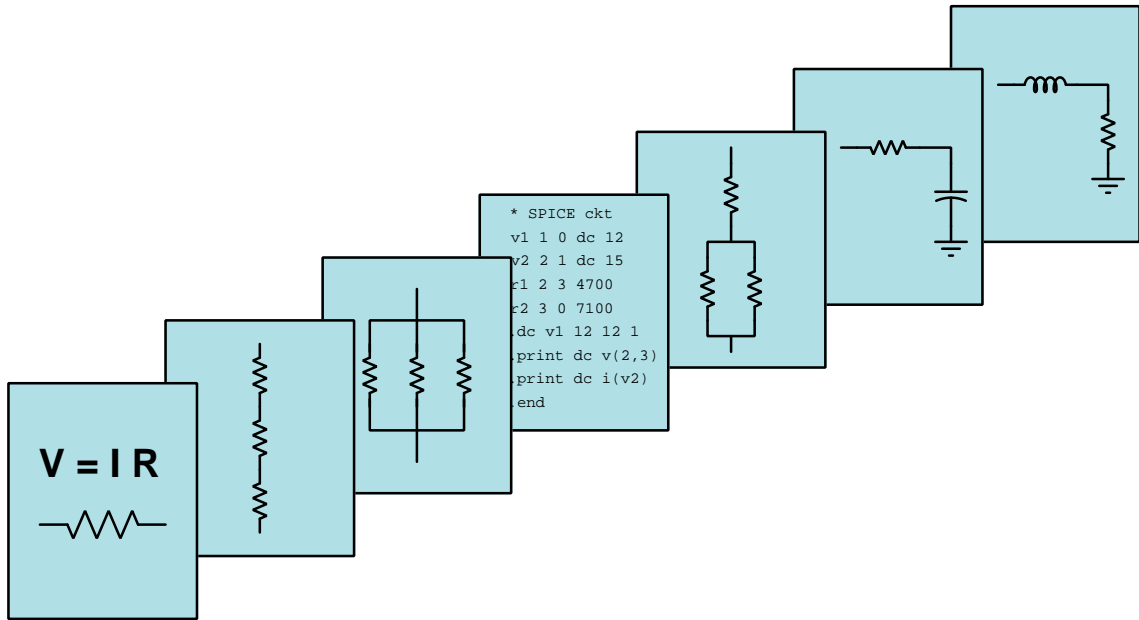


MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



THYRISTORS

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Chapter 1

Introduction

1.1 Recommendations for students

An important classification of semiconductor device is the *thyristor*, characterized by its hysteretic behavior: once turned on, it tends to remain on; once turned off, it tends to remain off. These devices are popularly used for electronic power control, because their tendency to “latch” in the conductive state results in quick switching and low voltage drop, both of which minimize power dissipation in the device. Some thyristors are passive while others come equipped with “gate” terminals for triggering by external signals. Gated thyristors are the most versatile, the two predominant types being *silicon-controlled rectifiers (SCRs)* and *TRIACs*, the former being DC-only and the latter able to switch AC. Thyristors find widespread application as high-power control devices, rivaling transistors in their ability to quickly turn on and to conduct large currents with minimal power dissipation. This module explores the basic behavior of several types of thyristors as well as power-control applications.

Important concepts related to thyristors include positive **feedback**, **hysteresis**, **PN junctions**, **bipolar junction transistor behavior**, **breakdown voltage**, **breakover**, **low-current dropout**, **holding current**, **crowbar** circuits, properties of **series** versus **parallel** networks, **capacitor** behavior, **snubber** circuits, **active** versus **passive** components, **rectification**, **commutation**, **extracting gate current**, and operational **quadrants**.

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

- How might an experiment be designed and conducted to measure the holding current for a thyristor? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to measure the maximum rate of voltage rise for a thyristor? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some practical applications of thyristors?
- What is “hysteresis” and what are some practical applications of this concept?

- What conditions are necessary to turn on a bipolar junction transistor?
- What conditions are necessary or sufficient to turn on a thyristor?
- What can a transistor do that a thyristor cannot?
- What can a thyristor do that a transistor cannot?
- What does it mean to “fire” a thyristor?
- What does it mean to “latch” a thyristor?
- What does it mean to “commutate” a thyristor?
- How may a thyristor be *accidentally* fired?
- How may a thyristor be tested?
- What is *breakdown voltage*, and why is this important to the operation of a thyristor?
- What is a *thought experiment*, and how was this problem-solving technique applied in the tutorial? Hint: it was used more than once!
- What conditions are necessary or sufficient to turn off a thyristor?
- How does a “crowbar” help protect voltage-sensitive components?
- How does the rate-of-change of a variable differ from the instantaneous value of that same variable; e.g. Volts versus Volts-per-second, or kilometers versus kilometers-per-hour?
- Show how to calculate the voltage rate-of-change described in the Tutorial from the information found on the oscillograph.
- Why are thyristors difficult to turn off?
- How does the presence of a capacitor help commutation in a dual-thyristor power control circuit?
- What are some practical applications of thyristors?

1.2 Challenging concepts related to thyristors

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Hysteresis** – whenever a component or system tends to remain in its last state, we refer to that lagging tendency as *hysteresis*. There are many physical manifestations of hysteresis including *magnetic hysteresis* (where a magnetic material tends to remain magnetized after the magnetizing influence is removed), *thyristor devices* (electronic devices that tend to remain “on” even after the triggering stimulus is removed), and physical mechanisms having *friction* (where the mechanism's position tends to stay put after the influencing force is removed).
- **Rates of change** – thyristors are liable to triggering when subjected to excessive voltage rates-of-change, which requires one to be aware of how rapidly voltage varies and not just the value of that voltage. This is the first hurdle in calculus: to comprehend what a rate of change is, and it is far from obvious. A helpful strategy here is to relate electrical rates of change to other, more common, rates of change such as *speed* (i.e. the rate-of-change of physical position over time). Also helpful is to relate rates of change to the *slope* of a line or curve plotted on a graph, showing how *rise/fall over run* describes not only the phenomenon of a rate-of-change but also the appropriate units of measurement.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

Assessment – Students present their outlines of this module’s instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

Assessment – Students show how quantitative results were obtained by the author in the Tutorial chapter’s examples.

- **Outcome** – Distinguish between SCR and TRIAC behavior

Assessment – Compare and contrast the operation of two circuits, one using an SCR and the other a TRIAC to control power to a load; e.g. pose problems in the form of the “SCR versus TRIAC circuits” Conceptual Reasoning question.

- **Outcome** – Quantify voltage rates of change from an oscillograph

Assessment – Identify $\frac{dV}{dt}$ at various marked points of an oscillograph given the image as well as the oscilloscope’s vertical sensitivity and horizontal timebase settings; e.g. pose problems in the form of the “???” Quantitative Reasoning question.

- **Outcome** – Independent research

Assessment – Locate SCR datasheets and properly interpret some of the information contained in those documents including holding current, critical rate of voltage rise, maximum current rating, maximum voltage rating, etc.

Assessment – Locate TRIAC datasheets and properly interpret some of the information contained in those documents including holding current, critical rate of voltage rise, maximum current rating, maximum voltage rating, operating quadrant chart, etc.

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: measuring signal rates of change

Capacitors and inductors relate voltage to current by rates of change. For a capacitor, the amount of current is proportional to how quickly voltage across that capacitor either rises or falls over time ($I = C \frac{dV}{dt}$). For an inductor, the amount of voltage is proportional to how quickly current through that inductor rises or falls over time ($V = L \frac{dI}{dt}$).

For example, a 330 microFarad capacitor experiencing a voltage increasing at a rate of 45 Volts per second will pass 14.85 milliAmperes. If the voltage happens to decrease at an equivalent rate (i.e. $\frac{dV}{dt} = -45$ Volts per second) then the 14.85 milliAmpere current will reverse direction through the capacitor compared to how it flowed with the increasing voltage.

Similarly, a 100 milliHenry inductor experiencing a current increasing at a rate of 5 Amperes per second will induce a voltage of 500 milliVolts. If the current happens to decrease at an equivalent rate (i.e. $\frac{dI}{dt} = -5$ Amperes per second) then the 500 milliVolt voltage induced across the inductor will reverse polarity from what it was during the period of increasing current.

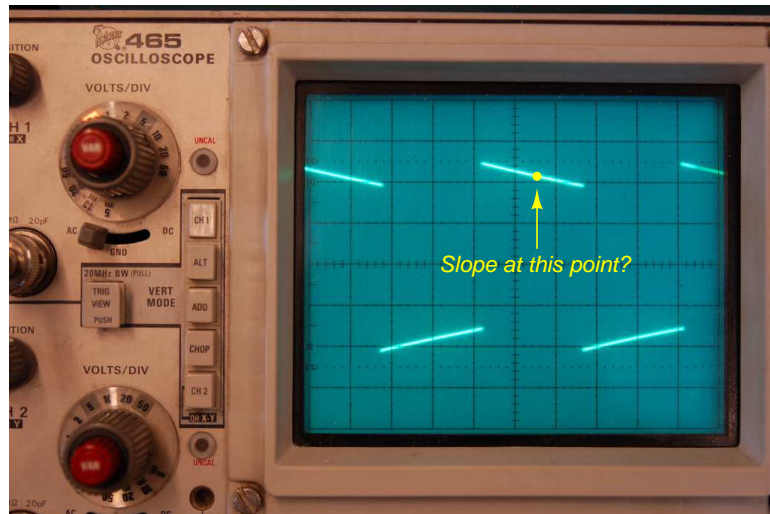
Not only are rates-of-change important in determining how energy-storing devices such as capacitors and inductors will respond in circuits, but rates-of-change are also important for determining how *parasitic* capacitances and inductances will affect intended circuit behavior. Parasitic capacitance exists between any two conducting surfaces separated by an electrically insulating medium, and parasitic inductance exists along any length of conductor. This means any rate-of-change of voltage over time between two separated conductors will cause some amount of current to “pass” between them, and that any rate-of-change of current over time through any single conductor will cause some amount of voltage to drop across its length. In many circuits these parasitic effects are negligible, but in circuits experiencing extremely fast rates of change for voltage and/or current the effects can be significant or even severe.

Oscilloscopes are ideal for performing empirical measurements of voltage rates-of-change, and of current rates-of-change given the proper accessories¹. Some skill is required to do this, though, and here we will explore practical examples to show how it is done.

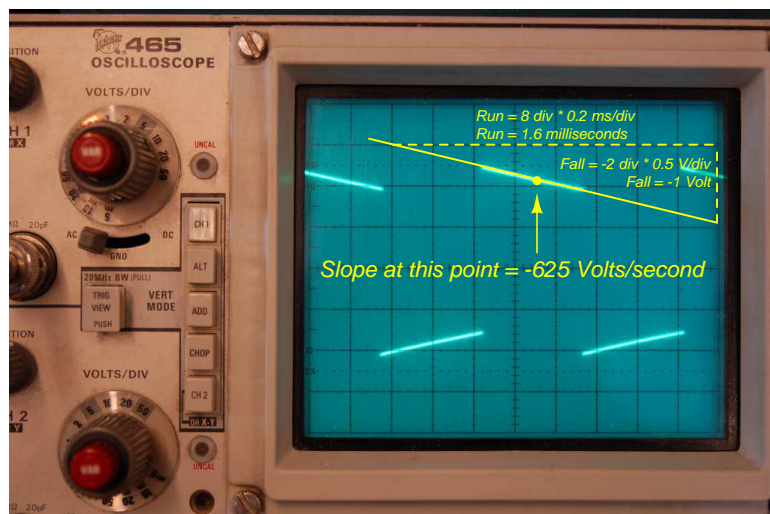
For any signal plotted in the time domain, where the horizontal axis of the plot is expressed in units of seconds, milliseconds, microseconds, etc., the signal’s rate of change at any given point will be the *slope* or *pitch* of the waveform, mathematically defined as its *rise over run*. A great aid to discerning slope at any location on a waveform is to sketch a straight line visually matching the wave’s slope at that point, then use locations along that straight line to more easily discern how far it rises (or falls) over some “run” of time. We call this straight line a *tangent line*.

¹For example, a *current probe* converting a sensed current into a voltage the oscilloscope may directly sense, or a *shunt resistor* placed in the circuit developing an oscilloscope-measurable voltage drop for any current passing through.

Here we see an example of a waveform with sloping sections. In the first image we see a specific location on the waveform where we wish to measure voltage rate-of-change ($\frac{dV}{dt}$):



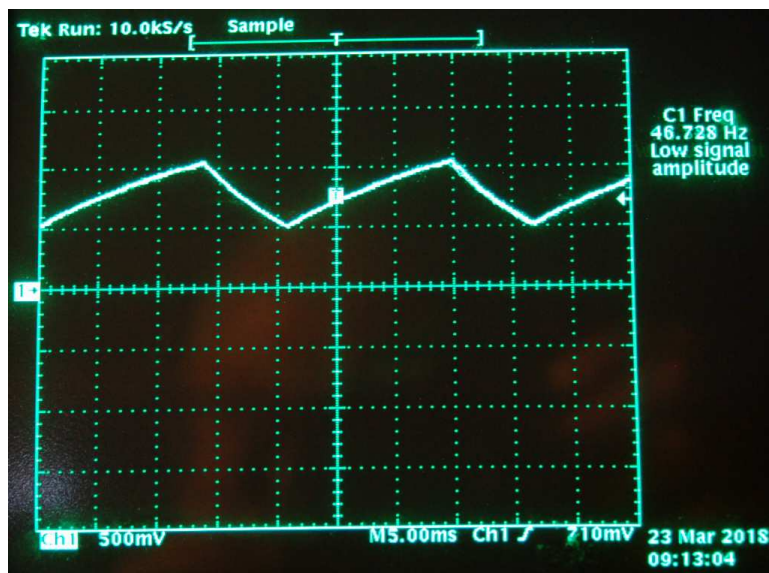
Next we see a tangent line drawn to match the slope of the waveform at the specified location, with convenient points for fall/run measurements taken on that line against the oscilloscope grid's major divisions. In this example, the oscilloscope's vertical sensitivity has been set for 0.5 Volts per division, and the horizontal timebase for 0.2 milliseconds per division:



As we can see, the tangent line falls 2 vertical divisions (-1 Volt) over a timespan of 8 horizontal divisions (1.6 milliseconds), yielding a $\frac{dV}{dt}$ quotient of -625 Volts per second, which may also be expressed as -0.625 Volts per millisecond. The negative sign is important, as it distinguishes this particular rate-of-change as *falling* rather than rising over time.

Such rate-of-change measurements are necessarily approximate, as they require us to visually gauge where a tangent line may be overlaid on the waveform's oscillograph, and also to visually assess the slope of that tangent line using the grid provided on the instrument's display screen. However, in most applications extremely precise rate-of-changes are not necessary, and such techniques suffice quite well.

Below is another example of a waveform with sloping sections, the oscilloscope configured for 500 milliVolts per division on the vertical axis and 5 milliseconds per division on the horizontal:

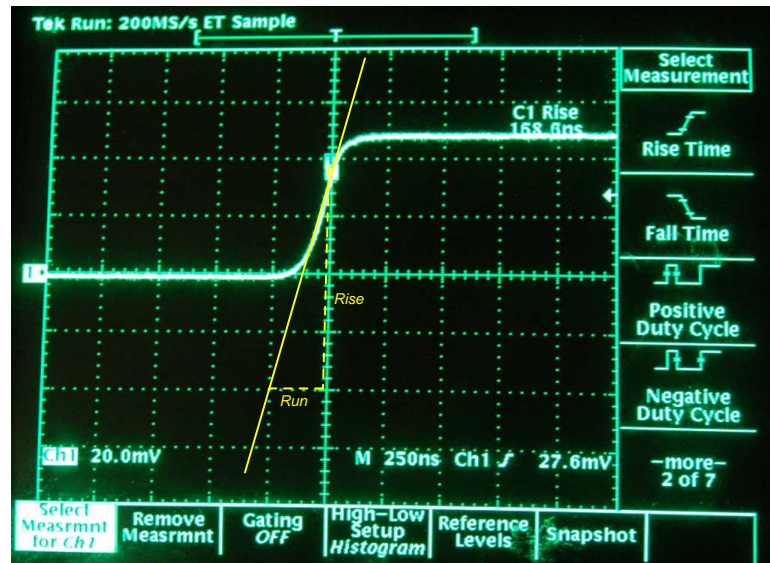


Approximating the slope for each rising section of this wave, we count one division of rise over 2.8 divisions of run, or 500 milliVolts rise over 14 milliseconds of run. This is a rate-of-rise of +35.7 Volts per second.

Approximating the slope for each falling section of this wave, we count one division of fall over 1.4 divisions of run, or -500 milliVolts fall over 7 milliseconds of run. This is a rate-of-fall of -71.4 Volts per second.

If these rates-of-change appear suspiciously large compared to the actual amplitude of the waveform, which barely crests over +1 Volt on the oscillograph, bear in mind that we are calculating *rates of change* for voltage and not absolute values of voltage itself. This is analogous to the distinction between *speed* and *distance*: traveling at a rate of 30 kilometers per hour does not necessarily mean you will travel 30 kilometers, as the actual distance traveled depends on how long that speed is sustained. A voltage rising at a rate of 35.7 Volts per second would indeed rise 35.7 Volts *if given a full second to do so*, but since each rising/falling portion of this waveform is so short in duration the actual amount of rise or fall in each case is only one-half of one Volt. It is therefore perfectly appropriate to consider any $\frac{dV}{dt}$ value as being the *speed* at which a voltage increases or decreases over time, distinct from the actual value of that voltage at any particular moment in time.

Here we see another oscillograph, this one zoomed into the rising edge of a square wave. For this measurement the oscilloscope was configured for 20 milliVolts per division of vertical sensitivity and a timebase of 250 nanoseconds per division on the horizontal:



The tangent line overlaid on this screenshot for the purpose of measuring the pulse edge's rate-of-change rises approximately 4 vertical divisions over a run of 1 division, which is 80 milliVolts of rise over 250 nanoseconds of run. The pulse edge's rate-of-change, therefore, is approximately +320,000 Volts per second, or +320 Volts per millisecond, or +0.32 Volts per microsecond (all equivalent expressions of $\frac{dV}{dt}$).

Chapter 3

Tutorial

3.1 Hysteresis

Hysteresis is that property of any component or system which fails to return to its original state after removal of stimulus. A very simple example of hysteresis is the mechanical action of a toggle switch: when the lever is pushed, it flips to one position and will remain there even after the lever is no longer being pushed. The only way for the toggle switch to return to its original position is if you apply force in the opposite direction. Contrast this against the action of a spring-loaded pushbutton switch, which actuates when pressed and immediately de-actuates when you stop pressing it.

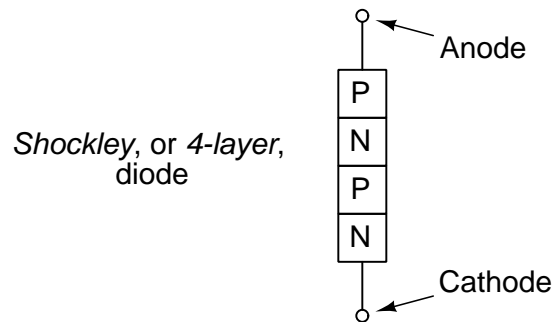
Most electronic devices are non-hysteretic: that is to say, they return to their default states upon removal of their control signals. Transistors, both bipolar and field-effect, are non-hysteretic because they always return to their default states when their controlling signals (e.g. base current for a BJT, gate-source voltage for a FET) cease. However, a class of semiconductor devices called *thyristors* exist which are intentionally constructed to be hysteretic. Once a thyristor has been “triggered” into its *on* state, it will continue to conduct current even after the triggering signal ceases. Like a toggle switch, a thyristor remains on after being turned on, and remains off after being turned off. As such, thyristors are only useful as on/off switching devices, unable to “throttle” between these two extreme states like a transistor.

Thyristors are constructed of PN semiconductor junctions just like BJTs, and achieve their hysteretic action by means of *positive feedback*. This is where a portion of their controlled current is directed in such a way that it maintains forward-bias in one of the PN junctions to hold the other junctions in their conductive states. In other words, once triggered “on” by an external signal, the thyristor’s own controlled current functions as a controlling signal to keep it on. Once forced “off” by some external circumstance, the thyristor’s lack of controlled current will also mean it lacks that self-driving stimulus resulting from a portion of the controlled current to hold itself in the “on” state, and so it remains off.

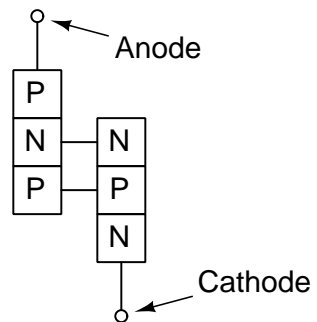
This positive-feedback action not only produces the hysteresis effect, but it also results in the thyristor having a very low voltage drop while conducting. The more current it conducts, the more it turns itself on, resulting in more controlled current, and so on until the device utterly saturates in the “on” state. Thyristors, therefore, are ideal for high-power switching applications where significant voltage drop would lead to excessive heat dissipation. Unlike a power *transistor* which could be damaged by its own heat dissipation if not “driven” to saturation by an appropriately large controlling signal, a power *thyristor* only needs a small driving signal to turn on, after which it very quickly forces itself into saturation and dissipates minimal heat. In fact, this positive feedback effect is so strong that it is often more difficult to make a thyristor turn back *off* than it is to trigger it on!

3.2 Shockley diodes and DIACs

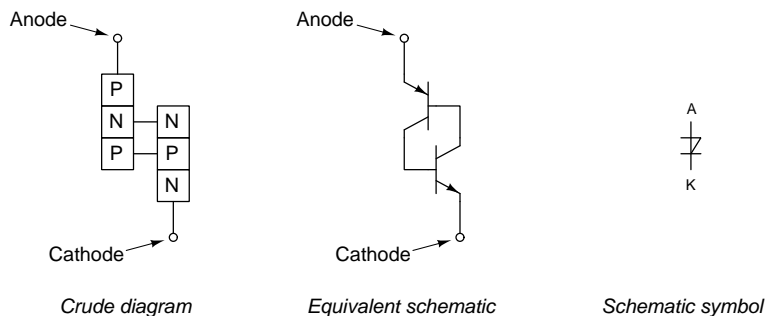
Perhaps the most basic form of thyristor is the *four-layer diode*, also known as a *PNPN diode*, or a *Shockley diode* after its inventor, William Shockley. This is not to be confused with a *Schottky diode*, that two-layer metal-semiconductor device known for its high switching speed. A crude illustration of the Shockley diode, often seen in textbooks, is a four-layer sandwich of P-N-P-N semiconductor material:



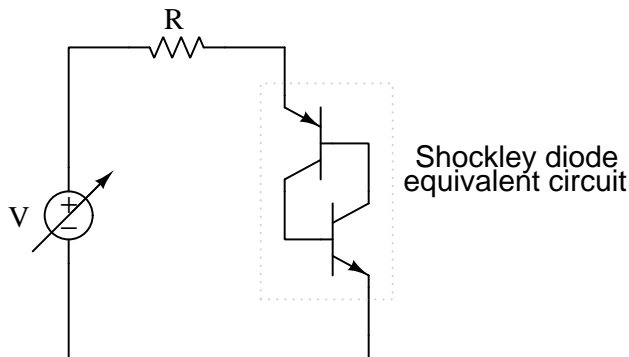
This rendering of a Shockley diode, though, does little to explain how it functions. It would appear to be nothing more than a bipolar junction transistor with an additional layer and corresponding junction. A more useful illustration represents the four-layer semiconductor structure as a pair of interconnected three-layer structures, essentially a PNP and NPN transistor pair:



A schematic representation of the Shockley diode clarifies which terminals are emitter and collector between the two transistors:



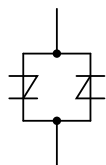
A test circuit will help us perform a *thought experiment* on the Shockley diode:



If we imagine the variable-voltage source V being adjusted from zero upwards, it would appear the Shockley diode never conducts current. Its constituent BJTs are, of course, *normally-off* devices, requiring base current before any collector current may flow. However, since the base of each BJT connects to the collector of the other, it would seem both transistors are essentially “waiting” for the other to turn on, and since neither of them are able, they both remain off.

However, this is what a pair of *ideal* BJTs would do. In practice, reverse-biased PN junctions – such as the base-collector junctions of the two transistors – have *breakdown voltage* limits, beyond which some current will pass “backwards” through the junction. If the applied DC voltage exceeds this limit for either of the two equivalent transistors within the Shockley diode, as soon as one of the reverse-biased base-collector junctions breaks down it will pass a small amount of current to the base of the other transistor, properly turning that transistor on. Once turned on, that other transistor allows base current through the first, properly turning it on as well, at which point the two BJTs mutually driving one another into saturation and hold each other in their “on” states even if the applied voltage were decrease below the initial breakdown point. The Shockley diode will remain conducting current until the source voltage decreases nearly to zero, at which point current ceases and the two BJTs return to their “off” states.

So we see that a Shockley diode's behavior is hysteretic: *once off it tends to remain off, and once on it tends to remain on*. It is also unidirectional, with the anode needing to be + and the cathode needing to be – in order to conduct current. If we parallel another Shockley diode (facing the reverse direction), we will have a device known as a *DIAC* which is bidirectional:



DIAC equivalent circuit



DIAC schematic symbol

Some special terms exist for all PNPN-type thyristors. First is the term used to describe its “on” state: *latched*. The word “latch” is reminiscent of a door lock mechanism, which tends to keep the door closed once it has been pushed shut. The term *firing* refers to the initiation of a latched state. In order to get a Shockley diode to latch, the applied voltage must be increased until *breakover* is attained. Despite the fact that this action is best described in terms of transistor *breakdown*, the term *breakover* is used instead because the end result is a pair of transistors in mutual saturation rather than destruction as would be the case with a normal transistor. A latched Shockley diode is re-set back into its nonconducting state by reducing current through it until *low-current dropout* occurs. The minimum amount of anode-cathode current necessary to guarantee the thyristor remains in its conductive state is called the *holding current*.

Shockley diodes and DIACs alike are useful as *triggering* and as *crowbar* devices. As a triggering device, it passes no current until the impressed voltage exceeds the breakover value at which point it turns on fully, this sudden onset of current useful as a controlling impulse signal for some other circuit component. As a crowbar device, it is connected in parallel with the power terminals of voltage-sensitive components, drawing no current unless and until a condition of excessive voltage occurs, at which point it fires and “shorts out” the offending over-voltage¹ and in so doing protects all the other parallel-connected components.

¹The colorful term “crowbar” evokes the image of a metal pry-bar intentionally dropped across two bare conductors for the purpose of causing an intentional short-circuit. While no doubt a desperate measure, presumably the consequences of allowing an over-voltage condition would be worse for the other paralleled components than the consequences for the crowbar or any other components in the fault-current path. If the notion of an electronic “crowbar” strikes you as humorous, you are in good company: I actually laughed out loud when I first learned there was such a thing.

3.3 Critical rate of voltage rise

PNPN-type thyristors may fire by means other than breakover voltage: excessive *voltage rate of rise*² ($\frac{dV}{dt}$) may cause thyristors to fire prematurely. This is when the applied voltage across the thyristor increases at a high rate of change, causing latching due to inherent junction capacitances within all non-conducting PN junctions. Recall that current “through” a capacitance is proportional to the applied voltage’s rate-of-change ($I = C \frac{dV}{dt}$). If the applied voltage between anode and cathode rises too quickly, the intrinsic capacitances of the reverse-biased PN junctions will permit enough current during that time to activate the transistor pair, firing the thyristor.

Measuring a voltage signal’s *rate-of-change* is best done using an oscilloscope which graphs voltage on the vertical axis and time on the horizontal. The example below shows a signal captured with the sensitivity set for 100 milliVolts per division (vertical square) and the timebase set for 20 nanoseconds per division (horizontal square):

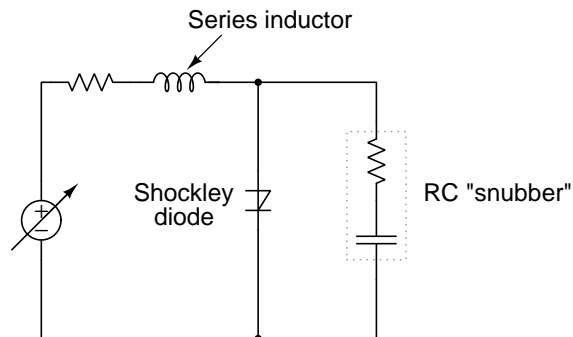


This signal’s highest peak voltage is slightly less than 300 milliVolts (i.e. just under three divisions of height), yet its *rate of change* during the rising interval marked by the red diagonal line³ superimposed on the oscillograph is steeper than *35 million Volts per second* (i.e. more than 700 milliVolts of rise over less than 20 nanoseconds of time)! 35 million Volts per second, more commonly expressed as $35 \text{ V}/\mu\text{s}$, is an extremely high rate of change which could in principle fire a thyristor even though the peak voltage of $< 300 \text{ mV}$ is too low to cause breakover.

²The rate-of-change of any variable is a measure of how *quickly* its value changes over time. You may think of rate-of-change as being akin to the *speed* of a variable, versus its actual value at any given time. In fact, distance (x) and velocity ($\frac{dx}{dt}$) represent this same distinction: the former representing the length of some physical span, and the latter representing how rapidly that length varies over time. In the case of thyristors, the rate of the applied voltage’s change over time is relevant because a high rate of “speed” for this voltage is capable of triggering the thyristor even in cases where the actual voltage value is significantly less than the breakover voltage.

³This red line is sketched as a visual aid to determining the signal’s rate-of-change for that rising interval, allowing us to more easily discern its slope, its rise exceeding seven vertical divisions over a horizontal run of one division.

A performance parameter specified in thyristor datasheets is the device's *critical rate of voltage rise*, which is the steepest rate-of-change of applied voltage it may tolerate without firing. Since it is usually undesirable for thyristors to fire by steep rates-of-change, it is important to have mitigation techniques for this possibility. One common strategy is to block fast voltage rises from reaching the thyristor using series inductors and/or parallel resistor-capacitor networks called *snubbers*:



Both the series inductor and the parallel resistor-capacitor "snubber" circuit help minimize the Shockley diode's exposure to excessively rising voltages.

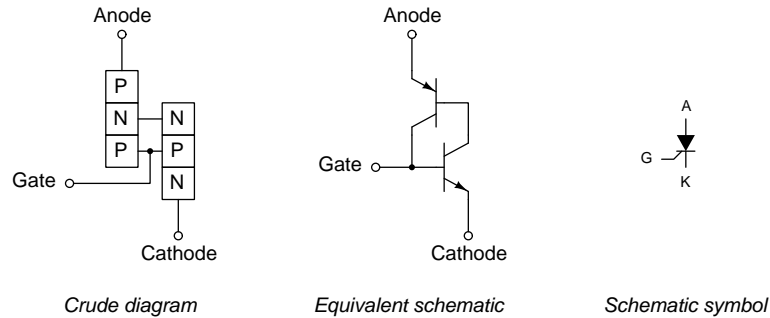
The inductor's task is to limit high rates-of-change of current by dropping voltage (as a load) if ever the source's current rises or falls rapidly ($V = L \frac{dI}{dt}$). The capacitor's task is to directly limit high rates-of-change of voltage across the thyristor by passing current (as a load) if the thyristor's terminal voltage rises rapidly ($I = C \frac{dV}{dt}$). Acting together, these two devices help shield the thyristor from experiencing too steep of a voltage rate-of-change.

Another mechanism of false firing for thyristors is excessive temperature, causing greater "leakage" current when the device is supposed to be in its "off" state.

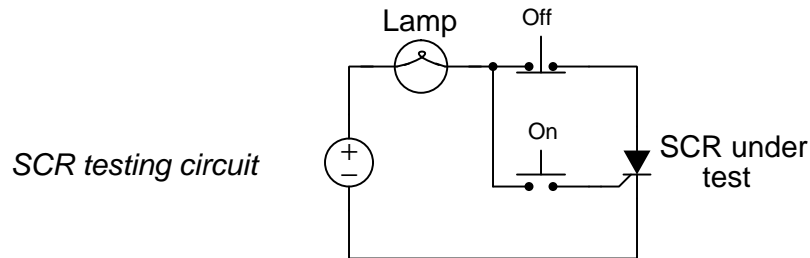
3.4 SCRs and GTOs

As interesting and useful as Shockley diodes and DIACs are, though, they would be even more interesting and more useful if we could *control* them with weak electrical signals as we can transistors. We call such controllable components *active*, in contrast with *passive* components such as resistors, inductors, capacitors, and diodes. It was the desire for “active” behavior that led to the development of vacuum tubes and transistors, and ushered in the era of truly *electronic* circuits. So it is here, where we would like to be able to exert control over a thyristor’s state using a relatively small electrical signal, rather than only have it passively respond to impressed voltage.

A simple modification of the Shockley diode yields this valuable active characteristic: attaching a third terminal to the PNPN structure which we will label the *gate*. The following illustration shows the crude diagram, equivalent schematic, and symbol for the resulting device, called a *silicon-controlled rectifier* or *SCR*:



Applying a small voltage signal between the gate (+) and cathode (–) terminals “triggers” the SCR into its conductive state without requiring a large anode-cathode applied voltage, enabling us to drive it “on” at will. Once triggered “on” the SCR will remain on so long as sufficient current passes from anode to cathode to sustain the two internal transistors’ mutual conductance. A very simple demonstration circuit proves this hysteretic behavior:

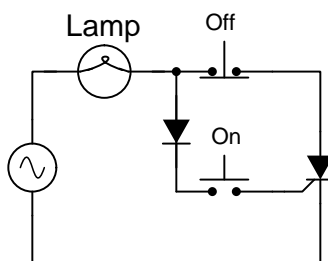


Momentarily pressing the normally-open “On” pushbutton switch fires the SCR and energizes the lamp. Once latched, the lamp remains illuminated until the normally-closed “Off” pushbutton is pressed.

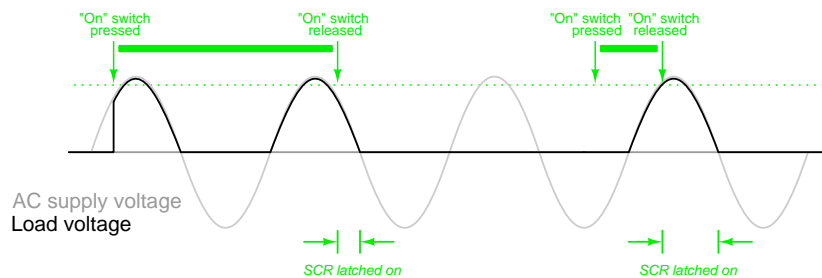
This circuit not only proves the principle of SCR latching, but it also serves as a convenient means of *testing* an SCR for proper function. Given a source voltage and load current within the SCR’s ratings, the circuit has every reason to function as previously described. An important design

element of this test circuit is load current, as even a good SCR may fail to latch if the load current is less than the SCR's rated *holding current*. A lamp with too much filament resistance may not draw enough current to keep an SCR latched when gate current ceases, thus giving the false impression of a bad (unlatchable) SCR in the test circuit. Holding current values for different SCRs should be available from the manufacturers. Typical holding current values range from 1 milliAmperes to 50 milliAmperes or more for larger units.

SCRs are, after all, controlled *rectifiers*, and as such they are more commonly found in AC-powered circuits than DC-powered circuits. If we replace the DC voltage source in our test circuit with an AC voltage source (and add a diode in series with the “on” switch so that the gate-cathode PN junction of the SCR is never reverse-biased), we will notice different behavior:



In this circuit, the “Off” pushbutton switch serves no useful purpose, because the lamp de-energizes every time the “On” pushbutton is released. At first this may seem strange given the clear latching behavior of the DC-sourced test circuit, but it makes sense once we carefully consider the *alternating* nature of the AC source. Twice per cycle, the AC naturally reverses direction, and at these points in time the SCR “drops out” and requires re-triggering to turn on again.



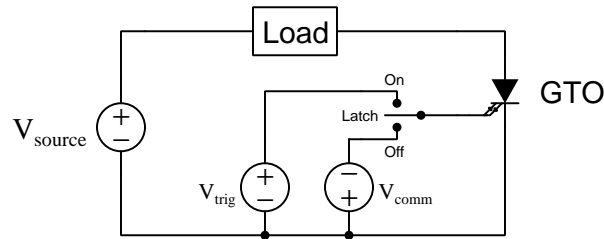
For certain high-voltage applications, special thyristors are manufactured with *optical* triggering capability, called *Light-Triggered Thyristors (LTTs)*. Instead of relying on an electrical pulse at a gate terminal to trigger, an optical pulse signal guided to the core of the semiconductor structure of the thyristor via a glass fiber-optic cable directly excites one of the PN junctions. Glass fiber-optic cables, of course, are entirely non-conducting to electricity, and so this design of thyristor provides complete electrical isolation between the high-voltage power circuit and the triggering control circuit (using a light source such as an LED or a semiconductor laser to send optical pulses to the LTT).

Thyristor *triggering* (i.e. turning on) tends to be easier⁴ than thyristor *commutation* (i.e. turning

⁴In fact, a bare SCR is so easily triggered that typically gate currents in the *microAmpere* range are sufficient.

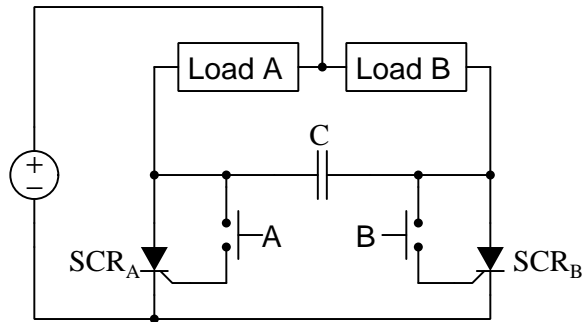
off). This is due to the positive feedback design of PNPN-type thyristors, where the controlled (load) current acts to hold the device in its “on” state. Since thyristors such as SCRs are often used in high-current applications, the amount of current available through the load to latch the thyristor into its “on” state is normally quite large, and must be either diverted or halted by some other means in order for the thyristor to turn off. In the example circuit shown with an AC source, the natural cessation of current every time the AC source crosses zero is called *line commutation* or *natural commutation*: the alternating nature of the source solves the problem of commutation for us.

Forcing a thyristor to turn off when full load current is still present is a more challenging matter. SCRs, for example, are extremely difficult if not impossible to commutate using a reverse-polarity pulse signal between gate and cathode (sometimes called an *extracting gate current*; i.e. a current exiting the gate terminal, diverting enough of the current from the upper equivalent transistor to cause the lower equivalent transistor to turn off). Specially-designed thyristors called *Gate Turn-Off*, or *GTO*, thyristors are manufactured for the purpose of being able to turn both on and off via gate current, but even the GTO which is designed to be easier to commutate via the gate terminal than a regular SCR requires negative gate currents as large as one-fifth to one-third the anode (load) current! A simple DC-powered demonstration circuit for a GTO thyristor appears here:



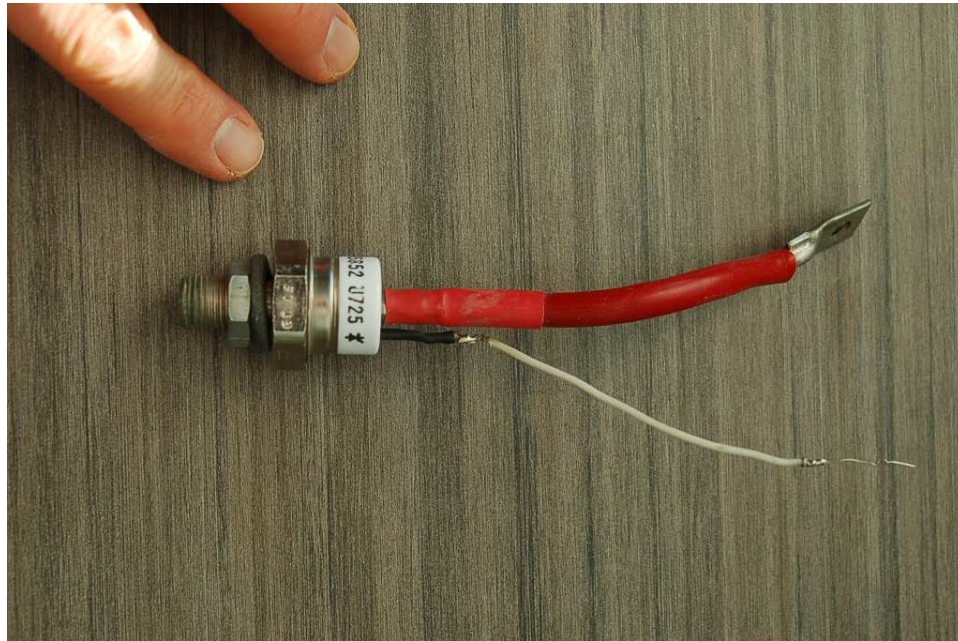
This can be problematic, as small amounts of “noise” current at the gate of such an SCR may unintentionally trigger it. Many SCRs are therefore manufactured to have *de-sensitized* gates requiring more substantial current to trigger, in order to avoid false triggering.

When two SCRs are used to exclusively switch DC power between two loads, a common method of forced thyristor commutation uses the stored energy within a capacitor to force one SCR to commutate when the other is triggered:



A thought experiment reveals how this circuit functions. Imagine SCR_A conducting and SCR_B non-conducting, energizing load A while maintaining load B in the de-energized state. In this condition, capacitor *C* drops load A's full voltage, positive on right and negative on left. If someone presses pushbutton B, SCR_B will trigger on and cause the capacitor (acting as a voltage source) to deliver a surge of current from left to right. This surge diverts load A's current through the capacitor and down to ground through SCR_B while impressing a reverse bias across SCR_A (+ on cathode and - on anode). The surge of current through SCR_B secures it in the "on" state while the reverse bias across SCR_A forces it off. Load A's current decays to zero as the capacitor accumulates a voltage (+ on left, - on right), while Load B's current remains steady. Load B will remain energized and load A de-energized until someone presses pushbutton A.

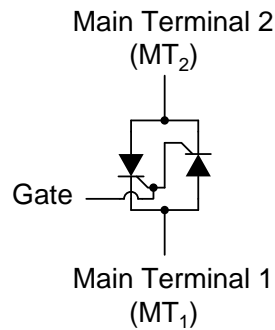
SCRs find application in many high-power electronic circuits because once triggered they will force themselves into a condition of saturation which means low voltage drop and therefore low power dissipation when conducting high values of current. An example of an SCR built for very high-current applications (up to 500 Amperes!) appears in the photograph below:



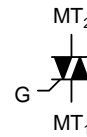
The heavy-gauge red-insulated cable connects to the cathode (K) on this SCR, while the light-gauge white wire connects to the gate (G). The Anode (A) is not a wire connection at all, but rather the threaded metal base, which means this device is intended to *bolt* to a solid metal receiving piece functioning as both a heat sink and an electrical bus.

3.5 TRIACs

Just as we created a DIAC by paralleling two reverse-facing Shockley diodes, we may create a new type of controlled thyristor by paralleling two reverse-facing SCRs. The resulting device is called a *TRIAC*:



TRIAC equivalent circuit



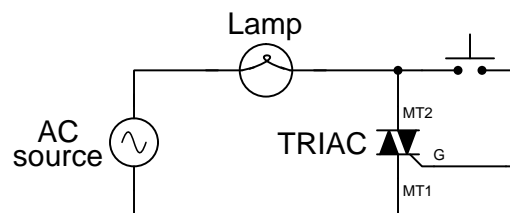
TRIAC schematic symbol

Because individual SCRs are more flexible⁵ to use in advanced control systems, they are more commonly seen in circuits like motor drives, while TRIACs are usually seen in simple, low-power applications like residential lamp dimmer switches and electric hand tool speed controls.

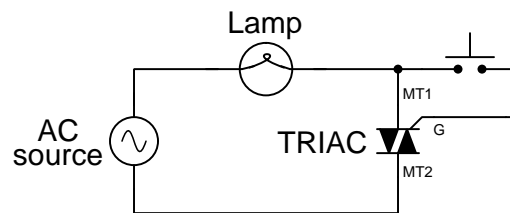
⁵One example of flexibility using SCRs rather than TRIACs, is that by using pairs of SCRs one for the positive half-cycle and another for the negative half-cycle, it becomes possible to independently control each half-cycle of the waveform, which can be very useful. A TRIAC cannot do the same without relying on precise timing to fire the gate during selected half-cycles.

From the equivalent circuit diagram shown earlier, one might think that main terminals 1 and 2 were interchangeable. They are not! Although it is helpful to imagine the TRIAC as being composed of two SCRs joined together, it in fact is constructed from a single piece of semiconducting material, appropriately doped and layered. The actual operating characteristics may differ slightly from that of the equivalent model. This fact is proven by contrasting two simple TRIAC test circuits, one that works and one that doesn't.

The following circuit will function to control power to the lamp using a relatively small triggering current at the TRIAC's gate. Pressing the normally-open pushbutton switch energizes the lamp, and releasing the pushbutton switch allows the TRIAC to drop out at the next zero-crossing point of the AC wave:

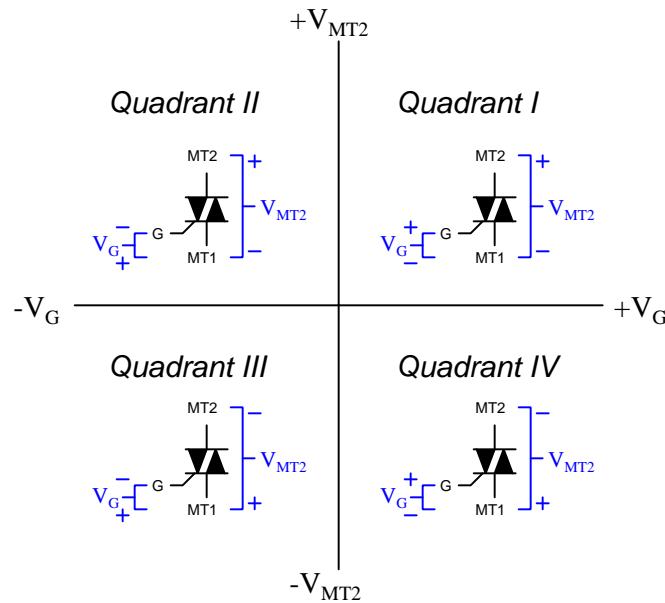


Suppose we were to swap the two main terminals of the TRIAC around. According to the equivalent circuit diagram shown earlier in this section, the swap should make no difference and the following circuit *ought* to work:



However, if this circuit is built, it will be found that it does not work! The load will receive no power, the TRIAC refusing to fire at all regardless of pushbutton status. The key to successfully triggering a TRIAC is to make sure the gate receives its triggering current from the *main terminal 2* side of the circuit (the main terminal on the opposite side of the TRIAC symbol from the gate terminal). Identification of the MT₁ and MT₂ terminals must be done via the TRIAC's part number with reference to a data sheet or book.

A more detailed characterization of TRIAC firing requirements is often represented by *operating quadrant*. This odd-sounding phrase originates from a two-dimensional plot of main terminal 2 voltage versus gate voltage (both with reference to MT1), with each quadrant of the graph representing a different combination of polarities:



TRIAC datasheets will commonly list triggering parameters such as gate voltage and gate current separately for each quadrant of operation, with quadrants I and III typically requiring the least gate signal energy to successfully trigger.

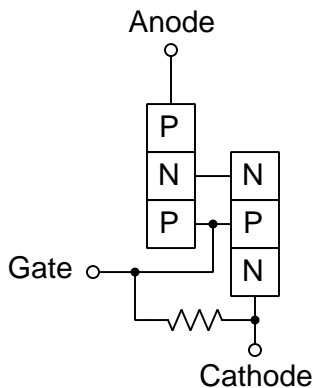
3.6 Thyristor gate sensitivity

Thyristors differ from other active semiconductor devices primarily in their ability to “latch” into a conductive state once triggered. For gated thyristors such as SCRs and TRIACs, the amount of gate current required for triggering is very small compared to the amount of current the device is rated to conduct to a load. The positive-feedback nature of a thyristor means that the conducted load current itself acts to hold the device in its conductive state, taking over the role previously fulfilled by the gate current.

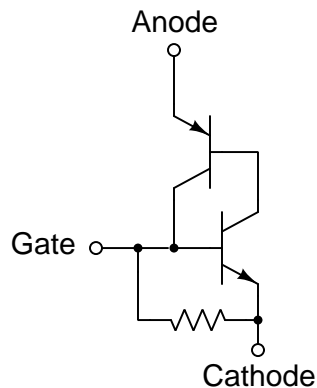
This positive-feedback behavior means the amount of gate current required to trigger an SCR or TRIAC under the right conditions may be quite trivial, less than a single microAmpere. Such sensitivity can pose a problem for these devices when used within power-control applications, since high voltages and high currents tend to make coupled “noise” inevitable. If a surge of high current and/or a transient voltage pulse at one thyristor happens to induce enough of a current through the gate terminal of an adjacent thyristor to trigger it, the result could be catastrophic!

One way to “de-sensitize” a thyristor in order to mitigate this problem is to connect an internal resistance across the gate’s PN junction, like this:

De-sensitized SCR



Crude diagram



Equivalent schematic

Now there must be enough gate current flowing through this internal resistance to produce a 0.7 Volt drop before the gate-cathode PN junction becomes forward-biased to trigger the SCR into conduction. Without that resistance in place, *any* current passing through the gate-cathode PN junction is liable to trigger the device.

Gated thyristors are often labeled as being either *sensitive-gate* devices or *standard-gate* devices, to differentiate between the non-resistor and resistor versions. Again, sensitive-gate thyristor gate trigger currents are often less than 1 mA in contrast to standard-gate trigger currents which may be tens of milliAmperes.

Chapter 4

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

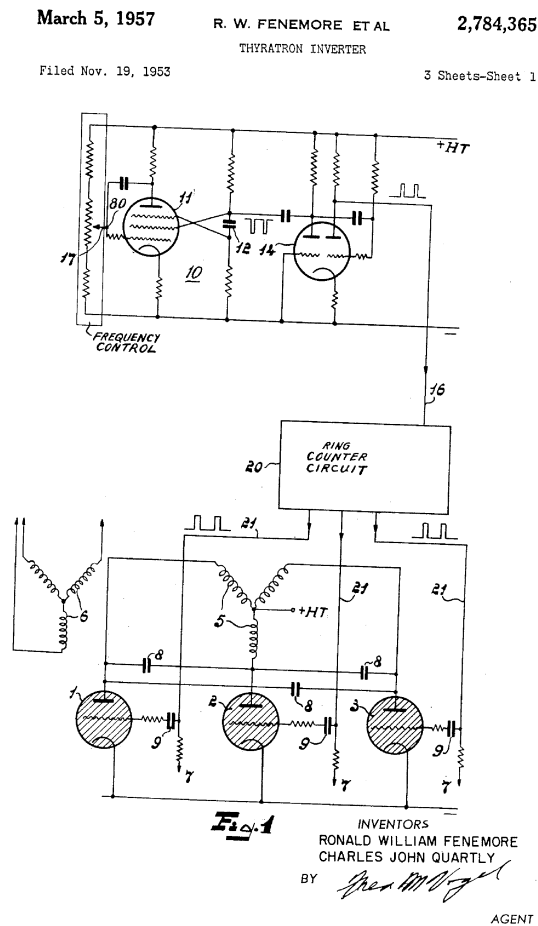
It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . [page xi]

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

4.1 Thyatron inverter patent

A predecessor to the solid-state thyristor was the gaseous-tube *thyatron*, similar in construction to a vacuum tube except with a low-pressure gas fill rather than a hard vacuum. The ionization effect of the filling gas provided a similar hysteresis effect for the thyatron tube as the interconnected-transistor structure provides hysteresis for a thyristor: once triggered, a thyatron tube would continue to conduct electricity until something *commutated* it.

The following diagram comes from a United States patent (number 2,784,365 granted 5 March 1957) submitted by inventors Ronald William Fenemore and Charles John Quartly of England, illustrating a circuit designed in invert DC into three-phase AC:



Three thyatron tubes near the bottom of the diagram handle the power switching, each one dedicated to a phase of a Wye-connected transformer primary. The positive pole of the DC supply (+HT) connects to the center of the transformer primary Wye, while the negative pole connects to

the cathodes of all three thyatron tubes. A *ring counter* circuit sends triggering pulses to the grid electrodes of the thyatron tubes, equivalent to the gate terminals of three SCRs.

Like SCRs, thyatrons are impractical to commutate via a negative pulse applied to the gate (grid) terminal, and instead must be commutated by other means. In this case, the conducting tube is commutated by firing another tube, and the key to the success of this scheme is the three capacitors (labeled 8 on the diagram). The inventors describe how this works, which could have easily described how a capacitor-commutated SCR circuit would function if SCRs were invented at the time:

Three capacitors 8 are connected in a ring or delta between the anodes of the thyatrons 1, 2, 3 and operate in such manner as to extinguish automatically one thyatron when the next thyatron is fired. For example, if tube 2 is conducting at a particular instant and tube 3 is then fired by a pulse, the anode of the latter tube will drop in potential due to the current taken. This potential drop will be passed momentarily to the anode of tube 2 and will be sufficient to extinguish tube 2 in the absence of a firing pulse. The anode drop will also be communicated to tube 1, but ineffectively, since tube 1 will already be in the extinguished condition.

Chapter 5

Derivations and Technical References

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

5.1 Lightning bolts, relaxation oscillators, and thyatron tubes

If you've ever witnessed a lightning storm, you've seen electrical hysteresis in action. The action of wind and/or rainfall accumulates tremendous static electric charges between cloud and earth, and between clouds as well. Electric charge imbalances manifest themselves as high voltages, and when the electrical resistance of air can no longer withstand the intense electric fields, the air molecules ionize and become electrically conductive, allowing huge surges of current between opposing poles of electrical charge which we call *lightning*.

The buildup of high voltage by wind and rain is a fairly continuous process, the rate of charge accumulation increasing under the proper atmospheric conditions. However, lightning bolts are anything but continuous: they exist as momentary surges rather than continuous discharges. Why is this? Why don't we see soft, glowing lightning *arcs* instead of violently brief lightning *bolts*? The answer lies in the nonlinear (and hysteretic) resistance of air.

Under ordinary conditions, gases such as air have extremely high electrical resistance. This resistance is so high, in fact, that we typically treat its resistance as infinite and electrical conduction through the air as negligible. When a sufficient electric field intensity develops across a sample of gas, though, its electrical properties change: electrons become "stripped" from their normal positions around their respective atoms and are liberated to function as mobile electric charge carriers. In this state, air is considered to be *ionized* and is referred to as a *plasma*¹ rather than a normal *gas*.

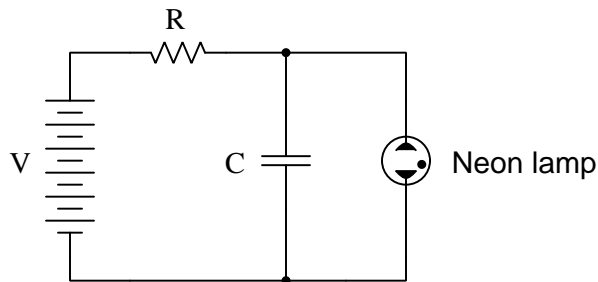
An electric current moving through the plasma dissipates energy because the plasma is not a perfect conductor. In the case of lightning, this dissipated energy translates into extremely high temperatures. High temperatures are *also* sufficient to convert gaseous air into a plasma independent of any electric fields. As the voltage between cloud and earth, or between cloud and cloud, decreases as the electric charge imbalance neutralizes due to the current of the lightning bolt, the heat dissipated by the bolt maintains the air path in a plasma state to keep its resistance low. In other words, the lightning bolt *remains* in its plasma state until the temperature drops low enough. When this occurs, the air returns to its normal (gas) state and stops conducting current.

Note the air's electrical conductivity is hysteretic: when not conducting electricity it *remains an insulator* until voltage builds up past a critical threshold point; after becoming a plasma it *remains a conductor* until voltage falls below a lower critical threshold point. Once "turned on" the air tends to stay on, and once "turned off" it tends to stay off. This hysteresis, combined with a steady buildup of voltage due to the electrostatic effects of wind and rain, explains the phenomenon of lightning as brief bursts.

¹This usage of the word "plasma" is not to be confused with the medical term (meaning the fluid portion of blood), but is a fourth state of matter, the other three being solid, liquid, and vapor (gas). Plasma is a relatively good conductor of electricity, its specific resistance being much lower than that of the same substance in its gaseous state.

In electronic terms, lightning functions as a spectacular *relaxation oscillator*. Oscillators are electronic circuits that produce an oscillating (AC) voltage from a steady supply of DC power. A relaxation oscillator is one that works on the principle of a charging capacitance that is suddenly discharged every time its voltage reaches a critical threshold value. One of the simplest relaxation oscillators in existence is comprised of three components (not counting the DC power supply): a resistor, capacitor, and neon lamp:

Simple relaxation oscillator

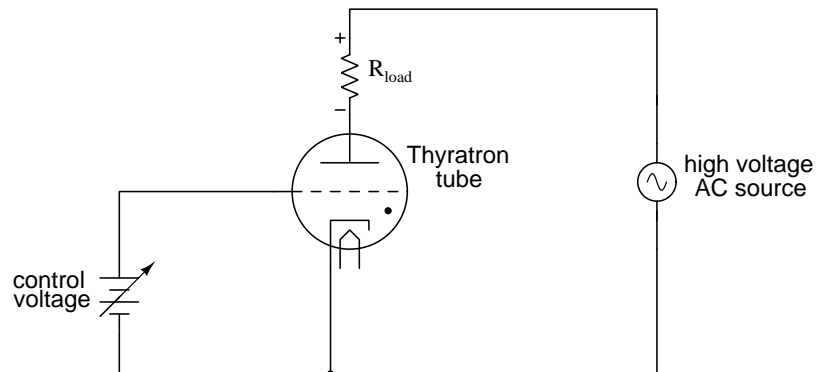


Neon lamps are nothing more than two metal electrodes inside a sealed glass bulb, separated by the neon gas inside. At room temperatures and with no applied voltage, the lamp has nearly infinite resistance. However, once a certain threshold voltage is exceeded (this voltage depends on the gas pressure and geometry of the lamp), the neon gas will become ionized (turned into a plasma) and its resistance dramatically reduced. In effect, the neon lamp exhibits the same characteristics as air in a lightning storm, complete with the emission of light as a result of the discharge, albeit on a much smaller scale.

The capacitor in the relaxation oscillator circuit shown above charges at an inverse exponential rate determined by the size of the resistor. When its voltage reaches the threshold voltage of the lamp, the lamp suddenly “turns on” and quickly discharges the capacitor to a low voltage value. Once discharged, the lamp “turns off” and allows the capacitor to build up a charge once more. The result is a series of brief flashes of light from the lamp, the rate of which dictated by battery voltage, resistor resistance, capacitor capacitance, and lamp threshold voltage.

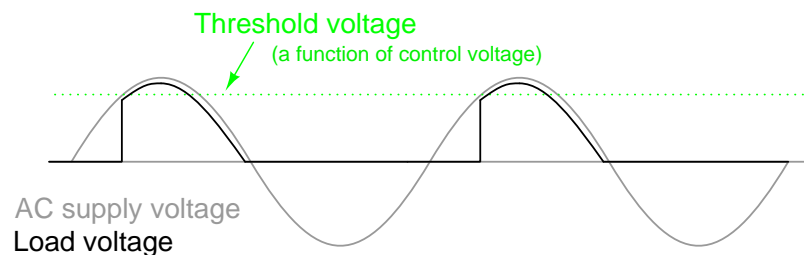
While gas-discharge lamps are more commonly used as sources of illumination, their hysteretic properties were exploited in slightly more sophisticated variants known as *thyatron tubes*. Essentially a gas-filled triode tube (a triode being a three-element vacuum electron tube performing much a similar function to the N-channel, D-type IGFET), the thyatron tube's threshold voltage could be adjusted by a small DC control voltage applied between grid and cathode.

(Simple) Thyatron control circuit



In essence, thyatron tubes were *controlled* versions of neon lamps built specifically for switching current to a load. The dot inside the circle of the schematic symbol indicates a gas fill, as opposed to the hard vacuum normally used in most other electron tube designs. In the circuit shown above, the thyatron tube allows current through the load in one direction (note the polarity across the load resistor) when triggered by the small DC control voltage connected between grid and cathode. Note that the load's power source is AC, which provides a clue as to how the thyatron turns off after it's been triggered on: since AC voltage periodically passes through a condition of 0 Volts between half-cycles, the current through an AC-powered load must also periodically halt. This brief pause of current between half-cycles gives the tube's gas time to cool, letting it return to its normal "off" state. Conduction may resume only if there is enough voltage applied by the AC power source (some other time in the wave's cycle) *and* if the DC control voltage allows it.

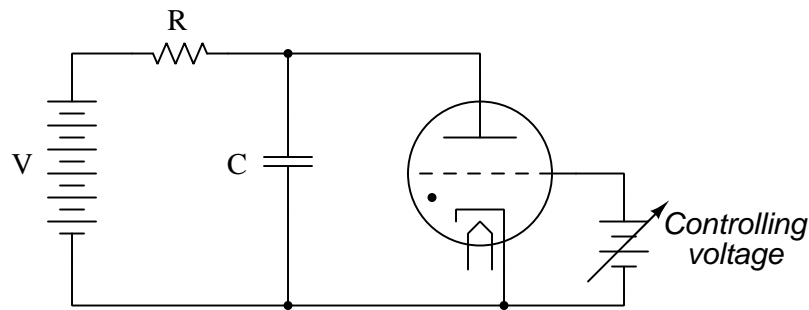
An oscilloscope display of load voltage in such a circuit would look something like this:



As the AC supply voltage climbs from zero Volts to its first peak, the load voltage remains at zero (no load current) until the threshold voltage is reached. At that point, the tube switches "on" and begins to conduct, the load voltage now following the AC voltage through the rest of the half cycle. Notice how there is load voltage (and thus load current) even when the AC voltage waveform

has dropped below the threshold value of the tube. This is hysteresis at work: the tube stays in its conductive mode past the point where it first turned on, continuing to conduct until there the supply voltage drops off to almost zero Volts. Because thyatron tubes are one-way (diode) devices, there is no voltage across the load through the negative half-cycle of AC. In practical thyatron circuits, multiple tubes arranged in some form of full-wave rectifier circuit to facilitate full-wave DC power to the load.

It would be possible to apply thyatron technology to a relaxation oscillator circuit and control the frequency with a small DC voltage between grid and cathode, making a crude voltage-controlled oscillator, otherwise known as a *VCO*. Relaxation oscillators tend to have poor frequency control, not to mention a very non-sinusoidal output, and so they exist mostly as demonstration circuits (as is the case here) or in applications where precise frequency control isn't important. Consequently, this use of a thyatron tube would not have been a very practical one.



I speak of thyatron tubes in the past tense for good reason: modern semiconductor components have obsoleted thyatron tube technology for all but a few very special applications. It is no coincidence that the word *thyristor* bears so much similarity to the word *thyatron*, for this class of semiconductor components does much the same thing: use *hysteretically* switch current on and off.

Chapter 6

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?

6.1 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.

6.1.1 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.

6.1.2 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.

Energy

Conservation of Energy

Thought experiments as a problem-solving strategy

Hysteresis

Positive feedback

Breakdown

Holding current

Crowbar

False triggering

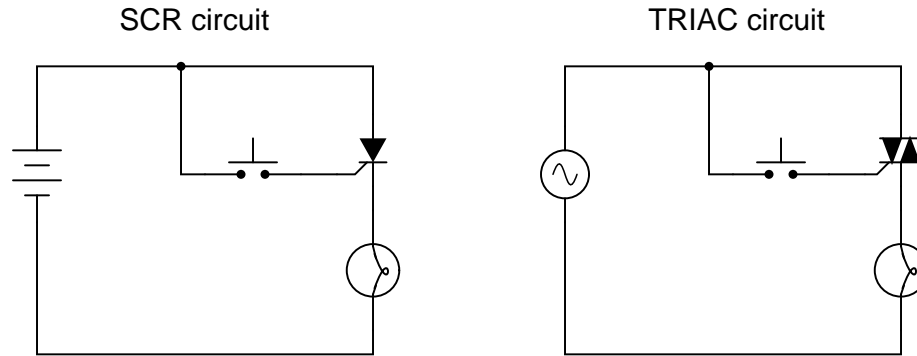
Commutation

Electrical source

Electrical load

6.1.3 SCR versus TRIAC circuits

Explain what happens in each of these circuits when the pushbutton switch is actuated and then released:



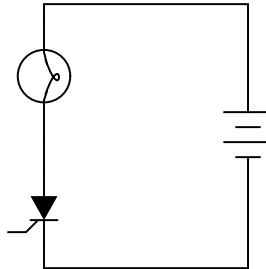
Which one of these circuits requires a second pushbutton switch to turn the lamp off? Where would this second switch need to be connected?

Challenges

- If an oscilloscope were connected across the load in each of these circuits, what would its display show?
- How would these two circuits function if both were sourced by DC?
- How would these two circuits function if both were sourced by AC?

6.1.4 Turning an SCR on and off

Explain what must be done to the SCR to make it turn on and send power to the light bulb:



Next, explain what must be done to turn the SCR off so that the light bulb de-energizes.

Challenges

- Explain how SCR behavior differs from that of BJT behavior.

6.1.5 SCR voltage drop

When an SCR latches “on”, it drops very little voltage between anode and cathode. Explain why this is, and what advantage this gives SCRs over transistors when conducting heavy load currents.

Challenges

- Explain why SCRs typically exhibit very fast turn-on times.

6.1.6 Sensitive-gate thyristors

Some SCRs and TRIACs are advertised as *sensitive-gate* devices. What does this mean? What is the difference between a “sensitive gate” SCR and an SCR with a “non-sensitive gate”?

Challenges

- Identify a practical application where a non-sensitive-gate thyristor would be preferable.

6.1.7 SCR-based amplifier

A student of electronics has just recently learned how to build audio amplifier circuits, and this inspires dreams of designing a super-powerful amplifier for a home entertainment system. One day, this student comes across a donation of electronic components from a local business, and in this donation are several industrial SCRs, rated at 20 Amperes each.

“Wow,” says the student, “these components look like really big transistors, but they’re rated for a lot of current. I could build a *huge* amplifier with these!”

The student approaches you for advice, because you’ve just recently learned how SCRs function in your electronics class. What do you tell the student, concerning the use of SCRs as audio amplification devices? How do you explain to this excited student that these devices will not work in an amplifier circuit?

Challenges

- Devise a demonstration circuit contrasting transistor behavior against SCR behavior, to make it clear to the enthusiastic student why their plan cannot work.

6.1.8 Different thyristor types

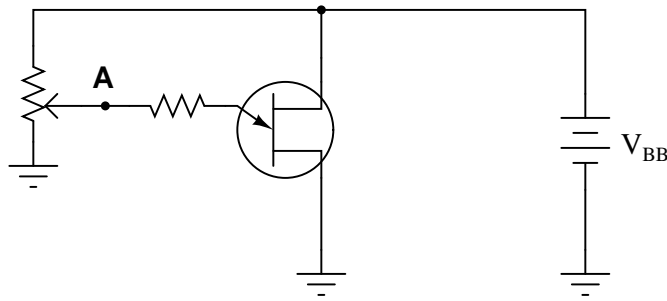
Identify at least three different types of thyristors (besides SCRs):

Challenges

- Which of these thyristors can *only* switch DC?
- Which of these thyristors can switch AC?
- Identify some unique characteristic of each thyristor listed.

6.1.9 UJT test circuit

Describe what happens to the UJT as the potentiometer is slowly adjusted upward to provide a variable voltage at point **A** in this circuit, starting from 0 Volts and ending at the trigger voltage V_P :



Now describe what must be done to the potentiometer to cause the UJT to turn back off again.

Challenges

- Explain how *hysteresis* plays a role in this circuit's behavior.

6.2 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.

6.2.1 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 (m³/kg-s²)

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** (W/m²·K⁴)

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.

6.2.2 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	

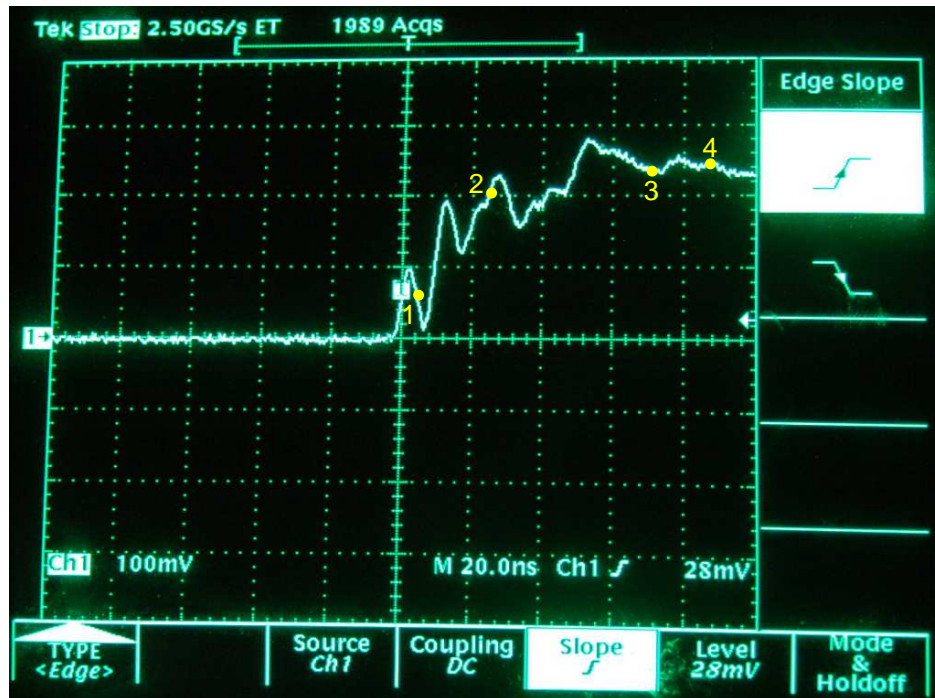
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary¹⁰ – all that matters is that they properly reference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

6.2.3 Voltage rate-of-change from oscillographs

First, identify at which of the numbered points is the waveform experiencing a positive rate-of-change versus a negative rate-of-change:



Next, estimate the voltage rate-of-change for this voltage signal at the points specified:

- Point #1 $\frac{dV}{dt} \approx$
- Point #2 $\frac{dV}{dt} \approx$
- Point #3 $\frac{dV}{dt} \approx$
- Point #4 $\frac{dV}{dt} \approx$

Challenges

- Identify points on the waveform where the rate-of-change is zero.
- Why, exactly, is a high voltage rate-of-rise troublesome for thyristors?

6.2.4 2N6403 specifications

Find a datasheet for a thyristor with the part number 2N6403, and answer the following questions:

- What type of thyristor is the 2N6403?
- What differentiates the 2N6403 from others in this series (e.g. 2N6401, 2N6402, etc.).
- Identify the holding current rating for this thyristor, and explain its significance.
- Identify the critical rate-of-rise for voltage, and explain its significance.
- Would a linear rise of V_{AK} from 0 Volts to 14 Volts over $0.2 \mu\text{s}$ be acceptable?
- Identify the typical gate trigger current for this thyristor. Would you classify this as a *sensitive-gate* or *standard* thyristor?
- How much voltage would you expect this thyristor to drop in the “on” state?

Challenges

- Suppose you needed a thyristor to build a circuit and the only one on hand had a “sensitive” gate. How could you intentionally “de-sensitize” the gate?

6.2.5 2N6344 specifications

Find a datasheet for a thyristor with the part number 2N6344, and answer the following questions:

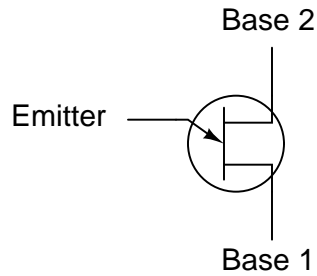
- What type of thyristor is the 2N6344?
- Identify the holding current rating for this thyristor, and explain its significance.
- Identify the critical rate-of-rise for voltage, and explain its significance.
- Would a linear rise of V_{AK} from 0 Volts to 25 Volts over 11 μs be acceptable?
- Identify the typical gate trigger current for this thyristor. Would you classify this as a *sensitive-gate* or *standard* thyristor?
- How much voltage would you expect this thyristor to drop in the “on” state?

Challenges

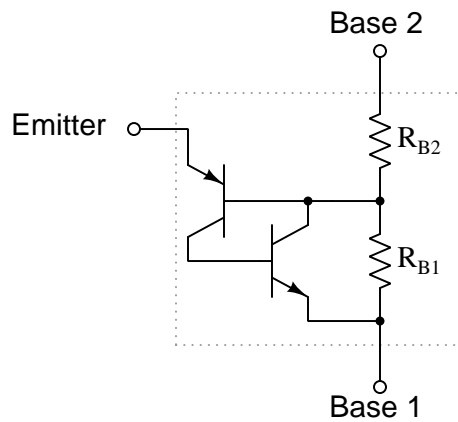
- Suppose you needed a thyristor to build a circuit and the only one on hand had a “sensitive” gate. How could you intentionally “de-sensitize” the gate?
- Some of the parameters for this thyristor vary with its *operating quadrant*. What does this refer to, and how is it significant?

6.2.6 UJT trigger voltage

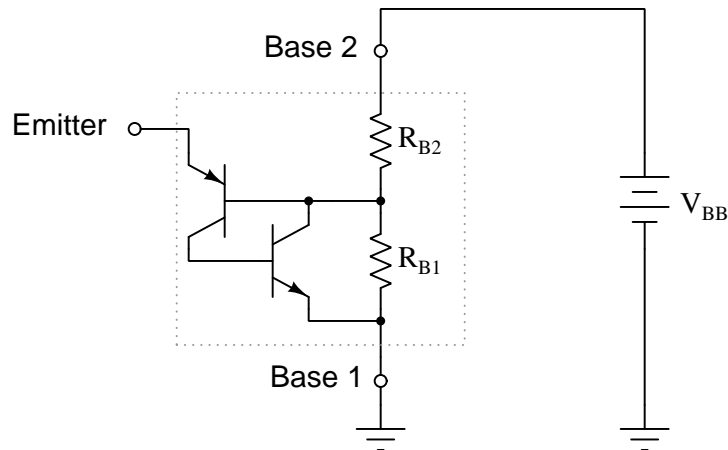
The *unijunction transistor*, or *UJT*, is an interesting device, exhibiting hysteresis just like SCRs and TRIACs. Its schematic symbol is as follows:



One equivalent circuit diagram for the UJT uses a pair of transistors and a pair of resistors:



When the two base terminals of a UJT are connected across a source of DC voltage, the two base resistances (R_{B1} and R_{B2}) form a voltage divider, splitting the applied voltage into lesser portions:



Calculate the voltage and determine the polarity which must be applied to the emitter terminal of the UJT to turn it on. Write an equation solving for the magnitude of this triggering voltage (symbolized as V_P), given R_{B1} , R_{B2} , and V_{BB} .

Challenges

- If V_{BB} increases, does V_P increase or decrease?
- How is the *standoff ratio* defined for a UJT, and how might this equation be re-written to include it?

6.2.7 UJT standoff ratio

A unijunction transistor with an intrinsic standoff ratio (η) of 0.8 is powered by a 15 volt DC source. Calculate the emitter voltage needed to “trigger” this UJT into its conductive state.

Challenges

- If the standoff ratio were less than it is, how would this affect V_P ?

6.3 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.

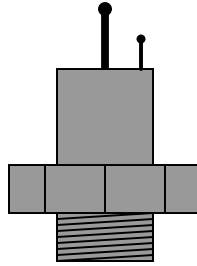
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

6.3.1 Identifying SCR terminals

Shown here is an illustration of a large “stud mount” type of SCR, where the body is threaded so as to be fastened to a metal base like a bolt threads into a nut:



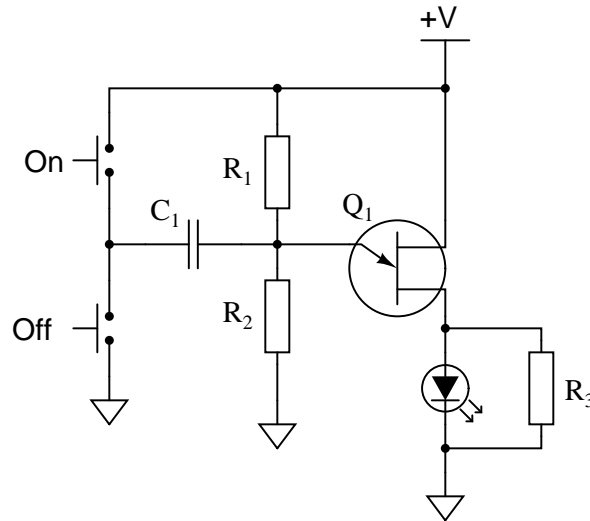
With no test instrument other than a simple continuity tester (battery and light bulb connected in series, with two test leads), how could you determine the identities of the three terminals on this SCR? Note that the threaded metal base of the SCR constitutes one of its three terminals.

Challenges

- When testing an SCR, it is best to do so under load. Describe how to set up a “loaded” test circuit and an SCR, and why load-testing is best.

6.3.2 Faults in a UJT circuit

Predict how the operation of this UJT latch circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no coincidental faults):



- Capacitor C_1 fails open:
- Capacitor C_1 fails shorted:
- Resistor R_1 fails open:
- Solder bridge (short) past resistor R_1 :
- Resistor R_2 fails open:
- Solder bridge (short) past resistor R_2 :

Challenges

- Explain how *momentary* pushbutton switches are able to make the LED *toggle* on and off.

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

Andrew D. Hwang's ePiX mathematical visualization programming library

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

gnuplot mathematical visualization software

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

Python programming language

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

Appendix D

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Appendix E

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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.

13 November 2024 – minor clarifications in the Tutorial section on critical rate of voltage rise to clarify concepts for readers less familiar with oscilloscopes. Also corrected a couple of typographical errors.

11 November 2024 – added a new Case Tutorial chapter with a section on measuring rates of voltage change over time.

25 October 2024 – added a new challenging concept to the Introduction chapter.

18 October 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors.

13 November 2023 – added some more comments on the action of positive feedback at the beginning of the Tutorial. Also removed references to “frequency” within the Tutorial chapter for those readers yet unfamiliar with AC. Also added a footnote to help clarify voltage rate-of-change.

7 November 2023 – edited image.6600 to better show rate-of-voltage rise.

21 April 2023 – added Tutorial content and Questions regarding $\frac{dV}{dt}$ rate-of-rise of voltage, and also edited Tutorial section names.

13 April 2023 – added some more detail about thyristor breakover and rate-of-rise firing.

2 December 2022 – added photograph of a large (500 Ampere rated) SCR to the Tutorial.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

10 November 2022 – added more questions to the Introduction chapter.

15 November 2021 – added a new section to the Tutorial to differentiate sensitive-gate versus non-sensitive-gate thyristors.

2 October 2021 – divided Tutorial into sections.

9 May 2021 – commented out or deleted empty chapters.

18 March 2021 – corrected multiple instances of “volts” that should have been capitalized “Volts”.

17 December 2020 – minor edit to Tutorial.

12 November 2020 – minor edit to image_2640.eps, labeling the switch as the “on switch” rather than just “switch” because there are actually two switches in the SCR circuit. Minor edit to image_2636, adding a blocking diode to the SCR circuit (and also commenting on this in the text). Also, added to the instructor notes in some of the questions.

24 September 2020 – added more content to the Introduction chapter, and also added a footnote to the Tutorial regarding voltage rate-of-change. Instantaneous rates of change (e.g. $\frac{dV}{dt}$) are a calculus concept, and therefore present a conceptual challenge for many students lacking a background in calculus. The purpose of the footnote was to relate this concept to something immediately familiar: *speed* as a time-based function of *distance* or *position*.

6 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.

7 July 2020 – minor edit to wording in Tutorial.

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

23 December 2019 – minor additions to a question.

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

6 December 2019 – finished the Tutorial chapter, added some questions, and also added a US patent reference.

5 December 2019 – finished most of the Tutorial chapter.

4 December 2019 – began writing Tutorial.

3 December 2019 – document first created.

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