

## Thyristors

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Resources and methods for learning about these subjects (list a few here, in preparation for your research):

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Question 1

All thyristor devices exhibit the property of *hysteresis*. From an electrical perspective, what is "hysteresis"? How does this behavior differ from that of "normal" active semiconductor components such as bipolar or field-effect transistors?

file 01089

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Answer 1

Once turned on, a thyristor tends to remain in the "on" state, and visa-versa.

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Notes 1

The hysteretic action of thyristors is often referred to as *latching*. Ask your students to relate this term to the action of a thyristor. Why is "latching" an appropriate term for this behavior? Can your students think of any applications for such a device?

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Question 2

What is required to make a *Shockley diode* or *DIAC* begin conducting current? What condition(s) have to be met in order for electrical conduction to occur through one of these devices?

Also, explain what must be done to stop the flow of electric current through a Shockley diode or a DIAC.

file 01090

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Answer 2

Turn on: voltage drop across device must exceed a certain threshold voltage (the *breakover voltage*) before conduction occurs.

Turn off: current through the device must be brought to a minimum level before the device stops conducting (*low-current dropout*).

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Notes 2

Although the answer may seem obvious to many, it is worthwhile to ask your students how the behavior of a Shockley diode compares to that of a normal (rectifying) diode. The fact that the Shockley diode is called a "diode" at all may have fooled some of your students into thinking that it behaves much like a normal diode.

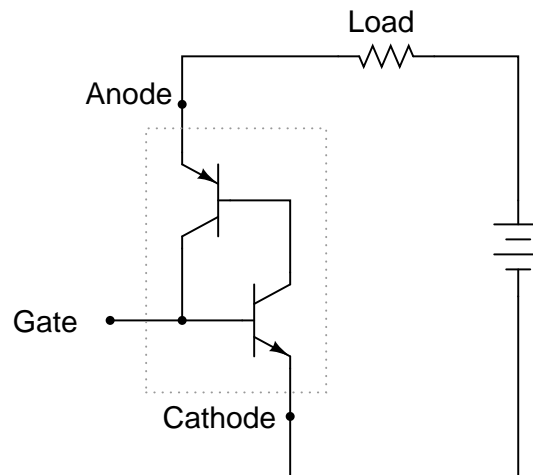
Ask your students to explain how these two devices (Shockley diodes versus rectifying diodes) are similar. In what ways are they different?

Another good discussion question to bring up is the difference between a *Shockley* diode and a *Schottky* diode. Although the names are very similar, the two devices are definitely not!

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### Question 3

Silicon-controlled rectifiers (SCRs) may be modeled by the following transistor circuit. Explain how this circuit functions, in the presence of and absence of a "triggering" voltage pulse at the gate terminal:



file 01088

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### Answer 3

The positive feedback intrinsic to this circuit gives it hysteretic properties: once triggered "on," it tends to stay on. When "off," it tends to stay off (until triggered).

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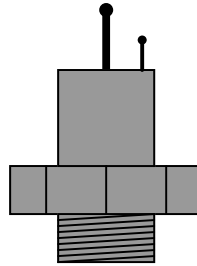
### Notes 3

Have students demonstrate the positive feedback "latching" action of this circuit by drawing directions of current on a diagram for the class to see (on the whiteboard, in view of everyone). Ask your students why the circuit "waits" until a triggering pulse to turn on, and why it "latches" on once triggered.

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#### Question 4

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?

Hint: The threaded metal base of the SCR constitutes one of the three terminals.

[file 01087](#)

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#### Answer 4

The smallest terminal (on top) is the gate. The identities of cathode and anode may be determined by connecting one test lead to the gate terminal, and touching the other test lead to either of the other terminals.

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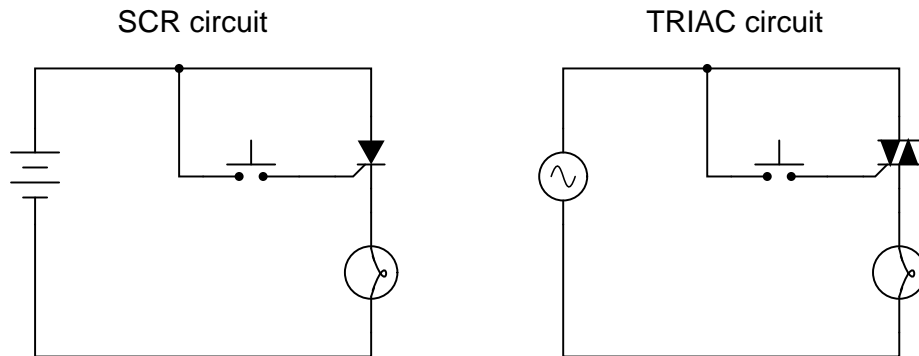
#### Notes 4

Ask your students how they know the gate terminal is the smallest one. Why would it be the smallest? Does it *have* to be the smallest terminal? Why? Also, ask them what continuity indication would distinguish cathode from anode in the continuity test described in the answer.

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### Question 5

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



[file 01094](#)

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### Answer 5

The SCR circuit's lamp will energize when the switch is actuated, and remain on after the switch is released. The TRIAC circuit's lamp will energize when the switch is actuated, and immediately de-energize when the switch is released.

Follow-up question: explain why these circuits do not behave identically. Aren't SCRs and TRIACs both thyristor (hysteretic) devices? Why doesn't the TRIAC remain in the "on" state after its triggering voltage is removed?

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### Notes 5

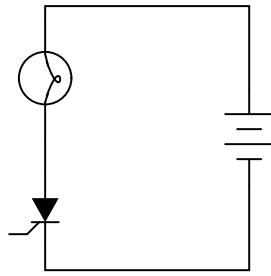
This question addresses a very common misunderstanding that students have about TRIACs in AC circuits. Students often mistakenly think that TRIACs will latch AC power just like an SCR latches DC power, simply because the TRIAC is also a hysteretic device. However, this is not true!

One might be inclined to wonder, of what benefit is the TRIAC's hysteresis in an AC circuit, then? If latching is impossible in an AC circuit, then why have TRIACs at all? This is a very good question, and its answer lies in the operation of a TRIAC *within the timespan of an AC power cycle*, which is much faster than human eyes can see.

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### Question 6

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.

file 02136

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### Answer 6

I'll let you research the answers to these questions!

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### Notes 6

Let students explain (or perhaps even demonstrate) their answers. It is extremely important for students to realize that SCR's are *thyristors*, "latching" on and off with transient stimuli. They differ significantly from transistors in this regard.

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Question 7

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.

file 02141

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Answer 7

The constituent transistors of an SCR become driven heavily into saturation in its conductive state, with a bare minimum of drive (gate) current necessary.

Follow-up question: how does the internal operation of an SCR explain its very fast turn-on time, in addition to explaining its low conducting voltage drop?

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Notes 7

The key to fully answering why an SCR drives itself so hard during conduction is found in the principle of *positive feedback*. Discuss this principle with your students if they have not already studied it. If they have already studied it, use this question as an opportunity for review.



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Question 8

Explain what a *TRIAC* is, and how it is at once similar and different from an SCR. What applications might a TRIAC be used in that an SCR would be inappropriate for?

file 02138

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Answer 8

A "TRIAC" functions as two reverse-parallel-connected SCR units, so as to be able to control AC and not just DC.

Follow-up question: draw the equivalent circuit for a TRIAC.

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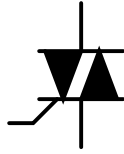
Notes 8

A popular application for TRIACs is lamp dimmer controls, for line-powered (50 or 60 Hz) incandescent lamps. If time permits, discuss with your students how these lamp dimmer circuits control power to the lamp in a manner reminiscent of PWM (Pulse-Width Modulation).

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Question 9

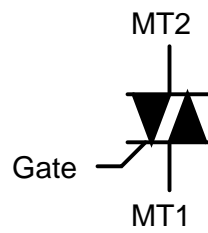
Label the terminals on a TRIAC with their proper designations:



file 03723

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Answer 9



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Notes 9

Ask your students where they found this information. Was it from a textbook, a datasheet, or some other source?

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Question 10

Explain how Silicon-Controlled Rectifiers (SCRs) differ from TRIACs, in terms of their respective behavior.

file 02346

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Answer 10

TRIACs are bilateral versions of SCRs.

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Notes 10

The answer I give is very minimal by design. Students need to know what "bilateral" means with reference to electronic components, but this question provides a good opportunity for them to learn in case they don't!

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### Question 11

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"?

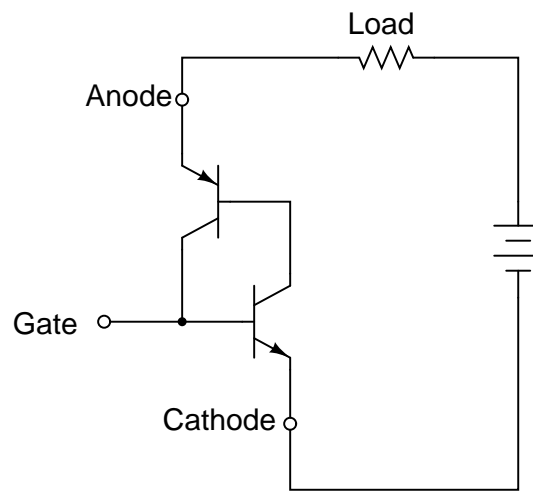
file 01093

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### Answer 11

SCRs and TRIACs with "sensitive gates" resemble the idealized devices illustrated in textbooks. SCRs and TRIACs with "non-sensitive" gates are intentionally "desensitized" by the addition of an internal loading resistor connected to the gate terminal.

Follow-up question: where would this loading resistor be connected, in the following equivalent diagram for an SCR?



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### Notes 11

Ask your students why a thyristor such as an SCR or a TRIAC would need to be "de-sensitized" by the addition of a loading resistor? What is wrong with having a "sensitive" thyristor in a circuit?

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Question 12

Explain what a *crowbar* circuit is, and how it employs an SCR to protect a circuit from excessive voltage.  
file 02137

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Answer 12

A "crowbar" circuit uses an SCR to clamp the output voltage of a DC power supply in the event of accidental overvoltage, in the same manner that a (literal) metal crowbar thrown across the terminals of a power supply would forcibly clamp the output voltage.

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Notes 12

Discuss with your students whether or not they think a crowbar circuit is the sort of mechanism that sees regular use, or whether it is seldom activated.

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Question 13

What is a *quadrac*, and how does it differ from a regular TRIAC?  
file 01422

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Answer 13

A "quadrac" is a TRIAC with a DIAC built-in, connected in series with the gate terminal.

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Notes 13

Ask your students what benefit a quadrac would be over a regular TRIAC.

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#### Question 14

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 amps 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?

file 01086

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#### Answer 14

I’ll let you determine the reason why SCRs cannot be used as audio amplification devices.

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#### Notes 14

Believe it or not, I was once approached by an enthusiastic student with this very question!

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### Question 15

One way that SCRs may be triggered into their "on" state is by a *transient* voltage applied between the anode and cathode terminals. Normally, this method of triggering is considered a flaw of the device, as it opens the possibility of unwanted triggering resulting from disturbances in the power supply voltage.

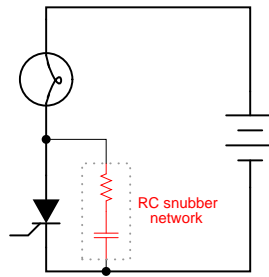
Explain why a high  $\frac{dv}{dt}$  present on the power supply rail is able to trigger an SCR, with reference to the SCR's equivalent circuit. Also suggest what means might be employed to prevent false triggering from power supply transients.

file 02142

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### Answer 15

Parasitic (Miller-effect) capacitances inside the SCR's bipolar structure make the device vulnerable to voltage transients, large  $\frac{dv}{dt}$  rates creating base currents large enough to initiate conduction. Snubber circuits are typically provided to mitigate these effects:



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### Notes 15

The expression  $\frac{dv}{dt}$  is, of course, a calculus term meaning rate-of-change of voltage over time. An important review concept for this question is the "Ohm's Law" formula for a capacitance:

$$i = C \frac{dv}{dt}$$

Only by understanding the effects of a rapidly changing voltage on a capacitance are students able to comprehend why large rates of  $\frac{dv}{dt}$  could cause trouble for an SCR.



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Question 16

Identify three different ways that an SCR or a TRIAC may be triggered into its "on" (conducting) state:

- 1.
- 2.
- 3.

file 02347

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Answer 16

1. Applying a voltage pulse at the gate terminal
2. Exceeding the anode-to-cathode "breakover" voltage
3. Exceeding the "critical rate of rise" for anode-cathode voltage ( $\frac{dv}{dt}$ )

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Notes 16

Although gate triggering is by far the most common method of initiating conduction through SCRs and TRIACs, it is important that students realize it is not the only way. The other two methods, both involving voltage applied between the anode and cathode terminals (or MT1-MT2 terminals) of the device, are often *accidental* means of triggering.

Be sure to discuss with your students the reason *why* excessive  $\frac{dv}{dt}$  can trigger a thyristor, based on an examination of inter-electrode capacitance within the transistors of a thyristor model.

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Question 17

Identify two different ways that an SCR or a TRIAC may be forced into its "off" (non-conducting) state:

- 1.
- 2.

file 02350

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Answer 17

1. Low current dropout (interrupting current with some other switching device)
2. "Reverse-firing" the gate with a voltage pulse of the "wrong" polarity

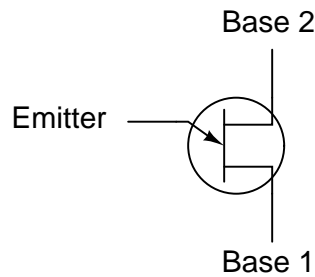
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Notes 17

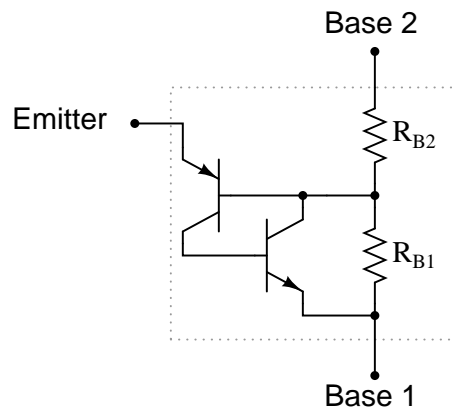
Although low-current dropout is the most common method of terminating conduction through SCRs and TRIACs, it is important that students realize it is not the only way. The other method, though, is often very difficult to achieve with ordinary SCRs or TRIACs.

Question 18

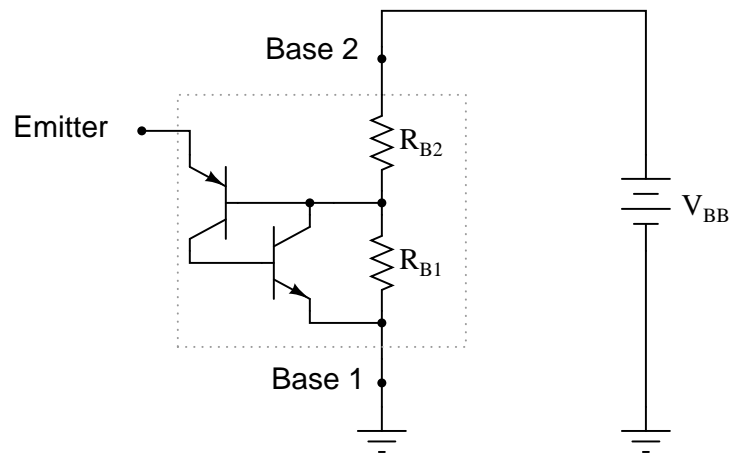
The *unijunction transistor*, or *UJT*, is an interesting device, exhibiting hysteresis just like SCRs and TRIACs. Its schematic symbol is as follows:



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:



How much voltage, and of what polarity, 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  $V_{BB}$ .

file 02139

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Answer 18

$$V_P \approx \frac{V_{BB}R_{B1}}{R_{B1} + R_{B2}} + 0.7$$

Follow-up question: how is the *standoff ratio* defined for a UJT, and how might this equation be re-written to include it?

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Notes 18

The standoff ratio is perhaps the most important UJT parameter, given the hysteretic switching function of this device. Writing the equation for trigger voltage ( $V_P$ ) and understanding the definition for standoff ratio requires that students remember the voltage divider formula from their studies in DC circuits:

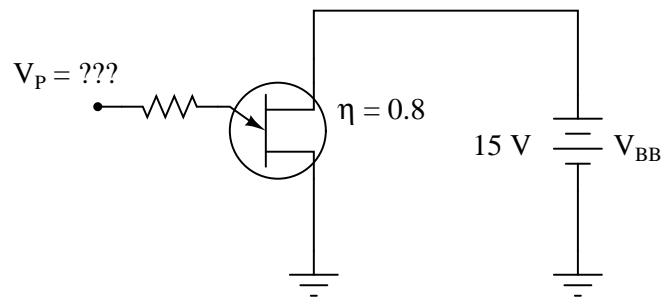
$$V_R = V_{total} \left( \frac{R}{R_{total}} \right)$$

This question provides a good opportunity to review the operation of voltage divider circuits, and this formula in particular.

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Question 19

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



file 02140

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Answer 19

$$V_P \approx 12.7 \text{ volts}$$

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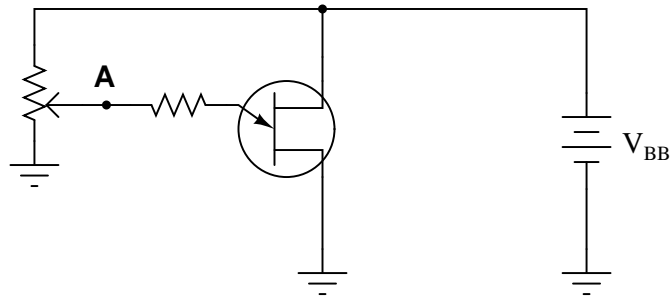
Notes 19

Nothing special here, just practice calculating the trigger voltage. Note to your students that the symbol for the intrinsic standoff ratio ( $\eta$ ) is the Greek letter "eta," which also happens to be used to symbolize efficiency.

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Question 20

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.  
[file 02144](#)

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Answer 20

The UJT will remain in the nonconducting state as the potentiometer voltage increases from 0 volts, until it reaches  $V_P$ . At that voltage, the UJT turns on and stays on. To turn the UJT off, the potentiometer must be adjusted back down in voltage until the current through point **A** decreases to a certain "dropout" value.

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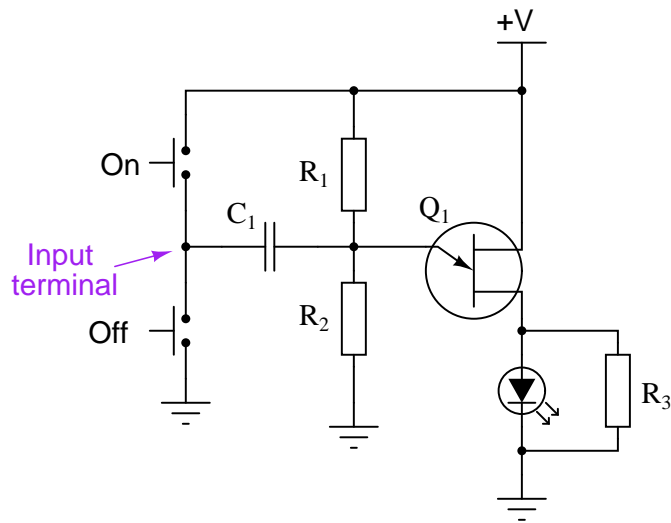
Notes 20

Ask your students to describe how hysteresis is exhibited by the UJT in this scenario.

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### Question 21

This circuit uses a *unijunction transistor* (UJT) to latch an LED in the "on" state with a positive pulse at the input terminal. A negative voltage pulse at the input terminal turns the LED off:



Explain how the unijunction transistor functions in this circuit.  
[file 01128](#)

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### Answer 21

Unijunction transistors are hysteretic, like all thyristors. A positive pulse to the emitter terminal latches the UJT, and a negative pulse makes it "drop out".

Challenge question: what is the purpose of resistor  $R_3$  in this circuit?

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### Notes 21

Ask your students to identify the terminals on the UJT. The designations for each terminal may be surprising to your students, given the names of bipolar transistor terminals!

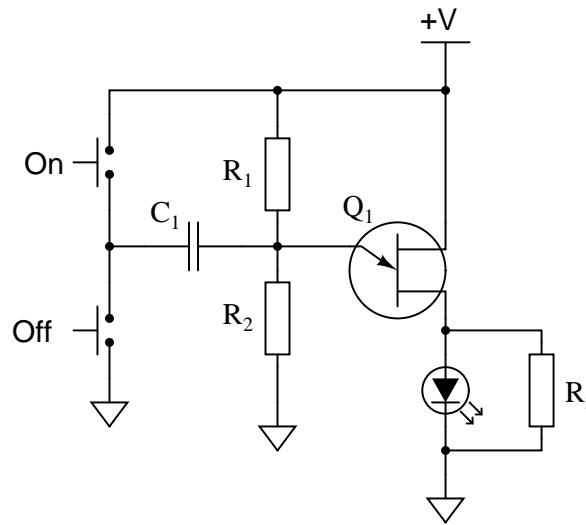
The challenge question may only be answered if one carefully considers the characteristics of an LED. Resistor  $R_3$  helps overcome problems that might potentially arise due to the nonlinearities of the diode in its off state.

I got this circuit from the October 2003 issue of Electronics World magazine, in their regular "Circuit Ideas" section. The design is attributed to André de Guérin.

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### Question 22

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 multiple 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  $R_2$ :

For each of these conditions, explain *why* the resulting effects will occur.

file 03729

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### Answer 22

- Capacitor  $C_1$  fails open: *Neither pushbutton switch has any effect on the LED.*
- Capacitor  $C_1$  fails shorted: *Circuit behaves normally.*
- Resistor  $R_1$  fails open: *LED always off, refuses to turn on.*
- Solder bridge (short) past resistor  $R_1$ : *LED always on, refuses to turn off.*
- Resistor  $R_2$  fails open: *LED always on, refuses to turn off.*
- Solder bridge (short) past resistor  $R_2$ : *LED always off, refuses to turn on.*

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### Notes 22

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.



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Question 23

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

- 1.
- 2.
- 3.

file 02351

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Answer 23

1. DIAC
2. TRIAC
3. Quadrac (TRIAC + DIAC)
4. Shockley diode
5. GTO
6. UJT
7. SCS

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Notes 23

Challenge your students to identify even more types of thyristors, if they can!

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#### Question 24

Find one or two silicon-controlled rectifiers and bring them with you to class for discussion. Identify as much information as you can about your SCRs prior to discussion:

- Terminal identification (which terminal is gate, anode, and cathode)
- Continuous voltage rating
- Continuous current rating
- Continuous power rating
- Whether or not it is a "sensitive gate" device

file 01167

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#### Answer 24

If possible, find a manufacturer's datasheet for your components (or at least a datasheet for a similar component) to discuss with your classmates.

Be prepared to *prove* the terminal identifications of your SCRs in class, by using a multimeter!

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#### Notes 24

The purpose of this question is to get students to kinesthetically interact with the subject matter. It may seem silly to have students engage in a "show and tell" exercise, but I have found that activities such as this greatly help some students. For those learners who are kinesthetic in nature, it is a great help to actually *touch* real components while they're learning about their function. Of course, this question also provides an excellent opportunity for them to practice interpreting component markings, use a multimeter, access datasheets, etc.

### Don't just sit there! Build something!!

Learning to mathematically analyze circuits requires much study and practice. Typically, students practice by working through lots of sample problems and checking their answers against those provided by the textbook or the instructor. While this is good, there is a much better way.

You will learn much more by actually *building and analyzing real circuits*, letting your test equipment provide the "answers" instead of a book or another person. For successful circuit-building exercises, follow these steps:

1. Carefully measure and record all component values prior to circuit construction, choosing resistor values high enough to make damage to any active components unlikely.
2. Draw the schematic diagram for the circuit to be analyzed.
3. Carefully build this circuit on a breadboard or other convenient medium.
4. Check the accuracy of the circuit's construction, following each wire to each connection point, and verifying these elements one-by-one on the diagram.
5. Mathematically analyze the circuit, solving for all voltage and current values.
6. Carefully measure all voltages and currents, to verify the accuracy of your analysis.
7. If there are any substantial errors (greater than a few percent), carefully check your circuit's construction against the diagram, then carefully re-calculate the values and re-measure.

When students are first learning about semiconductor devices, and are most likely to damage them by making improper connections in their circuits, I recommend they experiment with large, high-wattage components (1N4001 rectifying diodes, TO-220 or TO-3 case power transistors, etc.), and using dry-cell battery power sources rather than a benchtop power supply. This decreases the likelihood of component damage.

As usual, avoid very high and very low resistor values, to avoid measurement errors caused by meter "loading" (on the high end) and to avoid transistor burnout (on the low end). I recommend resistors between 1 k $\Omega$  and 100 k $\Omega$ .

One way you can save time and reduce the possibility of error is to begin with a very simple circuit and incrementally add components to increase its complexity after each analysis, rather than building a whole new circuit for each practice problem. Another time-saving technique is to re-use the same components in a variety of different circuit configurations. This way, you won't have to measure any component's value more than once.

[file 00505](#)

Let the electrons themselves give you the answers to your own "practice problems"!

It has been my experience that students require much practice with circuit analysis to become proficient. To this end, instructors usually provide their students with lots of practice problems to work through, and provide answers for students to check their work against. While this approach makes students proficient in circuit theory, it fails to fully educate them.

Students don't just need mathematical practice. They also need real, hands-on practice building circuits and using test equipment. So, I suggest the following alternative approach: students should *build* their own "practice problems" with real components, and try to mathematically predict the various voltage and current values. This way, the mathematical theory "comes alive," and students gain practical proficiency they wouldn't gain merely by solving equations.

Another reason for following this method of practice is to teach students *scientific method*: the process of testing a hypothesis (in this case, mathematical predictions) by performing a real experiment. Students will also develop real troubleshooting skills as they occasionally make circuit construction errors.

Spend a few moments of time with your class to review some of the "rules" for building circuits before they begin. Discuss these issues with your students in the same Socratic manner you would normally discuss the worksheet questions, rather than simply telling them what they should and should not do. I never cease to be amazed at how poorly students grasp instructions when presented in a typical lecture (instructor monologue) format!

A note to those instructors who may complain about the "wasted" time required to have students build real circuits instead of just mathematically analyzing theoretical circuits:

*What is the purpose of students taking your course?*

If your students will be working with real circuits, then they should learn on real circuits whenever possible. If your goal is to educate theoretical physicists, then stick with abstract analysis, by all means! But most of us plan for our students to do something in the real world with the education we give them. The "wasted" time spent building real circuits will pay huge dividends when it comes time for them to apply their knowledge to practical problems.

Furthermore, having students build their own practice problems teaches them how to perform *primary research*, thus empowering them to continue their electrical/electronics education autonomously.

In most sciences, realistic experiments are much more difficult and expensive to set up than electrical circuits. Nuclear physics, biology, geology, and chemistry professors would just love to be able to have their students apply advanced mathematics to real experiments posing no safety hazard and costing less than a textbook. They can't, but you can. Exploit the convenience inherent to your science, and *get those students of yours practicing their math on lots of real circuits!*