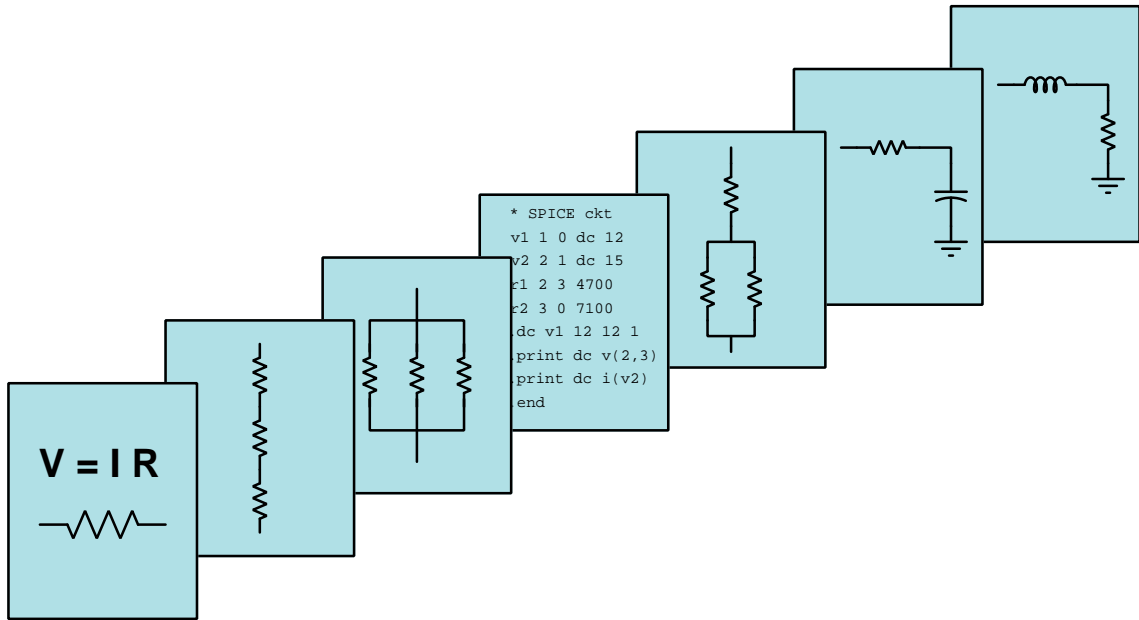


MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



555 TIMER CIRCUITS

© 2018-2024 BY TONY R. KUPHALDT – UNDER THE TERMS AND CONDITIONS OF THE
CREATIVE COMMONS ATTRIBUTION 4.0 INTERNATIONAL PUBLIC LICENSE

LAST UPDATE = 14 MARCH 2024

This is a copyrighted work, but licensed under the Creative Commons Attribution 4.0 International Public License. A copy of this license is found in the last Appendix of this document. Alternatively, you may visit <http://creativecommons.org/licenses/by/4.0/> or send a letter to Creative Commons: 171 Second Street, Suite 300, San Francisco, California, 94105, USA. The terms and conditions of this license allow for free copying, distribution, and/or modification of all licensed works by the general public.

Contents

1	Introduction	3
2	Case Tutorial	5
2.1	Example: astable 555 oscillator demonstration circuit	6
3	Tutorial	7
3.1	Relaxation oscillators	8
3.2	Internals of a 555 timer IC	10
3.3	Astable 555 operation	12
3.4	Monostable 555 operation	16
3.5	Altering trigger and threshold values	17
4	Questions	21
4.1	Conceptual reasoning	25
4.1.1	Reading outline and reflections	26
4.1.2	Foundational concepts	27
4.1.3	Applying foundational concepts to an astable 555 circuit	28
4.1.4	Adjustable duty cycle	29
4.1.5	Sequential timer circuit	30
4.1.6	Purpose of the Control terminal	31
4.1.7	Driving a heavy load	32
4.1.8	Capacitor energy	33
4.1.9	Battery-powered 555	34
4.1.10	555-based triangle and square wave oscillator	35
4.2	Quantitative reasoning	37
4.2.1	Miscellaneous physical constants	38
4.2.2	Introduction to spreadsheets	39
4.2.3	Astable charge and discharge times	42
4.2.4	Monostable circuit parameters	43
4.2.5	Energy delivered to load	44
4.3	Diagnostic reasoning	45
4.3.1	Faulted astable 555 circuit	46
4.3.2	Misplaced resistor	47
4.3.3	TLC555CP circuit problem	47

<i>CONTENTS</i>	1
4.3.4 Failed-low output	48
A Problem-Solving Strategies	49
B Instructional philosophy	51
C Tools used	57
D Creative Commons License	61
E References	69
F Version history	71
Index	72

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, **oscilloscopes**, 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

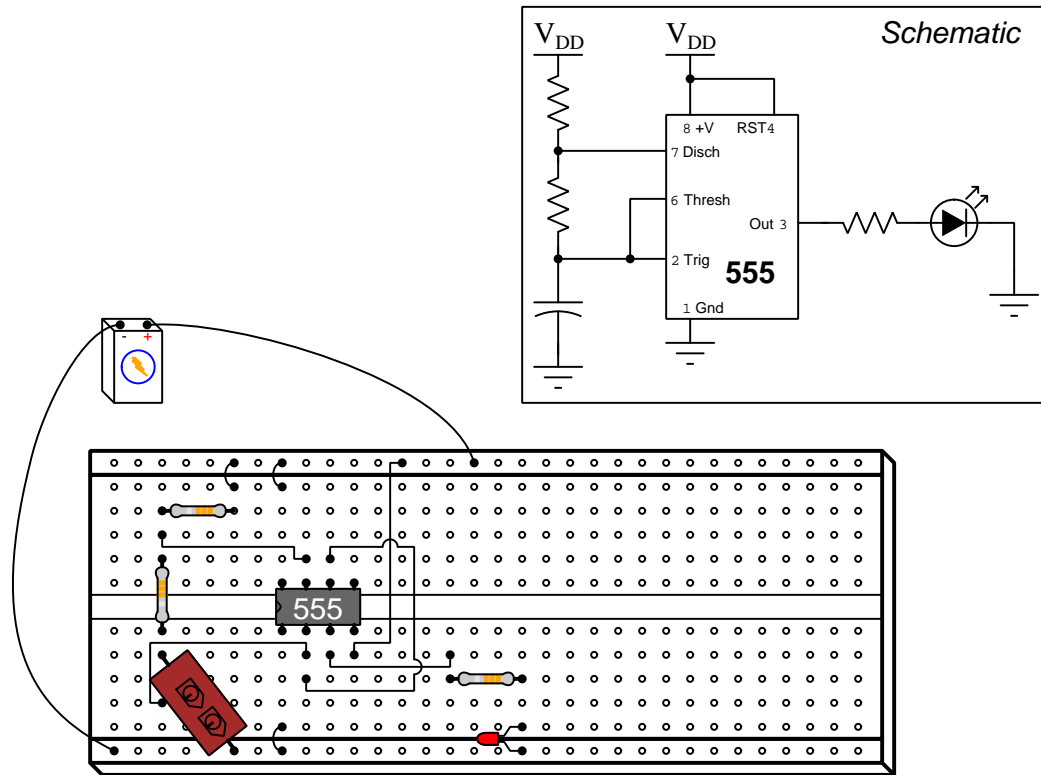
Case Tutorial

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.

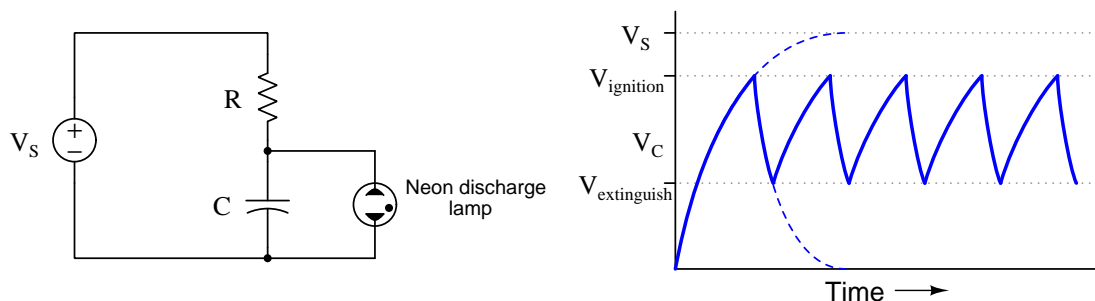
Note: you may find it helpful to connect a *decoupling capacitor* with a value of $1\ \mu\text{F}$ or so between the positive and negative DC power supply “rails” (not shown in the schematic or the pictorial illustration) to stabilize the source voltage. If the DC power source has significant internal 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).

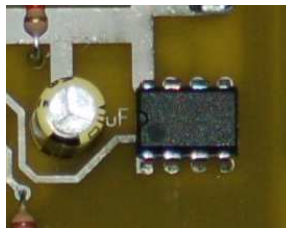
Neon lamps are quite unlike incandescent lamps, in that they conduct zero current unless and until the voltage impressed across their terminals exceeds the "ignition" voltage, which is the amount of voltage necessary to ionize the neon gas and make it electrically conductive. Once ionized, such a lamp 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 timer² has been soldered into a printed circuit board (PCB), to the right of an electrolytic capacitor:

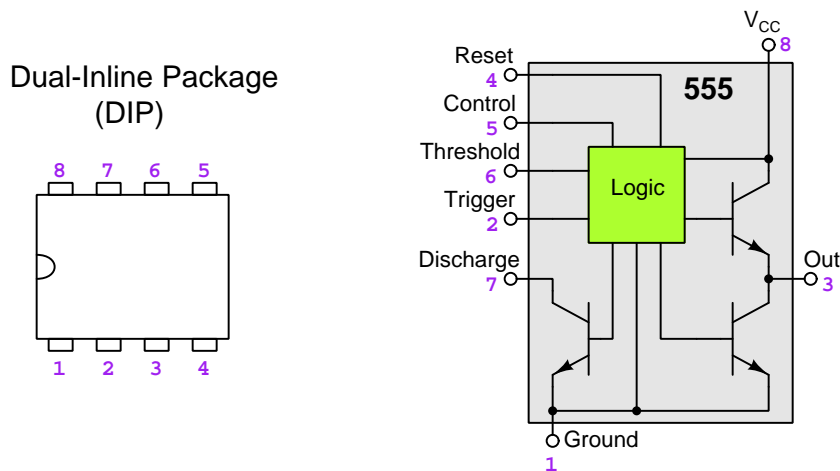


¹An “integrated circuit” is one where all components are built on a single wafer of semiconducting material, usually purified silicon. This manufacturing technique lends itself very well to mass-production, the goal being to produce electronic circuits of small size having exceptionally consistent performance.

²An 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:

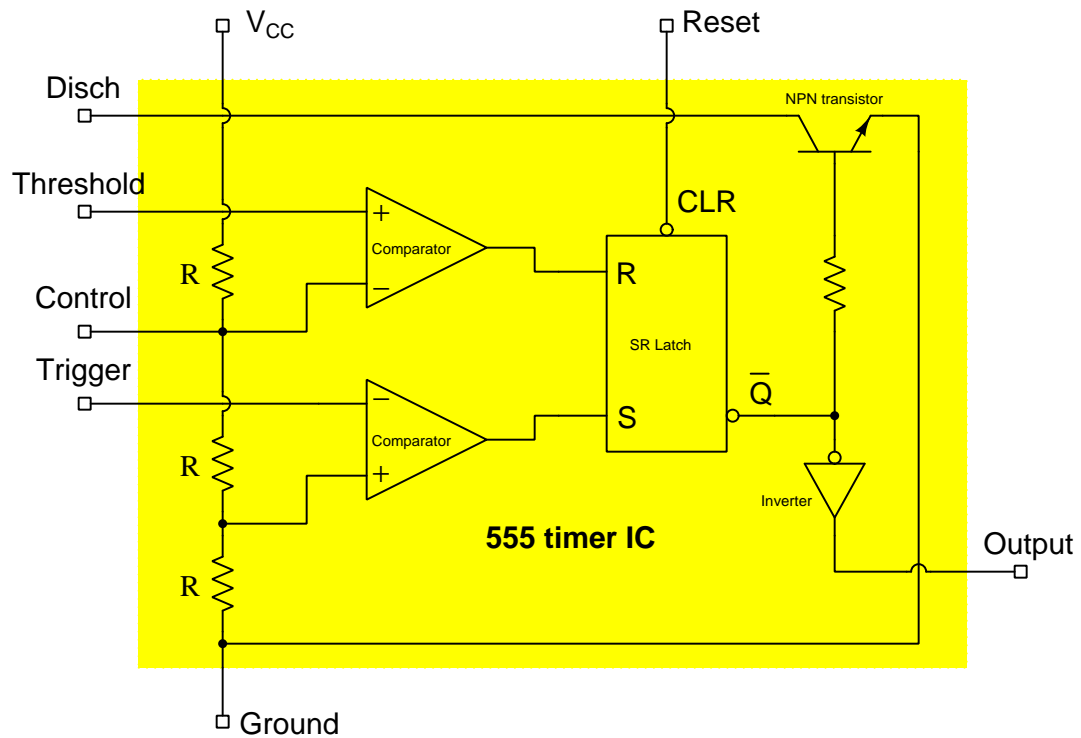


This functional diagram omits much of the complexity internal to the model 555 integrated circuit. The green-colored “logic” section, for example, contains over two dozen transistors and eleven resistors, and serves the purpose of switching the three transistors shown in this simplified diagram fully “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.

³The 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.

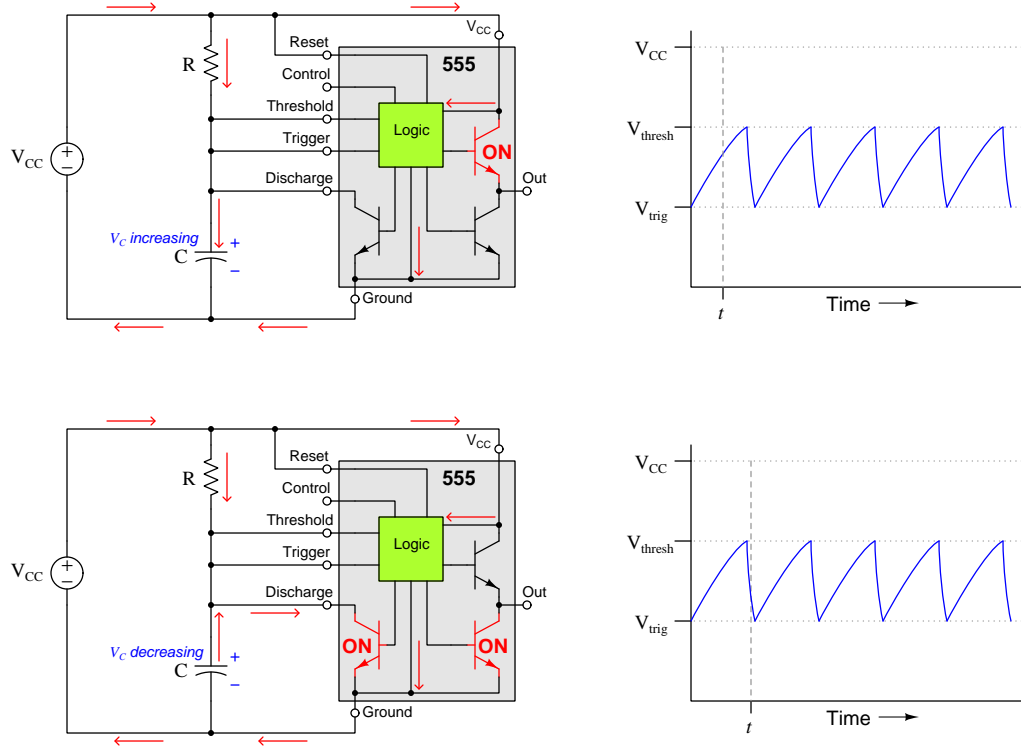
A more detailed view of the 555 timer's internal circuitry is shown in the following illustration:



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 oscillator⁴:



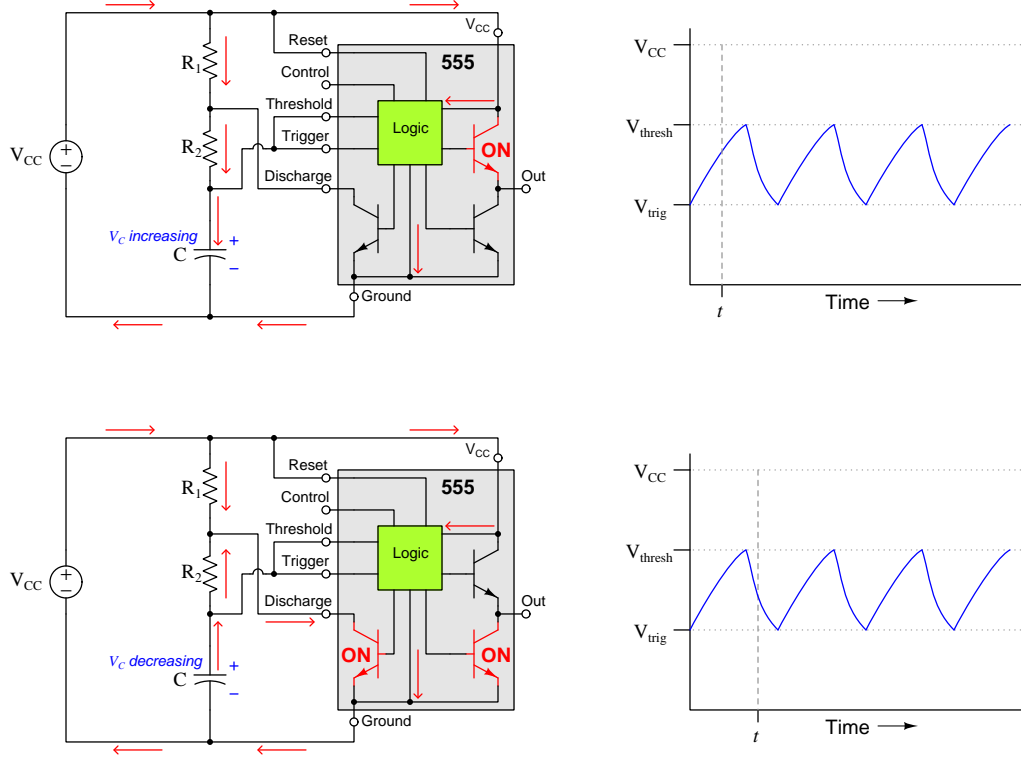
The “charge” portion of this oscillator’s cycle lasts for 69.3% of the RC time constant (τ), because this is the length of time required for an inverse exponential function to achieve the half-way⁵ point from where it begins (V_{trig}) to its ultimate end-point (V_{CC}). By contrast, the “discharge” 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.

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

⁴An 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.

⁵With 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 $0.5 = e^{-t/\tau}$ 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 :

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

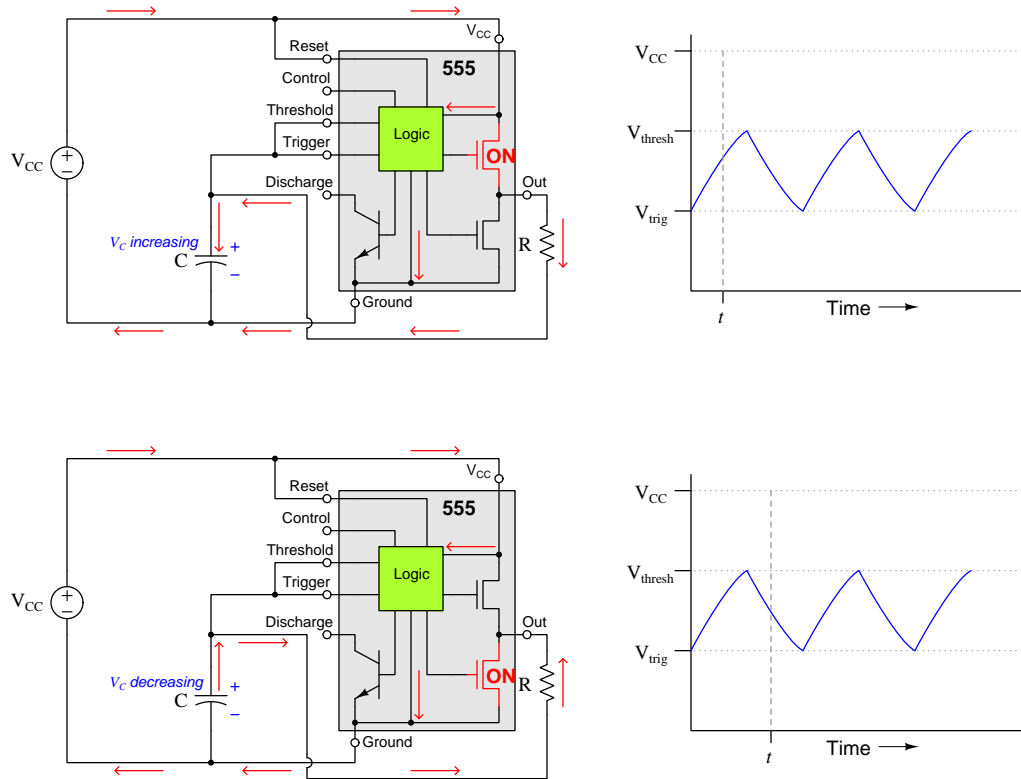
Total time for each complete cycle of the capacitor’s voltage is called the *period* of the signal, and is equal to the sum of charge and discharge times:

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

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:

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

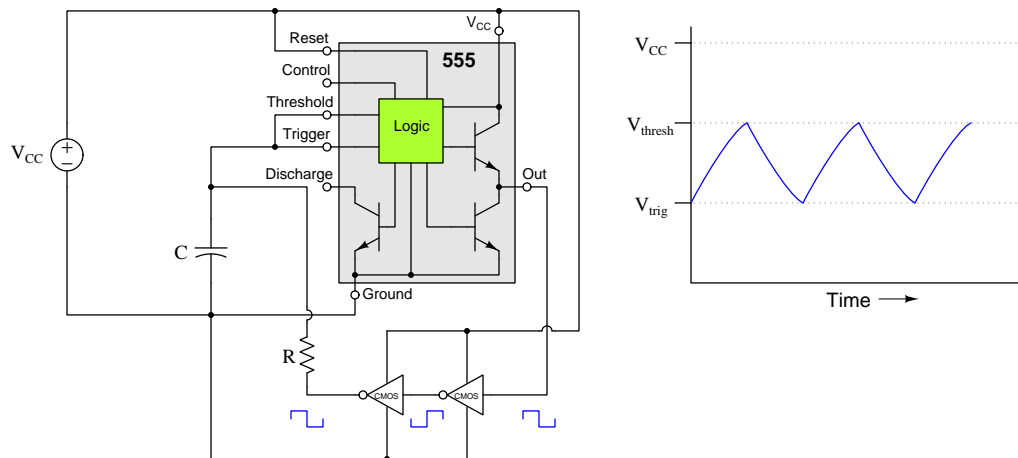
Total period for the cycle is simply the sum of charge and discharge times:

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

Frequency is of course the reciprocal of this total period:

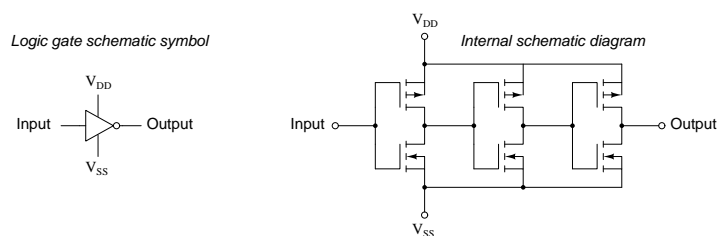
$$f = \frac{1}{1.386RC} = \frac{0.721}{RC}$$

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:

CMOS inverter (NOT) gate

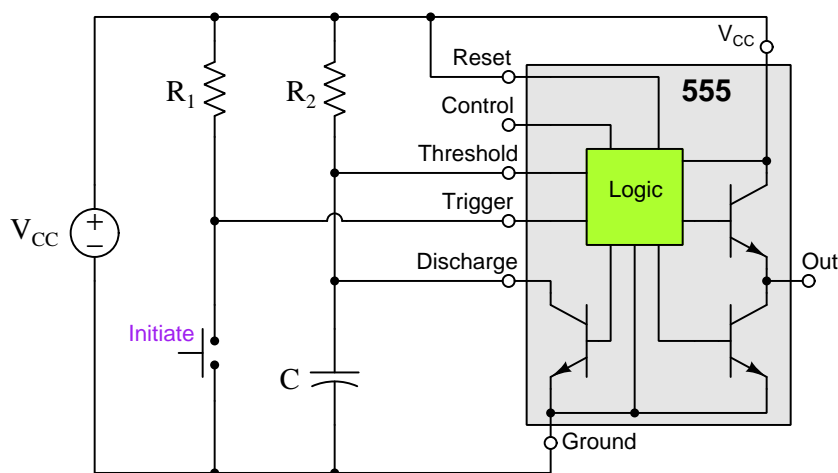


All the 555 timer’s output terminal potential needs to do is rise high enough for the first CMOS gate to properly interpret it as a “high” state, and fall low enough that the CMOS gate properly interprets it as a “low” state. Any asymmetry in the 555 timer’s “high” versus “low” output states is essentially 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:

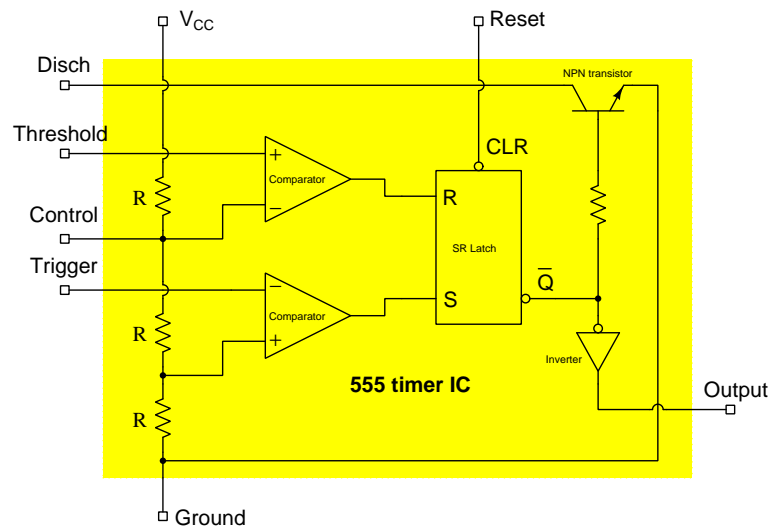


When the switch is unpressed, R_1 conducts negligible current and drops negligible voltage, which means the Trigger input senses a “high” voltage state with reference to ground and the 555 timer refuses to enter the “charge” state, remaining in the “discharge” state which leaves the capacitor voltage 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.

⁶Using 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 $1.099R_2C$.

3.5 Altering trigger and threshold values

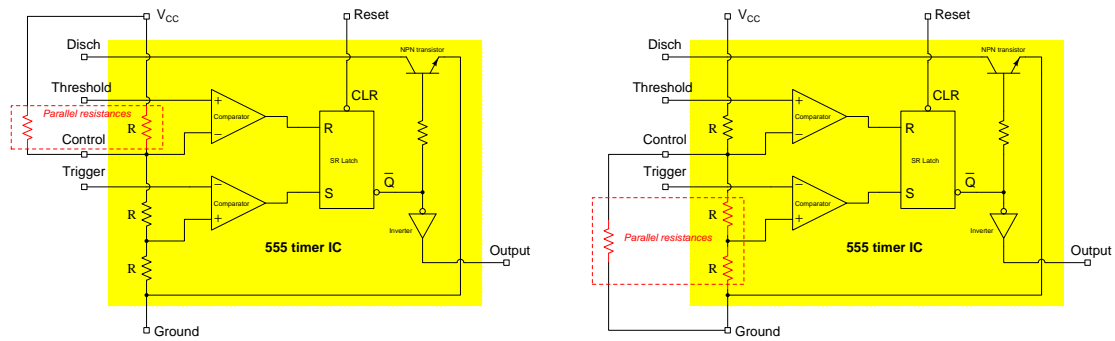
Inside every 555 timer IC is a three-element resistive voltage divider setting the voltage values at which the Trigger and Threshold inputs control the charging and discharging states. With the three resistors shown inside the 555 timer being of equal value, this divides the DC supply voltage into thirds, 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.

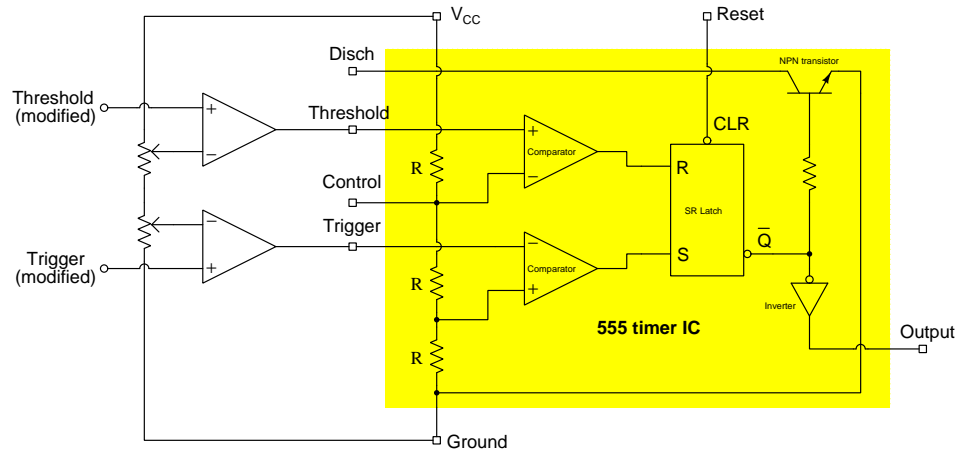
One way to alter the Threshold and Trigger voltage values is to connect a resistor between the Control pin of the 555 timer IC and either Ground or V_{CC} . This places another resistance in parallel with one or more of the 555 timer's internal resistors, thus modifying that resistance within a section 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 comparators⁷, 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.

⁷As 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

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 read¹ the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture², 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.

¹Technical 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 *Reading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms* by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

²Lecture 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?

4.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking³. 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.

4.1.1 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.

4.1.2 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

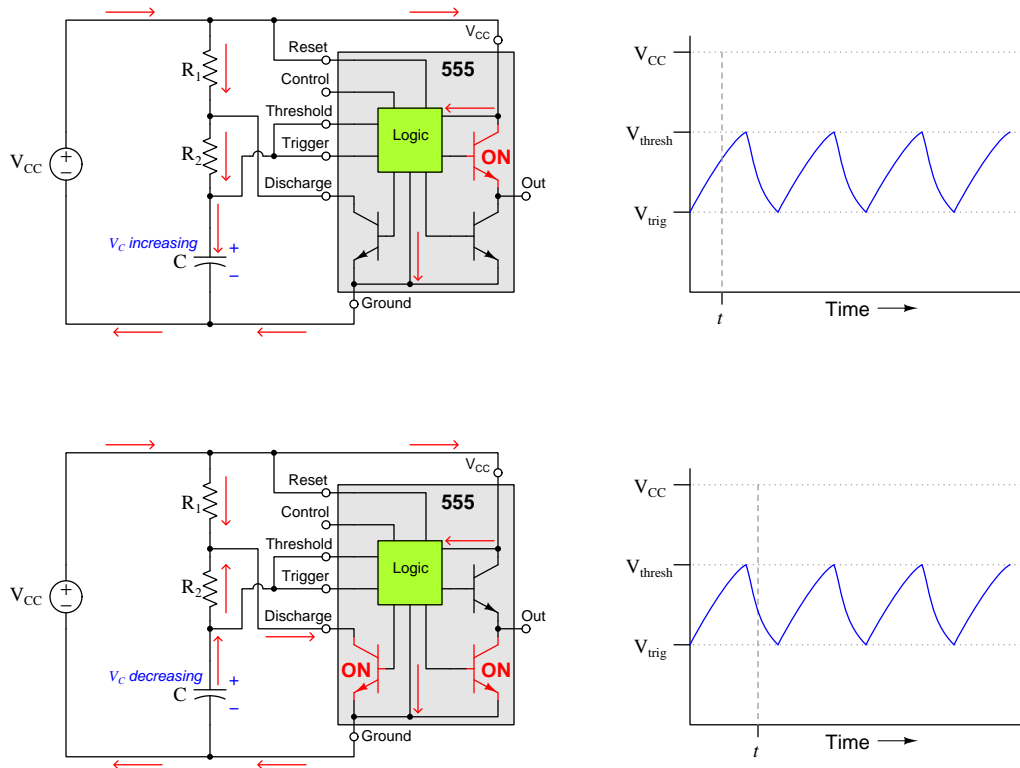
Voltage divider

Astable

Monostable

4.1.3 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.

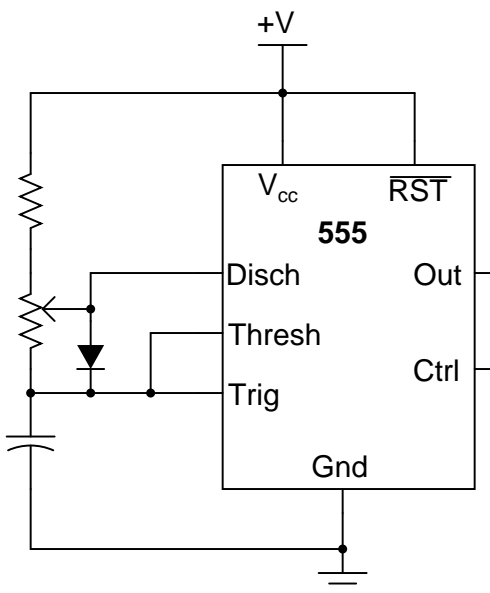
Challenges

- What are some practical applications for this timer circuit?

4.1.4 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:



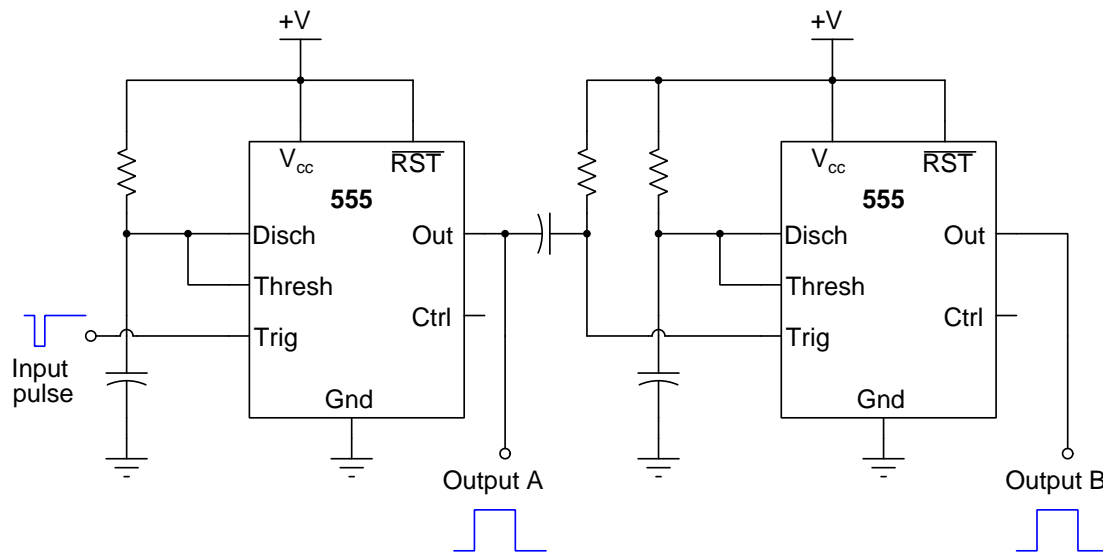
Identify which way the potentiometer’s wiper should be moved in order to increase this circuit’s duty cycle (i.e. lengthen the “charge” time in proportion to the total period).

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?

4.1.5 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?

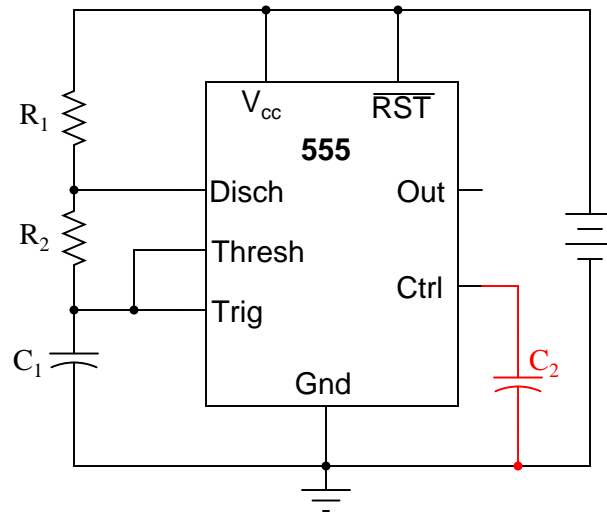
Suppose several monostable 555 timer circuits are cascaded together, following the same pattern as the circuit shown, and then the output of the last timer is connected to the input of the first in the same manner as the in-between stages are connected. How will this circuit function?

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.

4.1.6 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.



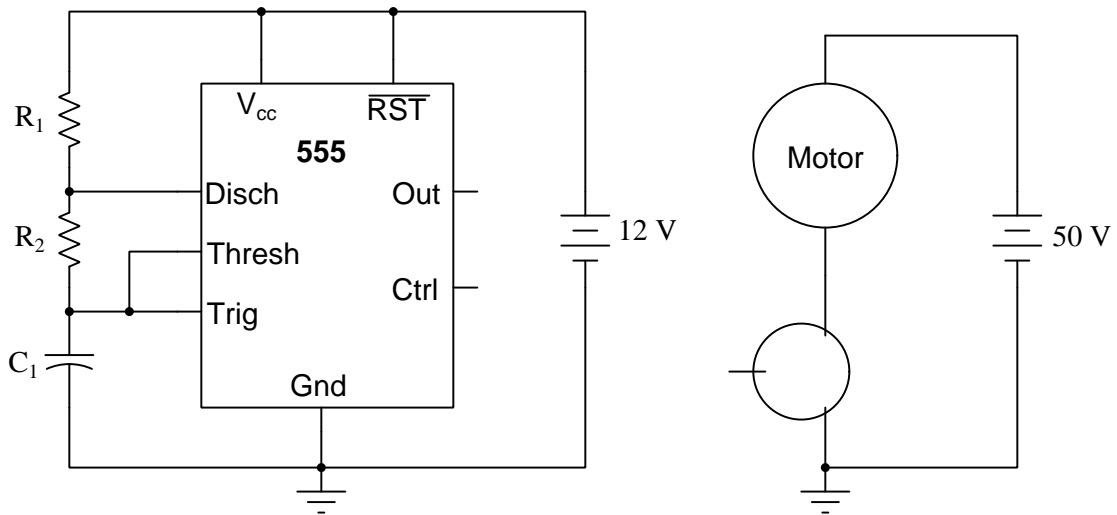
Explain what purpose the capacitor C_2 serves in this circuit.

Challenges

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

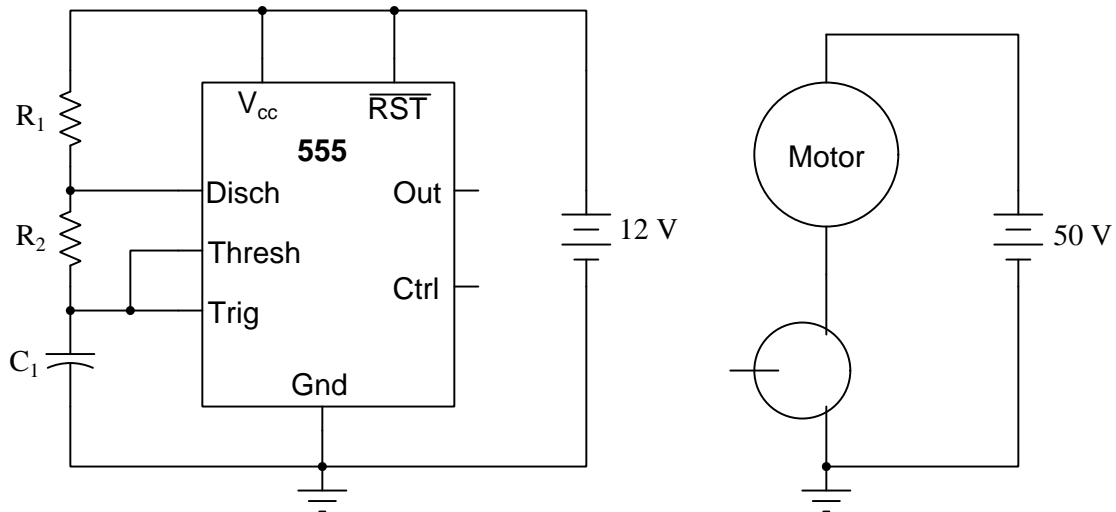
4.1.7 Driving a heavy load

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.

4.1.8 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.

4.1.9 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:

- $R_1 = 1 \text{ k}\Omega$; $R_2 = 470 \text{ }\Omega$; $C = 2.2 \text{ }\mu\text{F}$
- $R_1 = 10 \text{ k}\Omega$; $R_2 = 4.7 \text{ k}\Omega$; $C = 0.22 \text{ }\mu\text{F}$
- $R_1 = 100 \text{ k}\Omega$; $R_2 = 47 \text{ k}\Omega$; $C = 0.022 \text{ }\mu\text{F}$

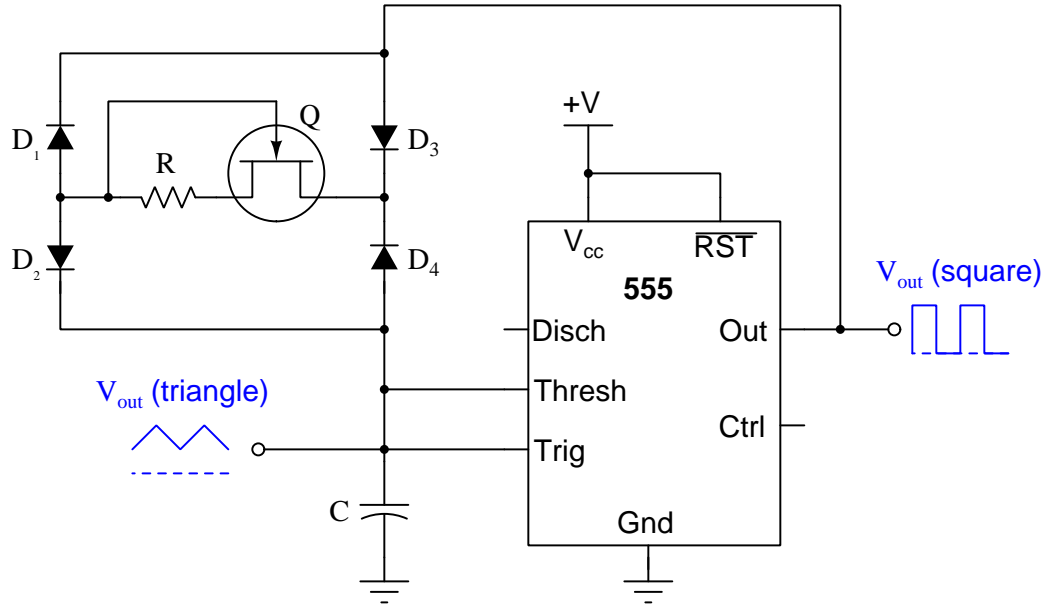
Which of these three options makes the most sense for a battery-powered oscillator circuit, and why?

Challenges

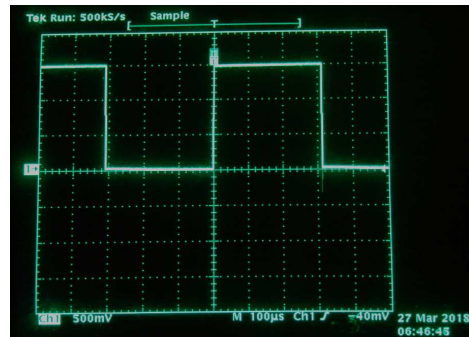
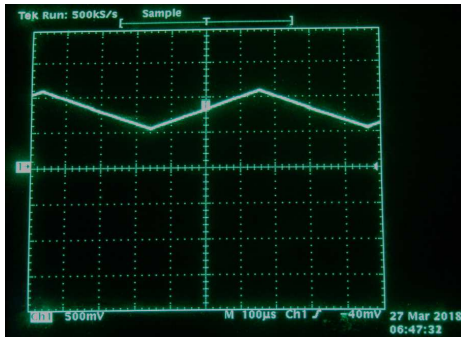
- Suppose the capacitance value within an astable 555 timer circuit is doubled. Identify the effects of this capacitance doubling, with regard to energy storage.

4.1.10 555-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 $R = 7 \text{ k}\Omega$, $C = 0.015 \text{ }\mu\text{F}$, $+V = 16 \text{ V}$, 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?

4.2 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 cases⁴” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely⁵ on an answer key!

⁴In 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.

⁵This 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.

4.2.1 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 ($\text{m}^3/\text{kg}\cdot\text{s}^2$)

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-Kelvin⁴** ($\text{W}/\text{m}^2\cdot\text{K}^4$)

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.

4.2.2 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.

⁶Spreadsheets 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.

Common⁷ 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 ensure⁸ 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 roots⁹ 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.

⁷Modern 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.

⁸Spreadsheet 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.

⁹Reviewing 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:

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

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

	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	

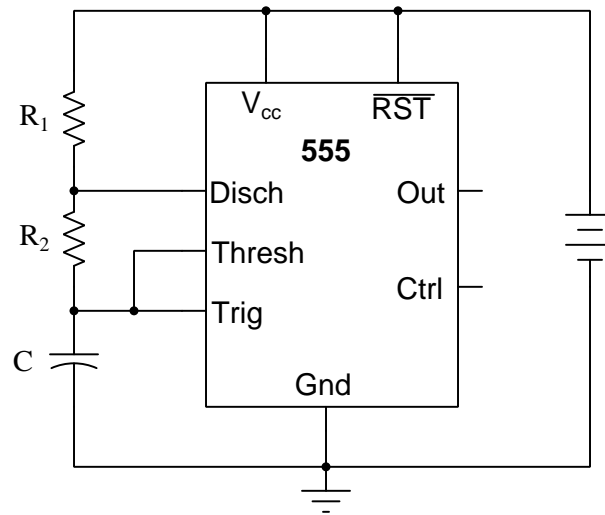
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary¹⁰ – all that matters is that they properly reference 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.

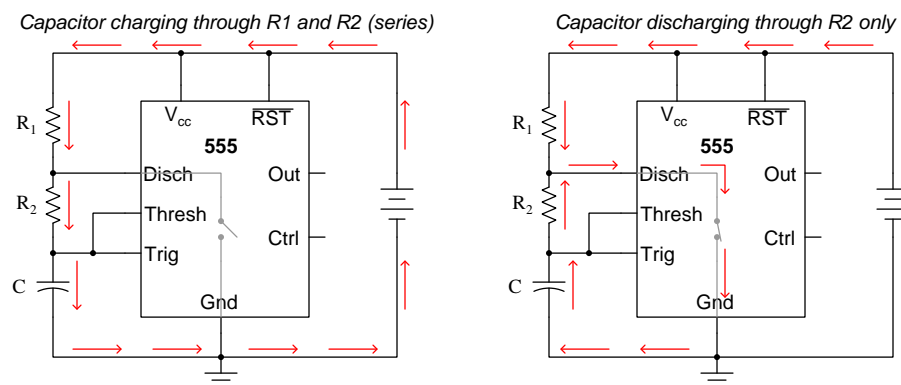
¹⁰My personal preference is to locate all the “given” data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring 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.*

4.2.3 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.

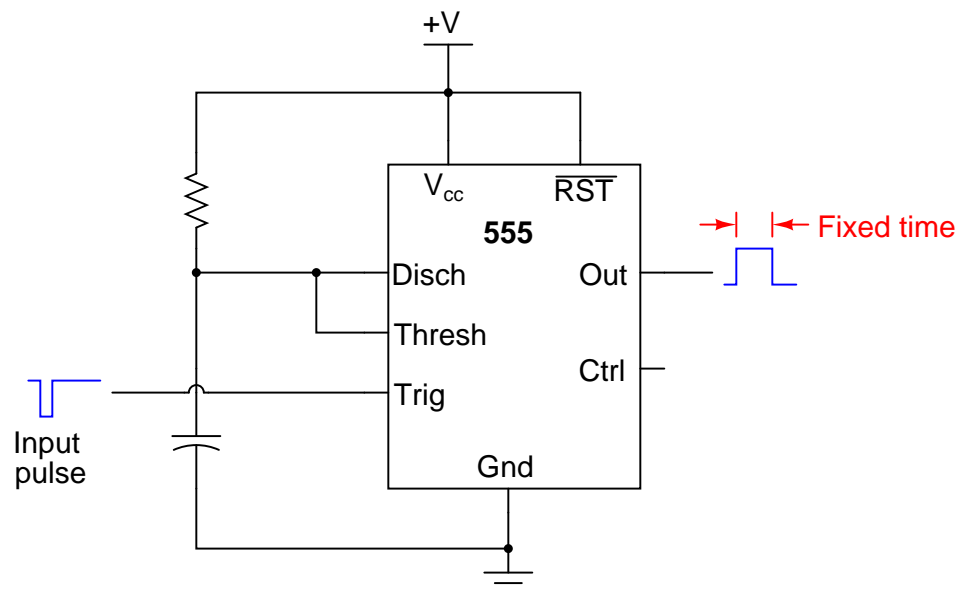
Develop two equations for predicting the “charge” time and “discharge” time of this 555 timer circuit, so that anyone designing such a circuit for specific time delays will know what resistor and capacitor values to use.

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?

4.2.4 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?

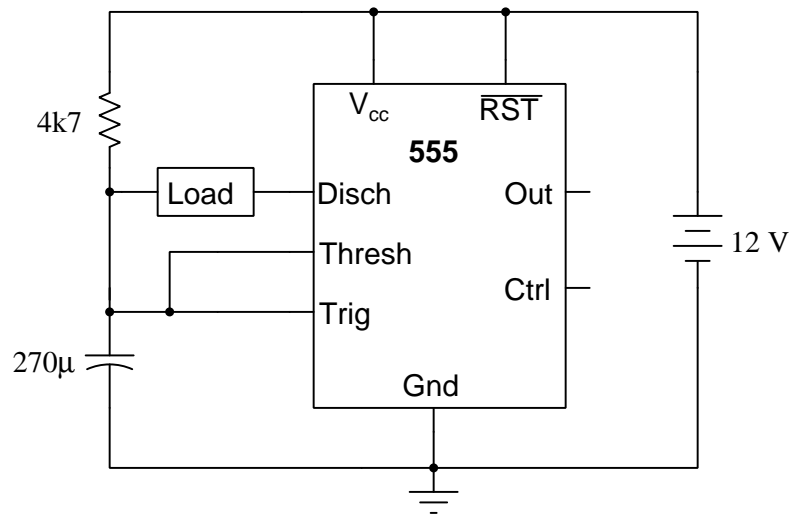
Also, write an equation specifying the width of this pulse, in seconds, given values of R and C . Hint: the magnitude of the supply voltage is irrelevant, so long as it does not vary during the capacitor's charging portion of the cycle. Show your work in obtaining the equation, based on equations of 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.

4.2.5 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 k Ω resistor value varies?
- Will this amount of energy change if the source voltage varies?

4.3 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.

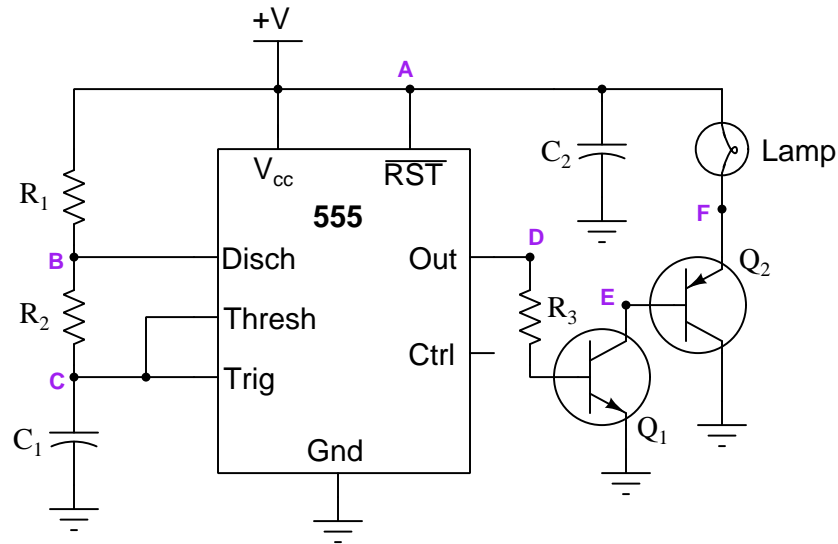
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of 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.

4.3.1 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):



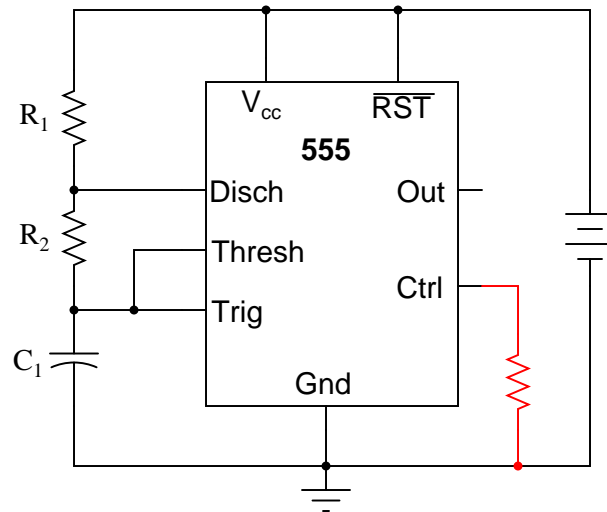
- Transistor Q_1 fails open (collector-to-emitter):
- Transistor Q_2 fails open (collector-to-emitter):
- Resistor R_3 fails open:
- Transistor Q_1 fails shorted (collector-to-emitter):
- Capacitor C_1 fails shorted:

Challenges

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

4.3.2 Misplaced resistor

What would happen to the operation of this astable 555 timer circuit if a resistor were accidentally 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 its amplitude is affected, does it increase or decrease with the resistor in place?

4.3.3 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!).

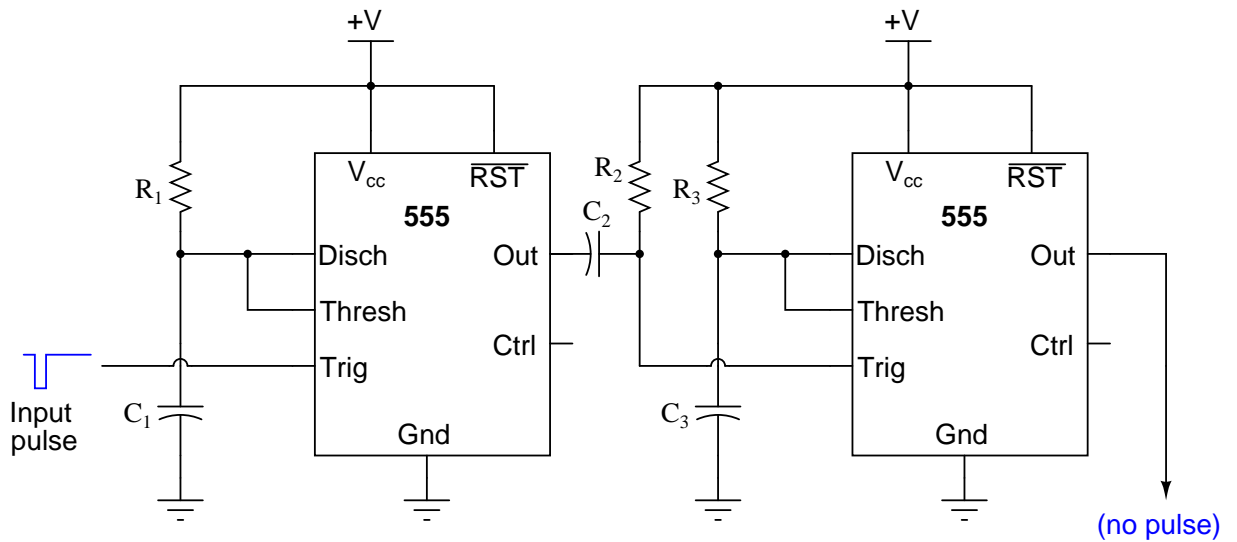
What could the student have done wrong in assembling this circuit to cause such a problem? What steps would you take to troubleshoot this problem?

Challenges

- Identify a remedy for this circuit's problems.

4.3.4 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

“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.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

- 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 environment¹ 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 Socratic² 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 absurdity³ 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

¹In 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.

²Socrates 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.

³This 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 characteristic of these learning modules is a lack of step-by-step instructions in the Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where step-by-step instructions are prescribed for each experiment, these modules take the approach that students must learn to closely read the tutorials and apply their own reasoning to identify the appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as a set of enumerated points. At other times certain steps are implied, an example being assumed competence in test equipment use where the student should not need to be told *again* how to use their multimeter because that was thoroughly explained in previous lessons. In some circumstances no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are foundational principles of this learning series, and in keeping with this philosophy all activities are designed to *require* those behaviors. Some students may find the lack of prescription frustrating, because it demands more from them than what their previous educational experiences required. This frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which must be corrected if the student is ever to become a self-directed learner and effective problem-solver. Ultimately, the need for students to read closely and think clearly is more important both in the near-term and far-term than any specific facet of the subject matter at hand. If a student takes longer than expected to complete a module because they are forced to outline, digest, and reason on their own, so be it. The future gains enjoyed by developing this mental discipline will be well worth the additional effort and delay.

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.

This methodology of assigning text-based modules to students for digestion and then using Socratic dialogue to assess progress and hone students’ thinking was developed over a period of several years by the author with his Electronics and Instrumentation students at the two-year college level. While decidedly unconventional and sometimes even unsettling for students accustomed to a more passive lecture environment, this instructional philosophy has proven its ability to convey conceptual mastery, foster careful analysis, and enhance employability so much better than lecture that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this “inverted” format where students must articulate and logically defend their reasoning. This, too, may be unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the “inverted” session instructor in order that students never feel discouraged by having their errors exposed. *Everyone* makes mistakes from time to time, and learning is a lifelong process! Part of the instructor’s job is to build a culture of learning among the students where errors are not seen as shameful, but rather as opportunities for progress.

To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, *the fundamental goal of education is for each student to learn to think clearly and independently*. This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student's responsibility to do that hard work ultimately limits that student's potential and thereby does real harm.
- It is not only permissible, but encouraged, to answer a student's question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.
- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one's own reasoning.
- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an "Outline and reflections" question as well as a "Foundational concepts" question in the Conceptual reasoning section, to prompt reflective reading.
- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to *variations* of that question. This is why module questions typically contain multiple "Challenges" suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own "Challenges" as they are able, in order to have a multitude of ways ready to probe students' understanding.
- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done "live" before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.

Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea *in your own words, using your own examples*.
- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.
- Never take the easy path of highlighting or underlining important text. Instead, *summarize* and/or *comment* on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.
- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least *imagine* yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.
- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of *circuit simulation software*, checking to see if your simulated results agree with the results shown in the text.
- 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 varied⁴ effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge⁵ one another.

To high standards of education,

Tony R. Kuphaldt

⁴As 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.

⁵Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one’s life through the improvement of clear and independent thought, literacy, expression, and various practical skills.

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

Creative Commons License

Creative Commons Attribution 4.0 International Public License

By exercising the Licensed Rights (defined below), You accept and agree to be bound by the terms and conditions of this Creative Commons Attribution 4.0 International Public License (“Public License”). To the extent this Public License may be interpreted as a contract, You are granted the Licensed Rights in consideration of Your acceptance of these terms and conditions, and the Licensor grants You such rights in consideration of benefits the Licensor receives from making the Licensed Material available under these terms and conditions.

Section 1 – Definitions.

a. **Adapted Material** means material subject to Copyright and Similar Rights that is derived from or based upon the Licensed Material and in which the Licensed Material is translated, altered, arranged, transformed, or otherwise modified in a manner requiring permission under the Copyright and Similar Rights held by the Licensor. For purposes of this Public License, where the Licensed Material is a musical work, performance, or sound recording, Adapted Material is always produced where the Licensed Material is synched in timed relation with a moving image.

b. **Adapter’s License** means the license You apply to Your Copyright and Similar Rights in Your contributions to Adapted Material in accordance with the terms and conditions of this Public License.

c. **Copyright and Similar Rights** means copyright and/or similar rights closely related to copyright including, without limitation, performance, broadcast, sound recording, and Sui Generis Database Rights, without regard to how the rights are labeled or categorized. For purposes of this Public License, the rights specified in Section 2(b)(1)-(2) are not Copyright and Similar Rights.

d. **Effective Technological Measures** means those measures that, in the absence of proper authority, may not be circumvented under laws fulfilling obligations under Article 11 of the WIPO Copyright Treaty adopted on December 20, 1996, and/or similar international agreements.

e. **Exceptions and Limitations** means fair use, fair dealing, and/or any other exception or

limitation to Copyright and Similar Rights that applies to Your use of the Licensed Material.

f. **Licensed Material** means the artistic or literary work, database, or other material to which the Licensor applied this Public License.

g. **Licensed Rights** means the rights granted to You subject to the terms and conditions of this Public License, which are limited to all Copyright and Similar Rights that apply to Your use of the Licensed Material and that the Licensor has authority to license.

h. **Licensor** means the individual(s) or entity(ies) granting rights under this Public License.

i. **Share** means to provide material to the public by any means or process that requires permission under the Licensed Rights, such as reproduction, public display, public performance, distribution, dissemination, communication, or importation, and to make material available to the public including in ways that members of the public may access the material from a place and at a time individually chosen by them.

j. **Sui Generis Database Rights** means rights other than copyright resulting from Directive 96/9/EC of the European Parliament and of the Council of 11 March 1996 on the legal protection of databases, as amended and/or succeeded, as well as other essentially equivalent rights anywhere in the world.

k. **You** means the individual or entity exercising the Licensed Rights under this Public License. **Your** has a corresponding meaning.

Section 2 – Scope.

a. License grant.

1. Subject to the terms and conditions of this Public License, the Licensor hereby grants You a worldwide, royalty-free, non-sublicensable, non-exclusive, irrevocable license to exercise the Licensed Rights in the Licensed Material to:

A. reproduce and Share the Licensed Material, in whole or in part; and

B. produce, reproduce, and Share Adapted Material.

2. Exceptions and Limitations. For the avoidance of doubt, where Exceptions and Limitations apply to Your use, this Public License does not apply, and You do not need to comply with its terms and conditions.

3. Term. The term of this Public License is specified in Section 6(a).

4. Media and formats; technical modifications allowed. The Licensor authorizes You to exercise the Licensed Rights in all media and formats whether now known or hereafter created, and to make technical modifications necessary to do so. The Licensor waives and/or agrees not to assert any right or authority to forbid You from making technical modifications necessary to exercise the Licensed Rights, including technical modifications necessary to circumvent Effective Technological Measures.

For purposes of this Public License, simply making modifications authorized by this Section 2(a)(4) never produces Adapted Material.

5. Downstream recipients.

A. Offer from the Licensor – Licensed Material. Every recipient of the Licensed Material automatically receives an offer from the Licensor to exercise the Licensed Rights under the terms and conditions of this Public License.

B. No downstream restrictions. You may not offer or impose any additional or different terms or conditions on, or apply any Effective Technological Measures to, the Licensed Material if doing so restricts exercise of the Licensed Rights by any recipient of the Licensed Material.

6. No endorsement. Nothing in this Public License constitutes or may be construed as permission to assert or imply that You are, or that Your use of the Licensed Material is, connected with, or sponsored, endorsed, or granted official status by, the Licensor or others designated to receive attribution as provided in Section 3(a)(1)(A)(i).

b. Other rights.

1. Moral rights, such as the right of integrity, are not licensed under this Public License, nor are publicity, privacy, and/or other similar personality rights; however, to the extent possible, the Licensor waives and/or agrees not to assert any such rights held by the Licensor to the limited extent necessary to allow You to exercise the Licensed Rights, but not otherwise.

2. Patent and trademark rights are not licensed under this Public License.

3. To the extent possible, the Licensor waives any right to collect royalties from You for the exercise of the Licensed Rights, whether directly or through a collecting society under any voluntary or waivable statutory or compulsory licensing scheme. In all other cases the Licensor expressly reserves any right to collect such royalties.

Section 3 – License Conditions.

Your exercise of the Licensed Rights is expressly made subject to the following conditions.

a. Attribution.

1. If You Share the Licensed Material (including in modified form), You must:

A. retain the following if it is supplied by the Licensor with the Licensed Material:

i. identification of the creator(s) of the Licensed Material and any others designated to receive attribution, in any reasonable manner requested by the Licensor (including by pseudonym if designated);

ii. a copyright notice;

- iii. a notice that refers to this Public License;
- iv. a notice that refers to the disclaimer of warranties;
- v. a URI or hyperlink to the Licensed Material to the extent reasonably practicable;

B. indicate if You modified the Licensed Material and retain an indication of any previous modifications; and

C. indicate the Licensed Material is licensed under this Public License, and include the text of, or the URI or hyperlink to, this Public License.

2. You may satisfy the conditions in Section 3(a)(1) in any reasonable manner based on the medium, means, and context in which You Share the Licensed Material. For example, it may be reasonable to satisfy the conditions by providing a URI or hyperlink to a resource that includes the required information.

3. If requested by the Licensor, You must remove any of the information required by Section 3(a)(1)(A) to the extent reasonably practicable.

4. If You Share Adapted Material You produce, the Adapter's License You apply must not prevent recipients of the Adapted Material from complying with this Public License.

Section 4 – Sui Generis Database Rights.

Where the Licensed Rights include Sui Generis Database Rights that apply to Your use of the Licensed Material:

- a. for the avoidance of doubt, Section 2(a)(1) grants You the right to extract, reuse, reproduce, and Share all or a substantial portion of the contents of the database;
- b. if You include all or a substantial portion of the database contents in a database in which You have Sui Generis Database Rights, then the database in which You have Sui Generis Database Rights (but not its individual contents) is Adapted Material; and
- c. You must comply with the conditions in Section 3(a) if You Share all or a substantial portion of the contents of the database.

For the avoidance of doubt, this Section 4 supplements and does not replace Your obligations under this Public License where the Licensed Rights include other Copyright and Similar Rights.

Section 5 – Disclaimer of Warranties and Limitation of Liability.

a. Unless otherwise separately undertaken by the Licensor, to the extent possible, the Licensor offers the Licensed Material as-is and as-available, and makes no representations or warranties of any kind concerning the Licensed Material, whether express, implied, statutory, or other. This includes, without limitation, warranties of title, merchantability, fitness for a particular purpose, non-infringement, absence of latent or other defects, accuracy, or the presence or absence of errors,

whether or not known or discoverable. Where disclaimers of warranties are not allowed in full or in part, this disclaimer may not apply to You.

b. To the extent possible, in no event will the Licensor be liable to You on any legal theory (including, without limitation, negligence) or otherwise for any direct, special, indirect, incidental, consequential, punitive, exemplary, or other losses, costs, expenses, or damages arising out of this Public License or use of the Licensed Material, even if the Licensor has been advised of the possibility of such losses, costs, expenses, or damages. Where a limitation of liability is not allowed in full or in part, this limitation may not apply to You.

c. The disclaimer of warranties and limitation of liability provided above shall be interpreted in a manner that, to the extent possible, most closely approximates an absolute disclaimer and waiver of all liability.

Section 6 – Term and Termination.

a. This Public License applies for the term of the Copyright and Similar Rights licensed here. However, if You fail to comply with this Public License, then Your rights under this Public License terminate automatically.

b. Where Your right to use the Licensed Material has terminated under Section 6(a), it reinstates:

1. automatically as of the date the violation is cured, provided it is cured within 30 days of Your discovery of the violation; or

2. upon express reinstatement by the Licensor.

For the avoidance of doubt, this Section 6(b) does not affect any right the Licensor may have to seek remedies for Your violations of this Public License.

c. For the avoidance of doubt, the Licensor may also offer the Licensed Material under separate terms or conditions or stop distributing the Licensed Material at any time; however, doing so will not terminate this Public License.

d. Sections 1, 5, 6, 7, and 8 survive termination of this Public License.

Section 7 – Other Terms and Conditions.

a. The Licensor shall not be bound by any additional or different terms or conditions communicated by You unless expressly agreed.

b. Any arrangements, understandings, or agreements regarding the Licensed Material not stated herein are separate from and independent of the terms and conditions of this Public License.

Section 8 – Interpretation.

a. For the avoidance of doubt, this Public License does not, and shall not be interpreted to, reduce, limit, restrict, or impose conditions on any use of the Licensed Material that could lawfully

be made without permission under this Public License.

b. To the extent possible, if any provision of this Public License is deemed unenforceable, it shall be automatically reformed to the minimum extent necessary to make it enforceable. If the provision cannot be reformed, it shall be severed from this Public License without affecting the enforceability of the remaining terms and conditions.

c. No term or condition of this Public License will be waived and no failure to comply consented to unless expressly agreed to by the Licensor.

d. Nothing in this Public License constitutes or may be interpreted as a limitation upon, or waiver of, any privileges and immunities that apply to the Licensor or You, including from the legal processes of any jurisdiction or authority.

Creative Commons is not a party to its public licenses. Notwithstanding, Creative Commons may elect to apply one of its public licenses to material it publishes and in those instances will be considered the “Licensor.” Except for the limited purpose of indicating that material is shared under a Creative Commons public license or as otherwise permitted by the Creative Commons policies published at creativecommons.org/policies, Creative Commons does not authorize the use of the trademark “Creative Commons” or any other trademark or logo of Creative Commons without its prior written consent including, without limitation, in connection with any unauthorized modifications to any of its public licenses or any other arrangements, understandings, or agreements concerning use of licensed material. For the avoidance of doubt, this paragraph does not form part of the public licenses.

Creative Commons may be contacted at creativecommons.org.

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.

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.

Index

- Adding quantities to a qualitative problem, 50
- Annotating diagrams, 49
- Astable, 16

- Capacitor, decoupling, 6
- Checking for exceptions, 50
- Checking your work, 50
- CMOS, 15
- Code, computer, 57
- Comparator, 11
- Cycles per second, 13

- Decoupling capacitor, 6
- Dimensional analysis, 49
- DIP, 10
- Dual inline package, 10

- Edwards, Tim, 58
- Electrically common points, 19

- Frequency, 13

- Graph values to solve a problem, 50
- Greenleaf, Cynthia, 21

- Hertz, 13
- How to teach with these modules, 52
- Hwang, Andrew D., 59

- IC, 9
- Identify given data, 49
- Identify relevant principles, 49
- Instructions for projects and experiments, 53
- Integrated circuit, 3, 9
- Intermediate results, 49
- Inverted instruction, 52

- Knuth, Donald, 58

- Lampert, Leslie, 58
- Latch, 11
- Limiting cases, 50
- Logic gate, 15

- Metacognition, 26
- Monostable, 16
- Moolenaar, Bram, 57
- Murphy, Lynn, 21

- Open-source, 57
- Oscillator, 8

- Parallel resistances, 18
- PCB, 9
- Period, 13
- Printed circuit board, 9
- Problem-solving: annotate diagrams, 49
- Problem-solving: check for exceptions, 50
- Problem-solving: checking work, 50
- Problem-solving: dimensional analysis, 49
- Problem-solving: graph values, 50
- Problem-solving: identify given data, 49
- Problem-solving: identify relevant principles, 49
- Problem-solving: interpret intermediate results, 49
- Problem-solving: limiting cases, 50
- Problem-solving: qualitative to quantitative, 50
- Problem-solving: quantitative to qualitative, 50
- Problem-solving: reductio ad absurdum, 50
- Problem-solving: simplify the system, 8, 49
- Problem-solving: thought experiment, 49
- Problem-solving: track units of measurement, 49
- Problem-solving: visually represent the system, 49
- Problem-solving: work in reverse, 50

- Qualitatively approaching a quantitative problem, 50
- Reading Apprenticeship, 21
- Reductio ad absurdum, 50–52
- Relaxation oscillator, 8
- Schoenbach, Ruth, 21
- Scientific method, 26
- Simplifying a system, 8, 49
- Socrates, 51
- Socratic dialogue, 52
- SPICE, 21
- SR latch, 11
- Stallman, Richard, 57
- Thought experiment, 49
- Torvalds, Linus, 57
- Units of measurement, 49
- Visualizing a system, 49
- Work in reverse to solve a problem, 50
- WYSIWYG, 57, 58