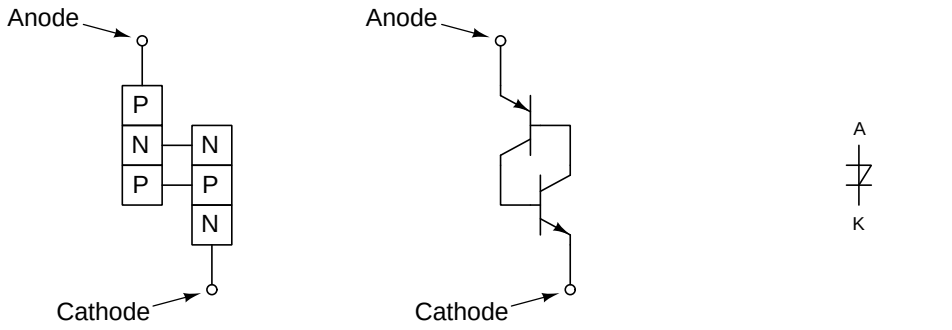
This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

4.1 Latch-up in integrated circuits

An often bewildering phenomenon for students of electronics is something called *latch-up*, known to plague certain forms of integrated circuit. "Latch-up" describes a condition where the IC suddenly ceases to function properly, and instead draws an unreasonably high amount of current from the DC power source, sometimes to the point of catastrophic failure. What is more, this sudden and unexpected high-current draw refuses to stop unless and until the DC power source is interrupted.

Close examination of the afflicted IC's internal schematic diagram is unhelpful, as no apparent cause for latch-up will ever be evident upon inspection. This is because latch-up is a phenomenon rooted in *parasitic* transistor structures within the IC itself resulting from the monolithic form of the circuit (i.e. being fabricated on a single wafer of semiconducting material). In fact, if the IC were constructed from a large collection of discrete components on a printed circuit board, latch-up could never occur!

In order to understand what latch-up is and why it occurs, we must first review a class of semiconductor devices called *thyristors*. A "thyristor" by definition is any semiconductor device manifesting *hysteresis*: the tendency to remain on once triggered on and to remain off once turned off. Thyristors include devices such as DIACs, TRIACs, silicon-controlled rectifiers (SCRs), Shockley diodes, and unijunction transistors. Among these various thyristor devices, the most elementary is the Shockley diode, illustrated below:



Crude diagram *Equivalent schematic* *Schematic symbol*

If we examine the equivalent Shockley diode schematic consisting of two interconnected bipolar junction transistors, one NPN and the other PNP, we find that it should not conduct current between the anode and cathode terminals. The only way for one of these transistors to ever turn on is to first initiate base current through it, but the interconnection with the other transistor makes base current for one contingent on collector current of the other, which cannot occur unless and until that other transistor's base is also activated by current. In other words, we have a "Catch-22" scenario where the NPN transistor cannot turn on until the PNP transistor turns on, and vice-versa. Therefore, Shockley diodes – and by extension all thyristors – naturally assume an "off" state and tend to maintain that state even as external voltage is applied across the two end-terminals.

If, however, we imagine *something* turning on one of these transistors, the resulting current would immediately turn on the other transistor, which in turn would hold the first transistor in its "on" state after the initiating event passed. Therefore, Shockley diodes – and by extension all

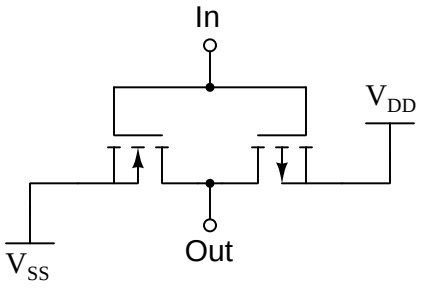
thyristors – tend to remain in their "on" states once triggered. Turning off a thyristor necessitates some external interruption of current. That "something" initially triggering the thyristor could be excessive applied voltage resulting in BJT breakdown, an extremely rapid rate-of-voltage change applied across the thyristor resulting in displacement current "through" one of the transistor's otherwise non-conducting depletion regions, excessive device temperature, a photon of light striking the depletion region and liberating an electron-hole pair, etc. Thyristors designed as controllable devices (e.g. SCRs, TRIACs, unijunction transistors) provide a third terminal to apply a triggering current.

Monolithic integrated circuit construction – where the entire circuit is built on a single wafer of semiconducting material – often results in parasitic PN junctions, and sometimes even parasitic NPN and PNP junction sets. If parasitic NPN and PNP junctions happen to coexist on the silicon die to form the equivalent of a Shockley diode thyristor structure, we will find that circuit susceptible to the unfortunate phenomenon of latch-up. These parasitic thyristors exist within many different types of integrated circuits, from logic gates to amplifiers to comparators to timers such as the popular model 555. They are guaranteed to exist within integrated circuits using complementary pairs of N-channel and P-channel MOSFETs as final "push-pull" output driver stages.

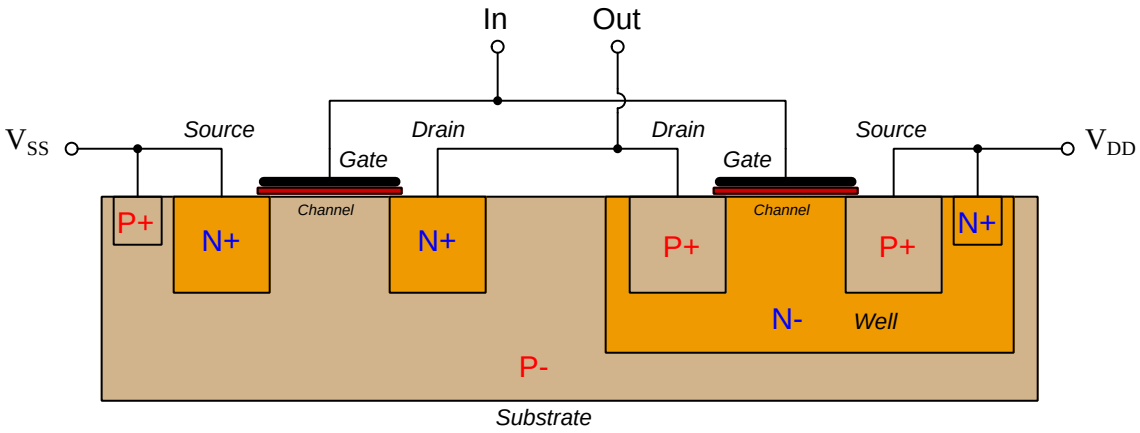
Sometimes the potential for latch-up is communicated in the form of a warning within IC datasheets, but other times not. Inconsistent and incomplete documentation, added to the fact that an examination of an IC's internal schematic does not necessarily reveal the presence of parasitic thyristors, makes latch-up risk a difficult thing to predict.

Let's begin our exploration of these parasitic structures by closely examining one of the most basic building-blocks of CMOS (Complementary Metal-Oxide Semiconductor) circuitry, the so-called *inverter*. A CMOS inverter network is nothing more than a P-channel enhancement-type MOSFET connected to an N-channel enhancement-type MOSFET, as shown below both in schematic form as well as semiconductor wafer cross-section. This complementary MOSFET pair acts as a "push-pull" transistor amplifier, capable of either sourcing current to a load or sinking current from one:

Schematic of an integrated CMOS inverter

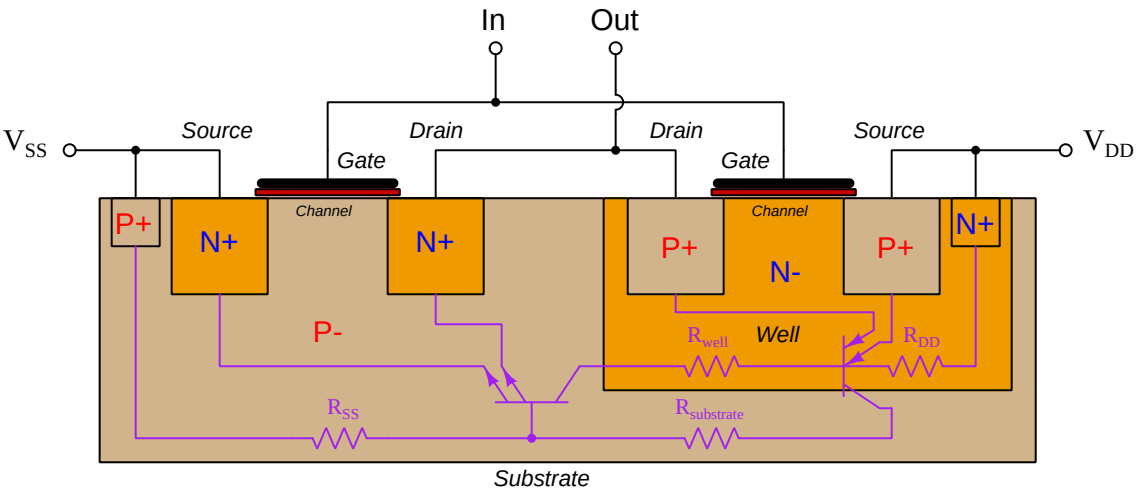


Cross-section of an integrated CMOS inverter

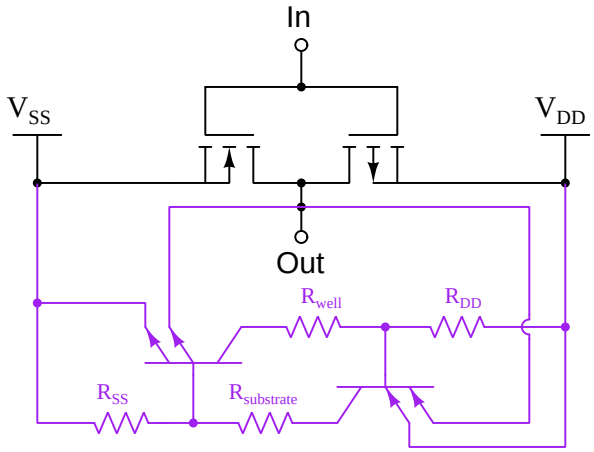


Each of the doped semiconductor layers in the cross-section are noted with their respective dopant concentration levels, a "+" meaning a high concentration of dopant and "−" meaning a low concentration of dopant. Strongly-doped P-type and N-type layers are shown as P+ and N+, respectively. Lightly-doped P-type and N-type layers are shown as P− and N−, respectively. Note how the source and drain regions are all heavily-doped in order to provide a rich reservoir of majority charge carriers to fill in each of the channels when prompted by a sufficient gate-to-substrate electric field.

Now we will include within this cross-sectional illustration some the parasitic transistors[1] and resistances formed by the P and N type doped regions:



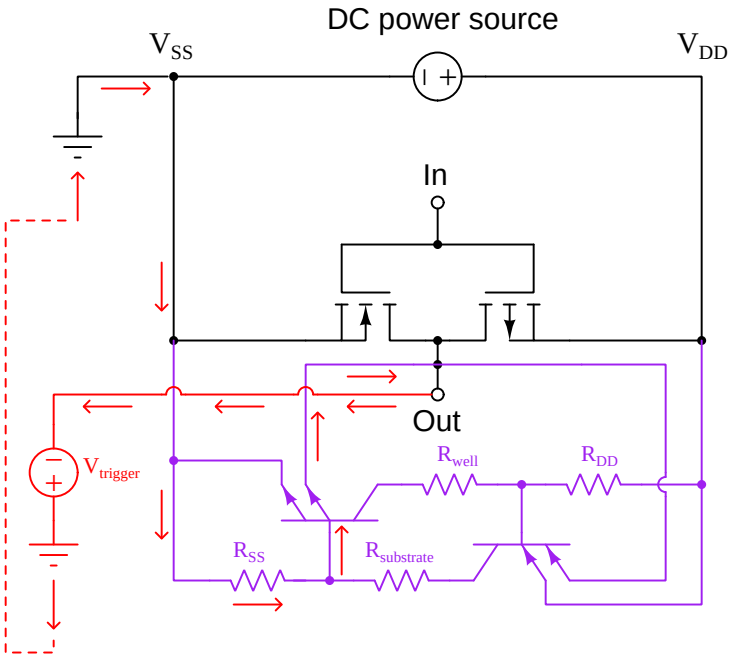
Including these parasitic components into the CMOS inverter schematic diagram:



Now it should be clear that a Shockley diode structure exists within the CMOS inverter's integrated circuit. Furthermore, with each bipolar transistor having two emitters, one each connected to the inverter's output terminal, that output terminal becomes a pathway to externally trigger this thyristor structure and thereby throw the IC into a state of latch-up.

[1] It is helpful to recall that the emitter region of any bipolar junction transistor is more heavily doped than the collector, in order to provide an abundance of charge carriers to inject into the base region as minority carriers. This is why the emitters of the PNP are P+ doped and the collector P− doped, and why the emitters of the NPN are N+ doped and the collector N− doped. Multiple emitters in a BJT simply mean more than one location from which charge carriers may be injected into the base and thereby render the transistor conductive between emitter and collector.

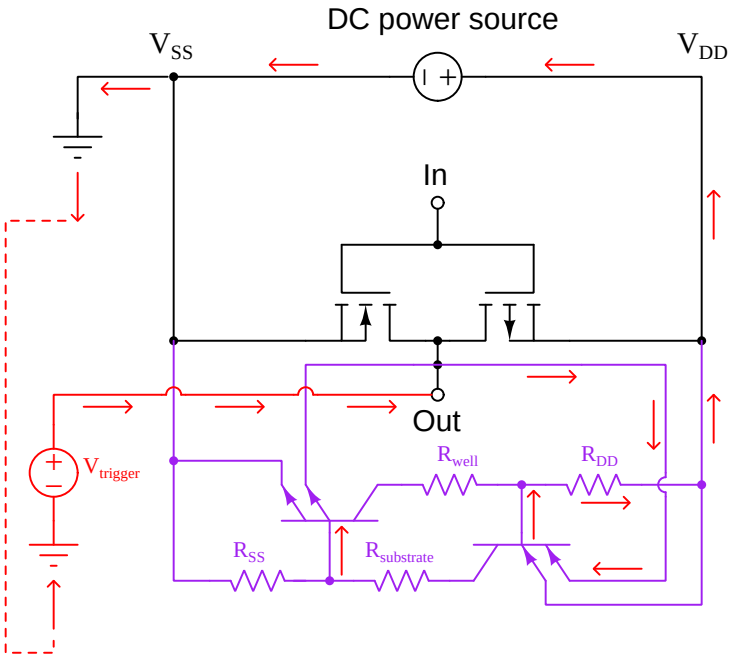
Triggering a latch-up condition is as simple as something external to the inverter IC driving its output terminal below V_{SS} potential or above V_{DD} potential. In the next example we will see a below-V_{SS} potential initiating latch-up:



In this scenario, external source $V_{trigger}$ forced the inverter's output terminal to a potential lower than ground (V_{SS}), and this in turn prompts a current through one of the emitters of the parasitic NPN transistor, injecting electrons into its P-type base region and turning it on. Once the NPN transistor turns on, its collector current permits base current through the PNP transistor, turning it on as well, and thus the two parasitic transistors latch each other into conductive states.

Once latched on, the parasitic thyristor creates a V_{DD}-to-V_{SS} short-circuit. Excessive current now passes through the DC power source and through the parasitic resistances of R_{well} and $R_{substrate}$, possibly damaging the entire integrated circuit by excessive heating. Only an interruption of the DC power source will halt the latch-up condition.

Next, we will see an above-V_{DD} potential initiating latch-up:



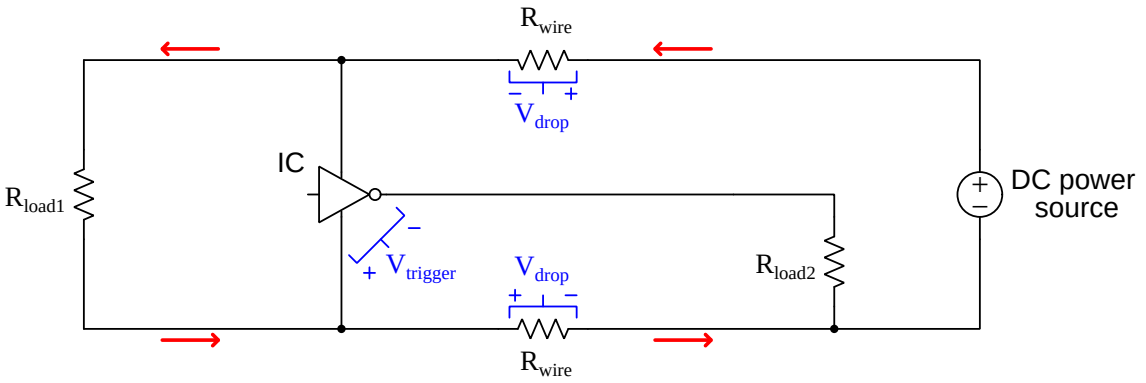
In this scenario, external source $V_{trigger}$ forced the inverter's output terminal to a potential higher than that of the DC source voltage (V_{DD}), and this in turn prompts a current through one of the emitters of the parasitic PNP transistor, injecting holes into its N-type base region and turning it on. Once the PNP transistor turns on, its collector current permits base current through the NPN transistor, turning it on as well, and thus the thyristor formed by the two parasitic transistors becomes latched in its "on" state.

Again, once the parasitic thyristor is latched in its "on" state it will create a V_{DD}-to-V_{SS} short-circuit. Excessive current will now pass through the DC power source and through the parasitic resistances of R_{well} and $R_{substrate}$, possibly damaging the entire integrated circuit by excessive heating. Only an interruption of the DC power source will abort the latch-up condition.

Clearly, one of the causes of latch-up is some external electrical source attempting to force the output terminal either above V_{DD} potential or below V_{SS} potential, and as such we should strive to avoid such possibilities in all our circuit designs.

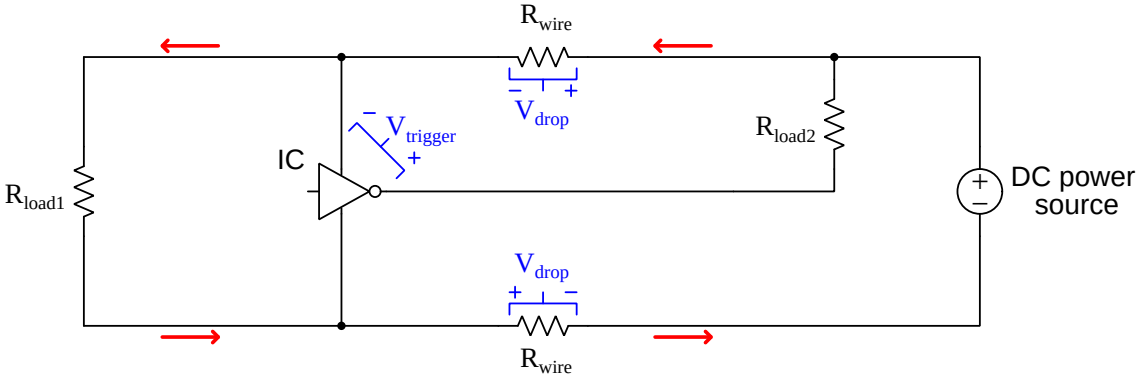
Another potential cause of latch-up is if the load driven by an IC output is too inductive. Inductance stores energy in magnetic fields, and the amount of energy is a function of the current through the inductance. If an inductive load is energized by the output of an IC and then the IC switches state to de-energize that load, the load inductance will become a temporary current source and try to force current through the IC's output, often generating surprisingly high voltages in the process. Such voltage transients may easily trigger latch-up in the IC.

Another possible cause of latch-up is power supply rail instability. That is, if something is causing an IC's positive and/or negative rail potentials to vary, and that same IC connects to some other device with higher positive or lower negative power supply rails, this may constitute a triggering mechanism for latch-up. Consider the following example:



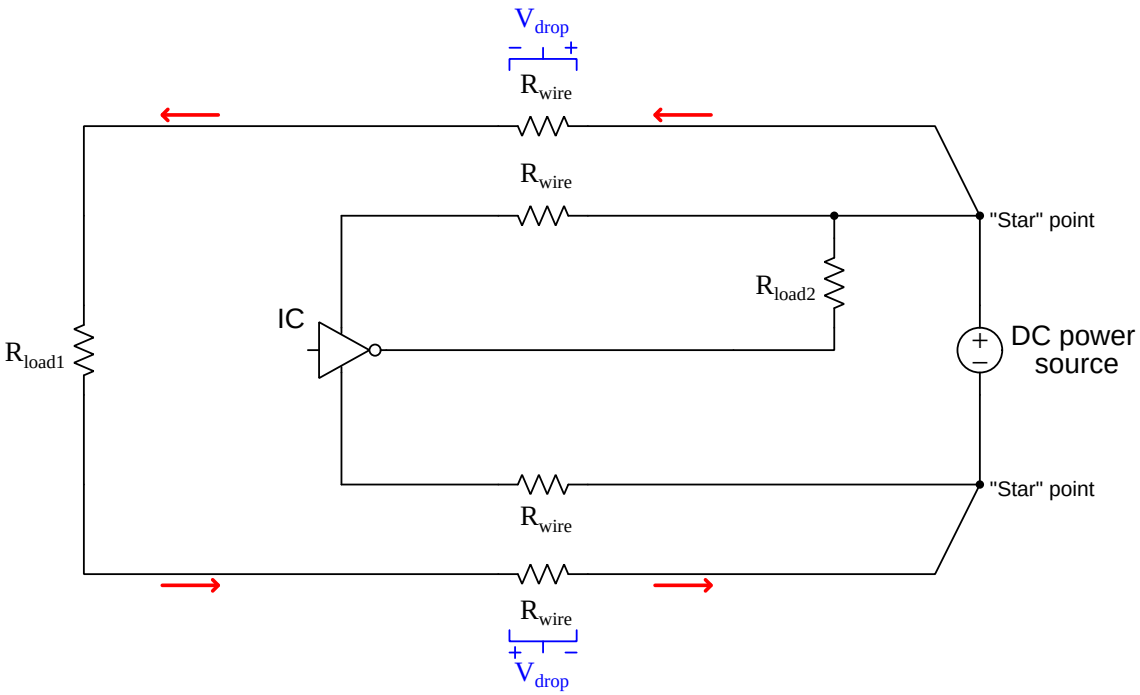
Here we see some voltage dropped along the conductors carrying current to a heavy load (R_{load1}), the effect of these voltage drops being to suppress the potential of the IC's positive rail terminal slightly below that of the power source's positive terminal, and to elevate the potential of IC's negative rail terminal slightly above that of the power source's negative terminal. In this case, with the IC's output connected to a second load (R_{load2}), we see that the voltage drop along the negative power conductor has the effect of making the IC's output terminal fall to a potential slightly less than its negative power terminal. As we have seen previously, this may be enough to trigger latch-up in that IC.

If R_{load2} happened to be connected to the positive conductor rather than the negative, we would similarly risk latch-up due to the load imposing a potential on the IC's output greater than that of its positive power terminal:



In either scenario the wiring voltage drop caused by the high current demand of R_{load1} risks latch-up in the IC by skewing its power-supply terminal potentials compared to the load it connects to. A

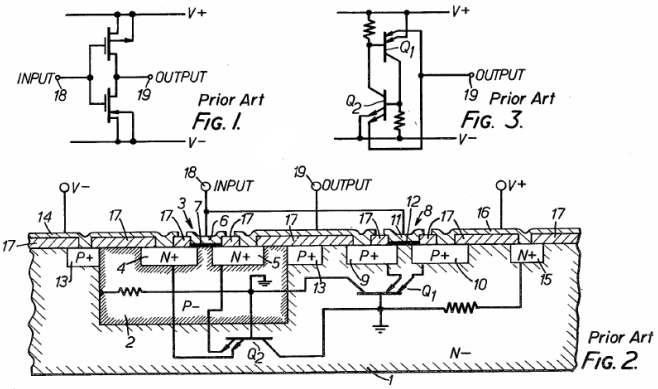
strategy for avoiding this problem is to provide high-current loads with their own dedicated power conductors, and not connect them to the same power conductors that sensitive ICs use for power delivery. This strategy is often referred to as *star-point grounding* or star-point power distribution:

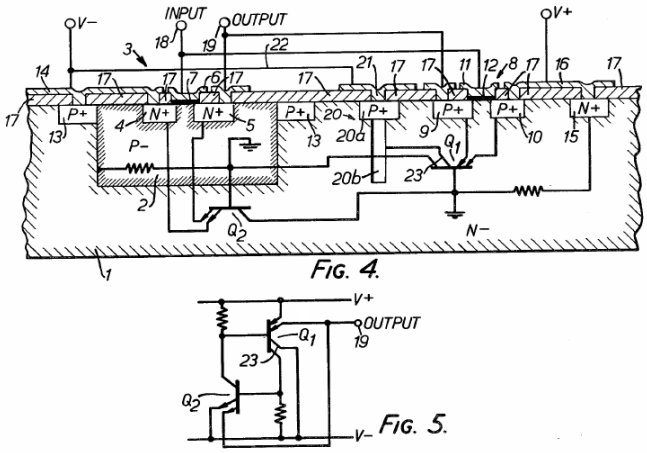


Star-point power connections do not eliminate voltage drop due to high load current, but they do isolate those voltage drops from affecting *other* loads such as ICs sensitive to latch-up.

Given the fact that Complementary MOSFET transistor pairs are so prevalent in modern integrated circuits (e.g. *all* CMOS digital logic) we must find mitigations for latch-up or else risk self-destruction of a great many ICs any time an output pin is subjected to even the briefest transient voltage outside of the DC power supply's rail potentials.

One such mitigation was invented by Alastair Stevenson of the Hughes Aircraft Company in 1978, consisting of an extra layer of implanted material in the semiconductor structure serving as a new collector of charge carriers. His patent ("CMOS Monolithic Integrated Circuit", US patent 4,173,767 filed 5 May 1978 and granted 6 November 1979) contrasts the "prior art" of CMOS inverter construction[2] (figures 1 through 3) against his innovation shown in figures 4 and 5:





In Stevenson's design we see the addition of a heavily-doped P+ region (20a in figure 4) near the surface of the semiconductor die connecting with a deeper region of lightly-doped P− material (20b in figure 4) inset into the N− substrate. This P− region serves to collect holes injected as minority

[2]Stevenson's prior art example happens to use an N-type substrate rather than a P-type substrate as I showed earlier, thus necessitating a P-type well surrounding the N-channel MOSFET rather than the N-type well surrounding the P-channel MOSFET in my illustrations.

carriers into the N− substrate that might otherwise travel to the P− well region of the N-channel MOSFET, essentially adding a second collector to the PNP parasitic transistor. The purpose for the P+ region interfacing the metal surface conductor to the deeper P− inset is to avoid "rectifying" contact between metal and semiconductor surfaces, the heavy doping of that P+ region (20a) serving instead to form an "ohmic" contact with the metal. This additional collector region serves to divert current away from the parasitic NPN transistor that would otherwise turn it on and ensure latch-up once the PNP transistor was triggered by an offending potential at the output terminal.

Stevenson describes how such current-collecting channels inserted into the substrate need only be placed between complementary MOSFETs at device input or output terminals, not between every pair of complementary MOSFETs, due to the fact that only those connecting to device pins are susceptible to the triggering that cause latch-up:

> It will be appreciated that the circuit arrangement shown in FIG. 4 represents only one small portion of the integrated circuit which will in fact include many more complementary MOS transistors. However, channels such as 20 need not necessarily be included between all adjacent complementary transistors in the circuit, and preferably channels such as 20 are only included between complementary transistors that constitute input or output stages of the circuit since it is only these transistors which will be subject to spurious voltage fluctuations which could trigger a bipolar conductive latch up in the circuit.

A final note on the topic of latch-up is that this term is unfortunately mis-used to describe a phenomenon plaguing certain comparators and operational amplifiers. In this other meaning of the term "latch-up", the comparator or opamp output terminal assumes an incorrect potential because one or more of the input terminal potentials has approached or exceeded a power supply rail potential. This kind of "latch-up" is sometimes referred to as *pseudo latch-up* because unlike the thyristor-based latch-up we've been exploring here, pseudo latch-up immediately ceases as soon as the offending input potential returns to normal. In the "real" form of latch-up, only interruption of DC power will cause the latching action to cease.

Chapter 5

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

5.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

5.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

5.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Capacitance

Capacitor

Simplification as a problem-solving strategy

Time constant

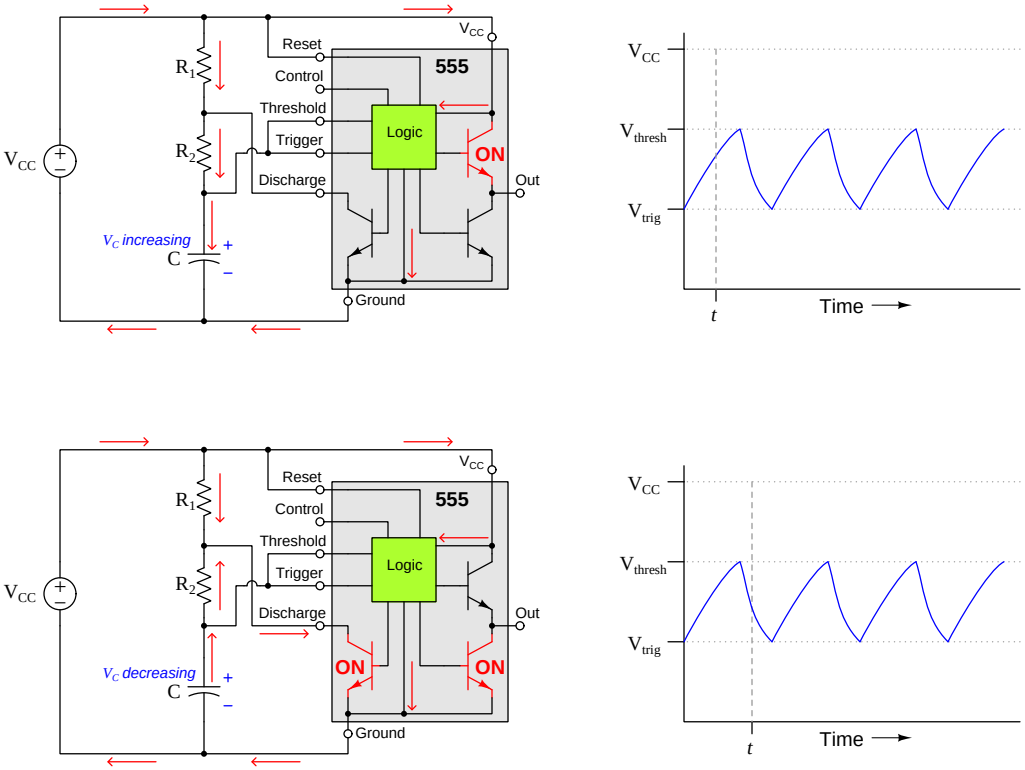
Voltage divider

Astable

Monostable

5.1.3 Applying foundational concepts to an astable 555 circuit

Identify which foundational concept(s) apply to each of the declarations shown below regarding the following circuit. If a declaration is true, then identify it as such and note which concept supports that declaration; if a declaration is false, then identify it as such and note which concept is violated by that declaration:



- When charging, the capacitor's voltage rises rapidly at first and then more slowly over time
- Capacitor charging time is longer than discharging time
- Resistor R_1's current is equal to that of the source
- The 555 timer IC becomes warm over time
- R_1 and R_2 must have the same voltage drop at all times

Here is a list of foundational concepts for your reference: **Conservation of Energy**, **Conservation of Electric Charge**, **behavior of sources vs. loads**, **Ohm's Law**, **Joule's Law**, **effects of open faults**, **effect of shorted faults**, **properties of series networks**, **properties of parallel networks**, **Kirchhoff's Voltage Law**, **Kirchhoff's Current Law**, **RC time constants**, **behavior of capacitors**. More than one of these concepts may apply to a

declaration, and some concepts may not apply to any listed declaration at all. Also, feel free to include foundational concepts not listed here.

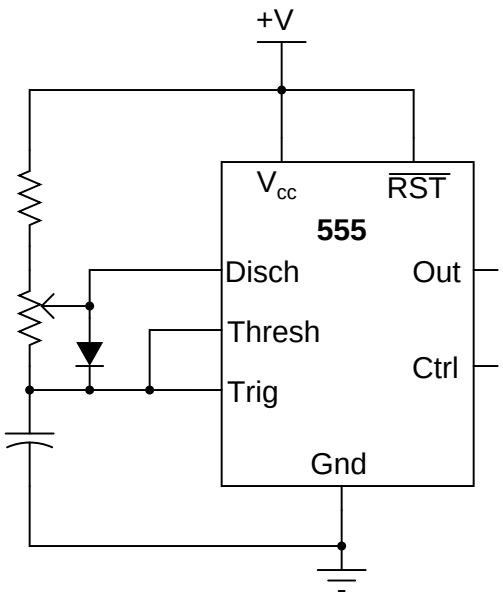
Challenges

- What are some practical applications for this timer circuit?

5.1.4 Adjustable duty cycle

The *duty cycle* of any oscillation is the ratio of "high" time to "total" period. In the case of an astable 555 timer circuit, the duty cycle of the Output terminal signal is the ratio of the 555 timer's "charging" time versus the period of the waveform (i.e. total cycle time, or "charging" plus "discharging" time).

We may make an astable 555 circuit with an adjustable duty cycle by incorporating a potentiometer and a diode as shown in this diagram:



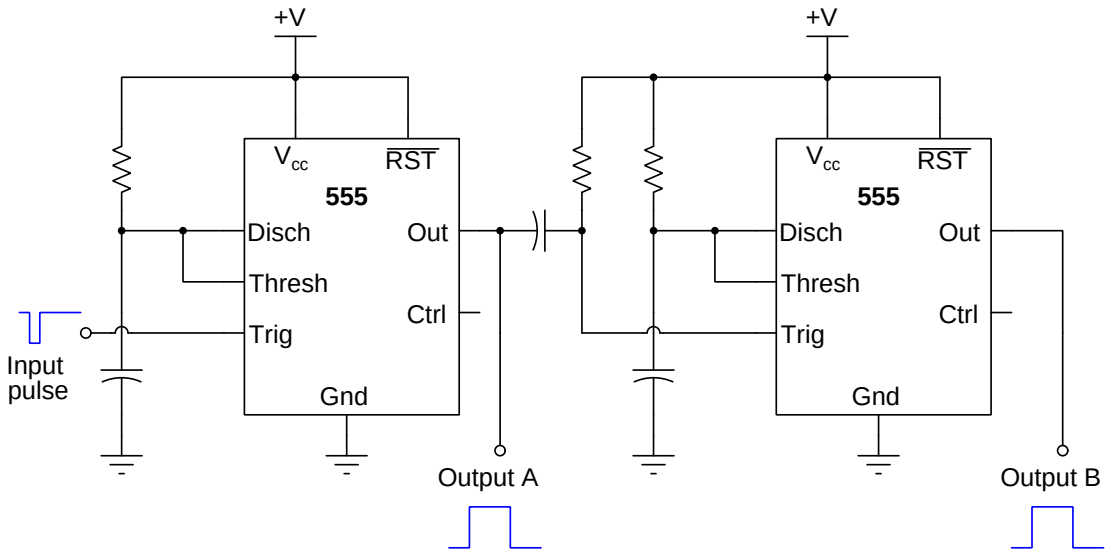
Identify which way the potentiometer's wiper should be moved in order to increase this circuit's duty cycle (i.e. lengthen the "charge" time in proportion to the total period).

Challenges

- What will happen in this circuit if the fixed resistor happens to fail open?
- What will happen in this circuit if the diode happens to fail open?

5.1.5 Sequential timer circuit

A *sequential* timer circuit may be constructed from multiple 555 timer ICs cascaded together. Examine this circuit and determine how it works:



Sketch a *timing diagram* showing all three pulse signals properly aligned with one another in time, so that the entire sequence may be clearly understood.

Can you think of any practical applications for a circuit such as this?

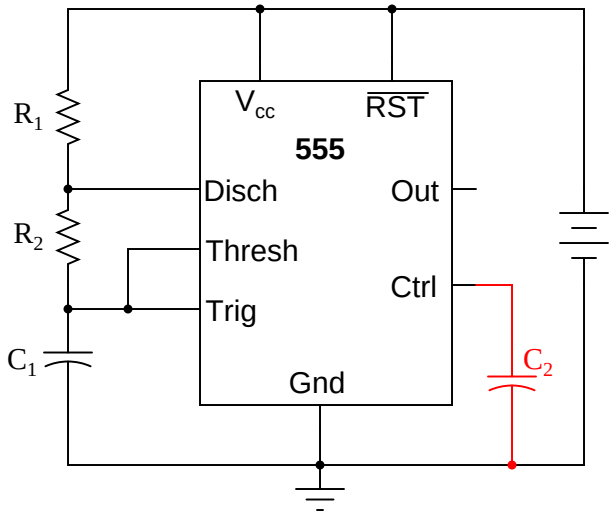
Suppose several monostable 555 timer circuits are cascaded together, following the same pattern as the circuit shown, and then the output of the last timer is connected to the input of the first in the same manner as the in-between stages are connected. How will this circuit function?

Challenges

- Explain the purpose of the resistor-capacitor "link" coupling these two 555 timer circuits together.
- Explain how you would determine suitable values for the resistor and the capacitor in the RC "link" coupling these two 555 timer circuits together.

5.1.6 Purpose of the Control terminal

It is common to see a capacitor connected between the "Control" terminal and ground in 555 timer circuits, especially when precise timing is important.



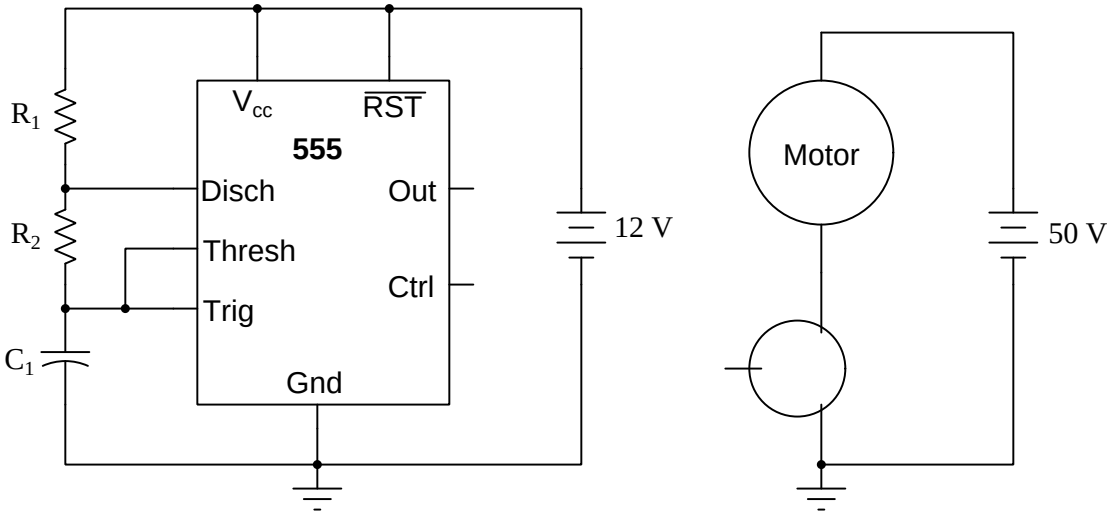
Explain what purpose the capacitor C_2 serves in this circuit.

Challenges

- What operational parameters of the circuit define the necessary capacitance value of C_2?

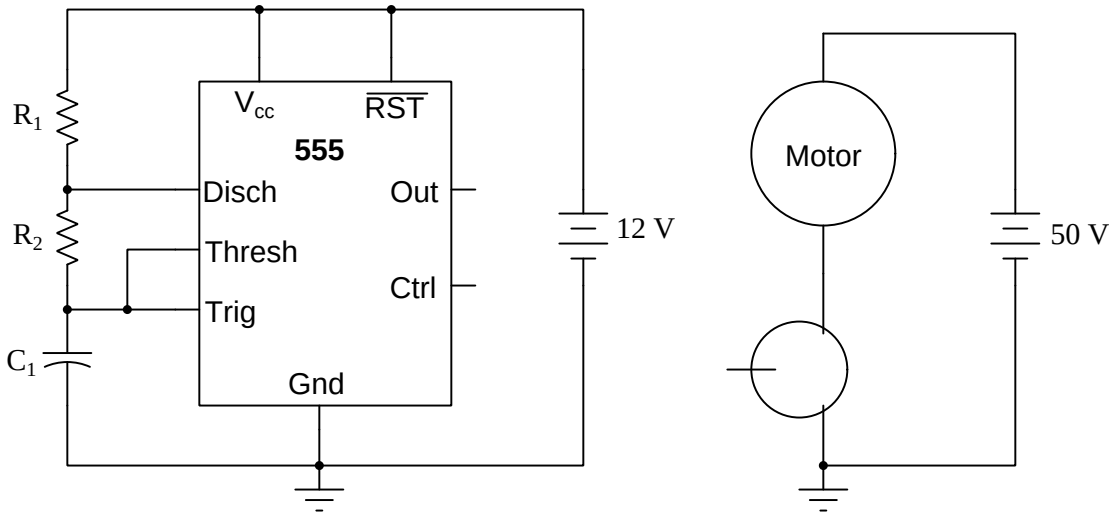
5.1.7 Driving a heavy load

Insert a bipolar junction transistor into this circuit so that the 555 timer is able to pulse a powerful electric motor on and off:



What device parameters would we need to check in order to choose a transistor appropriate for this application?

Now insert a field-effect transistor into this circuit so that the 555 timer is able to pulse a powerful electric motor on and off:



What device parameters would we need to check in order to choose a transistor appropriate for this application?

Challenges

- Insert a commutating diode into each of these circuits, for the transistors' safety.

5.1.8 Capacitor energy

Capacitors store energy in the form of an electric field, and this manifests as voltage between the capacitor terminals. The capacitor used in a 555 timer circuit is no exception to this, behaving as a load as it stores up energy during the "charging" portion of the cycle.

Explain what becomes of this stored energy during the "discharge" portion of the 555 timing cycle.

Challenges

- Suppose the capacitance value within an astable 555 timer circuit is doubled. Identify the effects of this capacitance doubling, with regard to energy storage.

5.1.9 Battery-powered 555

Suppose you are tasked with designing an astable 555 circuit that will be powered by a 9-Volt battery.

As the battery becomes depleted of energy and its terminal voltage decreases, will the 555's oscillation frequency change? Explain why or why not.

Suppose you were choosing the resistor and capacitor values for this circuit, and were faced with the following options given a limited supply of components to select from:

- $R_1 = 1$ kΩ ; $R_2 = 470$ Ω ; $C = 2.2$ μF
- $R_1 = 10$ kΩ ; $R_2 = 4.7$ kΩ ; $C = 0.22$ μF
- $R_1 = 100$ kΩ ; $R_2 = 47$ kΩ ; $C = 0.022$ μF

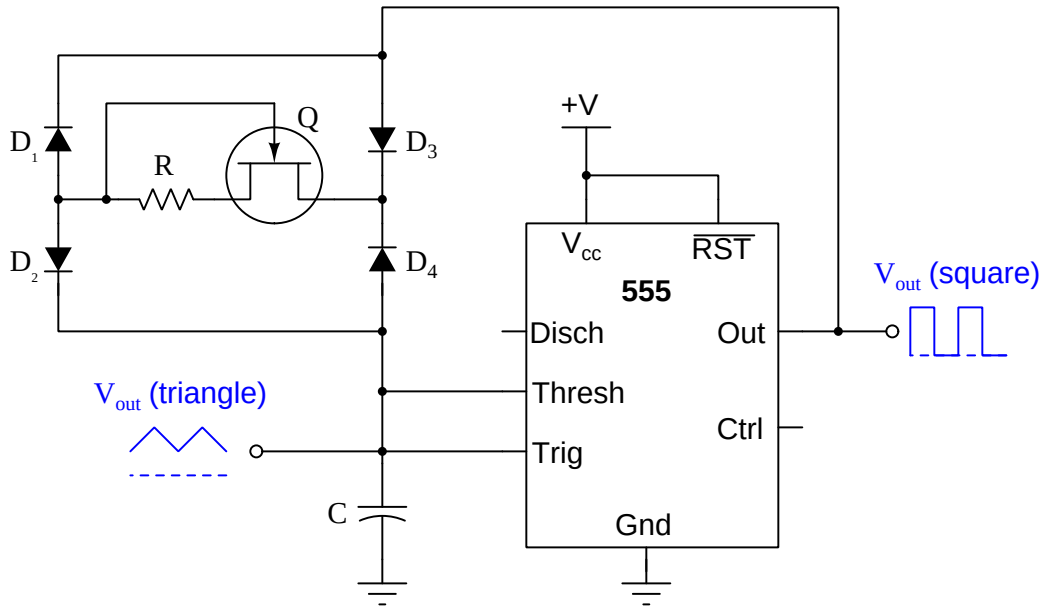
Which of these three options makes the most sense for a battery-powered oscillator circuit, and why?

Challenges

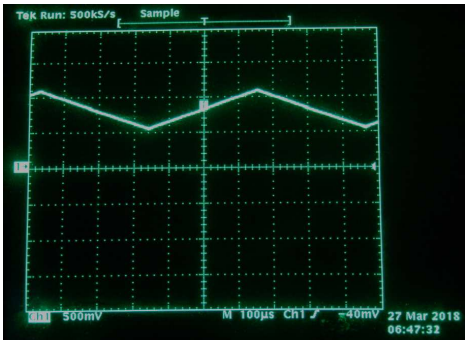
- Suppose the capacitance value within an astable 555 timer circuit is doubled. Identify the effects of this capacitance doubling, with regard to energy storage.

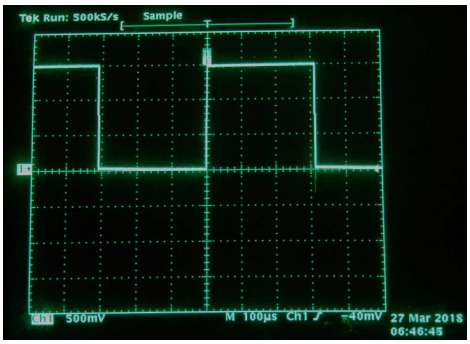
5.1.10 555-based triangle and square wave oscillator

The following circuit outputs both triangle-wave and square-wave voltage signals, using a 555 timer:



Screenshots of an oscilloscope showing the triangle and square wave outputs appear below, using a 10:1 probe. For this test $R = 7$ kΩ, $C = 0.015$ μF, $+V = 16$ V, an MPF102 was used as the transistor, and 1N4148 diodes were used throughout:





Based on your analysis of the schematic diagram, answer the following questions:

- What purpose do the four diodes serve?
- What purpose does the JFET serve?
- If the DC power supply voltage is 15 Volts, what will be the peak values of the triangle wave?
- If the DC power supply voltage is 15 Volts, what will be the peak values of the square wave?
- What will happen to output frequency if C is made smaller?
- What will happen to output frequency if R is made smaller?
- Modify this circuit to make its frequency easily adjustable by the user.
- Will the duty cycle of the triangle and square waves be symmetrical (i.e. 50%) or not?

Challenges

- Will signal amplitude vary as frequency is adjusted?

5.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

5.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

5.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

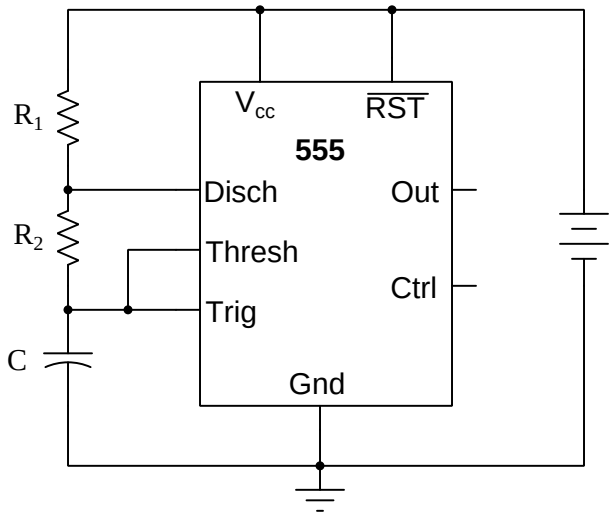
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

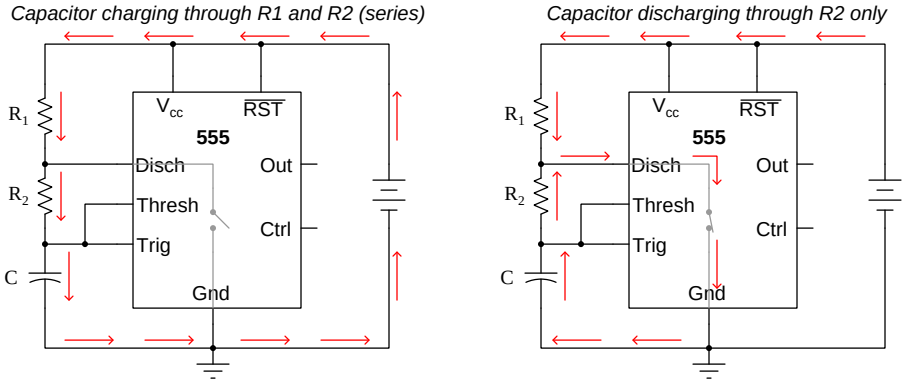
[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

5.2.3 Astable charge and discharge times

The model 555 integrated circuit is a very popular and useful "chip" used for timing purposes in electronic circuits. The basis for this circuit's timing function is a resistor-capacitor (RC) network:



In this configuration, the 555 chip acts as an *oscillator*: switching back and forth between "high" (full voltage) and "low" (no voltage) output states. The time duration of one of these states is set by the charging action of the capacitor, through both resistors (R_1 and R_2 in series). The other state's time duration is set by the capacitor discharging through one resistor (R_2):



Develop two equations for calculating time constants, one for the "charging" time constant and another for the "discharging" time constant.

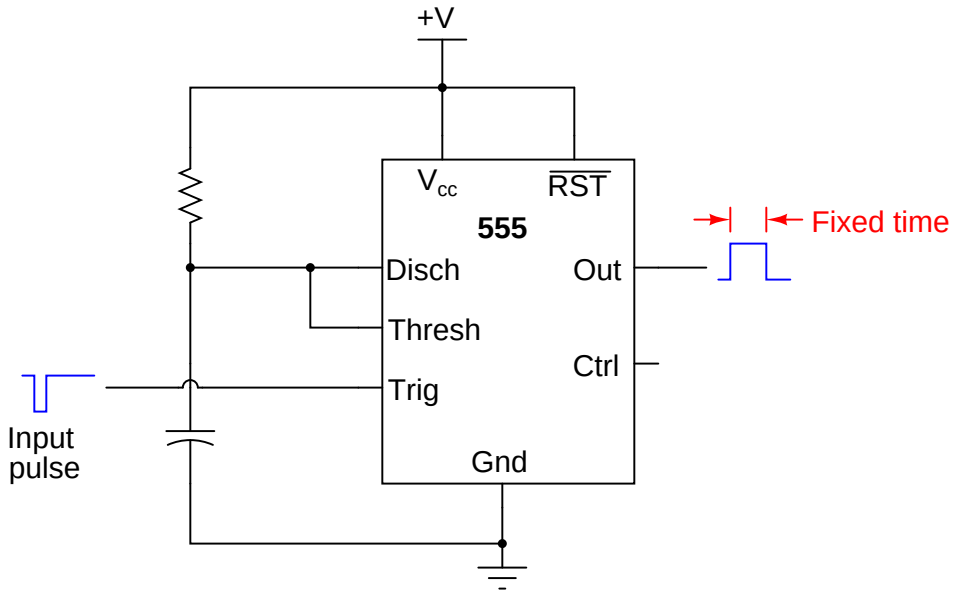
Develop two equations for predicting the "charge" time and "discharge" time of this 555 timer circuit, so that anyone designing such a circuit for specific time delays will know what resistor and capacitor values to use.

Challenges

- This astable circuit is slightly more complex than the simple astable circuit introduced in the Tutorial. How does this circuit differ, and why do you suppose this design difference matters?
- If the capacitor is replaced with another having a greater capacitance, will this affect the charging time, the discharging time, or both?

5.2.4 Monostable circuit parameters

A popular use of the 555 timer is as a *monostable* multivibrator. In this mode, the 555 will output a pulse of fixed length when commanded by an input pulse:



How low does the triggering voltage have to go in order to initiate the output pulse?

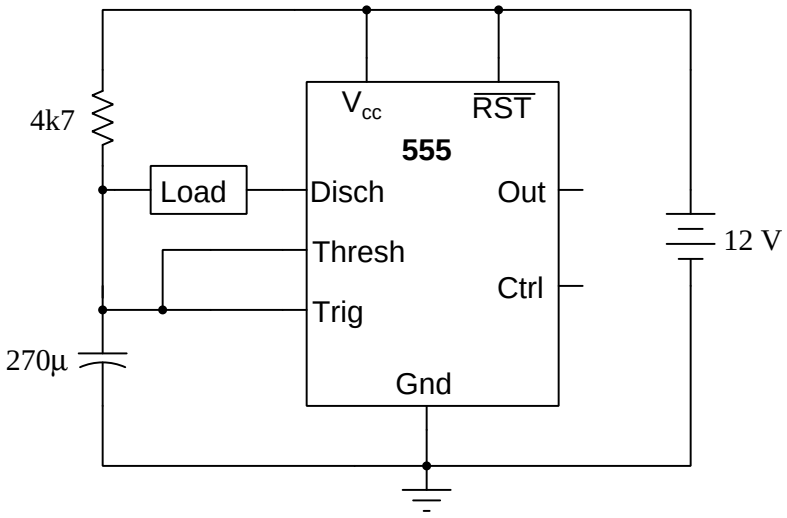
Also, write an equation specifying the width of this pulse, in seconds, given values of R and C. Hint: the magnitude of the supply voltage is irrelevant, so long as it does not vary during the capacitor's charging portion of the cycle. Show your work in obtaining the equation, based on equations of RC time constants. Don't just copy the equation from a book or datasheet!

Challenges

- Identify how you could lengthen the pulse output by this circuit.

5.2.5 Energy delivered to load

In this astable 555 circuit, a load is repeatedly energized by the energy stored up within the capacitor. Calculate the quantity of energy delivered to this load with every "discharge" portion of the circuit's cycle:



Challenges

- Will this amount of energy change if the 4.7 kΩ resistor value varies?
- Will this amount of energy change if the source voltage varies?

5.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

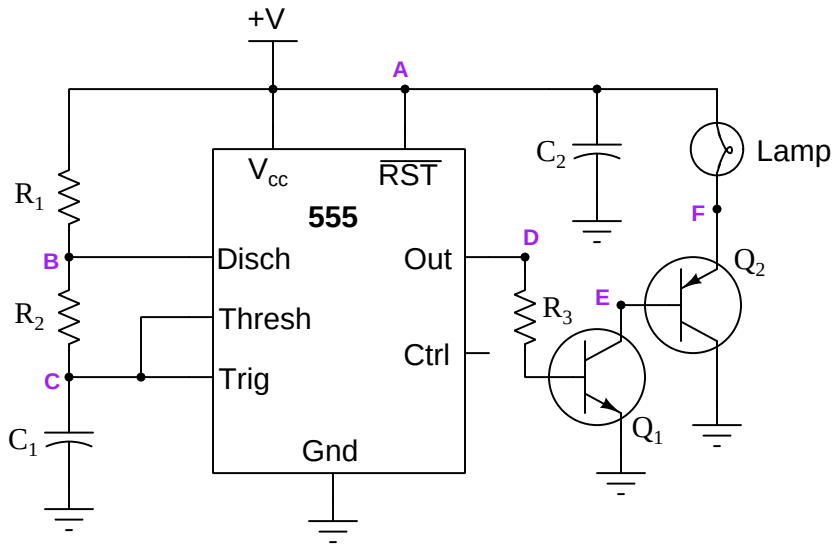
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

5.3.1 Faulted astable 555 circuit

This circuit uses a "555" integrated circuit to produce a low-frequency square-wave voltage signal (seen between the "Out" terminal of the chip and ground), which is used to turn a pair of transistors on and off to flash a large lamp. Predict how this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no coincidental faults):



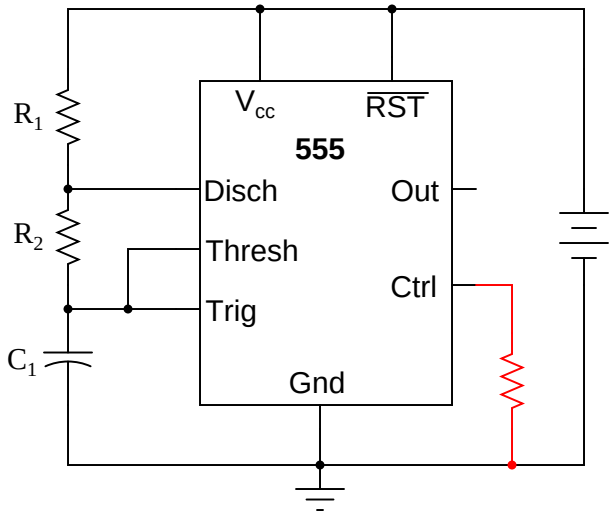
- Transistor Q_1 fails open (collector-to-emitter):
- Transistor Q_2 fails open (collector-to-emitter):
- Resistor R_3 fails open:
- Transistor Q_1 fails shorted (collector-to-emitter):
- Capacitor C_1 fails shorted:

Challenges

- Identify at least two different means of increasing this circuit's oscillation frequency.
- Explain the purpose of using *two* transistors in this circuit.

5.3.2 Misplaced resistor

What would happen to the operation of this astable 555 timer circuit if a resistor were accidently connected between the "Control" terminal and ground? Explain the reason for your answer.



Challenges

- Does the addition of this resistor affect the output signal (pin 3) amplitude as well? Explain why or why not. If it amplitude is affected, does it increase or decrease with the resistor in place?

5.3.3 TLC555CP circuit problem

A student builds their first astable 555 timer circuit, using a TLC555CP chip. Unfortunately, it seems to have a problem. Sometimes, the output of the timer simply stops oscillating, with no apparent cause. Stranger yet, the problem often occurs at the precise time anyone moves their hand within a few inches of the circuit board (without actually touching anything!).

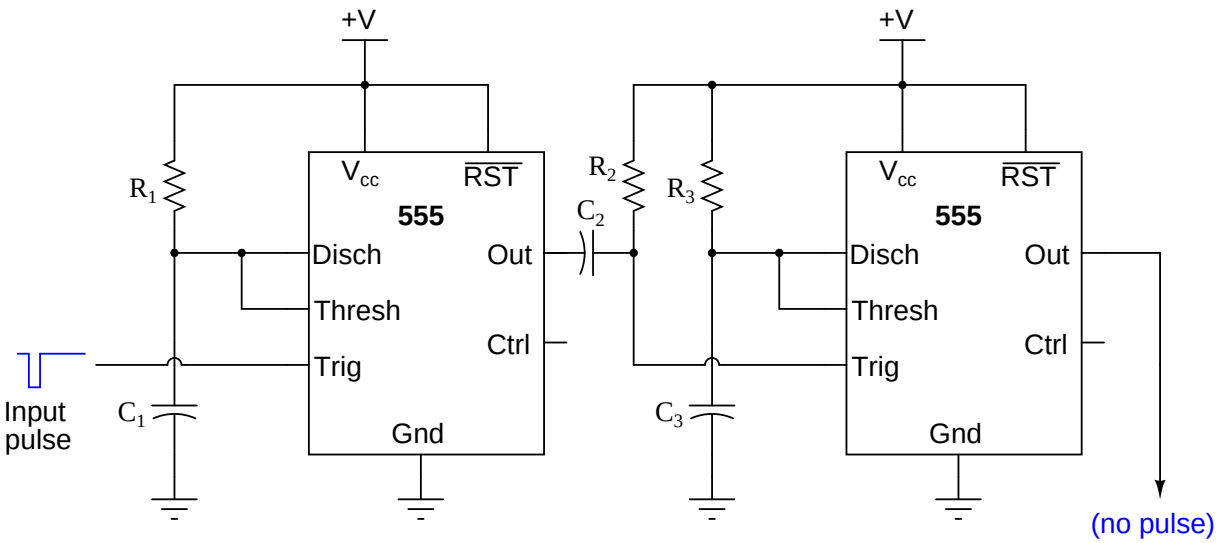
What could the student have done wrong in assembling this circuit to cause such a problem? What steps would you take to troubleshoot this problem?

Challenges

- Identify a remedy for this circuit's problems.

5.3.4 Failed-low output

Identify at least one component fault that would cause the final 555 timer output to always remain low:



For each of your proposed faults, explain *why* it will cause the described problem.

Challenges

- What purpose is served by cascading two 555 timers like this?

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

References

"LM555 Timer" datasheet DS007851, National Semiconductor, July 2006.

Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

20 September 2025 – added a Derivations and Technical references chapter, with a section exploring the phenomenon of latch-up.

14 March 2024 – added another page to the "Astable 555 operation" section of the Tutorial explaining how to use CMOS logic gates to obtain rail-to-rail output voltage necessary for symmetrical (i.e. 50% duty cycle) square wave oscillation.

15 November 2023 – edited image_6808 and image_6809 to show MOSFET outputs.

27 August 2023 – added a new Tutorial section discussing how to alter the trigger and threshold voltage values.

9 August 2023 – added another astable circuit example to the Tutorial, using the 555's Output terminal to charge and discharge the capacitor, thus providing a nearly perfect 50% duty cycle. Also added a Case Tutorial chapter with a section showing an astable 555 oscillator demonstration circuit.

18 November 2022 – corrected typographical error in image_5229 where the capacitor's voltage was incorrectly described as "increasing".

11 November 2021 – added a new Conceptual Reasoning question on driving a heavy load using an interposing transistor.

31 October 2021 – added a more detailed internal illustration of a 555 timer IC.

23 October 2021 – divided the Tutorial into sections.

21 July 2021 – added an "Applying foundational concepts..." question to the Conceptual Reasoning section of the Questions chapter.

15 June 2021 – added more content to the Tutorial on astable calculations.

8 May 2021 – commented out or deleted empty chapters.

21 April 2021 – added a second astable circuit to the Tutorial, with two resistors rather than one resistor.

25 November 2020 – added a Conceptual question on battery-powered 555 timer circuits.

11 November 2020 – made minor additions to the Introduction chapter.

28 September 2020 – added instructor notes to some of the questions, and made minor edits to the Introduction chapter.

14 September 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

26 March 2020 – added Conceptual Reasoning problem showing a simple triangle-wave oscillator circuit based on a 555 timer and a JFET current regulator.

9 February 2020 – added some problems, and added test points to the schematic of image_2334. Also added a footnote to the Tutorial mentioning the similar states of the Out and Discharge terminals.

24 January 2020 – added Foundational Concepts to the list in the Conceptual Reasoning section.

18 December 2019 – minor edits to diagnostic questions, replacing "no multiple faults" with "no coincidental faults".

13 January 2019 – renamed Simplified Tutorial to Tutorial, since I haven't written a Full Tutorial yet.

August 2018 – document first created.

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