ELTR 120 (Semiconductors 1), section 2

Recommended schedule

Day 1

Topics: *Bipolar junction transistor theory*
Questions: *1 through 15*
Lab Exercise: *BJT terminal identification (question 76)*
Demo: show that I_C is nearly independent of V_{CE} for a BJT

Day 2

Topics: *Bipolar junction transistor switching circuits*
Questions: *16 through 30*
Lab Exercise: *BJT switch circuit (question 77)*

Day 3

Topics: *Junction field-effect transistor (JFET) theory*
Questions: *31 through 45*
Lab Exercise: *JFET switch circuit (question 78)*

Day 4

Topics: *Insulated gate field-effect transistor (MOSFET) theory*
Questions: *46 through 60*
Lab Exercise: *Work on project*
MIT 6.002 video clip: Disk 1, Lecture 5; MOSFET V/I characteristic 44:33 to 45:41

Day 5

Topics: *Review*
Questions: *61 through 75*
Lab Exercise: *Work on project*

Day 6

Exam 2: *includes transistor switch circuit performance assessment*
Lab Exercise: *Work on project*

Troubleshooting practice problems
Questions: *80 through 89*

General concept practice and challenge problems
Questions: *90 through the end of the worksheet*

Impending deadlines
Project due at end of ELTR120, Section 3
Question 79: Sample project grading criteria

Skill standards addressed by this course section

EIA *Raising the Standard; Electronics Technician Skills for Today and Tomorrow,* June 1994

D Technical Skills – Discrete Solid-State Devices
D.03 Demonstrate an understanding of bipolar transistors.
D.04 Demonstrate an understanding of field effect transistors (FET's/MOSFET's).
E Technical Skills – Analog Circuits
E.07 Understand principles and operations of linear power supplies and filters.
E.08 Fabricate and demonstrate linear power supplies and filters.
E.09 Troubleshoot and repair linear power supplies and filters.

B Basic and Practical Skills – Communicating on the Job
B.01 Use effective written and other communication skills. *Met by group discussion and completion of labwork.*
B.03 Employ appropriate skills for gathering and retaining information. *Met by research and preparation prior to group discussion.*
B.04 Interpret written, graphic, and oral instructions. *Met by completion of labwork.*
B.06 Use language appropriate to the situation. *Met by group discussion and in explaining completed labwork.*
B.07 Participate in meetings in a positive and constructive manner. *Met by group discussion.*
B.08 Use job-related terminology. *Met by group discussion and in explaining completed labwork.*
B.10 Document work projects, procedures, tests, and equipment failures. *Met by project construction and/or troubleshooting assessments.*
C Basic and Practical Skills – Solving Problems and Critical Thinking
C.01 Identify the problem. *Met by research and preparation prior to group discussion.*
C.03 Identify available solutions and their impact including evaluating credibility of information, and locating information. *Met by research and preparation prior to group discussion.*
C.07 Organize personal workloads. *Met by daily labwork, preparatory research, and project management.*
C.08 Participate in brainstorming sessions to generate new ideas and solve problems. *Met by group discussion.*
D Basic and Practical Skills – Reading
D.01 Read and apply various sources of technical information (e.g. manufacturer literature, codes, and regulations). *Met by research and preparation prior to group discussion.*
E Basic and Practical Skills – Proficiency in Mathematics
E.01 Determine if a solution is reasonable.
E.02 Demonstrate ability to use a simple electronic calculator.
E.05 Solve problems and [sic] make applications involving integers, fractions, decimals, percentages, and ratios using order of operations.
E.06 Translate written and/or verbal statements into mathematical expressions.
E.09 Read scale on measurement device(s) and make interpolations where appropriate. *Met by oscilloscope usage.*
E.12 Interpret and use tables, charts, maps, and/or graphs.
E.13 Identify patterns, note trends, and/or draw conclusions from tables, charts, maps, and/or graphs.
E.15 Simplify and solve algebraic expressions and formulas.
E.16 Select and use formulas appropriately.
E.17 Understand and use scientific notation.

Common areas of confusion for students

**Difficult concept:** *Necessary conditions for transistor operation.*

It is vitally important for students to understand the conditions necessary for transistor operation, both for understanding how circuits work and for troubleshooting faulty circuits. Bipolar junction transistors require a base current (in the proper direction) to conduct, and the collector-to-emitter voltage must be of the correct polarity to push a collector current in the proper direction as well. Both currents join at the emitter terminal, making the emitter current the sum of the base and collector currents. Field-effect transistors are not so picky about the direction of the controlled current, and they only require the correct gate voltage (no gate current) to establish conduction. What makes this so confusing is that there are two types of bipolar transistors (NPN and PNP), two types of junction field-effect transistors (N-channel and P-channel), and four types of MOSFETs (E-type N-channel, E-type P-channel, D-type N-channel, and D-type P-channel).

Difficult concept: *Current sourcing versus current sinking.*

It is very common in electronics work to refer to current-controlling devices as either *sourcing* current to a load or *sinking* current from a load. This is an overt reference to conventional-flow notation, referring to whether the conventional flow moves *out* of the transistor from the positive power supply terminal to the load (sourcing), or whether the conventional flow moves *in* to the transistor from the load and then "down" to ground (sinking). Some students grasp this concept readily, while others seem to struggle mightily with it. It is something rather essential to understand, because this terminology is extensively used by electronics professionals and found in electronics literature. The key detail distinguishing the two conditions is which power supply rail (either +V or Gnd) is *directly* connected to the current-controlling device.

If we were to compare the energy diagrams for three pieces of semiconducting material, two "N" type and one "P" type, side-by-side, we would see something like this:
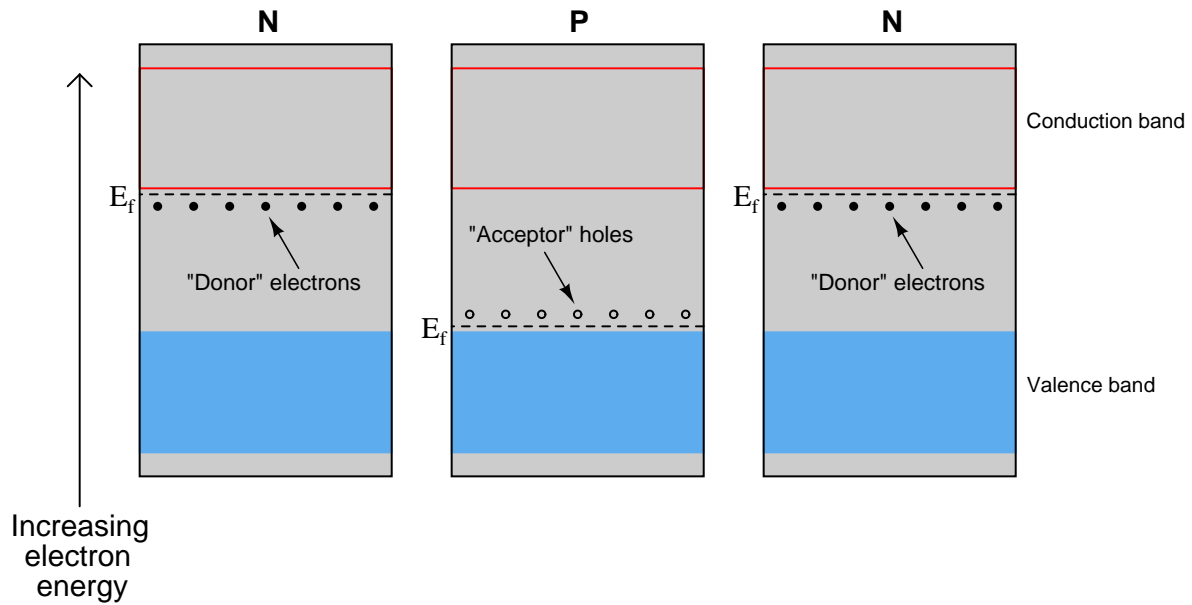
The presence of dopants in the semiconducting materials creates differences in the Fermi energy level (E_f) within each piece.

Draw a new energy diagram showing the equilibrium state of the three pieces after being joined together.
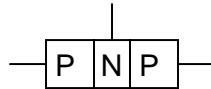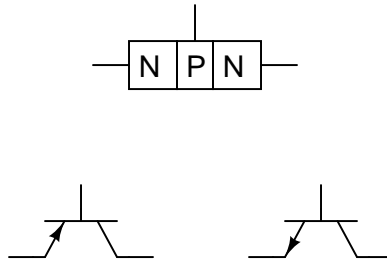
file 02032

Answer 1
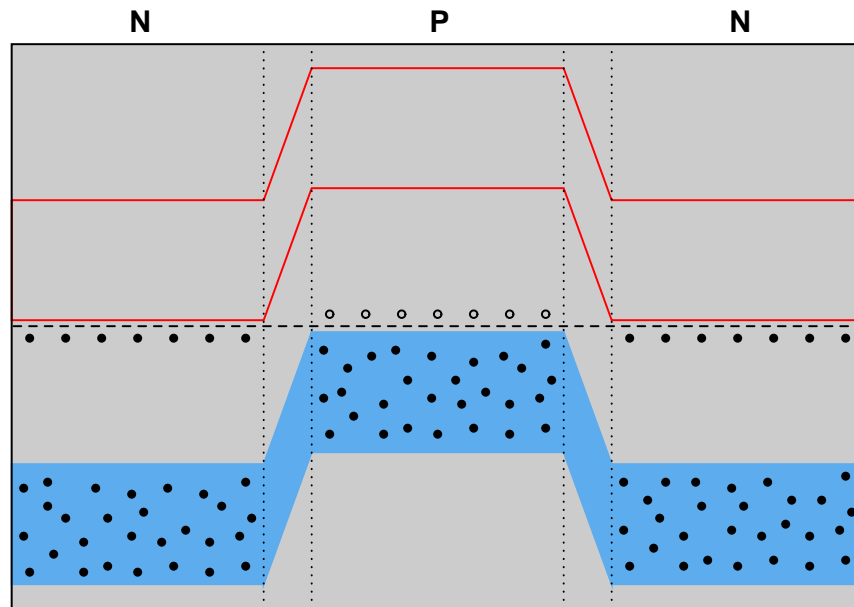
Notes 1

If students are familiar with energy band diagrams for PN diode junctions, they should have no great difficulty drawing an energy diagram for an NPN junction.

Question 2

Match the following bipolar transistor illustrations to their respective schematic symbols:

Answer 2
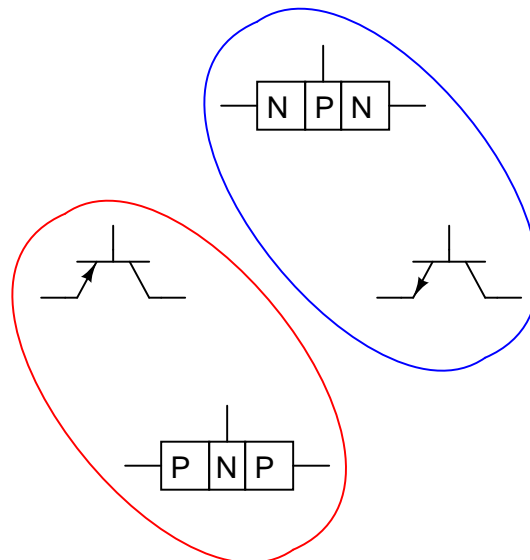
Follow-up question: identify the terminals on each transistor schematic symbol (base, emitter, and collector).

Notes 2

Be sure to ask your students which of these transistor symbols represents the "NPN" type and which represents the "PNP" type. Although it will be obvious to most from the "sandwich" illustrations showing layers of "P" and "N" type material, this fact may escape the notice of a few students.

It might help to review diode symbols, if some students experience difficulty in matching the designations (PNP versus NPN) with the schematic symbols.

Question 3

Trace the paths of *injection*, *diffusion*, and *collection* currents in this energy diagram for an NPN transistor as it is conducting:
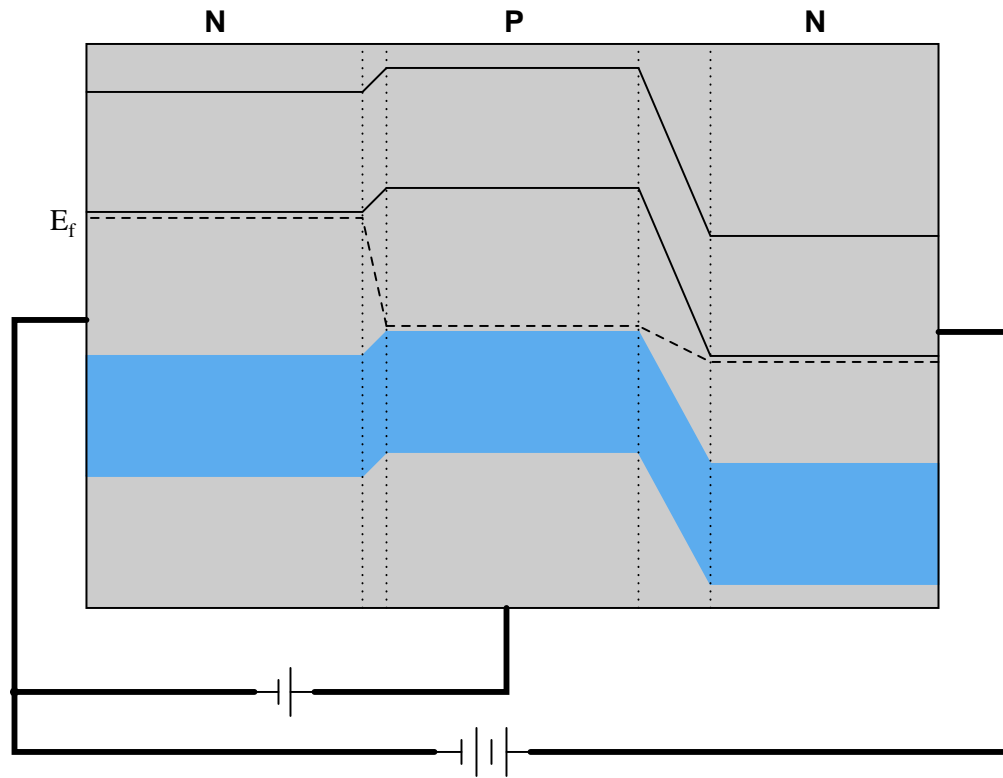

file 02034
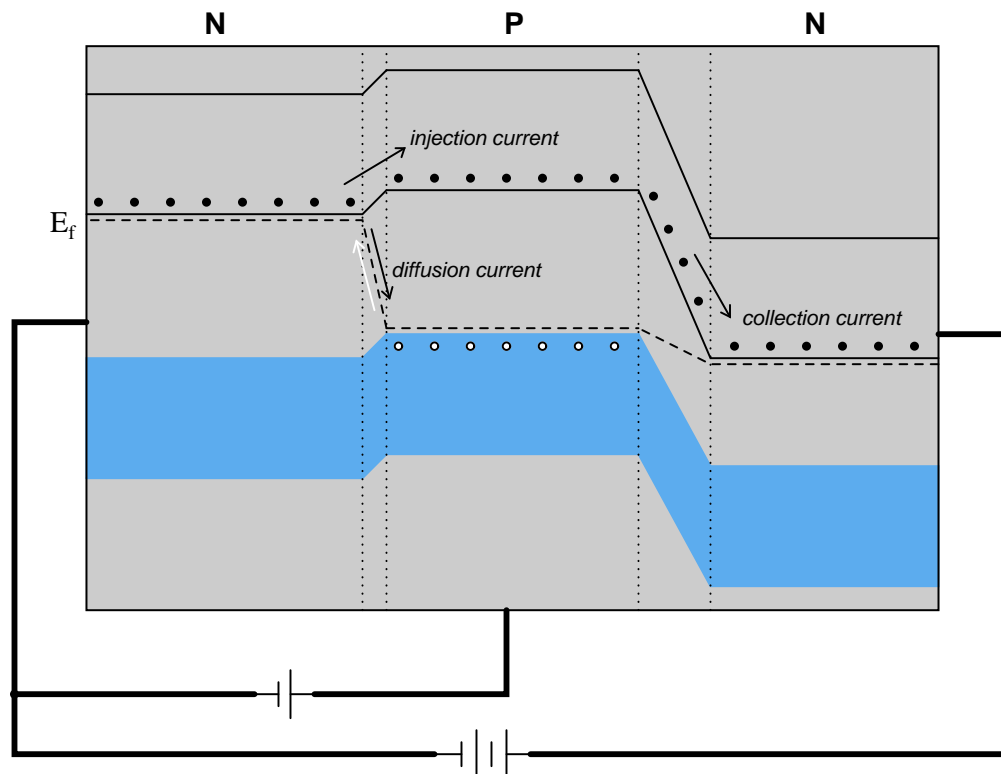
Notes 3

A picture is worth a thousand words, they say. For me, this illustration is the one that finally made transistors make sense to me. By forward-biasing the emitter-base junction, minority carriers are injected into the base (electrons in the "P" type material, in the case of an NPN transistor), which then fall easily into the collector region. This energy diagram is invaluable for explaining why collector current can flow even when the base-collector junction is reverse biased.

Question 4

Conduction of an electric current through the collector terminal of a bipolar junction transistor requires that minority carriers be "injected" into the base region by a base-emitter current. Only after being injected into the base region may these charge carriers be swept toward the collector by the applied voltage between emitter and collector to constitute a collector current:
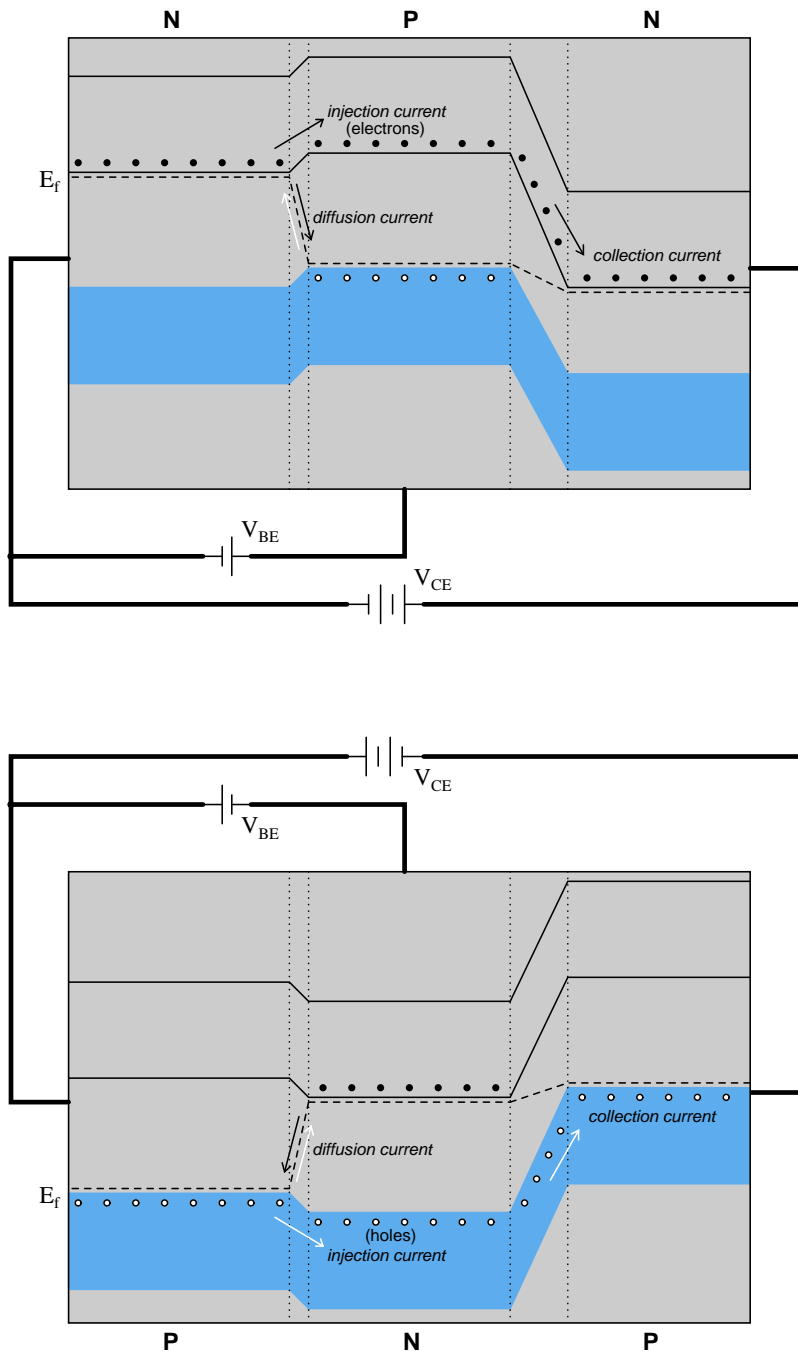
An analogy to help illustrate this is a person tossing flower petals into the air above their head, while a breeze carries the petals horizontally away from them. None of the flower petals may be "swept" away by the breeze until the person releases them into the air, and the velocity of the breeze has no bearing on

how many flower petals are swept away from the person, since they must be released from the person's grip before they can go anywhere.

By referencing either the energy diagram or the flower petal analogy, explain why the collector current for a BJT is strongly influenced by the base current and only weakly influenced by the collector-to-emitter voltage.

file 02482

Answer 4

The action of tossing flower petals into the air is analogous to base current injecting charge carriers into the base region of a transistor. The drifting of those tossed petals by the wind is analogous to the sweeping of charge carriers across the base and into the collector by V_{CE}. Like the number of flower petals drifting, the amount of collector current does not depend much on the strength of V_{CE} (the strength of the wind), but rather on the rate of charge carriers injected (the number of petals tossed upward per second).

Notes 4

This is one of my better analogies for explaining BJT operation, especially for illustrating the why I_C is almost independent of V_{CE}. It also helps to explain reverse recovery time for transistors: imagine how long it takes the air to clear of tossed flower petals after you stop tossing them, analogous to latent charge carriers having to be swept out of the base region by V_{CE} after base current stops.
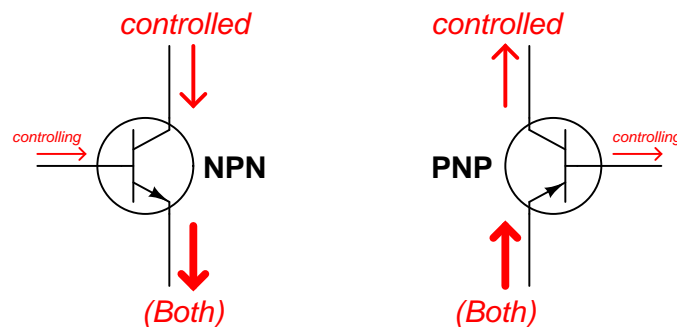
Question 5

Bipolar junction transistor (BJT) function is usually considered in terms of currents: a relatively small current through one of the transistor's terminals exerts control over a much larger current. Draw the directions of all currents for these two transistors (one NPN and one PNP), clearly identifying which of the currents is *doing* the control, and which of the currents is *being* controlled:
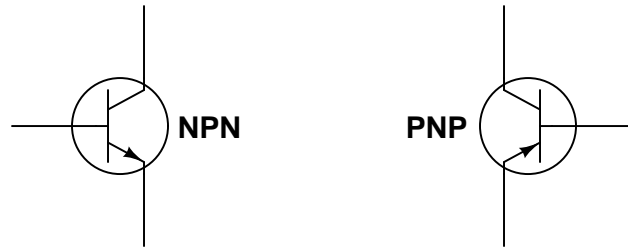

<u>file 02037</u>

Answer 5

All currents shown using conventional flow notation

Notes 5

I have heard questions of this sort asked on technician job interviews. Knowing which way currents go through a BJT is considered a very fundamental aspect of electronics technician knowledge, and for good reason. It is impossible to understand the function of many transistor circuits without a firm grasp on which signal exerts control over which other signal in a circuit.

Question 6

Compare the relative magnitudes of each current in this bipolar transistor circuit:
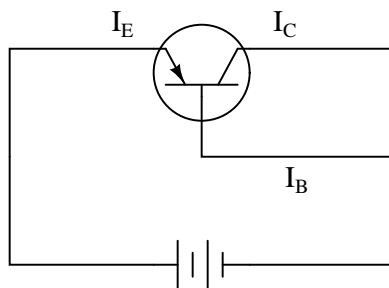
Which current is the smallest and which is the largest? Are there any two currents that are closer in magnitude than with the third? If so, which currents are they?

file 02405

Answer 6

$$I_E > I_C >> I_B$$

Notes 6

Note the brief nature of the answer. This mathematical expression says it all, and it is a good review of inequality symbols.

Question 7

The "beta" ratio (β) of a bipolar junction transistor, sometimes alternatively referred to as h_{FE}, is a very important device parameter. In essence, it describes the amplifying power of the transistor. Give a mathematical definition for this parameter, and provide some typical values from transistor datasheets.

file 02038

Answer 7

β is defined as the ratio between collector and base current. I'll let you research some typical values. Here are some transistor part numbers you could research datasheets for:

- 2N2222
- 2N2905
- 2N2907
- 2N3403
- 2N3703
- 2N3904
- 2N3906
- 2N4125
- 2N4403
- 2N3055
- TIP 29
- TIP 31
- TIP 32
- TIP 41
- TIP 42

Follow-up question #1: what conditions affect the β ratio of a transistor?

Follow-up question #2: re-write the β equation to solve for the other variables ($I_C = \cdots$, $I_B = \cdots$).

Notes 7

Ask your students to show you at least one datasheets for one of the listed transistors. With internet access, datasheets are extremely easy to locate. Your students will need to be able to locate component datasheets and application notes as part of their work responsibilities, so be sure they know how and where to access these valuable documents!

The follow-up question is an important one to discuss, as β is far from stable for most transistors! This point is often overlooked in basic electronics textbooks, leaving students with the false impression that transistor circuit calculations using β are far more accurate than they actually are.

Question 8

Are the collector and emitter terminals of a transistor interchangeable? If not, what is the physical difference between the emitter and collector?

file 00914

Answer 8

The emitter is smaller and more heavily "doped" than the collector.

Notes 8

Ask your students if there is any way to distinguish the emitter and collector terminals on a transistor, from external meter measurements. There is!

Question 9

Based on these DC continuity tester indications, what type of transistor is this, PNP or NPN?

- Resistance with negative test lead on pin 1, positive test lead on pin 2: *no continuity*
- Resistance with negative test lead on pin 1, positive test lead on pin 3: *no continuity*
- Resistance with negative test lead on pin 2, positive test lead on pin 1: *no continuity*
- Resistance with negative test lead on pin 2, positive test lead on pin 3: *no continuity*
- Resistance with negative test lead on pin 3, positive test lead on pin 1: **continuity**
- Resistance with negative test lead on pin 3, positive test lead on pin 2: **continuity**

Also, to the best of your ability, identify the transistor's three terminals (emitter, base, and collector).
file 00483

Answer 9

This is a PNP transistor. Pin 3 is the base, and pins 1 and 2 are emitter/collector or collector/emitter (can't be sure which).

Notes 9

Advise your students about the risks of using an analog multimeter (in ohmmeter mode) to test semiconductor components. Some inexpensive analog multimeter designs actually *switch* the polarity of the test leads when in the ohmmeter mode. In other words, the red test lead actually connects to the negative side of the meter's internal battery, while the black test lead connects to the positive side of the internal battery! If you are used to associating red with positive and black with negative, this switch will be quite a surprise.

Ask your students: what effect would a switch in polarity such as the one just described have on the determination of a transistor's identity? What if the person thought their meter's red lead was positive and the black lead negative, when in fact it was just the opposite? Would this affect their ability to accurately identify the transistor's terminals? Why or why not?

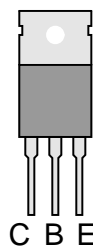Identify the terminals on this BJT, and also the type of BJT it is (*NPN* or *PNP*):
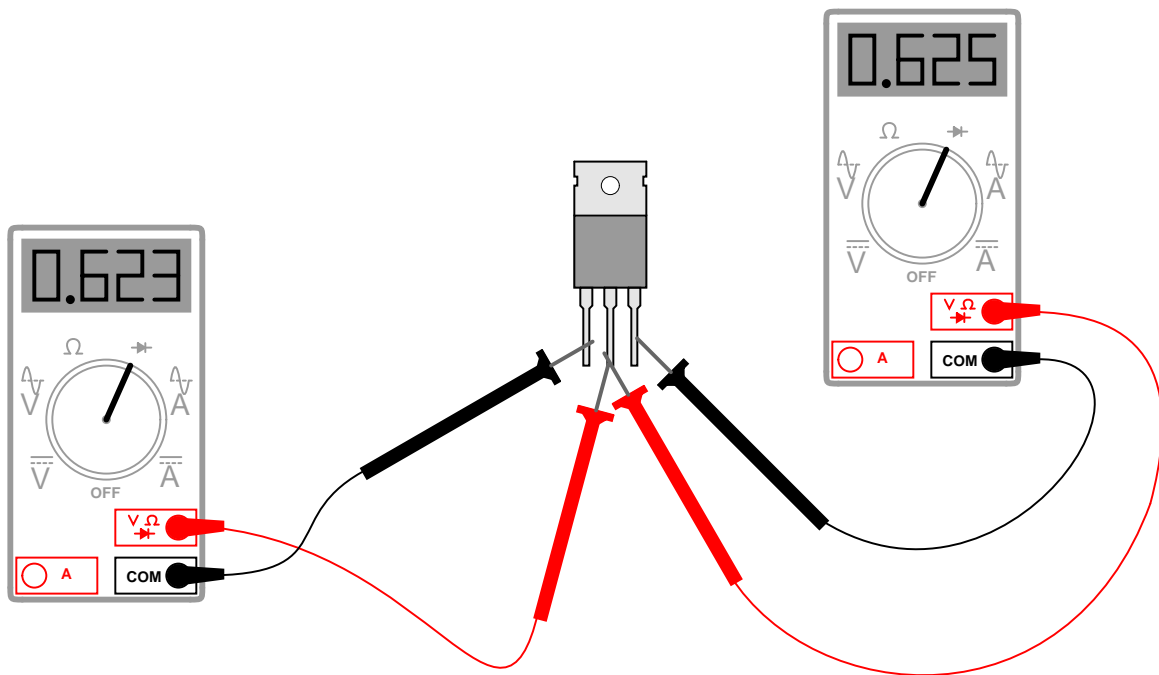
Answer 10

NPN transistor

C B E

Notes 10

I have found this "diode check" multimeter technique to be very successful for identifying BJT terminals.

Question 11

How would you explain the necessary conditions for conduction of an electric current through a BJT? Describe must be done to a BJT in order for it to conduct a current.

file 02403

Answer 11

The base-emitter PN junction must be forward-biased, and the polarity of voltage between collector and emitter must be such that the collector current adds with the base current to equal the emitter current.

Notes 11

This is perhaps the most important question your students could learn to answer when first studying BJTs. What, exactly, is necessary to turn one on? Have your students draw diagrams to illustrate their answers as they present in front of the class.

Question 12

Draw the polarities (+ and -) of the applied voltages necessary to turn both these transistors on:

Also, draw the direction of the *controlled* current (flowing between collector and emitter) that will result from a power source properly connected between these terminals.

file 02404

Answer 12
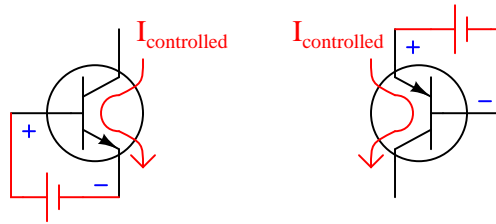
Arrows shown pointing in the direction
of "conventional flow" notation

Follow-up question: draw the voltage sources necessary for generating the "controlled" current traced in these diagrams, so that the applied voltage polarity between collector and emitter is evident.

Notes 12

This is a very important concept for students to grasp: how to turn a BJT on with an applied voltage between base and emitter, and also which direction the controlled current goes through it. Be sure to spend time discussing this, for it is fundamental to their understanding of BJT operation.

Question 13

Transistors act as *controlled current sources*. That is, with a fixed control signal in, they tend to regulate the amount of current going through them. Design an experimental circuit to prove this tendency of transistors. In other words, how could you *demonstrate* this current-regulating behavior to be a fact?

file 03722

Answer 13
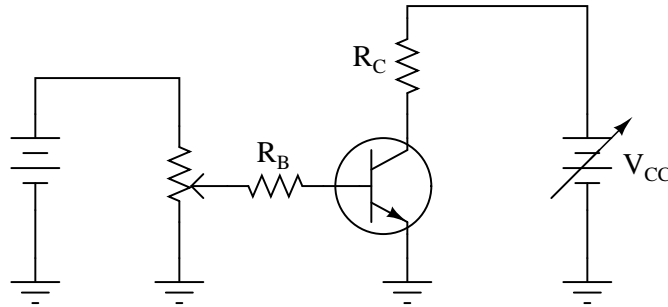
Procedure: measure the voltage dropped across R_C while varying V_{CC}, for several different values of I_B (inferred by measuring voltage drop across R_B).

Notes 13

Here, students must think like an experimental scientist: figuring out how to prove the relative stability of one variable despite variations in another, while holding the controlling variable constant. Encourage your students to actually build this circuit!

Question 14

Suppose we only knew the emitter and base currents for an operating transistor and wished to calculate β from that information. We would need a definition of beta cast in terms of I_E and I_B instead of I_C and I_B.

Apply algebraic substitution to the formula $\beta = \frac{I_C}{I_B}$ so that beta (β) is defined in terms of I_E and I_B. You may find the following equation helpful in your work:

$$I_E = I_C + I_B$$

file 02387

Answer 14

$$\beta = \frac{I_E}{I_B} - 1$$

Notes 14

This question is nothing more than an exercise in algebraic manipulation.

20

Question 15

The power dissipation of a transistor is given by the following equation:

$$P = I_C \left(V_{CE} + \frac{V_{BE}}{\beta} \right)$$

Manipulate this equation to solve for beta, given all the other variables.
<u>file 00502</u>

Answer 15

$$\beta = \frac{V_{BE}}{\frac{P}{I_C} - V_{CE}}$$

Notes 15

Although this question is essentially nothing more than an exercise in algebraic manipulation, it is also a good lead-in to a discussion on the importance of power dissipation as a semiconductor device rating.

High temperature is the bane of most semiconductors, and high temperature is caused by excessive power dissipation. A classic example of this, though a bit dated, is the temperature sensitivity of the original germanium transistors. These devices were extremely sensitive to heat, and would fail rather quickly if allowed to overheat. Solid state design engineers had to be very careful in the techniques they used for transistor circuits to ensure their sensitive germanium transistors would not suffer from "thermal runaway" and destroy themselves.

Silicon is much more forgiving then germanium, but heat is still a problem with these devices. At the time of this writing (2004), there is promising developmental work on silicon carbide and gallium nitride transistor technology, which is able to function under *much* higher temperatures than silicon.

Question 16

Solid-state switching circuits usually keep their constituent transistors in one of two modes: *cutoff* or *saturation*. Explain what each of these terms means.

file 02043

Answer 16

"Cutoff" refers to that condition where a transistor is not conducting any collector current (it is fully off). "Saturation" means that condition where a transistor is conducting maximum collector current (fully on).

Follow-up question: is there such a thing as a state where a transistor operates somewhere between cutoff (fully off) and saturation (fully on)? Would this state be useful in a switching circuit?

Notes 16

In all fairness, not all transistor switching circuits operate between these two extreme states. Some types of switching circuits fall shy of true saturation in the "on" state, which allows transistors to switch back to the cutoff mode faster than if they had to switch back from a state of full saturation. ECL (Emitter-Coupled Logic) digital circuits are an example of non-saturating switch circuit technology.

Question 17

Explain the function of this light-switching circuit, tracing the directions of all currents when the switch closes:
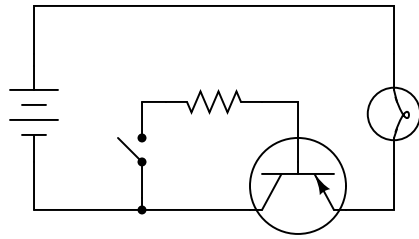
Answer 17
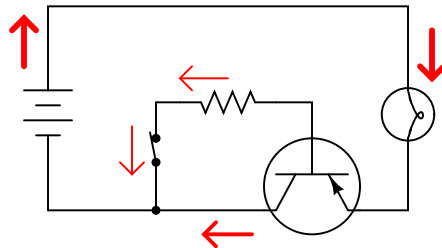
*All currents shown using
conventional flow notation*

Notes 17

Ask your students to explain what possible purpose such a circuit could perform.

Question 18

Trace the directions of all currents in this circuit, and determine which current is larger: the current through resistor R1 or the current through resistor R2, assuming equal resistor values.

SW2

R2

R1

SW1
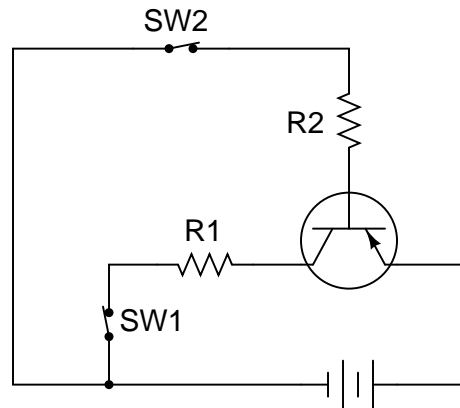
If switch SW2 were opened (and switch SW1 remained closed), what would happen to the currents through R1 and R2?

If switch SW1 were opened (and switch SW2 remained closed), what would happen to the currents through R1 and R2?

file 00522

Answer 18

I'll let you determine the directions of all currents in this circuit! Although it is impossible to tell with absolute certainty, the current through R1 is likely to be much greater than the current through R2.

If SW2 opens while SW1 remains closed, both currents will cease. If SW1 opens while SW2 remains closed, there will be no current through R1, but the current through R2 will actually increase.

Follow-up question: what does this indicate about the nature of the two currents? Which current exerts *control* over the other through the transistor?

Notes 18

The most important principle in this question is that of *dependency*: one of the transistor's currents needs the other in order to exist, but not visa-versa. I like to emphasize this relationship with the words *controlling* and *controlled*.

Calculate all component voltage drops in this circuit, assuming a supply voltage of 15 volts, an emitter-base forward voltage drop of 0.7 volts, and a (saturated) emitter-collector voltage drop of 0.3 volts:
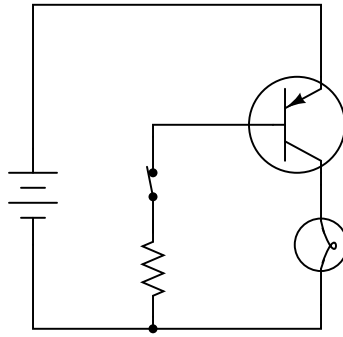
file 02050

Answer 19
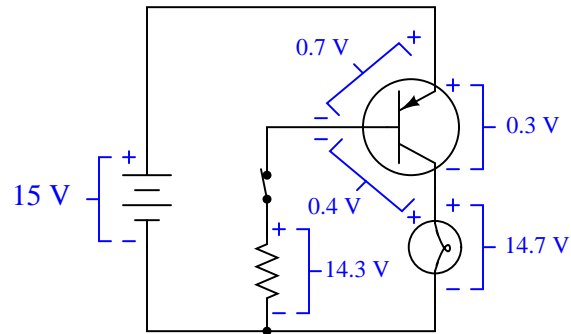
Notes 19

An interesting point that some students may bring up is the 0.4 volt drop across the base-collector junction. Attentive students will note that this junction is supposed to be reverse-biased, but Kirchhoff's Voltage Law clearly specifies the polarity of that 0.4 volt drop, and it is in the direction one would expect for *forward biasing* of that junction. An examination of the energy diagram for a conducting bipolar junction transistor is really necessary to explain why that junction is considered to be reverse-biased.

Question 20

A student attempts to build a circuit that will turn a DC motor on and off with a very delicate (low current rating) pushbutton switch. Unfortunately, there is something wrong with the circuit, because the motor does not turn on no matter what is done with the switch:

This circuit does not work!
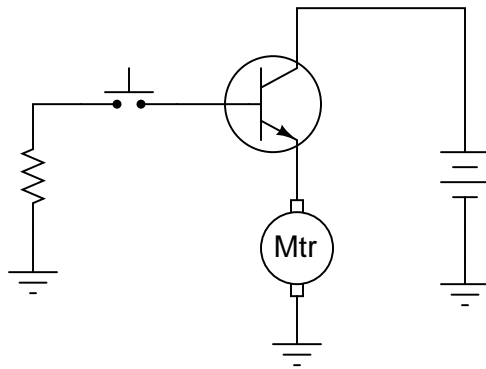
Correct the error(s) in this circuit, showing how it must be set up so that the transistor functions as intended.

file 02047

Answer 20
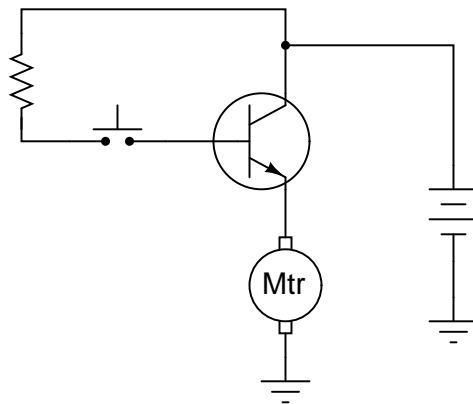
Notes 20

It is very important for your students to learn how the base current controls the collector current in a BJT, and how to use this knowledge to properly set up switching circuits. This is not difficult to learn, but it takes time and practice for many students to master. Be sure to spend adequate time discussing this concept (and circuit design techniques) so they all understand.

Question 21

Some of the following transistor switch circuits are properly configured, and some are not. Identify which of these circuits will function properly (i.e. turn on the load when the switch closes) and which of these circuits are mis-wired:

Circuit 1
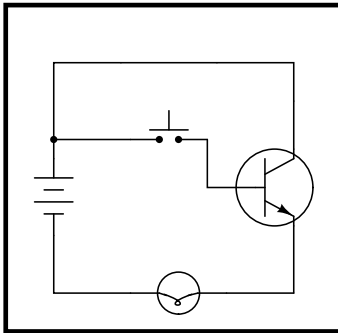
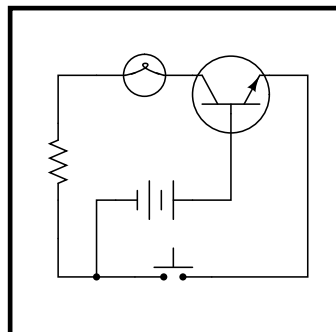Circuit 2
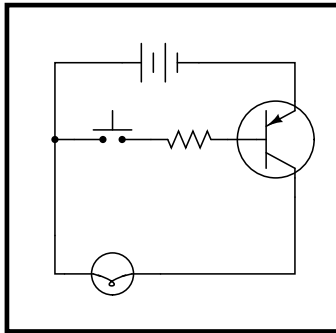
Circuit 3
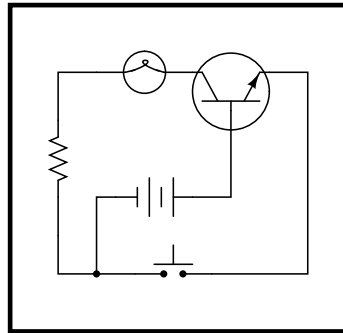
Circuit 4
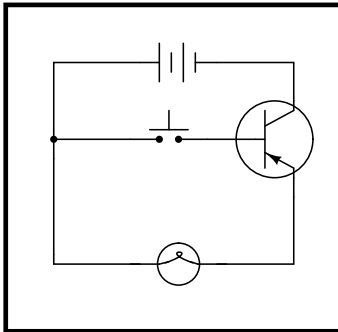
Circuit 5
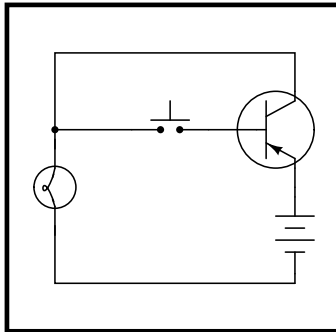
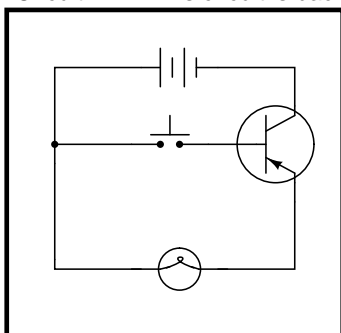Circuit 6
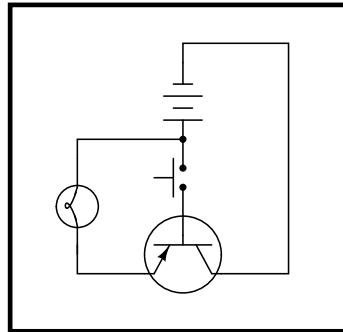
file 02409

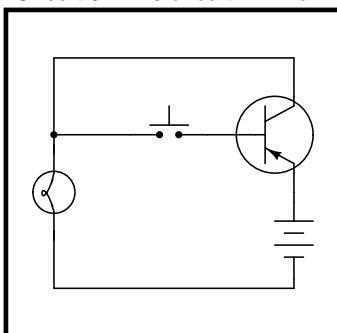Circuit 1 *This circuit will work!*
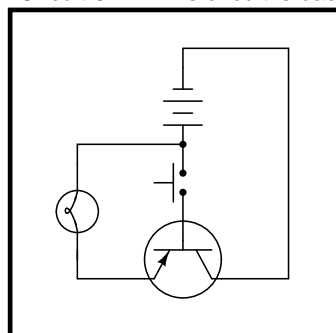Circuit 2   This circuit is bad
Circuit 3   This circuit is bad
Circuit 4   This circuit is bad
Circuit 5 *This circuit will work!*
Circuit 6   This circuit is bad
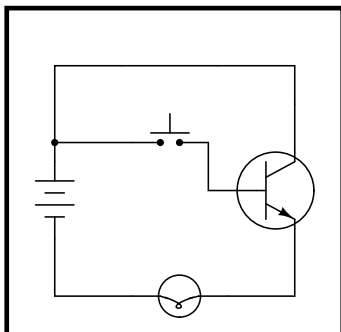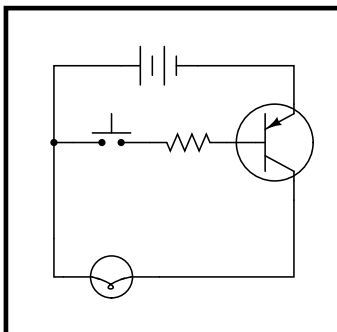
Follow-up question: circuit #3 is different from the other "bad" circuits. While the other bad circuits' lamps do not energize at all, the lamp in circuit #3 energizes weakly when the pushbutton switch is open (not actuated). Explain why.
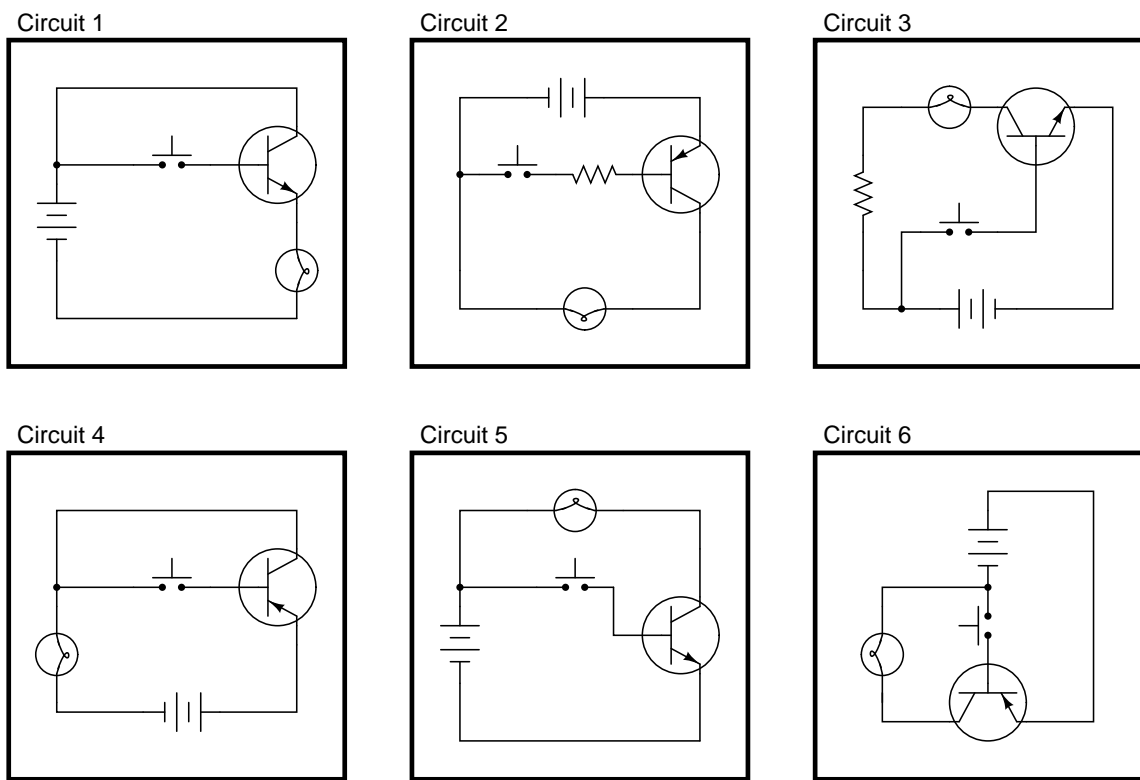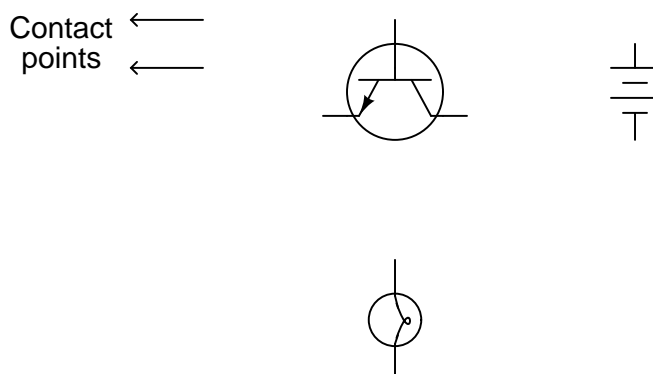
Notes 21

This is a very important concept for students to learn if they are to do any switch circuit design – a task not limited to engineers. Technicians often must piece together simple transistor switching circuits to accomplish specific tasks on the job, so it is important for them to be able to design switching circuits that will work.

Have your students describe to the class how they were able to determine the status of each circuit, so that everyone may learn new ways of looking at this type of problem. Also have them describe what would have to be changed in the "bad" circuits to make them functional.

Question 22

In each of the following circuits, the light bulb will energize when the pushbutton switch is actuated. Assume that the supply voltage in each case is somewhere between 5 and 30 volts DC (with lamps and resistors appropriately sized):

However, not all of these circuits are properly designed. Some of them will function perfectly, but others will function only once or twice before their transistors fail. Identify the faulty circuits, and explain why they are flawed.

file 02048

Answer 22

Circuits 3, 5, and 6 are flawed, because the emitter-base junctions of their transistors are overpowered every time the switch closes.

Hint: draw the respective paths of switch and lamp current for each circuit!

Notes 22

This is a very important concept for students to learn if they are to do any switch circuit design – a task not limited to engineers. Technicians often must piece together simple transistor switching circuits to accomplish specific tasks on the job, so it is important for them to be able to design switching circuits that will be reliable. A common mistake is to design a circuit so that the transistor receives full supply voltage across the emitter-base junction when "on," as three of the circuits in this question do. The result is sure destruction of the transistor if the supply voltage is substantial.

Circuit #3 is a tricky one! The presence of a resistor might fool some students into thinking base current is limited (as is the case with circuit #2).
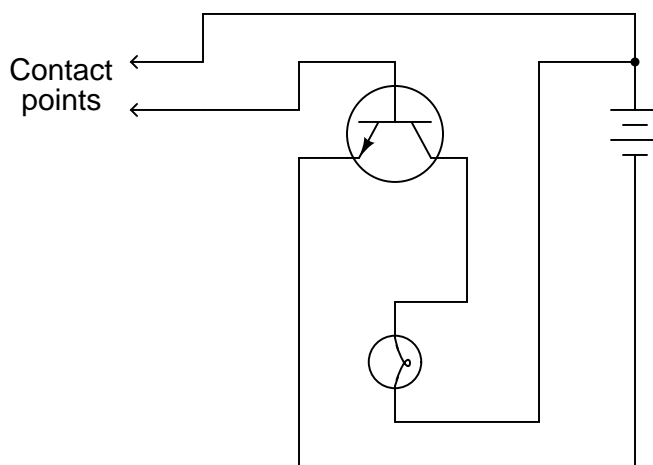
Question 23

Draw the necessary wire connections so that bridging the two contact points with your finger (creating a high-resistance connection between those points) will turn the light bulb on:

Answer 23

Notes 23

Once students learn to identify the two current paths (base versus collector), especially the proper directions of current for each, the interconnections become much easier to determine.

Some students may place the light bulb on the emitter terminal of the transistor, in a common-collector configuration. This is not recommended, since it places the light bulb in series with the controlling (base) current path, and this will have the effect of impeding base current, and therefore the controlled (light bulb) current. Given the very high electrical resistance of human skin, this circuit needs all the gain we can possibly muster!

This circuit works well if an LED is substituted for the incandescent lamp.

The ignition system of a gasoline-powered internal combustion automobile engine is an example of a transformer operated on DC by means of an oscillating switch contact, commonly referred to as the contact "points":
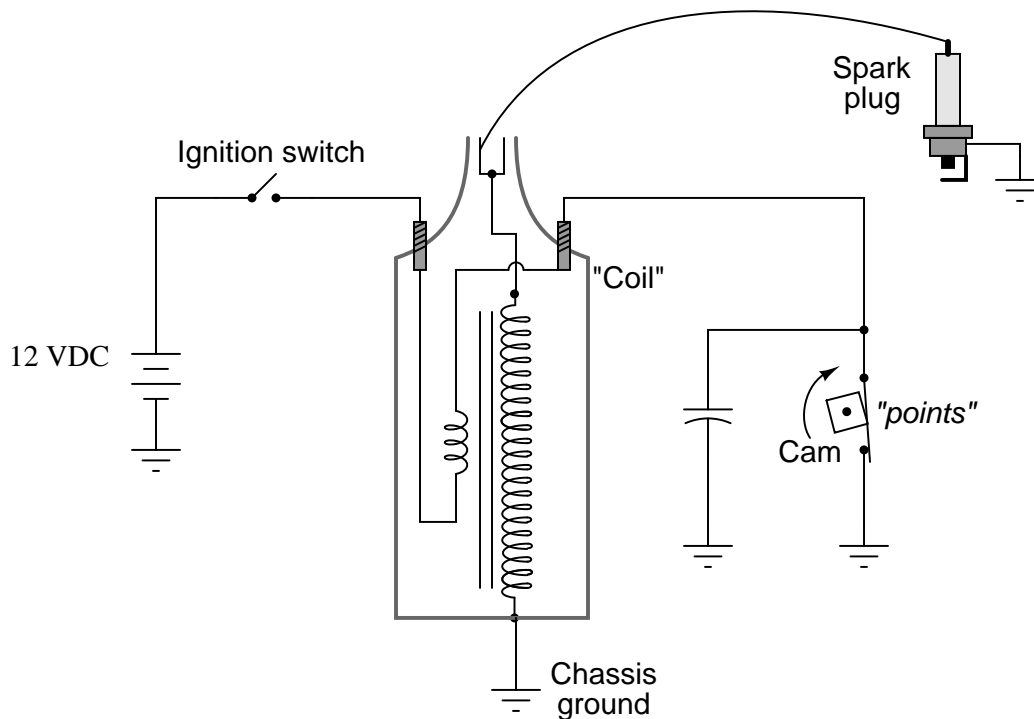

The cam-actuated "point" contacts open every time a spark is needed to ignite the air-fuel mixture in one of the engine's cylinders. Naturally, these contacts suffer a substantial amount of wear over time due to the amount of current they must make and break, and the frequency of their cycling.

This device was seen by automotive engineers as a prime candidate for replacement with solid-state technology (i.e., a transistor). If a transistor could take the place of mechanical "point" contacts for making and breaking the ignition coil's current, it should result in increased service life.

Insert a transistor into the following circuit in such a way that it controls the ignition coil's current, with the "point" contacts merely controlling the transistor's state (turning it on and off):

Ignition switch

Spark
plug

"Coil"

12 VDC

"points"

Cam

Chassis
ground
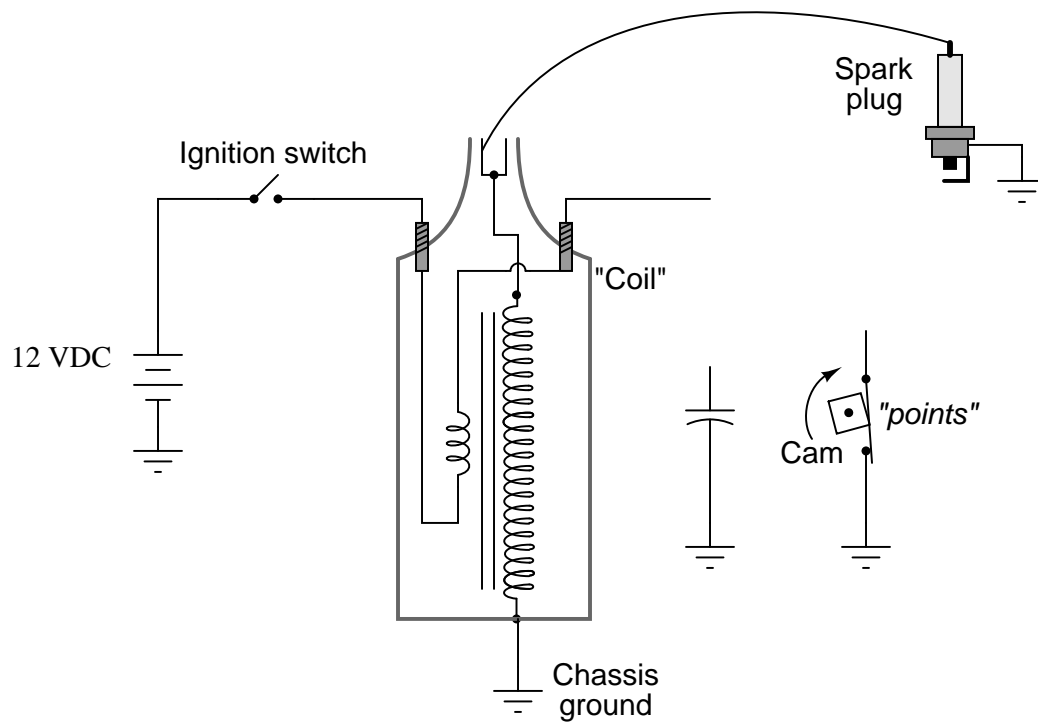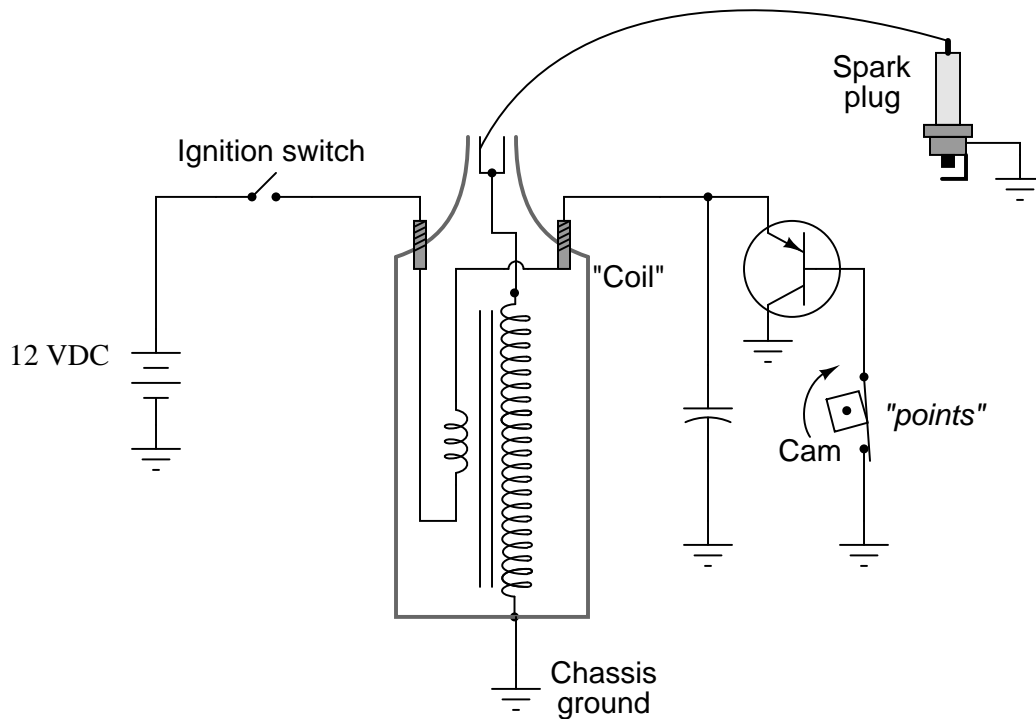
Follow-up question: assuming the primary winding of the "coil" has an inductance of 9 mH an a wire resistance of 0.4 Ω, determine the amount of time necessary to build to full current once the transistor or points have turned on (after 5 time constants' worth of time).

Notes 24

Ask your students, "what is the purpose of the capacitor in this circuit?" Inform them that without it, the points would have "burned up" very quickly, and that the transistor will fail almost immediately!

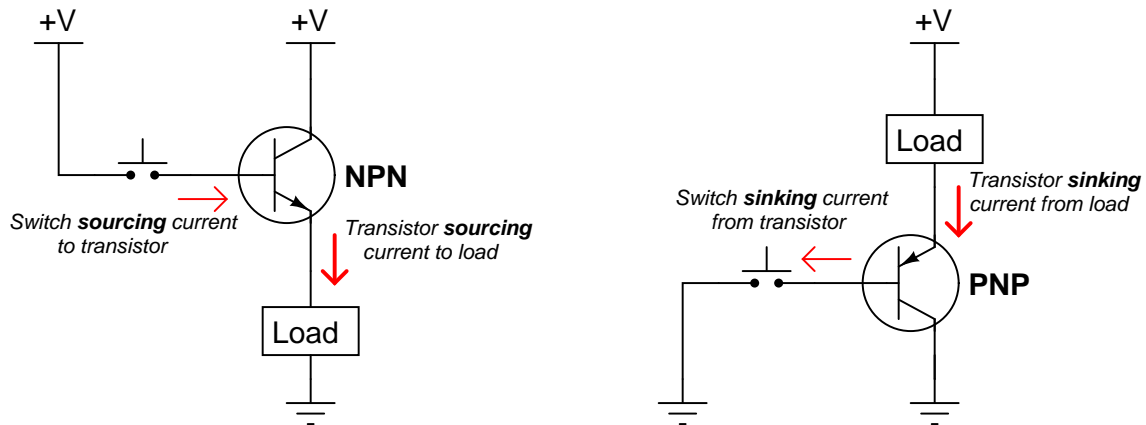Some of your students familiar with engine ignition systems will notice that there is no distributor for multiple spark plugs. In other words, this circuit is for a single-cylinder engine! I chose not to draw a distributor in this schematic just to keep things simple.

Question 25

Electronic ignition systems for gasoline-powered engines typically use a device called a *reluctor* to trigger the transistor to turn on and off. Shown here is a simple reluctor-based electronic ignition system:
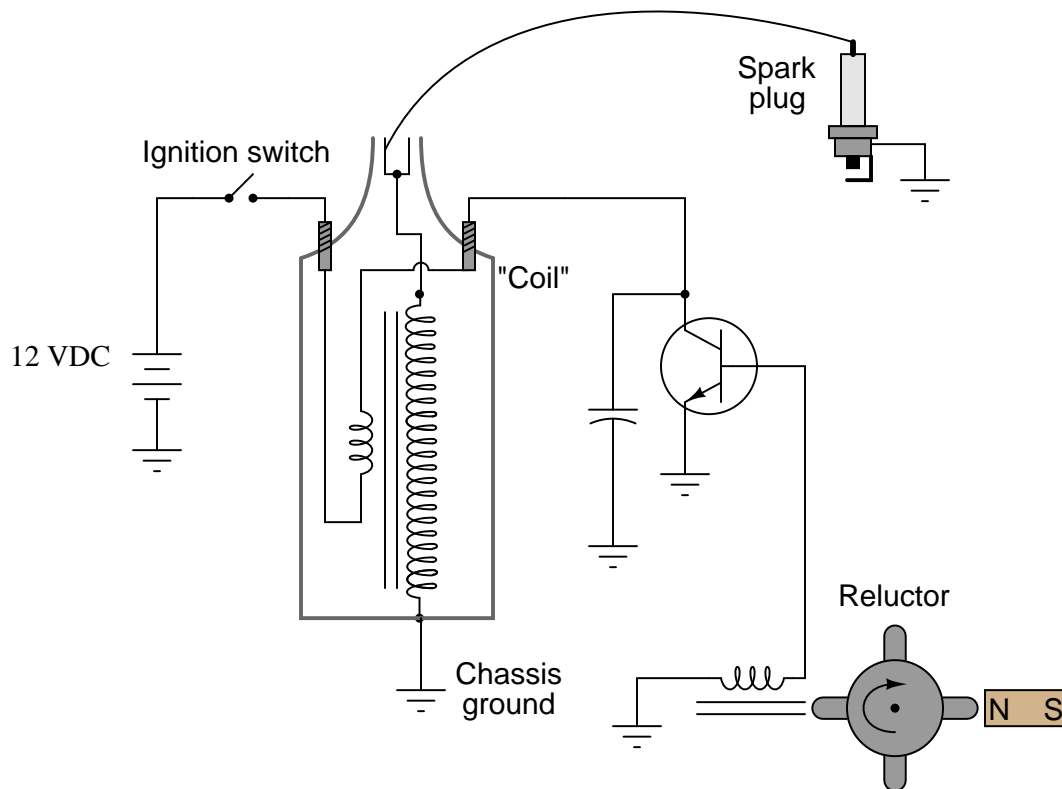
Explain how this circuit functions. Why do you think the triggering device is called a "reluctor"? What advantage(s) does this circuit have over a mechanical "point" operated ignition system?

file 00448

Answer 25

The "reluctor" generates pulses of current to the transistor's base to turn it on and off. The word "reluctor" is applied to this device in honor of a certain magnetic principle you should know!

Notes 25

Discuss the advantages of a reluctor-triggered ignition system with your students. As far as I am aware, the system possesses no disadvantages when compared against mechanical point-driven systems.

An interesting side note: one method of testing a reluctor-driven ignition system at high frequencies was to hold the tip of a soldering gun (not a soldering *iron*!) next to the pickup coil and pull the trigger. The strong magnetic field produced by the gun's high current (60 Hz AC) would trigger the ignition system to deliver 60 sparks per second.

Some of your students familiar with engine ignition systems will notice that there is no distributor for multiple spark plugs. In other words, this circuit is for a single-cylinder engine! I chose not to draw a distributor in this schematic just to keep things simple.
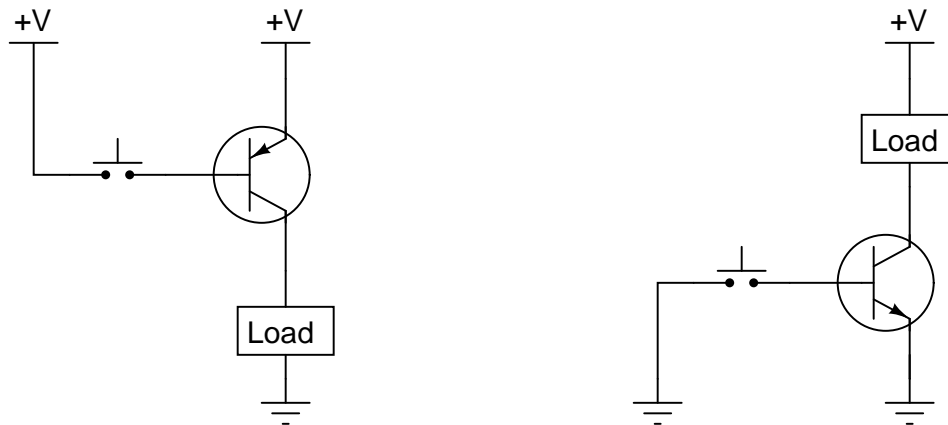
34

Question 26

Choose the right type of bipolar junction transistor for each of these switching applications, drawing the correct transistor symbol inside each circle:
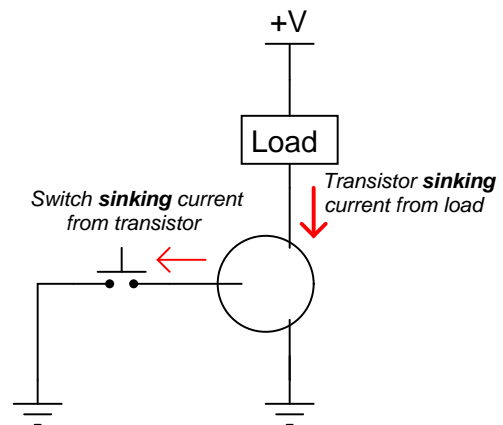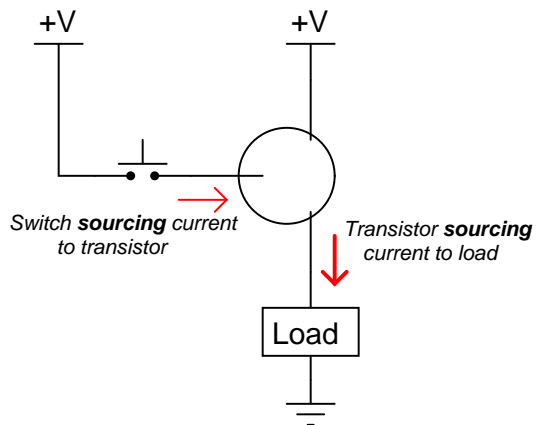
file 02407

Follow-up question: explain why neither of the following transistor circuits will work. When the pushbutton switch is actuated, the load remains de-energized:
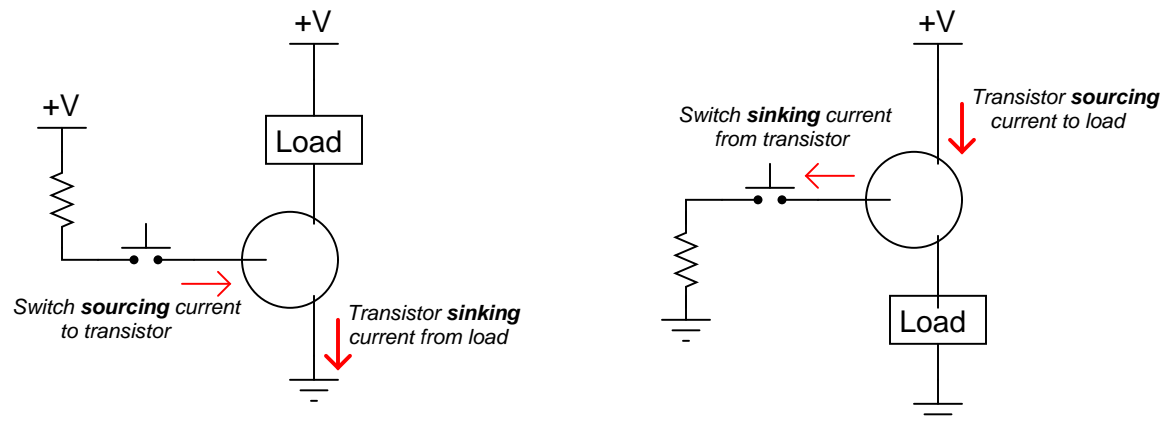
Discuss with your students the meaning of the words "sourcing" and "sinking" in case they are not yet familiar with them. These are very common terms used in electronics (especially digital and power circuitry!), and they make the most sense in the context of conventional flow current notation.

In order for students to properly choose and place each transistor to make the circuits functional, they must understand how BJTs are triggered on (forward-biasing of the base-emitter junction) and also which directions the currents move through BJTs. The two example circuits shown in this question are very realistic.
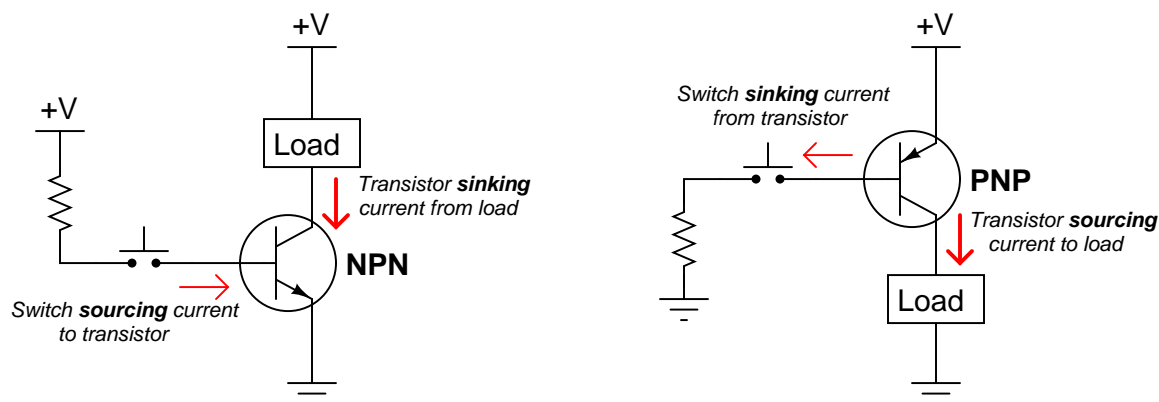
Question 27

Choose the right type of bipolar junction transistor for each of these switching applications, drawing the correct transistor symbol inside each circle:
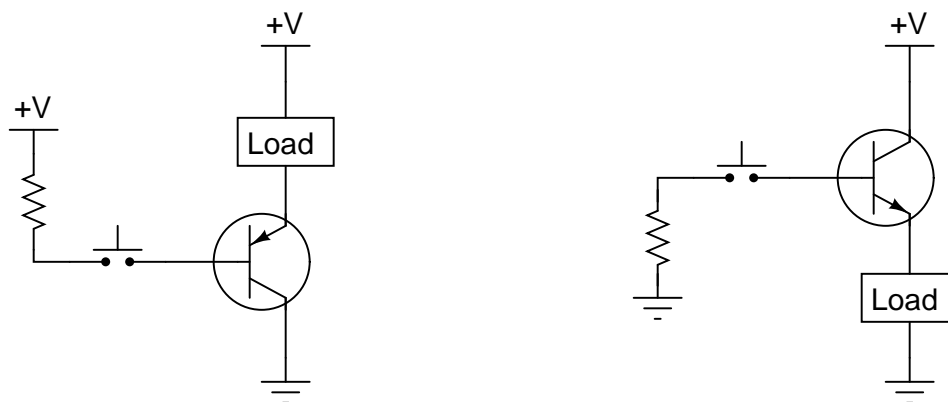

Also, explain why resistors are necessary in both these circuits for the transistors to function without being damaged.

file 02408

Answer 27

Follow-up question: explain why neither of the following transistor circuits will work. When the pushbutton switch is actuated, the load remains de-energized:

Notes 27

Discuss with your students the meaning of the words "sourcing" and "sinking" in case they are not yet familiar with them. These are very common terms used in electronics (especially digital and power circuitry!), and they make the most sense in the context of conventional flow current notation.

In order for students to properly choose and place each transistor to make the circuits functional, they must understand how BJTs are triggered on (forward-biasing of the base-emitter junction) and also which directions the currents move through BJTs. The two example circuits shown in this question are very realistic.
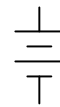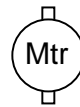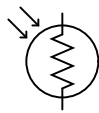
Question 28

An easy way to increase the effective current gain of a transistor is to "cascade" two of them in a configuration called a *Darlington pair*:
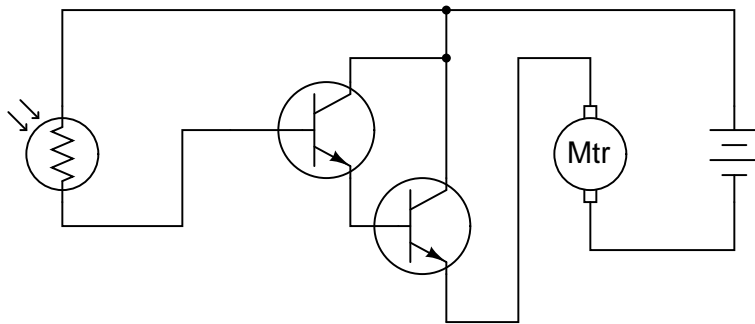
Darlington pair
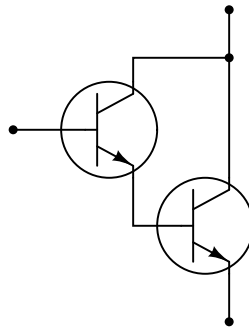
Complete this schematic diagram, showing how a Darlington pair could be used to enable a cadmium sulfide (CdS) photocell to turn a motor on and off:


file 00956

Answer 28

Notes 28

Ask your students to define "gain" as it applies to a transistor circuit. Ask them to explain why a Darlington pair has a greater current gain than a single transistor, and why that trait is important in a circuit such as this.

Question 29

Explain how the one toggle switch is able to switch *both* transistors on and off simultaneously in this motor control circuit:
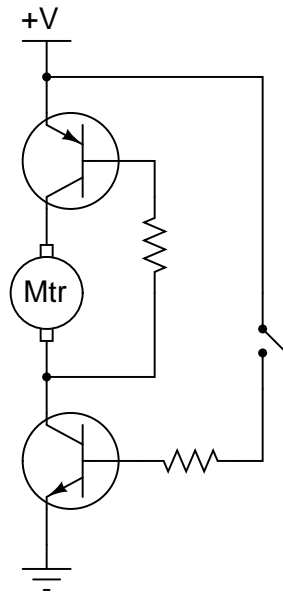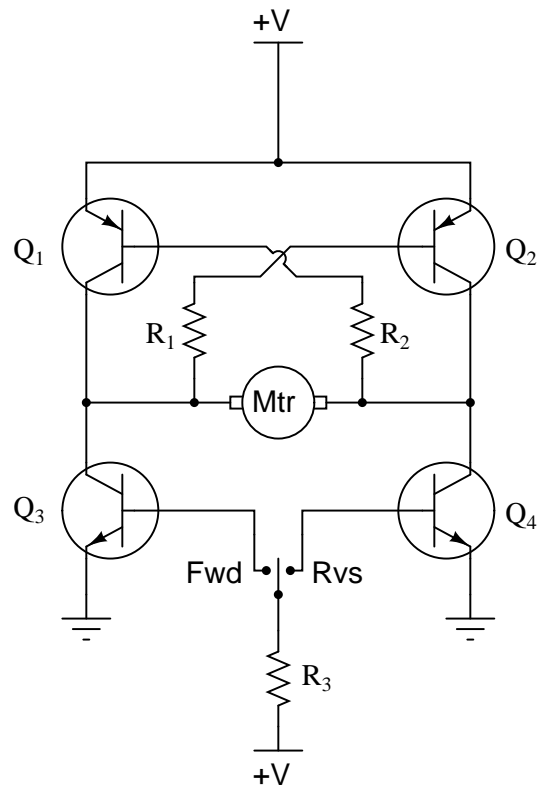

<u>file 02410</u>

Answer 29

The switch exerts direct control over the lower transistor, which then indirectly turns on the upper transistor. When both transistors are turned on, the motor runs.

Notes 29

This question is really a precursor to analyzing the H-bridge motor drive circuit.

Question 30

Explain the operation of this "H-bridge" motor control circuit:

At any given moment, how many transistors are turned on and how many are turned off? Also, explain what would happen to the function of the circuit if resistor R1 failed open.

file 00449

Answer 30

Two transistors are on at any given time, and the other two are off. If R1 fails open, the motor will not be able to go in the "forward" (Fwd) direction.

Challenge question: what type of DC motor is this drive circuit designed for? Shunt-wound, series-wound, compound, or permanent magnet? Explain your answer.

Notes 30

The "H-drive" circuit is a very common method of reversing polarity to a DC motor (or other polarity-sensitive load), using only a single-pole switch. Very, very large electric motor "drives" have been based on this same design.

Question 31

The dark shaded area drawn in this cross-section of a PN junction represents the *depletion region*:
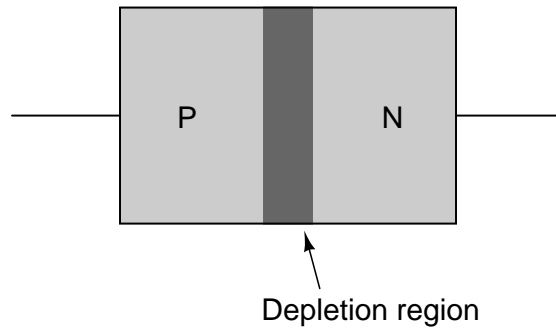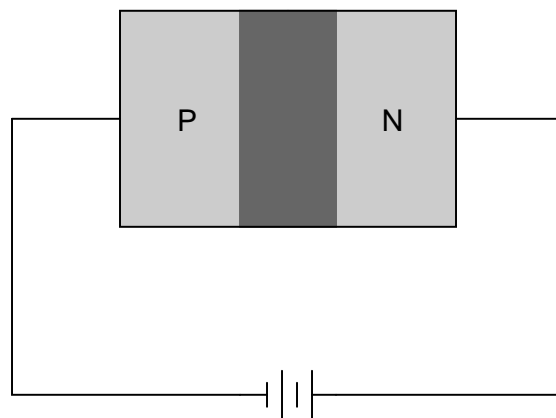

Re-draw the depletion region when the PN junction is subjected to a reverse-bias voltage:
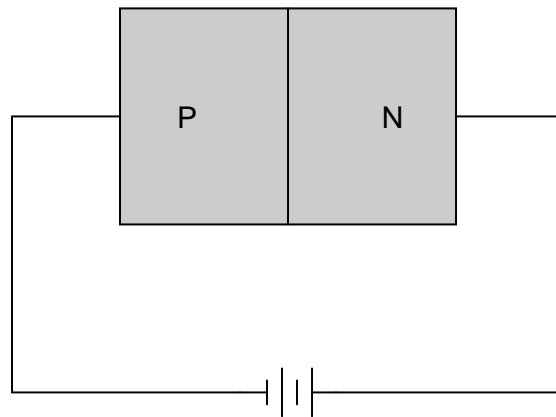

file 02053

Answer 31

Follow-up questions: describe the conductivity of the depletion region: is it high or low? What exactly does the word "depletion" refer to, anyway?

This question makes a good lead-in to a discussion of JFET operation, where the channel conductivity is modulated by the width of the gate-channel depletion region.

Question 32

A *field-effect transistor* is made from a continuous "channel" of doped semiconductor material, either N or P type. In the illustration shown below, the channel is N-type:
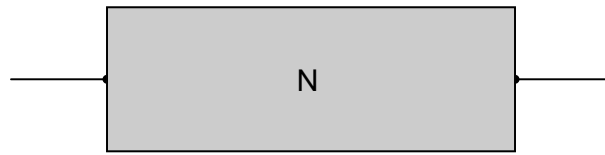
Trace the direction of current through the channel if a voltage is applied across the length as shown in the next illustration. Determine what type of charge carriers (electrons or holes) constitute the majority of the channel current:
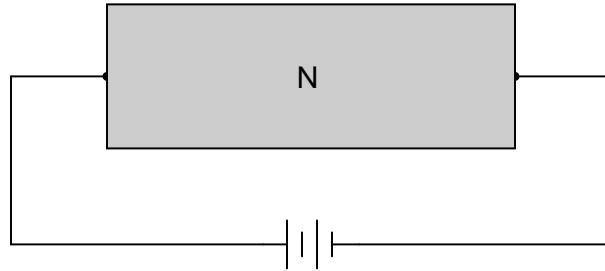

The next step in the fabrication of a field-effect transistor is to implant regions of oppositely-doped semiconductor on either side of the channel as shown in the next illustration. These two regions are connected together by wire, and called the "gate" of the transistor:
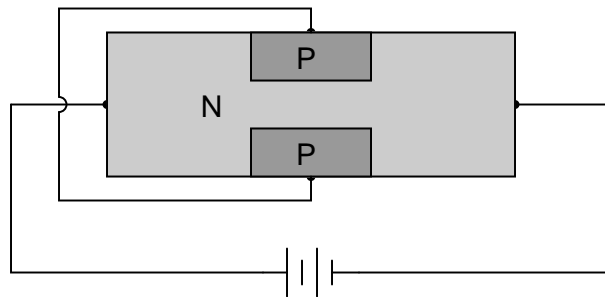
Show how the presence of these "gate" regions in the channel influence the flow of charge carriers. Use small arrows if necessary to show how the charge carriers move through the channel and past the gate regions of the transistor. Finally, label which terminal of the transistor is the *source* and which terminal is the *drain*, based on the type of majority charge carrier present in the channel and the direction of those charge carriers' motion.

file 02054

Answer 32

The majority charge carriers in this transistor's channel are electrons, not holes. Thus, the arrows drawn in the following diagrams point in the direction of electron flow:
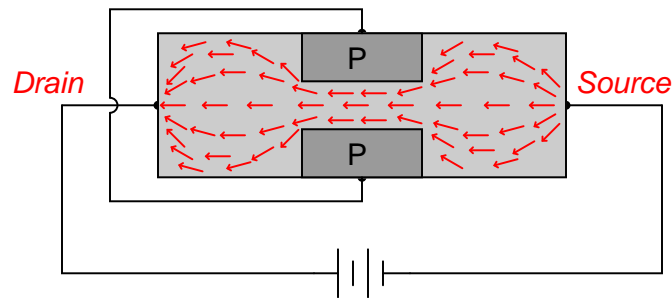
This makes the right-hand terminal the *source* and the left-hand terminal the *drain*.

Follow-up question: explain why the charge carriers avoid traversing the PN junctions formed by the gate-channel interfaces. In other words, explain why we do *not* see this happening:

Notes 32
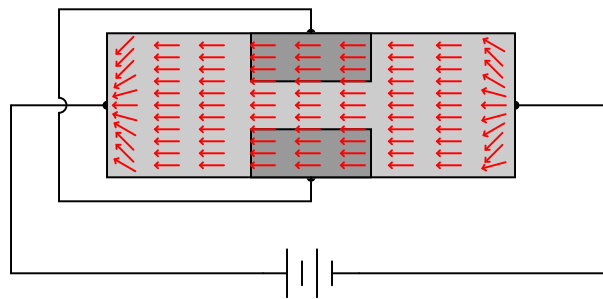
Students typically find junction field-effect transistors much easier to understand than bipolar junction transistors, because there is less understanding of energy levels required to grasp the operation of JFETs than what is required to comprehend the operation of BJTs. Still, students need to understand how different charge carriers move through N- and P-type semiconductors, and what the significance of a depletion region is.

Question 33

Field-effect transistors (FETs) exhibit depletion regions between the oppositely-doped gate and channel sections, just as diodes have depletion regions between the P and N semiconductor halves. In this illustration, the depletion region appears as a dark, shaded area:
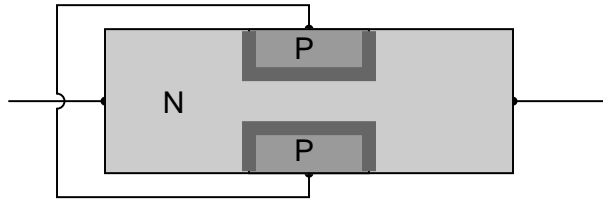
Re-draw the depletion regions for the following scenarios, where an external voltage (V_{GS}) is applied between the gate and channel:
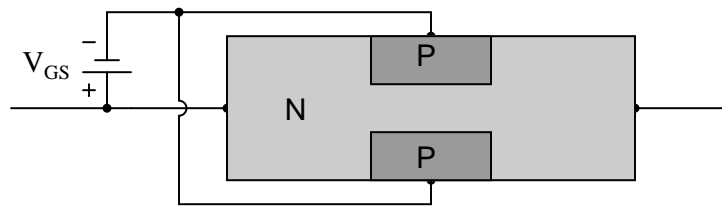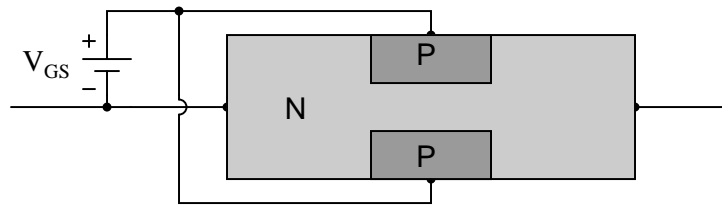
Note how the different depletion region sizes affect the conductivity of the transistor's channel.
file 02055
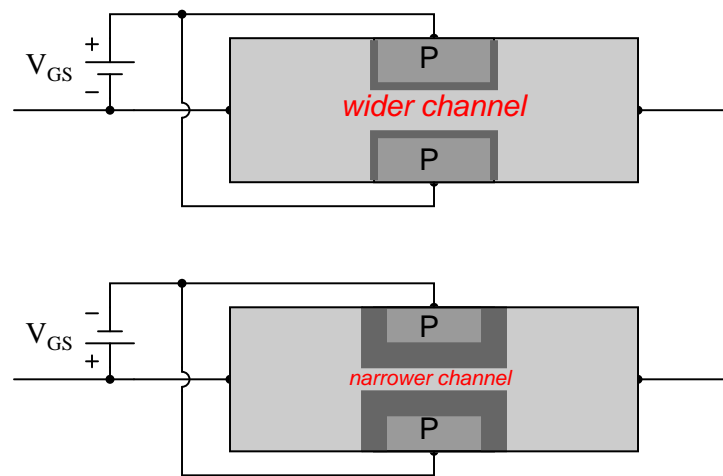
Follow-up question: why do you suppose this type of transistor is called a *field-effect* transistor? What "field" is being referred to in the operation of this device?

Notes 33

The effect that this external gate voltage has on the effective width of the channel should be obvious, leading students to understand how a JFET allows one signal to exert control over another (the basic principle of *any* transistor, field-effect or bipolar).

Question 34

Bipolar junction transistors (BJTs) are considered "normally-off" devices, because their natural state with no signal applied to the base is no conduction between emitter and collector, like an open switch. Are junction field-effect transistors (JFETs) considered the same? Why or why not?

file 02056

Answer 34

JFETs are "normally-on" devices.

Notes 34

Ask your students to elaborate on the answer given. Do not accept a mindless recitation of the answer, "JFETs are normally-on devices," but rather demand that some sort of explanation be given as to *why* JFETs are normally-on devices.

Question 35

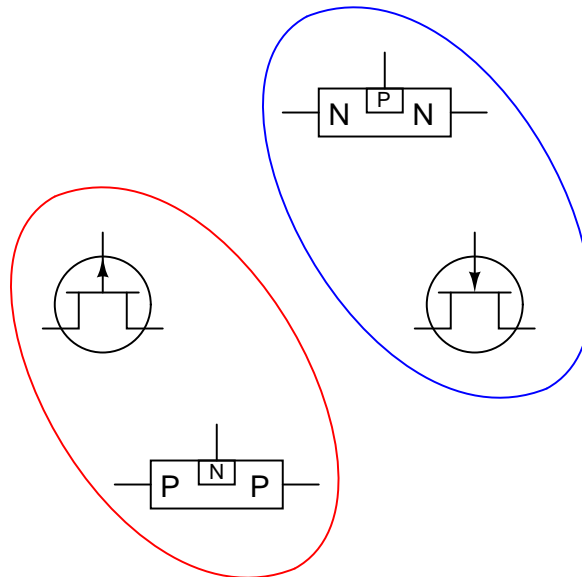Match the following field-effect transistor illustrations to their respective schematic symbols:
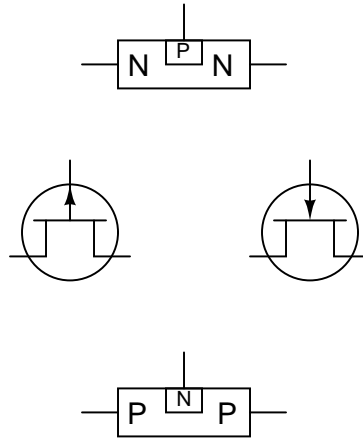
file 00986

Answer 35

Notes 35

Be sure to ask your students to identify which symbol is the "P-channel" and which is the "N-channel" transistor!

It might help to review diode symbols, if some students experience difficulty in matching the designations (P-channel versus N-channel) with the schematic symbols.

Question 36

Based on these DC continuity tester indications, what type of JFET is this, N-channel or P-channel?

- Resistance with negative test lead on pin 1, positive test lead on pin 2: *no continuity*
- Resistance with negative test lead on pin 1, positive test lead on pin 3: *no continuity*
- Resistance with negative test lead on pin 2, positive test lead on pin 1: **continuity**
- Resistance with negative test lead on pin 2, positive test lead on pin 3: **continuity**
- Resistance with negative test lead on pin 3, positive test lead on pin 1: **continuity**
- Resistance with negative test lead on pin 3, positive test lead on pin 2: **continuity**

Also, to the best of your ability, identify the transistor's three terminals (source, gate, and drain).
file 00992

Answer 36

This is an N-channel JFET. Pin 1 is the gate, and pins 2 and 3 are drain/source or source/drain (interchangeable).
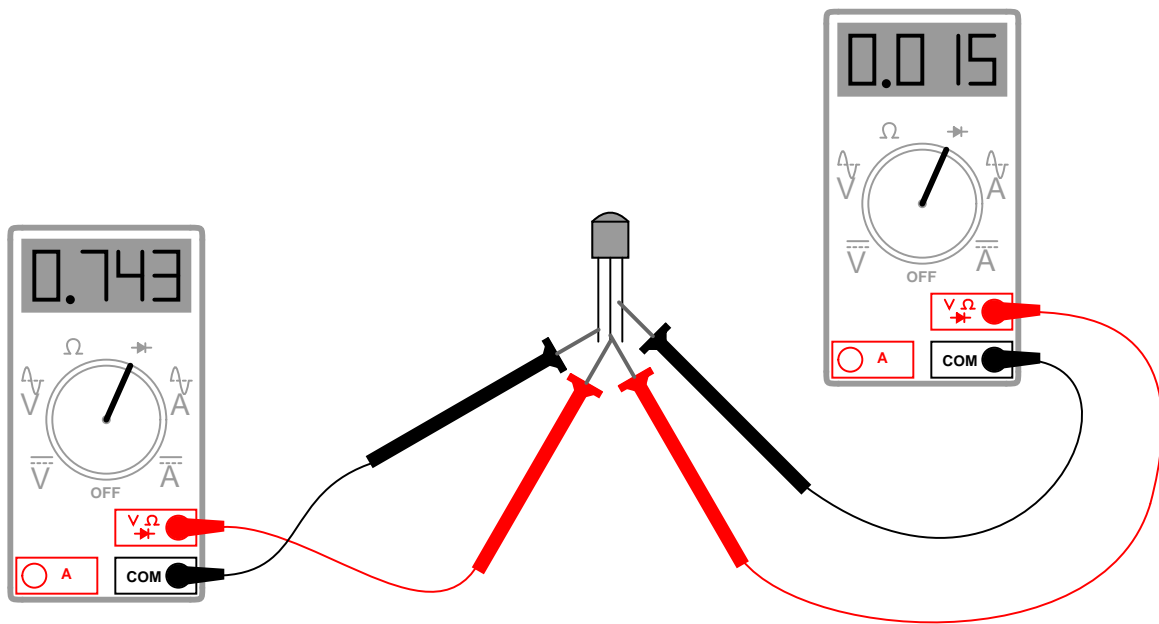
Notes 36

Advise your students about the risks of using an analog multimeter (in ohmmeter mode) to test semiconductor components. Some inexpensive analog multimeter designs actually *switch* the polarity of the test leads when in the ohmmeter mode. In other words, the red test lead actually connects to the negative side of the meter's internal battery, while the black test lead connects to the positive side of the internal battery! If you are used to associating red with positive and black with negative, this switch will be quite a surprise.

Ask your students: what effect would a switch in polarity such as the one just described have on the determination of a transistor's identity? What if the person thought their meter's red lead was positive and the black lead negative, when in fact it was just the opposite? Would this affect their ability to accurately identify the transistor's terminals? Why or why not?

Question 37

From the "diode check" measurements taken with these two meters, identify the terminals on this JFET, and also what type of JFET it is (N-channel or P-channel):


file 02058

Answer 37

The left-most terminal on this JFET is the gate, and the other two are source and drain. This is a P-channel JFET.

Notes 37

Ask your students to explain why the gate-channel junction registers a voltage drop of 0.743 volts, while the source-drain path only registers 15 millivolts of drop. What does this indicate about the conductivity of JFET compared to that of a BJT? Also, what does this suggest about the minimum source-drain voltage necessary for controlled current to go through the JFET?
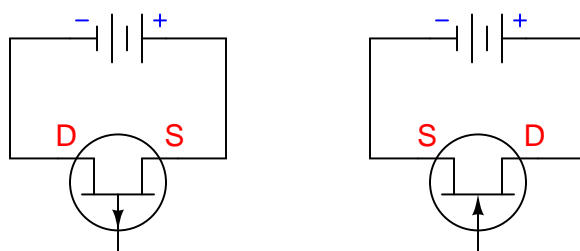
Question 38

Identify which transistor terminal functions as the *source* and which transistor terminal functions as the *drain* in both of these JFET circuits:
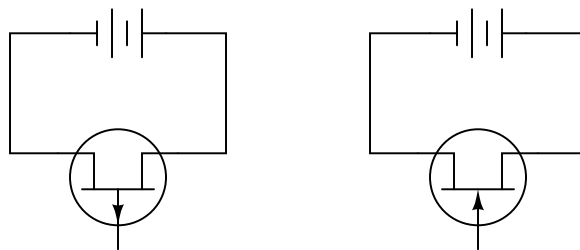
Most importantly, explain *why* we define the terminals as such, given the fact that is usually no physical difference between these two terminals of a JFET.

file 03842

Answer 38

The "why" answer is related to the type of majority charge carrier within the channel of each JFET.

Notes 38

The distinction between source and drain for any kind of FET (JFET or MOSFET) is important because the controlling voltage (V_{GS}) must be applied between gate and *source*, not between gate and *drain*.

Question 39

Junction field-effect transistors (JFETs) are *normally-on* devices, the natural state of their channels being passable to electric currents. Thus, a state of cutoff will only occur on command from an external source.

Explain what must be done to a JFET, specifically, to drive it into a state of cutoff.

file 02411

Answer 39

The gate-channel PN junction must be *reverse-biased*: a voltage applied between gate and source such that the negative side is connected to the "P" material and the positive side to the "N" material.

Follow-up question: is any gate *current* required to drive a JFET into the cutoff state? Why or why not?

Notes 39

This is perhaps the most important question your students could learn to answer when first studying JFETs. What, exactly, is necessary to turn one off? Have your students draw diagrams to illustrate their answers as they present in front of the class.

Question 40

Explain what *cutoff voltage* ($V_{GS(off)}$) is for a field-effect transistor. Research the datasheets for some of the following field-effect transistors and determine what their respective cutoff voltages are:

- J110
- J308
- J309
- J310
- MPF 102

file 02057

Answer 40

I'll let you research the definition of $V_{GS(off)}$ and the parameters of these specific field-effect transistors.

Follow-up question: based on your research of these datasheets, how constant is $V_{GS(off)}$ between different transistors? In other words, is this a parameter you can accurately predict from the datasheet before purchasing a transistor, or does it vary significantly from transistor to transistor (of the same part number)?

Notes 40

Discuss with your students the significance of $V_{GS(off)}$, especially its stability (or instability, as the case may be) between transistors. How does this impact the design of FET circuits?

Question 41

The equation solving for drain current through a JFET is as follows:

$$I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_{GS(off)}} \right)^2$$

Where,

I_D = Drain current

I_{DSS} = Drain current with the Gate terminal shorted to the Source terminal

V_{GS} = Applied Gate-to-Source voltage

$V_{GS(off)}$ = Gate-to-Source voltage necessary to "cut off" the JFET

Algebraically manipulate this equation to solve for V_{GS}, and explain why this new equation might be useful to us.

file 03710

Answer 41

$$V_{GS} = V_{GS(off)} \left(1 - \sqrt{\frac{I_D}{I_{DSS}}} \right)$$

Notes 41

This question is primarily an exercise in algebraic manipulation. Have your students show their work in front of the class, to show others the strategy involved to manipulate such an equation.

Question 42

The power dissipation of a JFET may be calculated by the following formula:

$$P = V_{DS}I_D + V_{GS}I_G$$

For all practical purposes, though, this formula may be simplified and re-written as follows:

$$P = V_{DS}I_D$$

Explain why the second term of the original equation ($V_{GS}I_G$) may be safely ignored for a junction field-effect transistor.

file 02063

Answer 42

I_G is zero for all practical purposes.

Notes 42

This question asks students to look beyond the equation to the device itself and think about the relative magnitudes of each variable. Many equations in electronics (and other sciences!) may be similarly simplified by recognizing the relative magnitudes of variables and eliminating those whose overall effect on the equation's result will be negligible. Of course, what constitutes "negligible" will vary from context to context.

Question 43

Identify each type of JFET (whether it is N-channel or P-channel), label the terminals, and determine whether the JFET in each of these circuits will be turned *on* or *off*:

file 02412

Answer 43
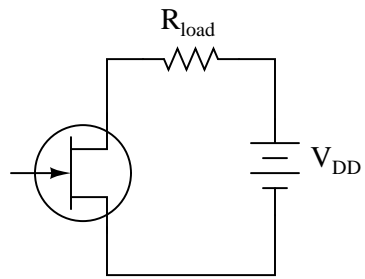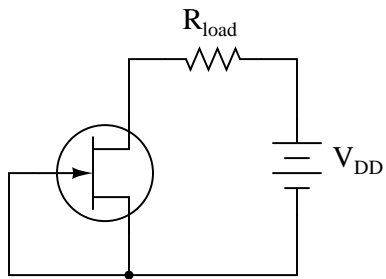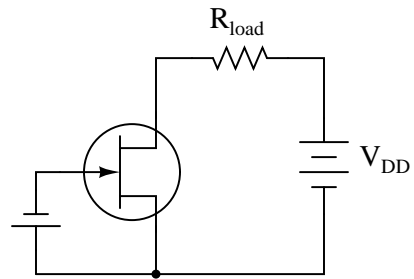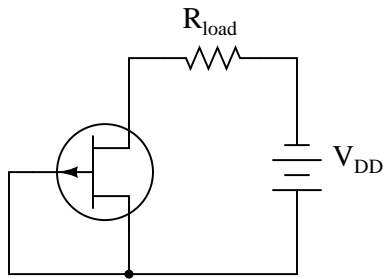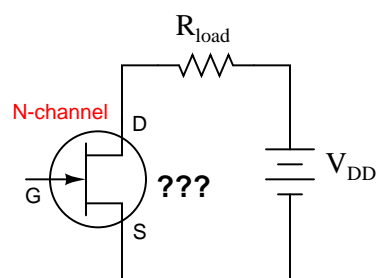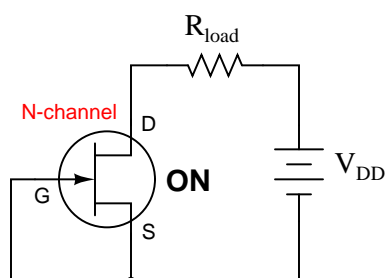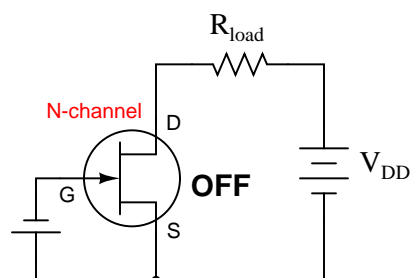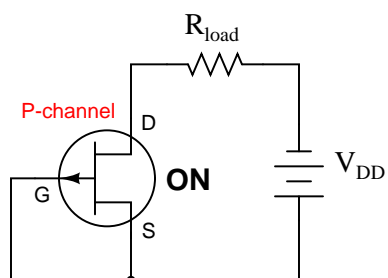
Follow-up question: explain why the lower-right circuit has question-marks next to the transistor. Why is the JFET's state uncertain?

Notes 43

It is very important for your students to understand what factor(s) in a circuit force a JFET to turn on or off. Be sure to ask your students to explain their reasoning for each transistor's status. What factor, or combination of factors, is necessary to turn a JFET on, versus off? One point of this question is to emphasize the non-importance of V_{DD}'s polarity when there is an external biasing voltage applied directly between gate and source.

Question 44

Identify each type of JFET (whether it is N-channel or P-channel), label the terminals, and determine whether the JFET in each of these circuits will be turned *on* or *off*:

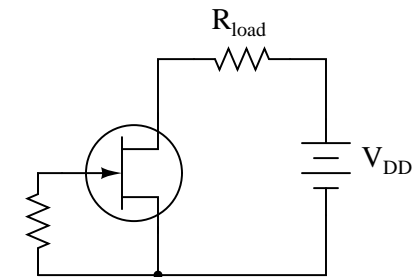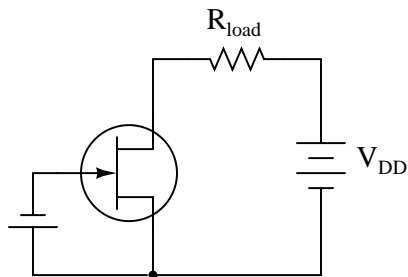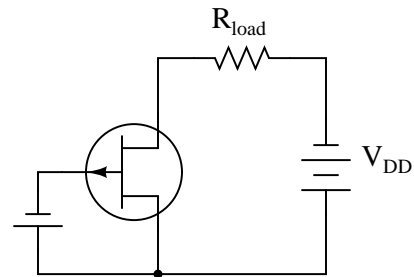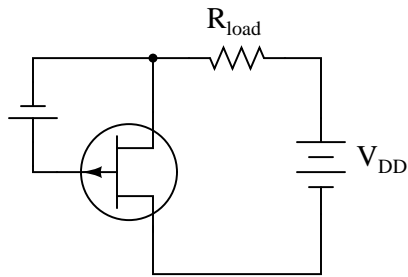Additionally, identify which of these four circuits places unnecessary stress on the transistor. There is one circuit among these four where the transistor is operated in a state that might lead to premature failure.
file 02413

59

Answer 44
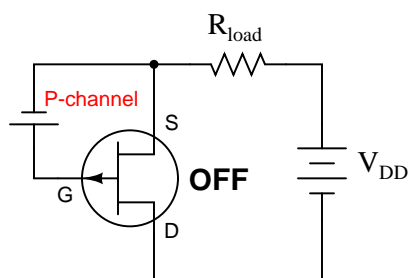
The upper-right circuit places unnecessary stress on the JFET.
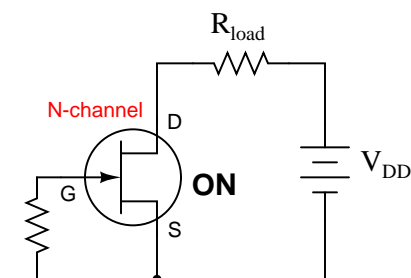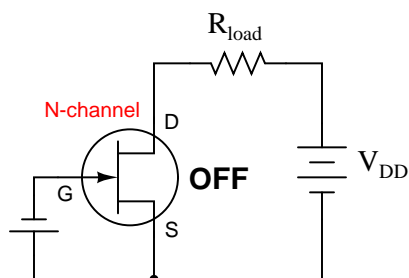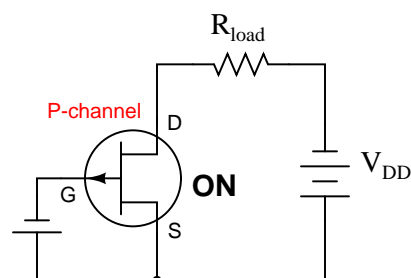
Notes 44

It is very important for your students to understand what factor(s) in a circuit force a JFET to turn on or off. Be sure to ask your students to explain their reasoning for each transistor's status. What factor, or combination of factors, is necessary to turn a JFET on, versus off? One point of this question is to emphasize the non-importance of V_{DD}'s polarity when there is an external biasing voltage applied directly between gate and source.

Discuss with your students precisely what is wrong with the upper-right JFET circuit. Why is the transistor being stressed? How do we avoid such a problem?

Question 45

When a reverse-bias voltage is applied between the gate and channel of a JFET, the depletion region within expands. The greater the reverse-bias voltage, the wider the depletion region becomes. With enough applied V_{GS}, this expansion will cut off the JFET's channel, preventing drain-source current:
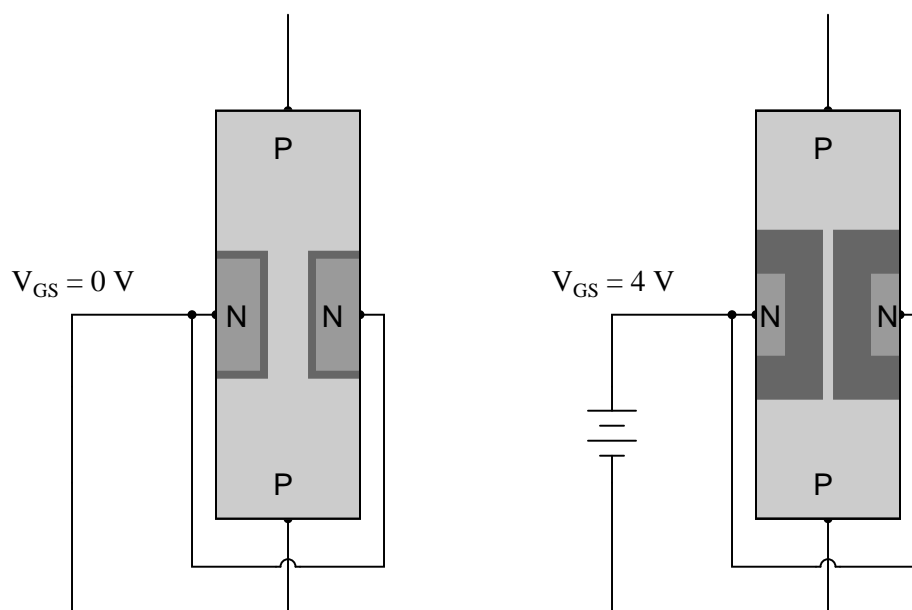
Something not immediately apparent about this effect is that the formation of a wide depletion region necessary for cut-off of a field-effect transistor is *also* affected by the drain-to-source voltage drop (V_{DS}).
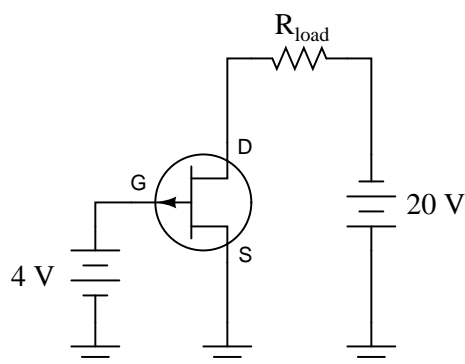
If we connect a gate-to-source voltage (V_{GS}) large enough to force the transistor into cutoff mode, the JFET channel will act as a huge resistance. If we look carefully at the voltages measured with reference to ground, we will see that the width of the depletion region must vary within the JFET's channel. Sketch this varying width, given the voltages shown in the illustration:

Sketch the depletion region within the JFET
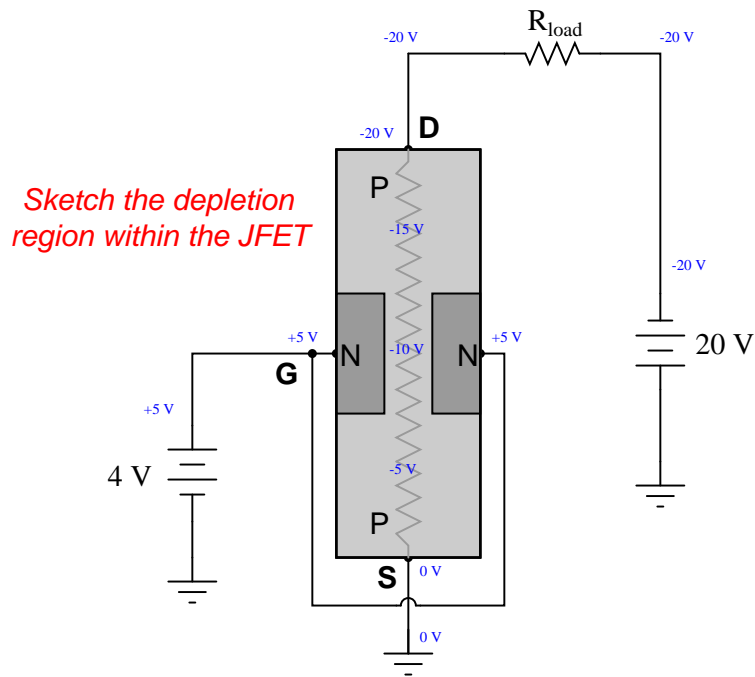
Something *really* interesting happens if we reverse the polarity of the 20 volt source: the relationship between drain and source changes, and so does the depletion region profile. Sketch the new varying width of the depletion region with the 20 volt source reversed, and comment on what you see:

Sketch the depletion region within the JFET
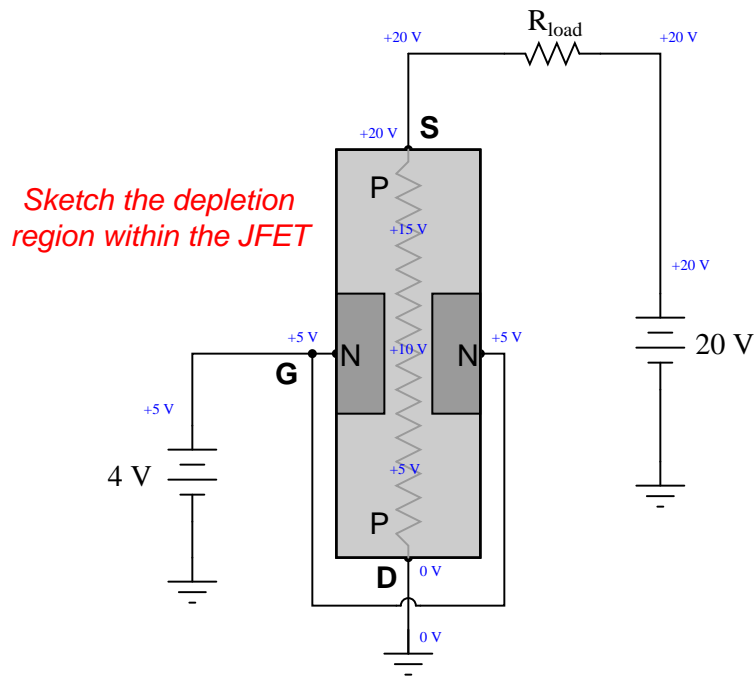
file 03843
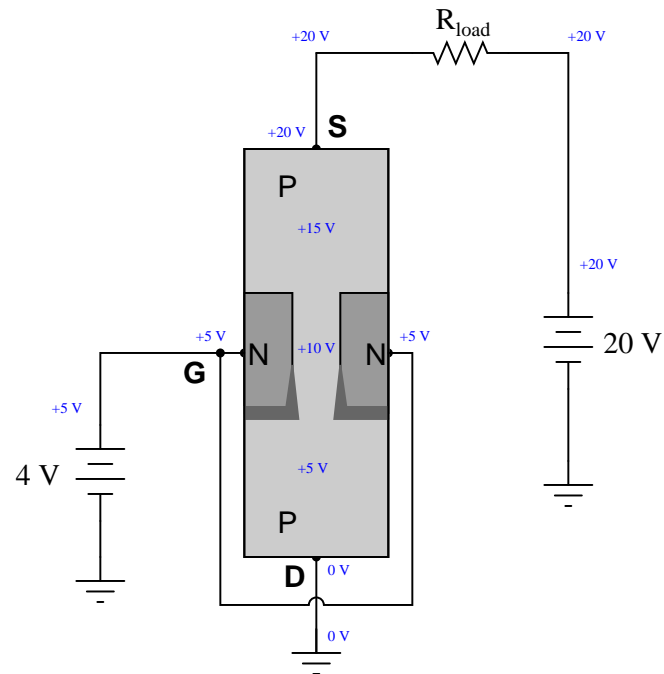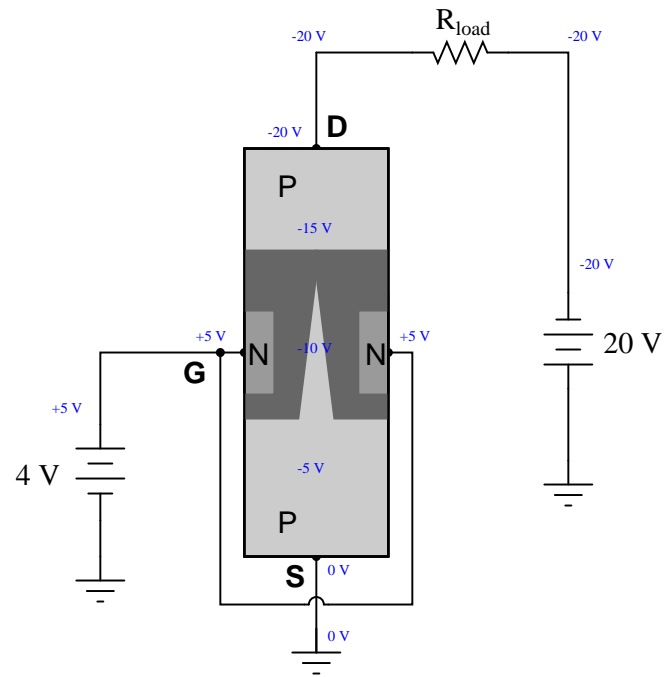
Follow-up question: you can see that the transistor doesn't even cut off as expected with the 20 volt source reversed. What would we have to do to get this JFET to cut off with a only 4 volt control signal, since having reversed the 20 volt source?

There is more than one correct answer for the follow-up question. Discuss this with your students, emphasizing the importance of properly identifying drain and source according to V_{DS} polarity.

Question 46

The following illustration is a cross-section of an *insulated gate field-effect transistor*, sometimes referred to as an *IGFET*:
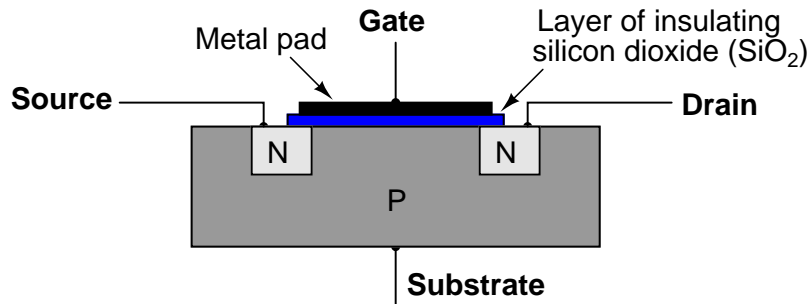
Explain what happens when a positive voltage is applied to the gate (with reference to the substrate), with regard to electrical conductivity between the source and drain:
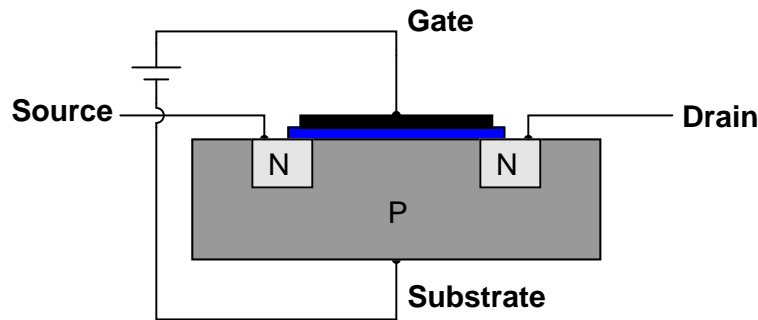
file 02070

Answer 46

When enough positive voltage is applied to the gate, an *inversion layer* forms just beneath it, creating an N-type channel for source-drain current:
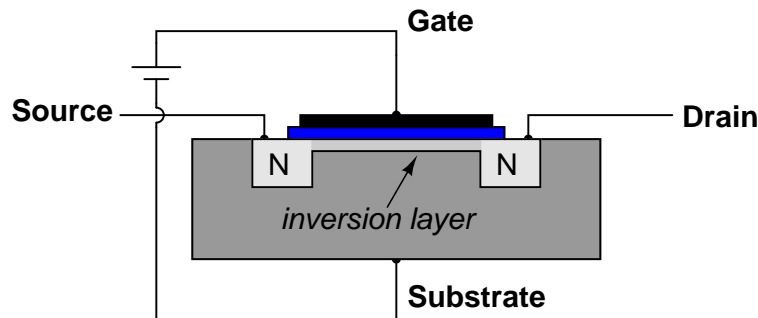
Notes 46

Ask your students to explain how the inversion layer forms, and what it means for source-drain conduction if no inversion layer is present.

Discuss with your students the fact that this inversion layer is incredibly thin; so this that it is often referred to as a two-dimensional "sheet" of charge carriers.

Also mention to your students that although "IGFET" is the general term for such a device, "MOSFET" is more commonly used as a designator due to the device's history.

Question 47

The letters "MOS" in the acronym "MOSFET" stand for "Metal Oxide Semiconductor". Describe what this means, in reference to the construction of a MOSFET.

file 02067

Answer 47

The "Oxide" referred to is a layer of insulating material placed between the Metal gate terminal and the Semiconducting field-effect channel.

Follow-up question: MOSFETs are sometimes referred to as "IGFETs". Explain what this other acronym stands for, and how it means the same thing as "MOSFET".

Notes 47

Explain to your students that IGFET is a more general term than MOSFET, as silicon dioxide is not the only suitable material from which to make an insulating layer for the gate.

Question 48

Some types of MOSFETs have a source-drain channel already formed with no applied gate voltage:
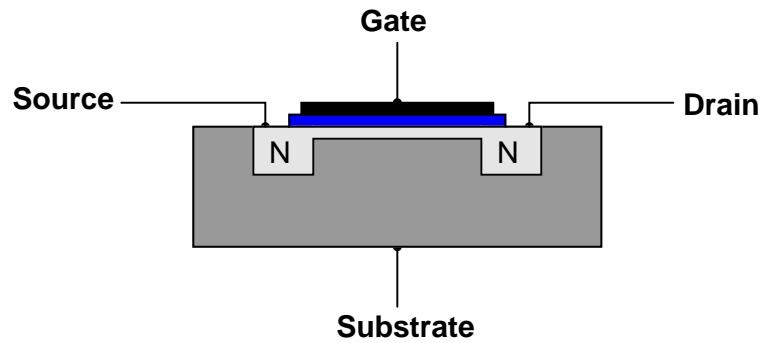
Explain what happens to source-drain conductivity with each of the following applied gate-to-substrate voltages. Modify the illustrations if necessary:

<u>file 02071</u>

Answer 48

channel enhanced   *channel depleted*
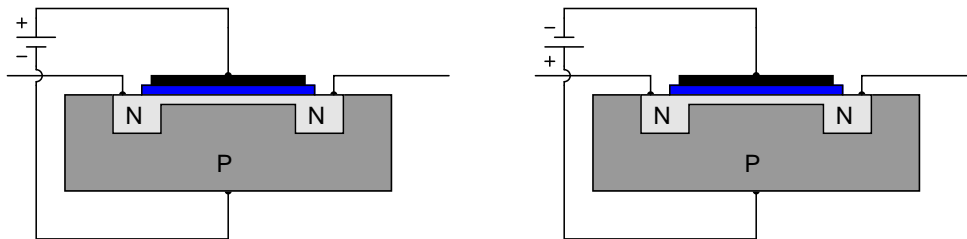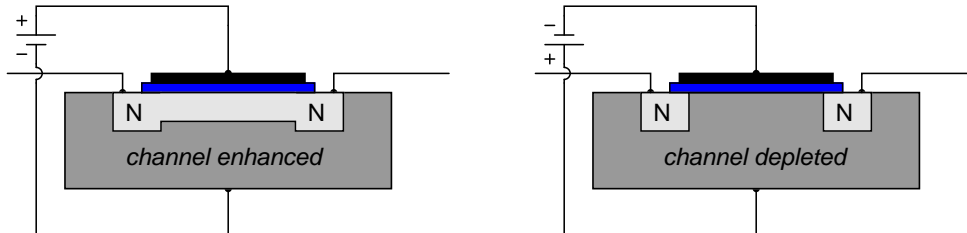
Notes 48

Ask your students to contrast the behavior of this type of MOSFET against the behavior of the type that requires a gate voltage to create an inversion layer.

Question 49

There are two general classes of MOSFETs: MOSFETs that conduct with no applied gate voltage, and MOSFETs that require a gate voltage to be applied for conduction. What are each of these MOSFET types called, and what are their respective schematic symbols?

Each of the symbols for these different types of MOSFETs hold clues to the transistor types they represent. Explain how the symbols hint at the characteristics of their respective transistor types.

file 01069

Answer 49

Depletion-type (D-type) MOSFETs conduct current with no applied gate voltage. *Enhancement-type* (E-type) MOSFETs require a gate voltage to be applied for conduction.
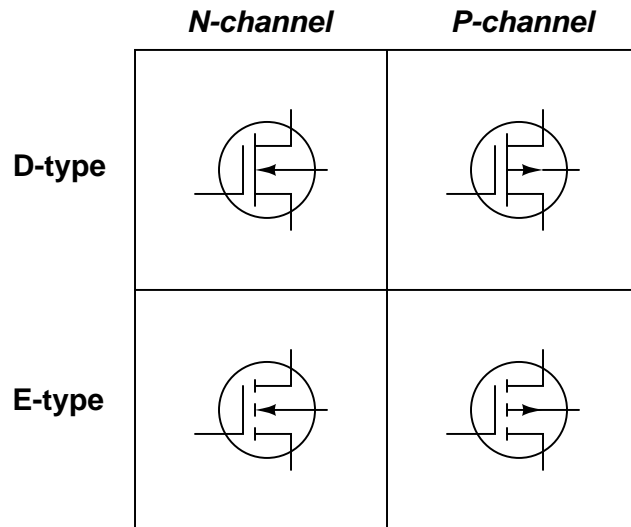
Notes 49

The part of this question asking about clues within the transistor symbols is very important. It will be far easier for your students to remember the function of each transistor type if they are able to recognize clues in the symbolism.

Question 50

E-type MOSFETs are *normally-off* devices just like bipolar junction transistors, the natural state of their channels strongly resisting the passage of electric currents. Thus, a state of conduction will only occur on command from an external source.

Explain what must be done to an E-type MOSFET, specifically, to drive it into a state of conduction (where a channel forms to conduct current between source and drain).

file 02416

Answer 50

A voltage must be applied between gate and substrate (or gate and source if the substrate is connected to the source terminal) in such a way that the polarity of the gate terminal electrostatically attracts the channel's majority charge carriers (forming an inversion layer directly underneath the insulating layer separating gate from channel).

Notes 50

This is perhaps the most important question your students could learn to answer when first studying E-type MOSFETs. What, exactly, is necessary to turn one on? Have your students draw diagrams to illustrate their answers as they present in front of the class.

Ask them specifically to identify what polarity of V_{GS} would have to be applied to turn on an N-channel E-type MOSFET, and also a P-channel E-type MOSFET.

Question 51

D-type MOSFETs are *normally-on* devices just like junction field-effect transistors, the natural state of their channels being passable to electric currents. Thus, a state of cutoff will only occur on command from an external source.

Explain what must be done to an D-type MOSFET, specifically, to drive it into a state of cutoff (where the channel is fully depleted).

file 02417

Answer 51

A voltage must be applied between gate and substrate (or gate and source if the substrate is connected to the source terminal) in such a way that the polarity of the gate terminal electrostatically repels the channel's majority charge carriers.

Follow-up question: unlike JFETs, D-type MOSFETs may be safely "enhanced" beyond the conductivity of their natural state. Describe what is necessary to "command" a D-type MOSFET to conduct better than it naturally does.

Notes 51

This is perhaps the most important question your students could learn to answer when first studying D-type MOSFETs. What, exactly, is necessary to turn one off? Have your students draw diagrams to illustrate their answers as they present in front of the class.

Ask them specifically to identify what polarity of V_{GS} would have to be applied to turn off an N-channel D-type MOSFET, and also a P-channel D-type MOSFET.

Identify each type of MOSFET (whether it is N-channel or P-channel, D-type or E-type), label the terminals, and determine whether the MOSFET in each of these circuits will be turned *on* or *off*:

file 01129

71
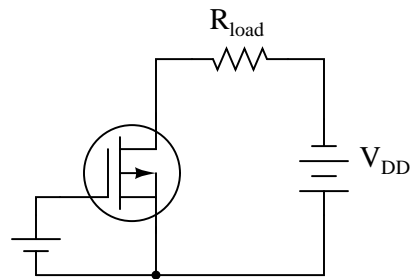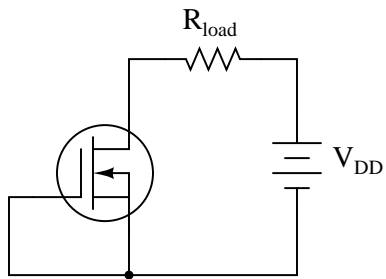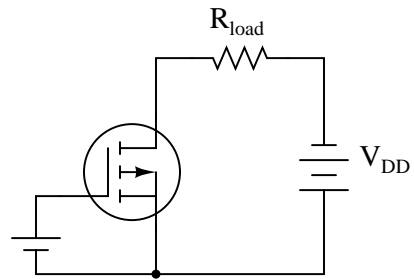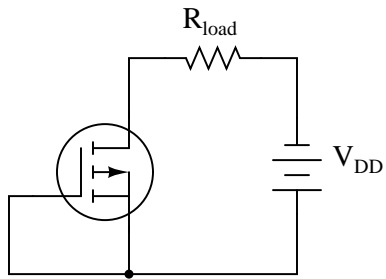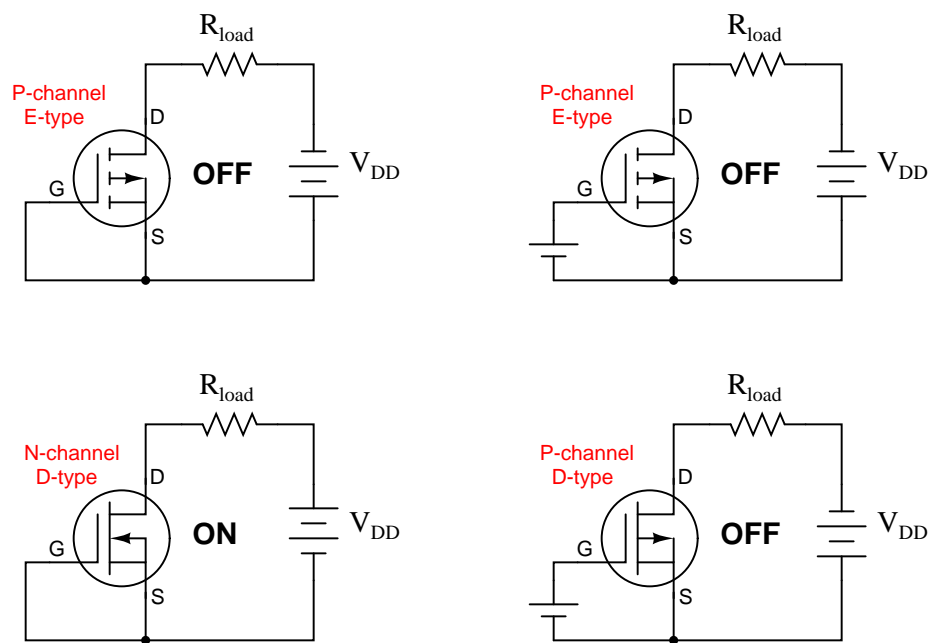
Follow-up question: which of these transistors is *depleted* and which is *enhanced*?

Notes 52

It is very important for your students to understand what factor(s) in a circuit force a MOSFET to turn on or off. Some of the information contained in the diagrams is relevant to the determination of each transistor's status, and some is not.

Be sure to ask your students to explain their reasoning for each transistor's status. What factor, or combination of factors, is necessary to turn a MOSFET on, versus off?

Identify each type of MOSFET (whether it is N-channel or P-channel, D-type or E-type), label the terminals, and determine whether the MOSFET in each of these circuits will be turned *on* or *off*:

file 02415
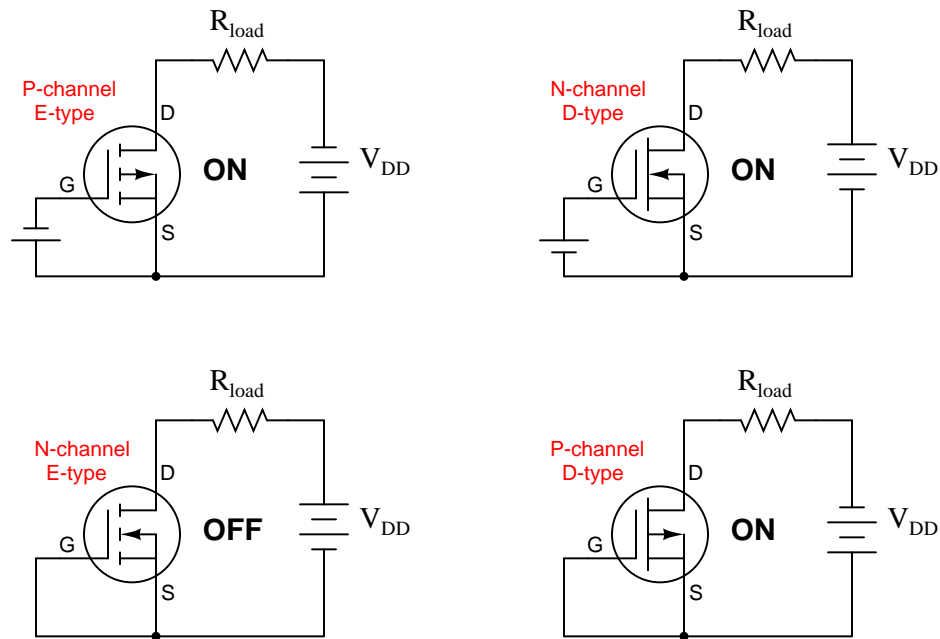
73

Follow-up question: which of these transistors is *depleted* and which is *enhanced*?

It is very important for your students to understand what factor(s) in a circuit force a MOSFET to turn on or off. Some of the information contained in the diagrams is relevant to the determination of each transistor's status, and some is not.

Be sure to ask your students to explain their reasoning for each transistor's status. What factor, or combination of factors, is necessary to turn a MOSFET on, versus off?

Identify each type of MOSFET (whether it is N-channel or P-channel, D-type or E-type), label the terminals, and determine whether the MOSFET in each of these circuits will be turned *on* or *off*:

file 01130

75

Follow-up question: which of these transistors is *depleted* and which is *enhanced*?

Notes 54

It is very important for your students to understand what factor(s) in a circuit force a MOSFET to turn on or off. Some of the information contained in the diagrams is relevant to the determination of each transistor's status, and some is not.
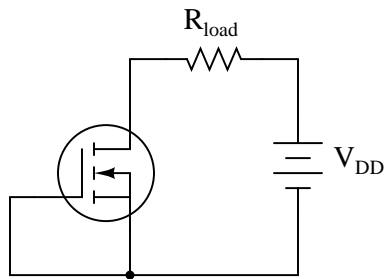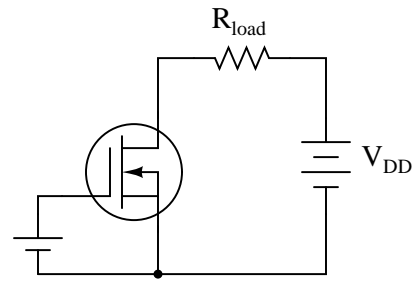
Be sure to ask your students to explain their reasoning for each transistor's status. What factor, or combination of factors, is necessary to turn a MOSFET on, versus off?

Question 55

This circuit uses a combination of capacitance and resistance to produce a time delay when the pushbutton switch is released, causing the lamp to remain on for a short while after the switch opens:
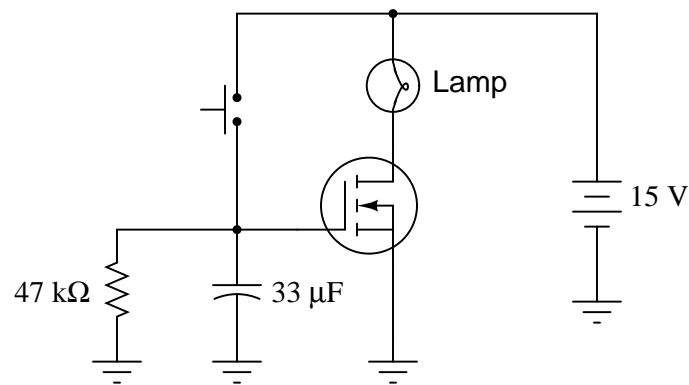
Calculate how long the lamp will remain on after the switch opens, assuming the MOSFET has a gate threshold (turn-on) voltage of $V_{GS(th)} = 4$ volts.
file 03721

Answer 55

$t_{delay} = 2.05$ seconds

Notes 55

In order to solve this problem, students must apply their knowledge of capacitive discharge circuits to find the correct equation for time. Ask them how they set up the solution, and how they knew what equation(s) to use.

Question 56

Explain why a circuit designer would choose a MOSFET over a bipolar transistor for a certain application. What advantage(s) does a MOSFET have over a bipolar transistor?

Challenge question: prove your point by comparing parametric ratings from two transistor datasheets, one bipolar and the other an insulated-gate field effect. Be sure these two transistors have similar controlled current ratings (maximum collector current and drain current, respectively).

file 01131

Answer 56

MOSFETs have extremely low input current "drive" requirements.

Notes 56

Ask your students to explain what "drive current" means in terms of transistor ratings. Also, ask them to explain *why* MOSFETs do not require as much drive current as bipolar transistors. Challenge them to prove their point by a comparison of datasheets.

Is low drive current the only advantage that MOSFETs enjoy over bipolar transistors? Pose this question to your students, to see if they investigated these respective devices any further than the question demanded.

Question 57

An important consideration when working around circuits containing MOSFETs is *electrostatic discharge*, or *ESD*. Describe what this phenomenon is, and why it is an important consideration for MOSFET circuits.

file 01067

Answer 57

"Electrostatic discharge" is the application of very high voltages to circuit components as a result of contact or proximity with an electrically charged body, such as a human being. The high voltages exhibited by static electricity are very damaging to MOSFETs. I'll let you research why!

Notes 57

Be sure to ask students to explain the mechanism of transistor damage resulting from ESD, and to discuss the sheer magnitude of static voltages typically generated in dry-air conditions. If you have any microphotographs of IC damage from ESD, present a few of them during discussion time for your students' viewing pleasure.

Question 58

The "substrate" connection in a MOSFET is often internally connected to the source, like this:
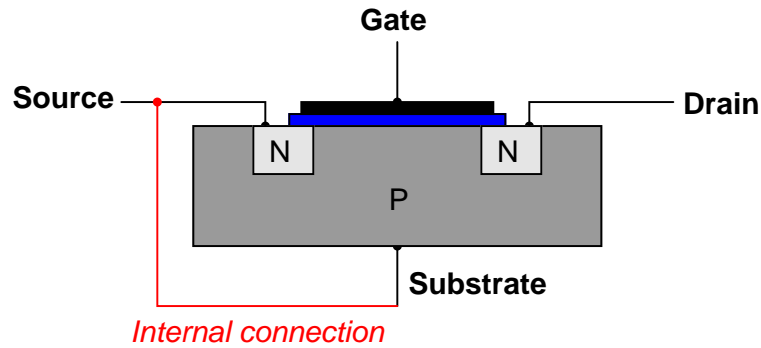
This turns the MOSFET from a four-terminal device into a three-terminal device, making it easier to use. One consequence of this internal connection, though, is the creation of a *parasitic diode* between the source and drain terminals: a PN junction that exists whether we want it to or not.

Add this parasitic diode to the MOSFET symbol shown here (representing the MOSFET cross-section shown above), and explain how its presence affects the transistor's use in a real circuit:
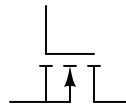
file 02361

Answer 58
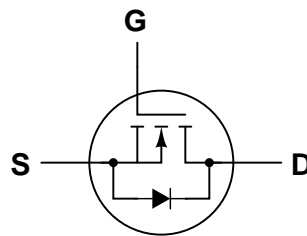
Follow-up question: how does the presence of this parasitic diode allow us to positively distinguish the source terminal from the gate terminal when identifying the terminals of a MOSFET with a multimeter?

Notes 58

The presence of this diode is a very important concept for students to grasp, as it makes the MOSFET a unilateral device for most practical purposes. Discuss the significance of this diode, and contrast the characteristics of a three-terminal MOSFET against the characteristics of a three-terminal JFET, which is a truly bilateral device.

Question 59

The typical amount of current through a MOSFET gate terminal is far less than the typical amount of current through a BJT base terminal, for similar controlled currents (drain or collector, respectively). Explain what it is about the construction and/or use of the MOSFET that limits the input current to almost nothing during normal operation.

file 02323

Answer 59

The gate is electrically insulated from the channel.

Notes 59

If need be, refer back to a "cut-away" diagram of a MOSFET to help your students understand why the input impedance of a MOSFET is what it is.

Question 60

Anti-static wrist straps are commonly worn by technicians when performing work on circuits containing MOSFETs. Explain how these straps are used, and how you would test one to ensure it is functioning properly.

file 01068

Answer 60
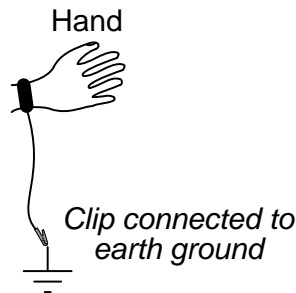
A simple ohmmeter test should reveal mega-ohm levels of resistance between the strap's skin contact point and the metal grounding clip.

Follow-up question: why is there resistance intentionally placed between the wrist strap and the grounding clip? What would be wrong with simply having a 0 Ω connection between the strap and earth ground (i.e. an uninterrupted length of wire)?

Notes 60

A good question to ask your students is *why* anti-static protection is important when working with MOSFET devices. You should never assume this is obvious, unless the subject was covered in a question immediately previous to this one!

Your students should have an anti-static wrist strap as part of their regular tool collection. When discussing this question, it would be good to have students use their ohmmeters to verify the operation of their wrist straps.

Question 61

Identify what each type of transistor is (MOSFET, JFET, or BJT; N-channel, P-channel, NPN, or PNP, E-type or D-type), and what must be connected to the controlling terminal of each transistor (base or gate) to turn each one *on* so that the light bulb energizes:

file 02420

Answer 61
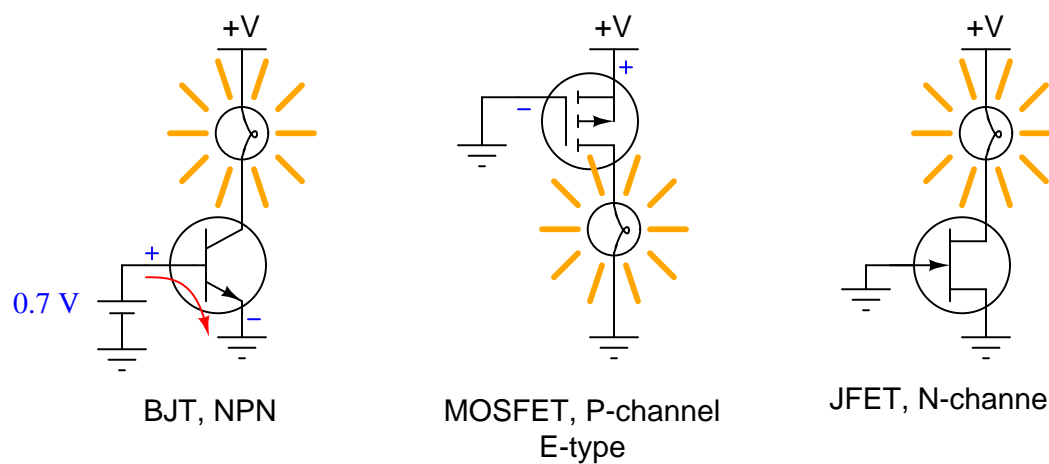
BJT, NPN

MOSFET, P-channel
E-type

JFET, N-channel

Follow-up question: for the JFET, which is already "on" with zero voltage applied to the gate, describe what would be necessary to force it into the "off" state.

Notes 61

It is very important for students to understand what conditions are necessary to drive any of these transistor types into their "on" states, as a precursor to understanding their function in linear (analog) circuitry.

Question 62

Identify what each type of transistor is (MOSFET, JFET, or BJT; N-channel, P-channel, NPN, or PNP, E-type or D-type), and what must be connected to the controlling terminal of each transistor (base or gate) to turn each one *on* so that the light bulb energizes:

file 02421

Answer 62
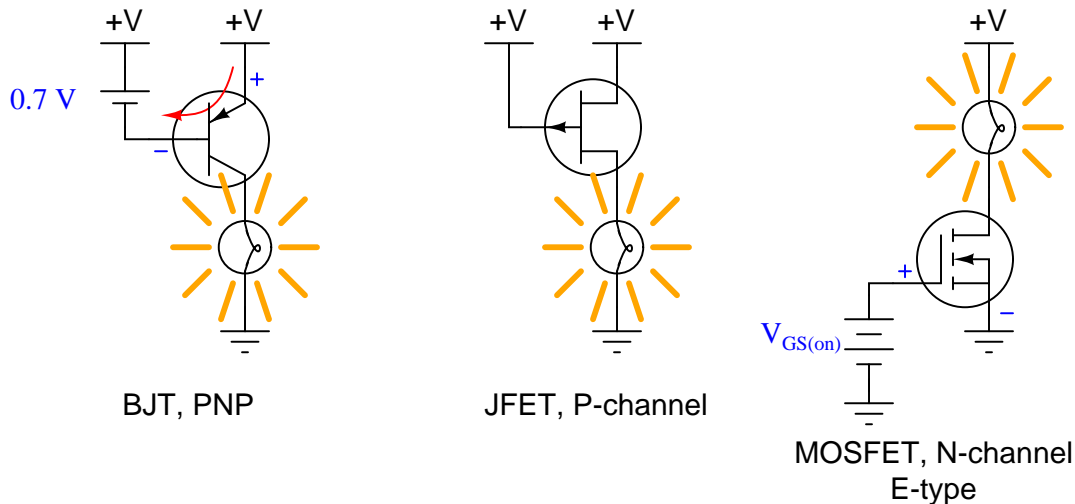
BJT, PNP   JFET, P-channel

MOSFET, N-channel
E-type

Follow-up question: for the JFET, which is already "on" with zero voltage applied to the gate, describe what would be necessary to force it into the "off" state.

Notes 62

It is very important for students to understand what conditions are necessary to drive any of these transistor types into their "on" states, as a precursor to understanding their function in linear (analog) circuitry.

Determine what status the LED will be in (either "on" or "off") for both switch positions in this JFET switching circuit:
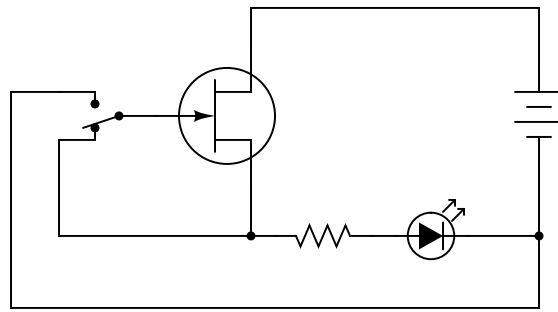
<u>file 02093</u>

Answer 63

The switch is shown in the "LED on" position.

Notes 63

Ask your students to explain their reasoning for their switch position determinations.

Question 64

This circuit has an unusual problem. When the switch is open, the LED turns on. When the switch is closed, the LED turns off. However, when the switch is opened again, the LED often does not turn back on until some time has passed. Others notice that sometimes the LED will turn on and off just by waving their hand next to it, with the switch in the open position.
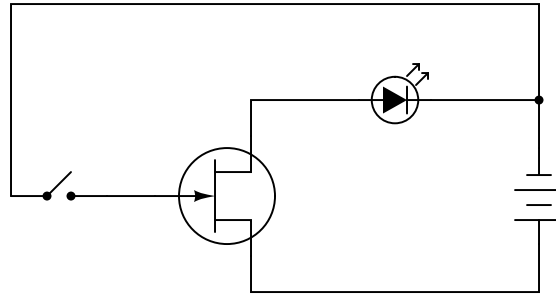
Explain what is happening here, and also propose a solution to eliminate the unpredictability when the switch is open.

file 00988

Answer 64

The LED status is unpredictable when the switch is open, because the transistor's gate is free to "pick up" static electric voltages induced by nearby objects. The solution is to provide a resistive path for any static voltage to discharge when the switch is open.

Notes 64

Challenge your students to place a resistor in this circuit in such a way as to meet the requirements of the given solution.

Incidentally, this circuit makes an excellent classroom demonstration for students to experiment with.

Question 65

What is wrong with this JFET circuit? What might happen to the transistor if this circuit is built and operated?
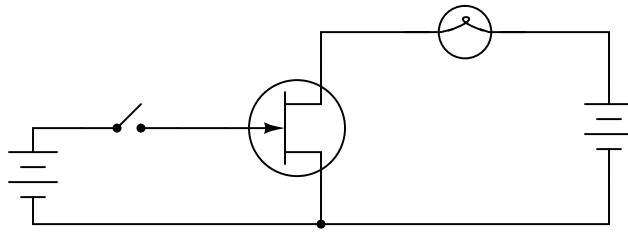
file 00989

Answer 65

The gate-channel PN junction inside a JFET is not designed to handle much forward current!

Notes 65

Have your students consult a typical JFET datasheet and research the maximum gate current parameter. Discuss this parameter with your students, and also talk about how we can make sure this limitation is not exceeded in any circuit design.

The latter subject is very important for students because I have seen many a JFET destroyed by this exact type of abuse.

Question 66

Draw the connecting wires to form a circuit where the transistor turns the LED *off* whenever the pushbutton switch is actuated:
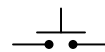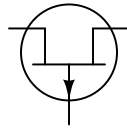
file 00987

Answer 66
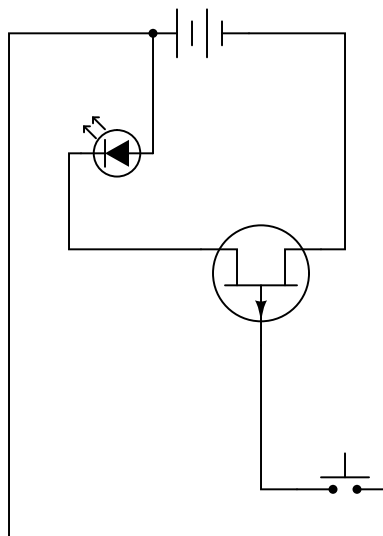
Notes 66

Ask your students to describe the biasing of the gate-channel junction inside the transistor when the switch is closed. Is this PN junction forward-biased, or reverse-biased? What does this biasing do inside the transistor to interrupt current to the LED?

Note that there is no resistor shown in this circuit, because many small-signal JFETs have values of I_{DSS} within the operating range of common LEDs. In other words, the JFET itself acts as a current-limiting device to protect the LED.

Junction field-effect transistors are very sensitive devices, requiring practically zero current to "drive" them into either cutoff or saturation. However, they usually cannot handle high drain currents – in other words, they are not considered "power" switching devices.

If we combine a JFET with a BJT, though, we may realize the best features of each transistor: low drive current requirements combined with a high controlled current rating. Examine the following hybrid JFET/BJT circuits, and explain how each one works to control power to the load:
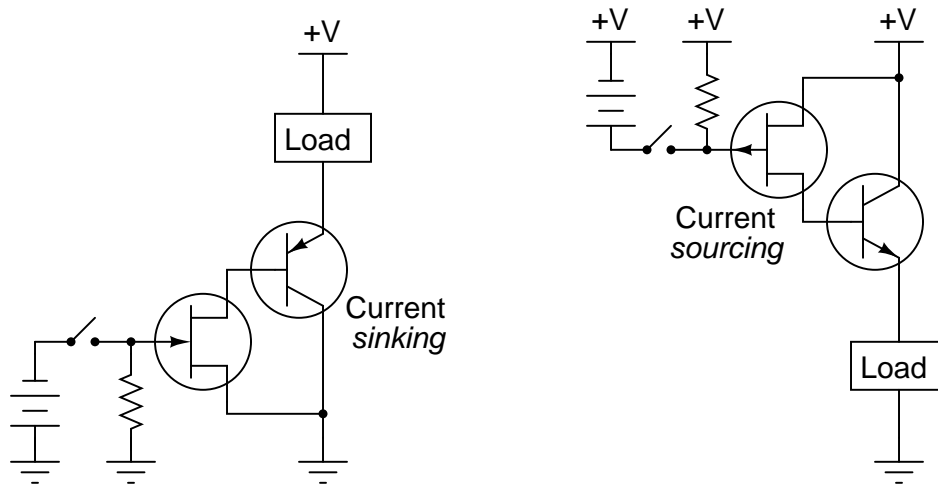
Determine for each circuit whether the load becomes energized when the switch is *closed* or when it is *opened*, and explain how each one works.

file 02426

Answer 67

In each case, the load de-energizes with switch closure, and energizes when the switch is opened.

Follow-up question: explain the purpose of the resistor in each circuit. What might happen if it were not there?

Notes 67

This question is a good review of both BJT and JFET operating theory, as well as a practical example of how "cascading" different types of transistors may result in "best of both worlds" performance.

Question 68

Junction field-effect transistors have the ability to perform some functions that are impossible with (single) bipolar junction transistors. Take this circuit, for example:
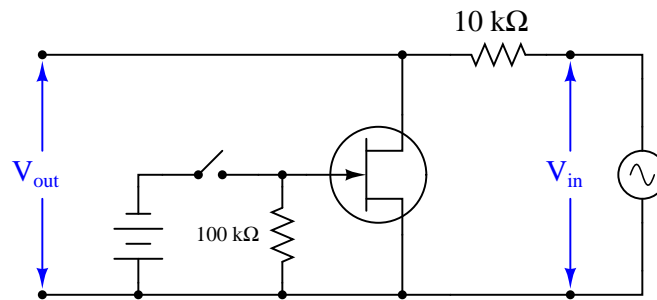
What effect will opening and closing the toggle switch have on the AC signal measured at the output terminals?

file 00996

Answer 68

When the toggle switch is open, the output signal will fall to (nearly) 0 volts AC. When the toggle switch is closed, the output signal will be (nearly) the same as V_{in}.

Notes 68

Discuss how the JFET is able to perform this AC signal "shunting" function, whereas a BJT would not be able to do the same. Can your students think of any practical applications of a circuit like this?

Question 69

Draw the proper wire connections necessary for "enhancing" this MOSFET with the solar cell's voltage, so that the battery energizes the relay whenever there is sufficient light exposure on the solar cell:
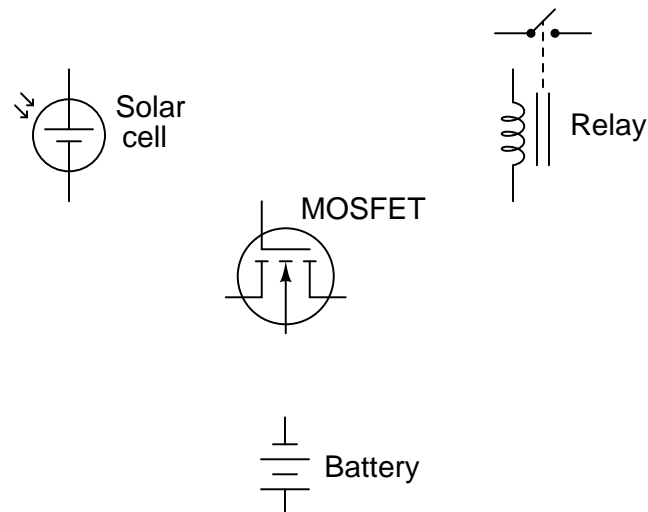
file 01070

Answer 69
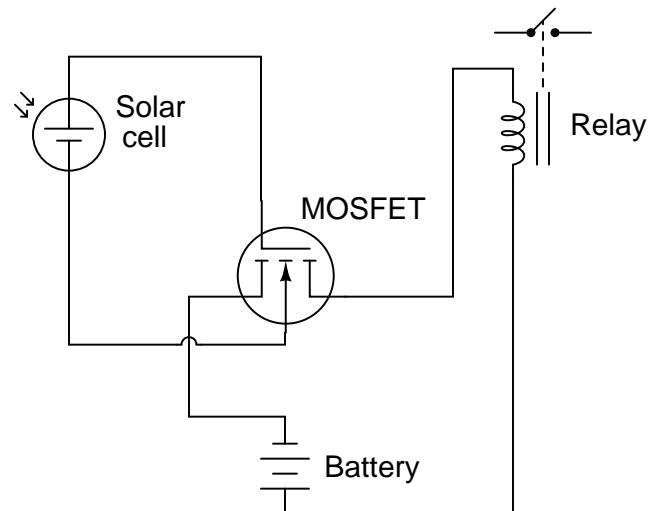
Challenge question: connect a commutating ("free-wheeling") diode into the circuit shown, so that inductive "kickback" from the relay de-energizing does not harm the MOSFET.

Notes 69

Students should note that the circuit shown is not the only possible way a MOSFET could be used to turn a relay on. Often, the substrate (SS) and source (S) terminals of the MOSFET are made common with each other, so that the controlling and controlled circuits share a common point (usually the system "ground" point).

Ask your students what would happen if the battery's polarity were reversed.

Shown here is the schematic diagram for a simple automotive ignition system, to produce pulses of high voltage sufficient to energize spark plugs in an engine:
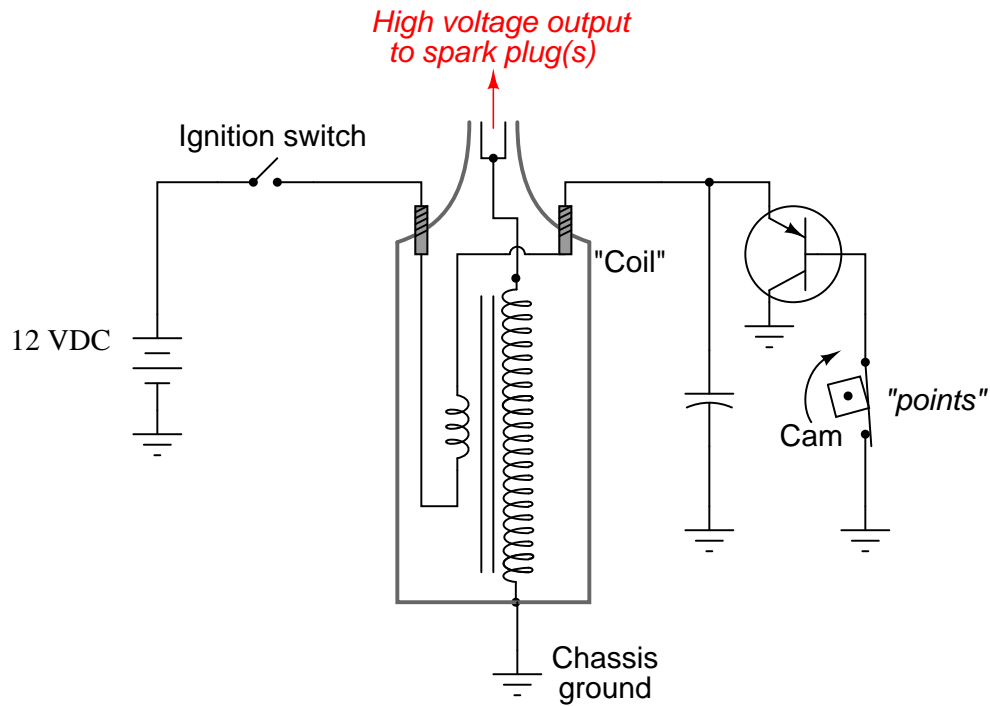
An engineer decides to replace the BJT with a MOSFET, and arrives at the following circuit design:
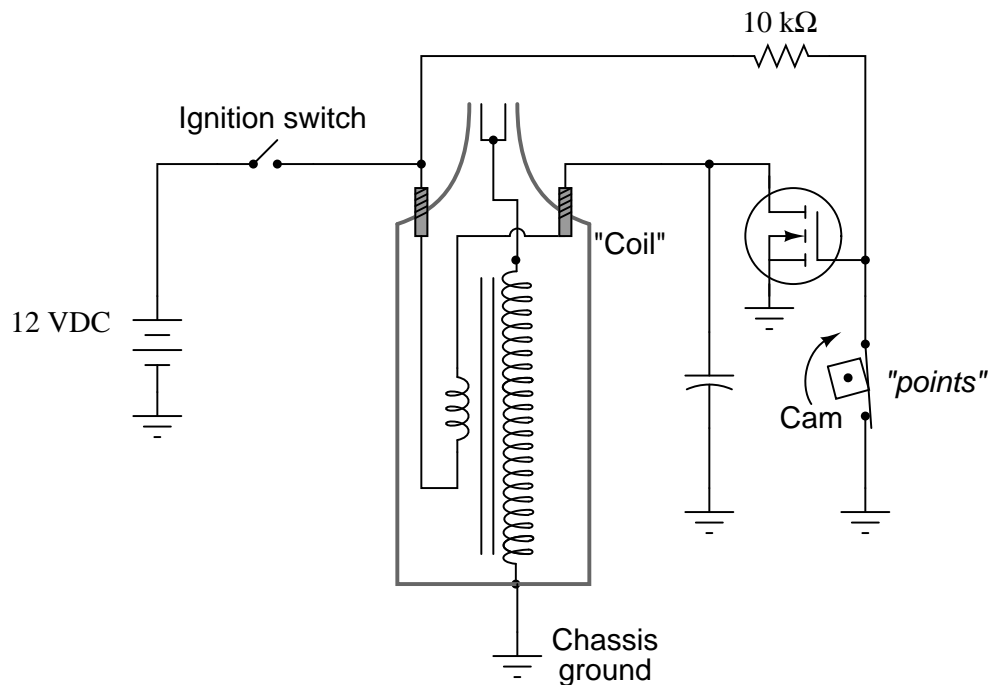
Explain how this revised circuit works. When does the MOSFET conduct current, when the point

contacts are open or closed? How does this compare to the working of the previous (BJT) circuit? What purpose does the 10 kΩ resistor serve?

file 02418

Answer 70

The MOSFET conducts current when the point contacts are open, which is opposite that of the BJT. I'll let you figure out what the purpose of the resistor is!

Notes 70

If this were a real ignition system, the timing would have to be adjusted, as the spark will now be produced every time the points *close* rather than every time the points *open* as it did before (with the BJT). Discuss the operation of this circuit with your students, asking them to explain how they know the MOSFET's status (and the BJT's status, for that matter).

Question 71

A *microcontroller* is a specialized type of digital computer used to provide automatic sequencing or control of a system. Microcontrollers differ from ordinary digital computers in being very small (typically a single integrated circuit chip), with several dedicated pins for input and/or output of digital signals, and limited memory. Instructions programmed into the microcontroller's memory tell it how to react to input conditions, and what types of signals to send to the outputs.

The simplest type of signal "understood" by a microcontroller is a discrete voltage level: either "high" (approximately +V) or "low" (approximately ground potential) measured at a specified pin on the chip. Transistors internal to the microcontroller produce these "high" and "low" signals at the output pins, their actions being modeled by SPDT switches for simplicity's sake:
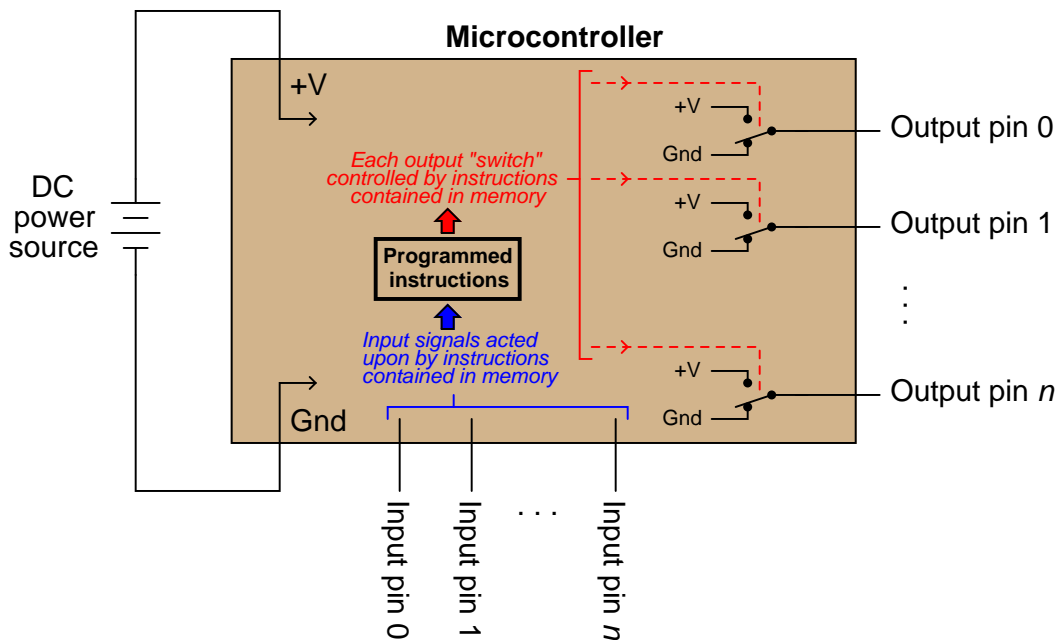
It does not require much imagination to visualize how microcontrollers may be used in practical systems: turning external devices on and off according to input pin and/or time conditions. Examples include appliance control (oven timers, temperature controllers), automotive engine control (fuel injectors, ignition timing, self-diagnostic systems), and robotics (servo actuation, sensory processing, navigation logic). In fact, if you live in an industrialized nation, you probably own several dozen microcontrollers (embedded in various devices) and don't even realize it!

One of the practical limitations of microcontrollers, though, is their low output drive current limit: typically less than 50 mA. The miniaturization of the microcontroller's internal circuitry prohibits the inclusion of output transistors having any significant power rating, and so we must connect transistors to the output pins in order to drive any significant load(s).

Suppose we wished to have a microcontroller drive a DC-actuated solenoid valve requiring 2 amps of current at 24 volts. A simple solution would be to use an NPN transistor as an "interposing" device between the microcontroller and the solenoid valve like this:
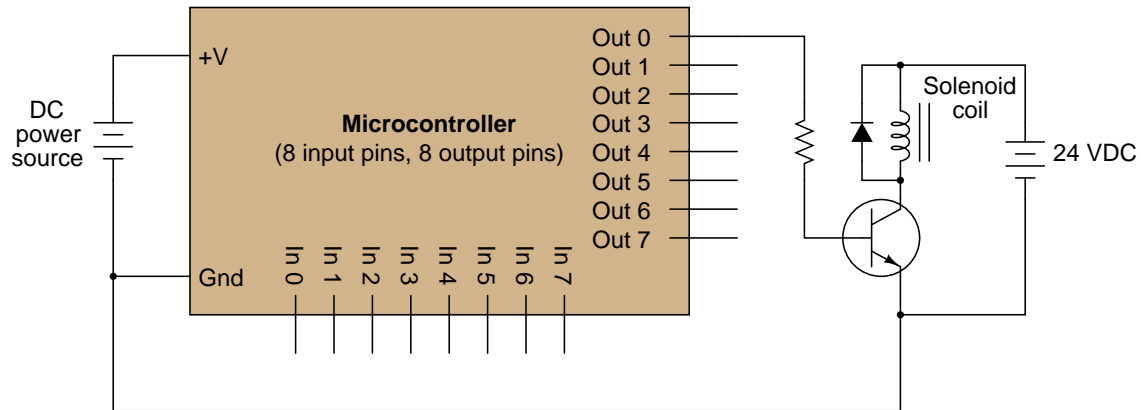
Unfortunately, a single BJT does not provide enough current gain to actuate the solenoid. With 20 mA of output current from the microcontroller pin and a β of only 25 (typical for a power transistor), this only provides about 500 mA to the solenoid coil.

A solution to this problem involves two bipolar transistors in a *Darlington pair* arrangement:
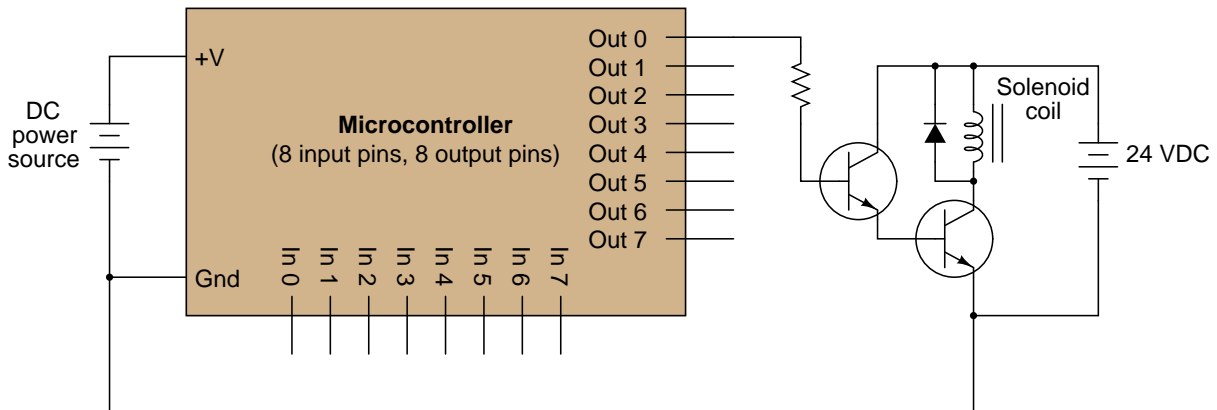
However, there is another solution yet – replace the single BJT with a single MOSFET, which requires no drive current at all. Show how this may be done:
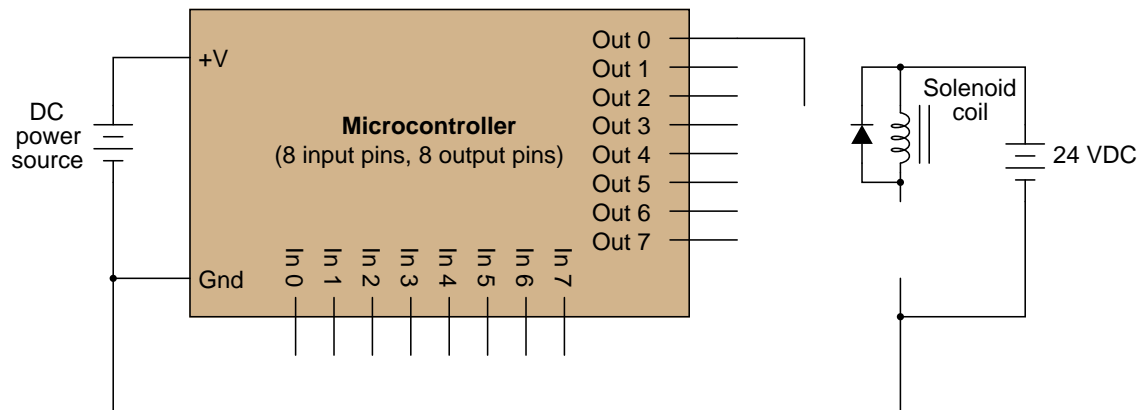
file 02422
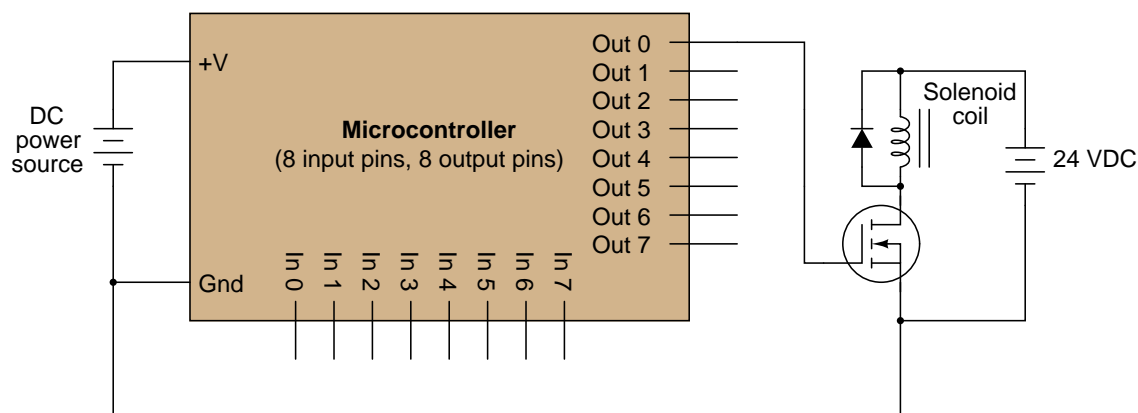
Answer 71

The purpose of this long-winded question is not just to have students figure out how to replace a BJT with a MOSFET, but also to introduce them to the concept of the microcontroller, which is a device of increasing importance in modern electronic systems.

Some students may inquire as to the purpose of the diode in this circuit. Explain to them that this is a *commutating diode*, sometimes called a *free-wheeling diode*, necessary to prevent the transistor from being overstressed by high-voltage transients produced by the solenoid coil when de-energized ("inductive kickback").

In this circuit, a microcontroller controls the rotation of a special type of motor known as a *stepper motor* by sequentially activating one transistor at a time (thus, energizing one motor coil at a time). With each step in the sequence, the motor rotates a fixed number of degrees, typically 1.8 degrees per step:
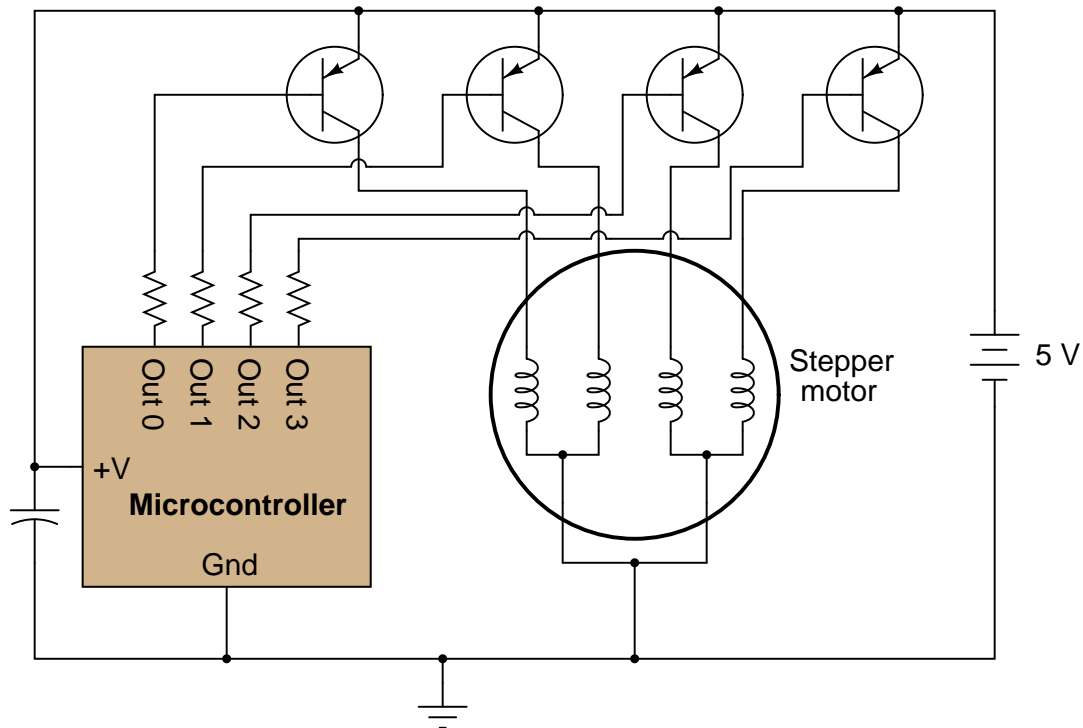
Each motor coil draws a relatively heavy current when energized, necessitating transistors to "interpose" between the microcontroller outputs and the motor coils.

Identify what type of logical signal ("high" or "low") from the output ports of the microcontroller is needed to energize each transistor. Also, show how the power losses and parts count may be reduced by replacing each bipolar junction transistor with a suitable MOSFET in the following diagram:

97

file 02423

Answer 72
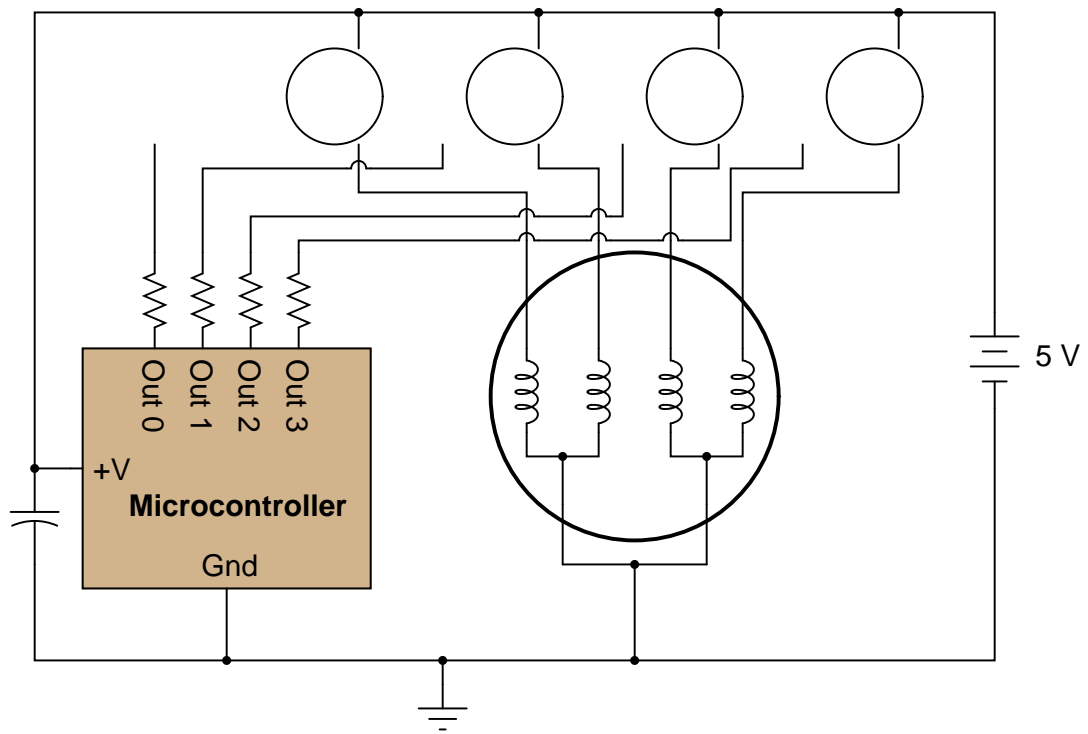
Each stepper motor coil becomes energized when the respective microcontroller output goes to a "low" (Ground potential) state.
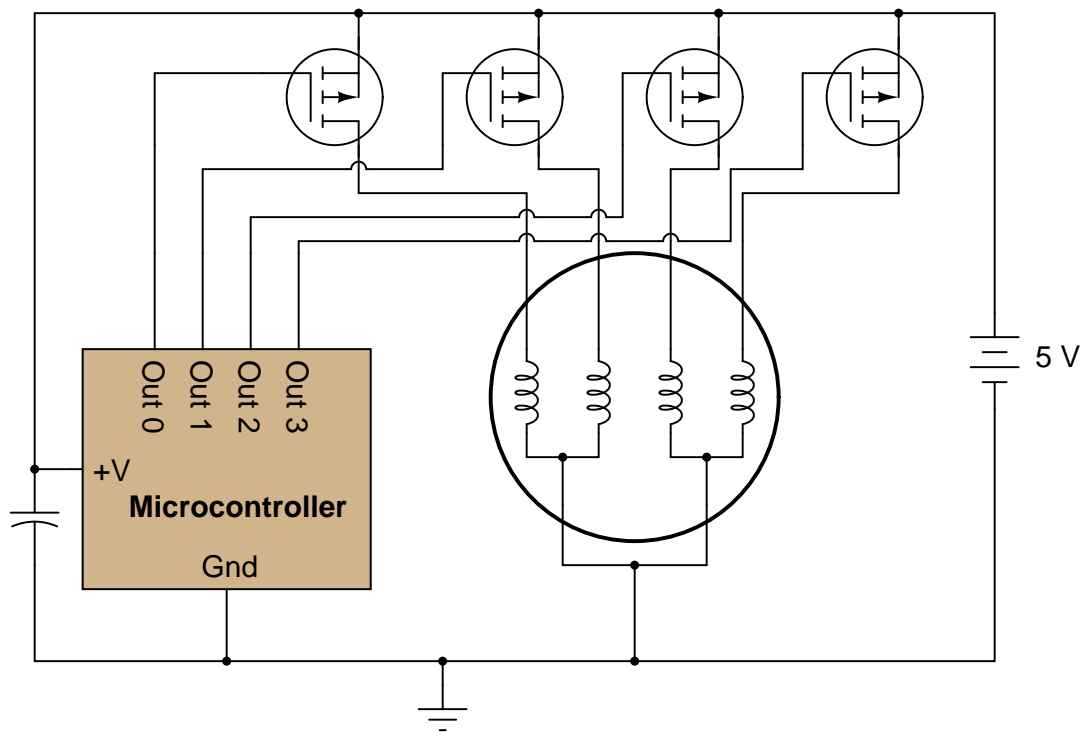
Follow-up question: if the resistors had to be left in place, would the modified (MOSFET instead of BJT) circuit still function properly?

Notes 72

The purpose of this long-winded question is not just to have students figure out how to replace a BJT with a MOSFET, but also to introduce them to the concept of the microcontroller, which is a device of increasing importance in modern electronic systems.

No commutating diodes have been shown in this circuit, for simplicity's sake. If any students ask about this, commend them for noticing!

Question 73

In this system, the voltage output of a digital timing circuit controls the charging and discharging of a resistor-capacitor network. The inner workings of the digital timing circuit are hidden for simplicity's sake, but we may model it as a two-position switch, outputting either a "high" voltage signal (full supply voltage) or a "low" voltage signal (ground potential) at regular intervals:
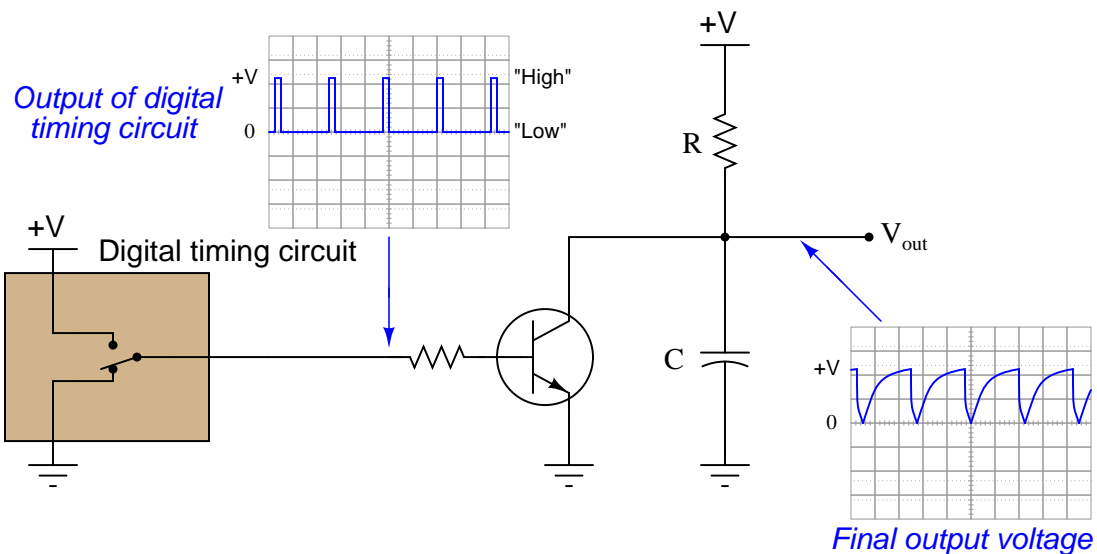
First, identify what signal level from the digital circuit ("high" or "low") causes the capacitor to charge, and what level causes it to discharge. Then, replace the BJT with a suitable MOSFET to accomplish the exact same timing function:

file 02419

100

Answer 73
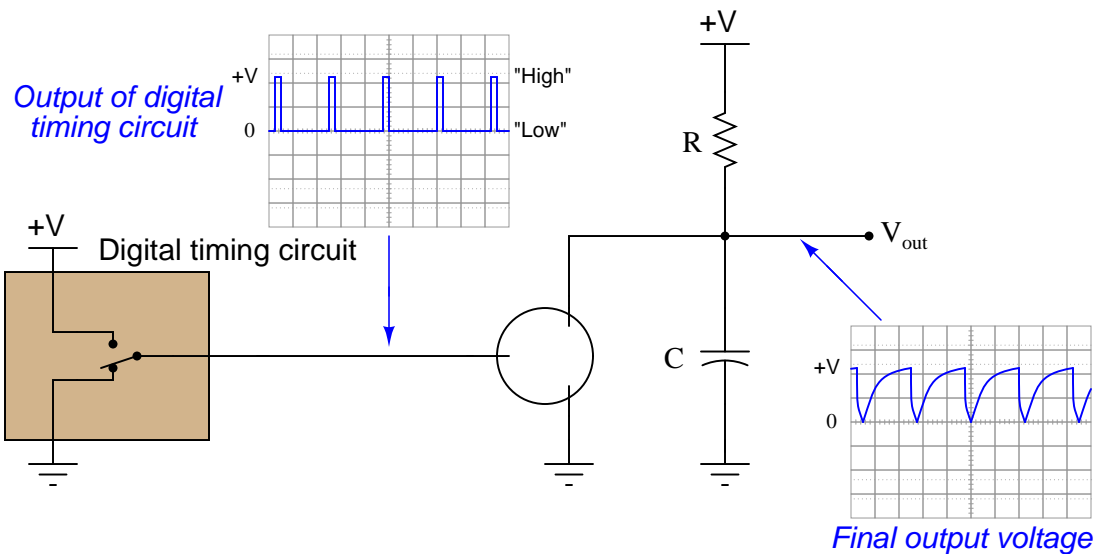
In the BJT version of the circuit, a "low" signal output by the digital circuit causes the capacitor to charge. The same thing happens in this MOSFET version of the circuit:
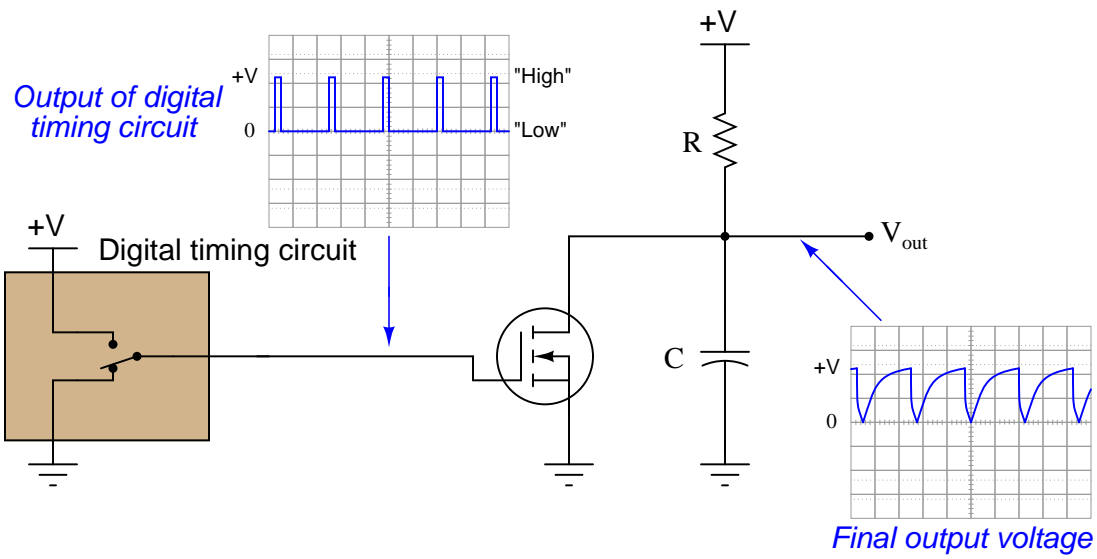
Follow-up question: explain why no resistor is required in series with the MOSFET gate as there was with the BJT base in the original circuit version.

Notes 73

This circuit could be used as an introduction to the 555 timer, since that IC uses the same scheme for capacitor discharge.

Question 74

It is often necessary to have a power transistor *source* current to a load (provide a path from the positive supply voltage rail to the load) rather than *sink* current from the load (provide a path from the load to the negative voltage rail or ground), because one side of the load is already connected to ground:
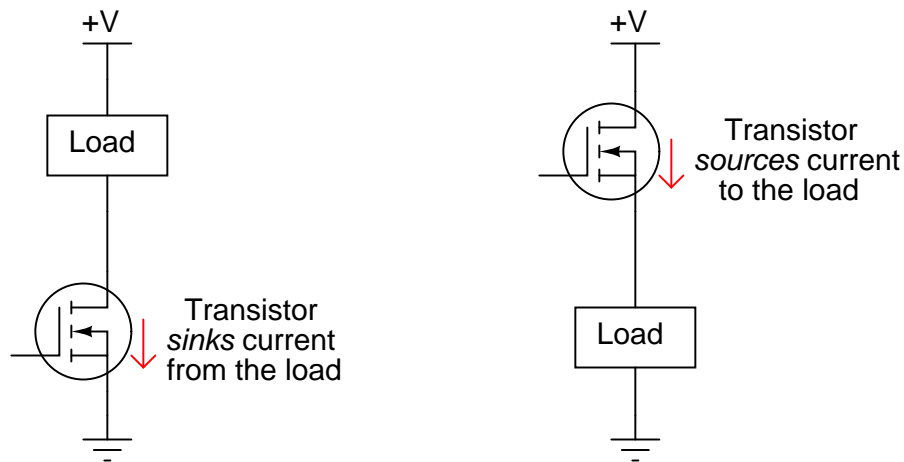
Current arrows drawn according to "conventional flow" notation

When the transistor sources current, it is often referred to as a *high-side* switch. Determine the driving voltage requirements for each of these high-side MOSFET switches; that is, determine what must be connected to the gate of each transistor to fully turn it on so that the load receives full power:

file 02125

Answer 74
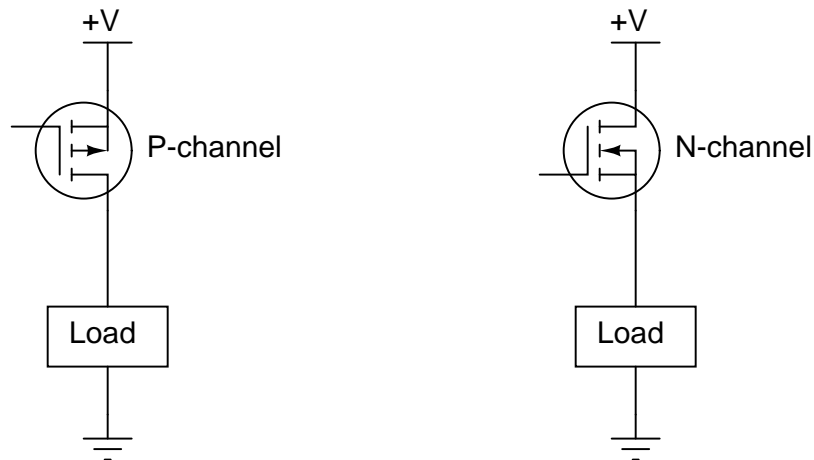
For the P-channel MOSFET, the gate simply needs to be grounded. For the N-channel MOSFET, the gate needs to be brought up to a positive voltage greater than $+V$ by at least $V_{GS}(on)$.

Follow-up question: discuss why the terms "sourcing" and "sinking" make the most sense when viewed from the perspective of *conventional flow* current notation. For contrast, here is the same circuit with the arrows drawn in the direction of electron flow:

Current arrows drawn according to
"electron flow" notation
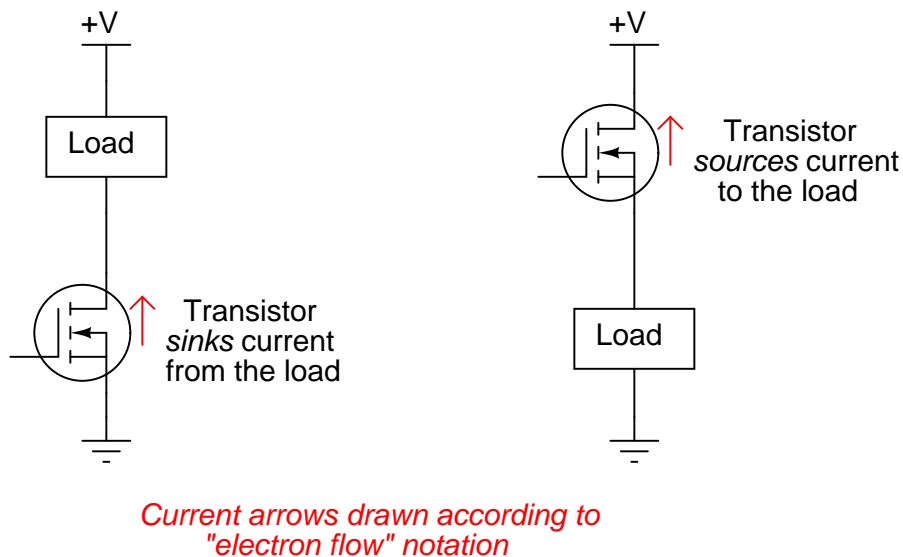
Challenge question: despite the more demanding gate drive requirements of the high-side N-channel MOSFET, these are often preferred over P-channel devices in practical circuit designs. Explain why. Hint: it has something to do with *carrier mobility*.

Notes 74

This is a good exercise in determining proper gate voltage polarity (and magnitude), as well as introducing the concepts of current sourcing and sinking, and high-side switching. Be sure to spend time discussing the matter of sourcing versus sinking, as this will be of greater importance later in your students' studies (especially in logic gate circuit design).

Question 75

What is an *Insulated Gate Bipolar Transistor* (IGBT), and what advantages does the IGBT provide over both power MOSFET and traditional BJT devices?

file 01191
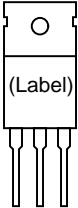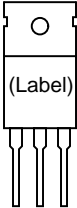
Answer 75

The IGBT is a hybrid device, combining the best attributes of MOSFET and BJT in a single component.

Follow-up question: describe some typical applications for the IGBT which make use of these advantages.

Notes 75

The given answer is accurate, yet not very specific. Ask your students to explain exactly what attributes of MOSFET and BJT are exhibited by the IGBT, and why.

Competency: **BJT terminal identification**   Version:

Description

> Identify the terminals (emitter, base, and collector)
> of a bipolar junction transistor using a multimeter.
> Then, compare your conclusions with information
> from a datasheet or cross-reference book.

Given conditions

Part number =

Parameters

Measured

$V_{bias(BE)}$ [   ]

$V_{bias(BC)}$ [   ]

Terminal identification   (Draw your own sketch if the one
                                  shown is not appropriate)

Advertised   Your conclusion

(Label)   (Label)
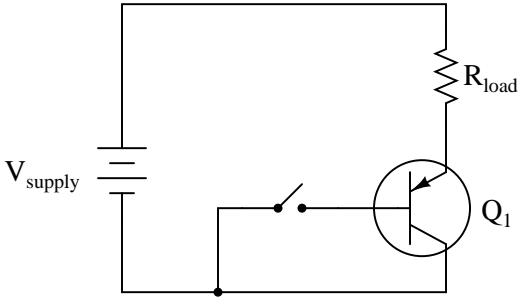
Answer 76

Contrary to what you might think, the datasheet or cross-reference is not the "final authority" for checking your meter-based conclusions! I have seen datasheets and cross-reference manuals wrong more than once!

Notes 76

Identification of BJT terminals is a very important skill for technicians to have. Most modern multimeters have a *diode check* feature which may be used to positively identify PN junction polarities, and this is what I recommend students use for identifying BJT terminals.

To make this a really good performance assessment, you might want to take several BJT's and scratch the identifying labels off, so students cannot refer to memory for pin identification (for instance, if they remember the pin assignments of a 2N2222 because they use it so often). Label these transistors with your own numbers ("1", "2", etc.) so *you* will know which is which, but not the students!

Competency: **Current-sinking BJT switch**   Version:

Schematic

Given conditions

$V_{supply} =$ $R_{load} =$ $\beta =$

Parameters

	Predicted	Measured		Calculated
I_{load}			β	
I_{switch}			P_{Q1}	

Fault analysis

Suppose component [ ] fails   ☐ open   ☐ other _____

☐ shorted

What will happen in the circuit?

file 01932

Answer 77

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 77

Being able to design a circuit using a BJT as a switch is a valuable skill for technicians and engineers alike to have. The circuit shown in this question is not the only possibility, but it is the simplest.

Remind your students that the equation for calculating BJT power dissipation is as follows:

$$P_Q = I_C \left(V_{CE} + \frac{V_{BE}}{\beta} \right)$$

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Competency: **Current-sinking JFET switch**　　　　　Version:

Schematic

Given conditions

$V_{supply} =$　　　　　$R_1 =$　　　　　$R_{dropping} =$

Parameters

	Predicted	Measured		
I_{LED} (max)				

	Advertised	Measured		Calculated
$V_{GS\,(off)}$			P_{Q1}	

Schematic 　　　(Draw a schematic diagram showing what
is necessary to turn the transistor fully *off*)

file 01973

Answer 78

Use circuit simulation software to verify your predicted and measured parameter values.

Notes 78

I strongly recommend a value for R1 of 1 MΩ or more, to protect the JFET gate from overcurrent damage. The students will calculate their own dropping resistor value, based on the supply voltage and the LED ratings.

This exercise lends itself to experimentation with static electricity. The input impedance of an average JFET is so high that the LED may be made to turn on and off with just a touch of the probe wire to a charged object (such as a person).

Using only the components shown, students may not be able to get their JFETs to completely turn off. This is left for them as a challenge to figure out!

I expect students to be able to figure out how to calculate the transistor's power dissipation without being told what measurements to take!

Question 79
NAME: _____   **Project Grading Criteria**   PROJECT: _____
    You will receive the highest score for which *all* criteria are met.

100 % *(Must meet or exceed all criteria listed)*
  A. Impeccable craftsmanship, comparable to that of a professional assembly
  B. No spelling or grammatical errors anywhere in *any* document, upon first submission to instructor

95 % *(Must meet or exceed these criteria in addition to all criteria for 90% and below)*
  A. Technical explanation sufficiently detailed to teach from, inclusive of every component (supersedes 75.B)
  B. Itemized parts list complete with part numbers, manufacturers, and (equivalent) prices for *all* components, including recycled components and parts kit components (supersedes 90.A)

90 % *(Must meet or exceed these criteria in addition to all criteria for 85% and below)*
  A. Itemized parts list complete with prices of components purchased for the project, plus total price
  B. No spelling or grammatical errors anywhere in *any* document upon final submission

85 % *(Must meet or exceed these criteria in addition to all criteria for 80% and below)*
  A. "User's guide" to project function (in addition to 75.B)
  B. Troubleshooting log describing all obstacles overcome during development and construction

80 % *(Must meet or exceed these criteria in addition to all criteria for 75% and below)*
  A. All controls (switches, knobs, etc.) clearly and neatly labeled
  B. All documentation created on computer, not hand-written (including the schematic diagram)

75 % *(Must meet or exceed these criteria in addition to all criteria for 70% and below)*
  A. Stranded wire used wherever wires are subject to vibration or bending
  B. Basic technical explanation of all major circuit sections
  C. Deadline met for working prototype of circuit (Date/Time = _____ / _____)

70 % *(Must meet or exceed these criteria in addition to all criteria for 65%)*
  A. All wire connections sound (solder joints, wire-wrap, terminal strips, and lugs are all connected properly)
  B. No use of glue where a fastener would be more appropriate
  C. Deadline met for submission of fully-functional project (Date/Time = _____ / _____) – supersedes 75.C if final project submitted by that (earlier) deadline

65 % *(Must meet or exceed these criteria in addition to all criteria for 60%)*
  A. Project fully functional
  B. All components securely fastened so nothing is "loose" inside the enclosure
  C. Schematic diagram of circuit

60 % *(Must meet or exceed these criteria in addition to being safe and legal)*
  A. Project minimally functional, with all components located inside an enclosure (if applicable)
  B. Passes final safety inspection (proper case grounding, line power fusing, power cords strain-relieved)

0 % *(If <u>any</u> of the following conditions are true)*
  A. Fails final safety inspection (improper grounding, fusing, and/or power cord strain relieving)
  B. Intended project function poses a safety hazard
  C. Project function violates any law, ordinance, or school policy
      file 03173

Answer 79

Be sure you meet with your instructor if you have any questions about what is expected for your project!

Notes 79

The purpose of this assessment rubric is to act as a sort of "contract" between you (the instructor) and your student. This way, the expectations are all clearly known in advance, which goes a long way toward disarming problems later when it is time to grade.

Question 80

Predict how all three transistor currents (I_B, I_C, and I_E) will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):
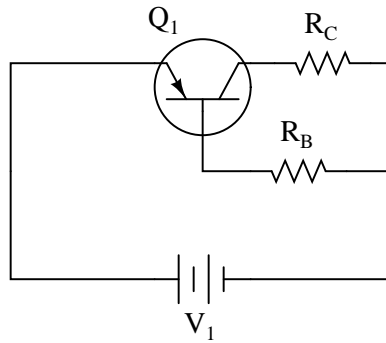
- Base resistor R_B fails open:
- Collector resistor R_C fails open:
- Solder bridge (short) past base resistor R_B:
- Solder bridge (short) past collector resistor R_C:

  For each of these conditions, explain *why* the resulting effects will occur.
  file 03711

Answer 80

- Base resistor R_B fails open: *All three currents stop.*

- Collector resistor R_C fails open: *Base current unchanged, collector current stops, emitter current decreases to value of base current ($I_E = I_B$).*

- Solder bridge (short) past base resistor R_B: *All three currents greatly increase, transistor will likely overheat and fail.*

- Solder bridge (short) past collector resistor R_C: *Base current unchanged, collector current increases slightly (ideally will not change at all!), transistor dissipates more power in the form of heat (may overheat).:*

Notes 80

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.

113

Predict how all component voltages and currents in this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):

- Transistor Q_1 fails open (collector-to-emitter):
- Transistor Q_1 fails shorted (collector-to-emitter):
- Reluctor magnet weakens:
- Capacitor C_1 fails shorted:
- Capacitor C_1 fails open:
- Transformer ("coil") T_1 primary winding fails open:
- Transformer ("coil") T_1 secondary winding fails open:

  For each of these conditions, explain *why* the resulting effects will occur.
  file 03712

Answer 81

- Transistor Q_1 fails open (collector-to-emitter): *No current through T_1 primary or secondary, no high-voltage pulses across T_1 secondary, full 12 volts (constant) across C_1, voltage pulses still seen across L_1, no spark at spark plug.*

- Transistor Q_1 fails shorted (collector-to-emitter): *Constant current through T_1 primary, no high-voltage pulses across T_1 secondary, nearly 0 volts across C_1, very weak voltage pulses across L_1, no spark at spark plug.*

- Reluctor magnet weakens: *Smaller voltage pulses across L_1, smaller current pulses through T_1 primary, smaller voltage pulses across T_2 secondary, weak or no spark at spark plug.*

- Capacitor C_1 fails shorted: *Constant current through T_1 primary, no high-voltage pulses across T_1 secondary, nearly 0 volts across C_1, normal voltage pulses across L_1, no spark at spark plug.*

- Capacitor C_1 fails open: *Excessive voltage pulses seen at Q_1 collector (with respect to ground), very rapid failure of Q_1.*

- Transformer ("coil") T_1 primary winding fails open: *No current through T_1 primary or secondary, no high-voltage pulses across T_1 secondary, zero volts (constant) across C_1, voltage pulses still seen across L_1, no spark at spark plug.*

- Transformer ("coil") T_1 secondary winding fails open: *All voltages and currents fairly normal except for no voltage across T_1 secondary and no spark at spark plug, perhaps slightly greater voltage pulses seen at Q_1 collector with respect to ground.*

Notes 81

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.

Predict how all component voltages and currents in this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):

- Transistor Q_2 fails open (collector-to-emitter):

- Transistor Q_1 fails shorted (collector-to-emitter):

- Capacitor C_1 fails shorted:

- Capacitor C_1 fails open:

- Reluctor coil L_1 fails open:

  For each of these conditions, explain *why* the resulting effects will occur.
  file 03713

Answer 82

- Transistor Q_2 fails open (collector-to-emitter): *No current through T_1 primary or secondary, no high-voltage pulses across T_1 secondary, full 12 volts (constant) across C_1, no current through any terminal of Q_1, voltage pulses still seen across L_1, no spark at spark plug.*

- Transistor Q_1 fails shorted (collector-to-emitter): *Constant current through T_1 primary, no high-voltage pulses across T_1 secondary, nearly 0 volts across C_1, voltage pulses still seen across L_1, no spark at spark plug.*

- Capacitor C_1 fails shorted: *Constant current through T_1 primary, no high-voltage pulses across T_1 secondary, nearly 0 volts across C_1, normal voltage pulses across L_1, no spark at spark plug.*

- Capacitor C_1 fails open: *Excessive voltage pulses seen at Q_1 collector (with respect to ground), very rapid failure of Q_1 and possibly Q_2.*

- Reluctor coil L_1 fails open: *No current through T_1 primary or secondary, no high-voltage pulses across T_1 secondary, full 12 volts (constant) across C_1, full 12 volts (constant) across Q_2 collector-to-emitter, no voltage pulses seen across L_1, no spark at spark plug.*

Notes 82

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.

Question 83

This circuit uses a "555" integrated circuit to produce a low-frequency square-wave voltage signal (seen between the "Out" terminal of the chip and ground), which is used to turn a pair of transistors on and off to flash a large lamp. Predict how this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):
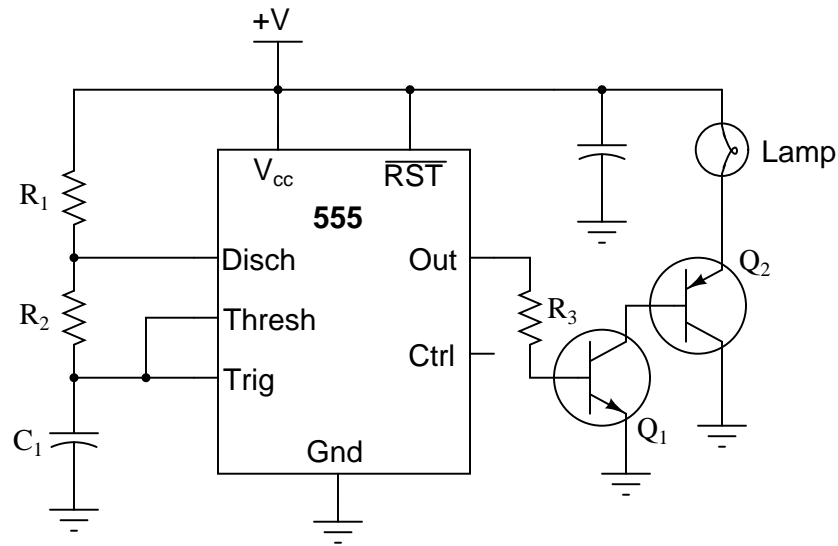
- Transistor Q_1 fails open (collector-to-emitter):

- Transistor Q_2 fails open (collector-to-emitter):

- Resistor R_3 fails open:

- Transistor Q_1 fails shorted (collector-to-emitter):

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

file 03715

Answer 83

- Transistor Q_1 fails open (collector-to-emitter): *Lamp remains off, no current through any terminal of Q_2.*

- Transistor Q_2 fails open (collector-to-emitter): *Lamp remains off, no current through any terminal of Q_2, normal base current through Q_1, no current through collector of Q_1.*

- Resistor R_3 fails open: *Lamp remains off, no current through any terminal of Q_1 or Q_2.*

- Transistor Q_1 fails shorted (collector-to-emitter): *Lamp remains on, full "on" current levels through terminals of Q_1 and Q_2.*

Notes 83

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.

Predict how the motor function in this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):
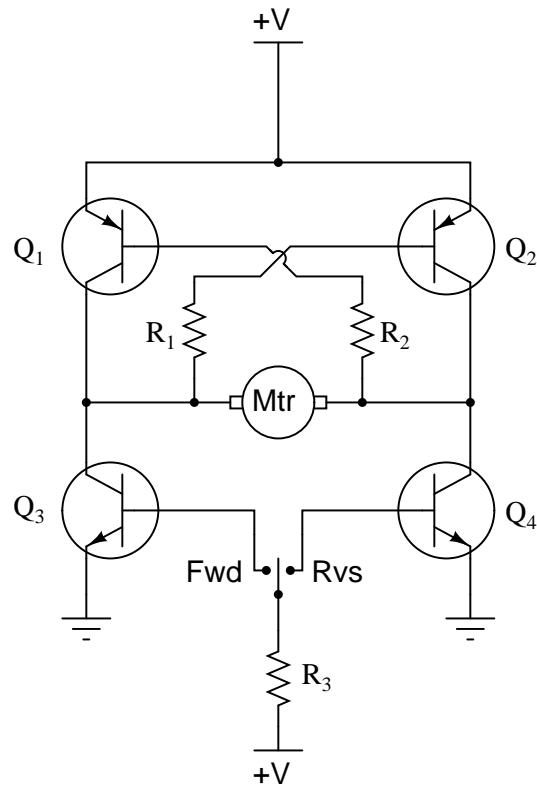
- Transistor Q_1 fails open (collector-to-emitter):
- Transistor Q_2 fails open (collector-to-emitter):
- Transistor Q_3 fails open (collector-to-emitter):
- Transistor Q_4 fails open (collector-to-emitter):
- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Resistor R_3 fails open:
- Transistor Q_3 fails shorted (collector-to-emitter):
- Transistor Q_4 fails shorted (collector-to-emitter):

For each of these conditions, explain *why* the resulting effects will occur.
file 03714

Answer 84

- Transistor Q_1 fails open (collector-to-emitter): *Motor fails to turn in "reverse" direction, can still turn in "forward" direction.*

- Transistor Q_2 fails open (collector-to-emitter): *Motor fails to turn in "forward" direction, can still turn in "reverse" direction.*

- Transistor Q_3 fails open (collector-to-emitter): *Motor fails to turn in "forward" direction, can still turn in "reverse" direction.*

- Transistor Q_4 fails open (collector-to-emitter): *Motor fails to turn in "reverse" direction, can still turn in "forward" direction.*

- Resistor R_1 fails open: *Motor fails to turn in "forward" direction, can still turn in "reverse" direction.*

- Resistor R_2 fails open: *Motor fails to turn in "reverse" direction, can still turn in "forward" direction.*

- Resistor R_3 fails open: *Motor cannot turn in either direction.*

- Transistor Q_3 fails shorted (collector-to-emitter): *Motor turns in "forward" direction even when the switch is in the center (off) position.*

- Transistor Q_4 fails shorted (collector-to-emitter): *Motor turns in "reverse" direction even when the switch is in the center (off) position.*

Notes 84

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.

Question 85

Predict how this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):
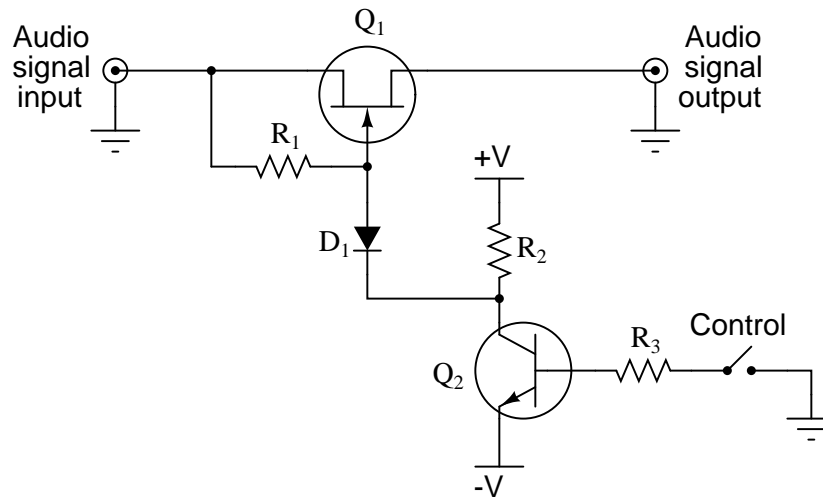
- Diode D_1 fails open:

- Transistor Q_1 fails shorted (drain-to-source):

- Transistor Q_1 fails open (drain-to-source):

- Transistor Q_2 fails shorted (collector-to-emitter):

  For each of these conditions, explain *why* the resulting effects will occur.
 file 03719

Answer 85

- Diode D_1 fails open: *Audio signal always passes through and cannot be turned off.*

- Transistor Q_1 fails shorted (drain-to-source): *Audio signal always passes through and cannot be turned off.*

- Transistor Q_1 fails open (drain-to-source): *Audio signal never passes through and cannot be turned on.*

- Transistor Q_2 fails shorted (collector-to-emitter): *Audio signal never passes through and cannot be turned on.*

Notes 85

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.

Question 86

Predict how this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):
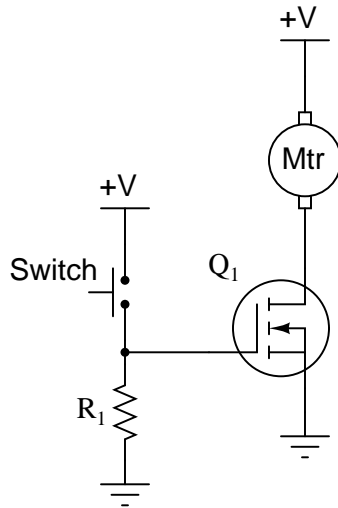
- Transistor Q_1 fails open (drain-to-source):
- Transistor Q_1 fails shorted (drain-to-source):
- Resistor R_1 fails open:

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

file 03716

Answer 86

- Transistor Q_1 fails open (drain-to-source): *Motor refuses to run.*
- Transistor Q_1 fails shorted (drain-to-source): *Motor runs all the time and will not turn off.*
- Resistor R_1 fails open: *Motor runs when switch is pressed, takes a long time to turn off when switch is released.*

Notes 86

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.

Question 87

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

- Transistor Q_1 fails shorted (collector-to-emitter):
- Transistor Q_2 fails open (drain-to-source):
- Resistor R_1 fails open:
- Resistor R_2 fails open:

For each of these conditions, explain *why* the resulting effects will occur.
<u>file 03717</u>

Answer 87

- Transistor Q_1 fails shorted (drain-to-source): *Motor runs all the time and will not turn off.*
- Transistor Q_2 fails open (drain-to-source): *Motor refuses to run.*
- Resistor R_1 fails open: *Motor refuses to run.*
- Resistor R_2 fails open: *Motor runs when switch is pressed, takes a long time to turn off when switch is released.*

Notes 87

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.

Question 88

Predict how this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):
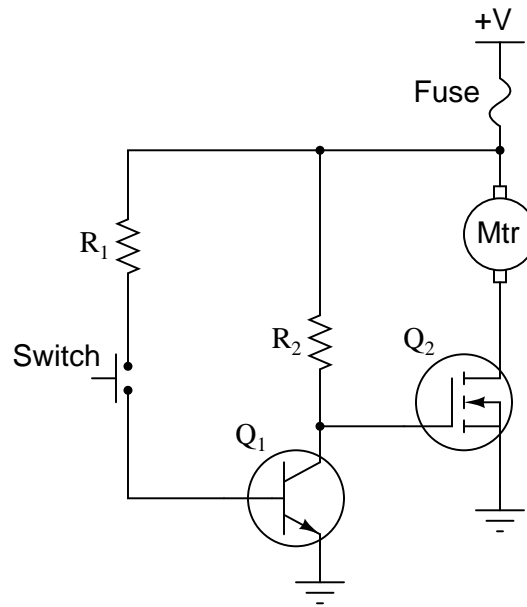
- Transistor Q_1 fails shorted (drain-to-source):
- Transistor Q_2 fails shorted (drain-to-source):
- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Solder bridge (short) past resistor R_1:

  For each of these conditions, explain *why* the resulting effects will occur.
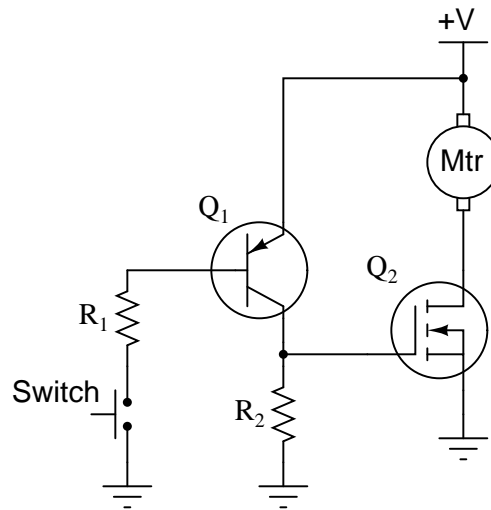 file 03718

Answer 88

- Transistor Q_1 fails shorted (drain-to-source): *Motor refuses to run.*
- Transistor Q_2 fails shorted (drain-to-source): *Motor runs all the time and will not turn off.*
- Resistor R_1 fails open: *Motor runs all the time and will not turn off.*
- Resistor R_2 fails open: *Motor refuses to run.*
- Solder bridge (short) past resistor R_1: *Motor runs when switch is initially unpressed (as it should), but transistor Q_1 will fail when switch is pressed. This may cause the motor to stop running or to never stop, depending on how Q_1 fails. The fuse may also blow as a result.*

Notes 88

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.

Question 89

The following circuit used to work fine, but does not work as it should anymore. The lamp does not come on, no matter what is done with the switch:
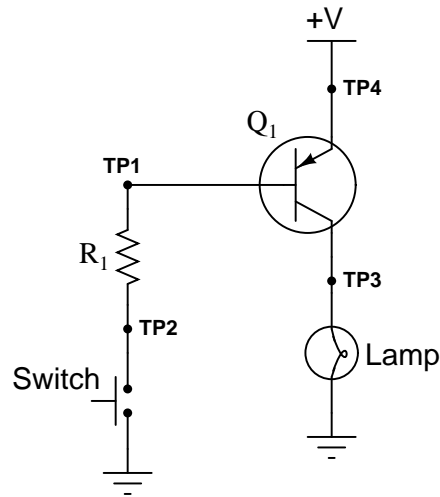
The very first thing you do is use your multimeter to check for source voltage, TP4 to ground. Between those points you find 24 volts DC, just as it should be. Next you measure voltage between TP2 and ground with the switch pressed and unpressed. With the switch pressed, there is no voltage between TP2 and ground, but there is voltage (about 23.5 volts) when the switch is unpressed.

From this information, determine at least two possible failures in the circuit which could cause the lamp not to energize, and also account for the voltage measurements taken.

file 03720

Answer 89

Possible circuit faults:

- Lamp burned out
- Transistor failed open at collector terminal
- Bad (open) connection between lamp and transistor
- Bad (open) connection between lamp and ground

Follow-up question: explain why we may say with confidence that there is no problem with the resistor or the switch.

Notes 89

Discuss with your students how to reason from the empirical data to a set of possible faults in the circuit, and also how certain areas of the circuit (or individual components) may be safely eliminated from the list of possible faults.

Question 90

Transistor operation may be explained in terms of three different currents: *injection*, *diffusion*, and *collection*. Describe what each of these currents are, and how they help explain the amplifying nature of a transistor.

file 00915

Answer 90

"Injection" current consists of those majority charge carriers (either electrons or holes, depending on the transistor type) that are "injected" from the emitter region into the base region of a transistor. "Diffusion" current is the current through the base terminal of the transistor resulting from recombination of electrons and holes in the emitter-base junction. Most of the injection current, however, becomes "collection" current and goes through the collector terminal of the transistor.

Notes 90

As students research and use these terms in their study of bipolar junction transistors, the theory of BJT operation should become more evident. The terms really are well-chosen, accurately representing the motions of charge carriers within the transistor structure.

The base is doped much lighter than the emitter so that the collection current will greatly exceed the diffusion current. If the two layers were equally doped, the base-emitter junction would tend to act as a normal diode, passing nearly all the injection current through the base terminal. As it is, only a small portion of the injected charge carriers diffuse into the base, the rest being "collected" by the collector layer.

The collector is not as heavily doped as the emitter, in order that the collector-base junction will have a greater reverse breakdown voltage. Since this junction typically operates in reverse-bias mode with a substantial voltage drop, the breakdown voltage rating is important.

Trace the paths of *injection*, *diffusion*, and *collection* currents in this energy diagram for a PNP transistor as it is conducting:

E_f

P   **N**   **P**
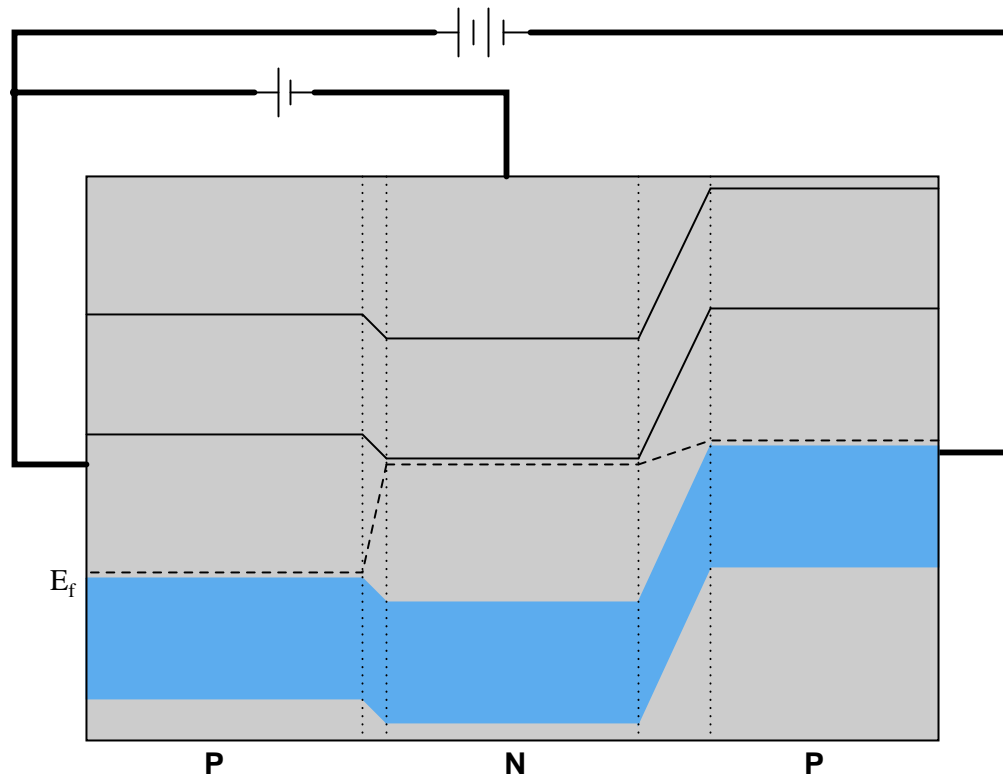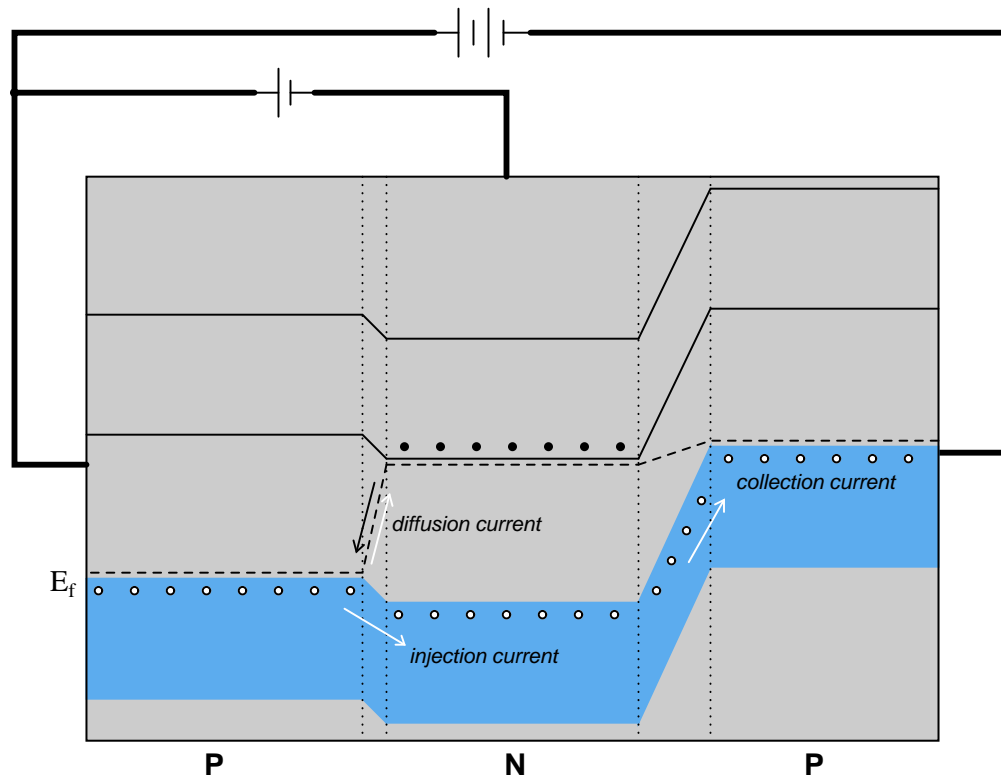
file 02481

A picture is worth a thousand words, they say. For me, this illustration is the one that finally made transistors make sense to me. By forward-biasing the emitter-base junction, minority carriers are injected into the base (holes in the "N" type material, in the case of a PNP transistor), which then rise easily into the collector region. This energy diagram is invaluable for explaining why collector current can flow even when the base-collector junction is reverse biased.

When looking at energy diagrams, it is helpful to think of natural hole motion as air bubbles in a liquid, trying to rise as high as possible within their designated band.

Question 92

Students new to the study of transistors often have difficulty remembering the proper directions of currents through bipolar junction transistors, since there are three different currents (I_B, I_C, I_E) and they must "mesh" through the transistor in a particular way.

Draw the proper current directions for each of these transistors, and explain how you are able to remember the correct directions they go:
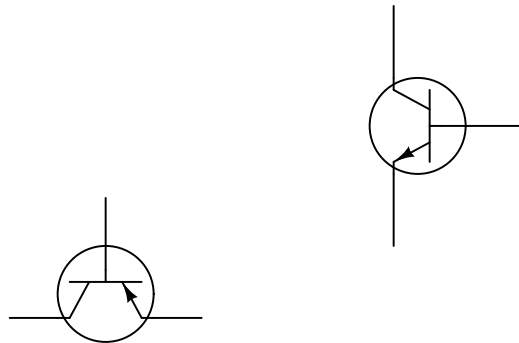
file 02406

Answer 92
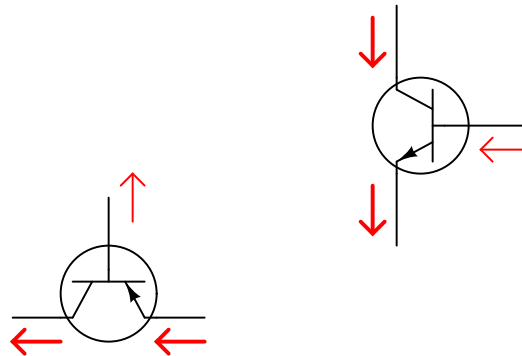
Arrows drawn in the direction
of conventional flow

Notes 92

Rather than present a "rule of thumb" to use in remembering the proper current directions, I opt to let the students figure this out on their own. An important element of this should be the mathematics of BJT currents, primarily this equation:

$$I_E = I_C + I_B$$

This relationship, combined with Kirchhoff's Current Law, should provide all the help necessary to formulate a rule.

Question 93

From an examination of the energy diagram for a BJT in its conducting mode (current existing through each of the three terminals: emitter, base, and collector), determine the biasing of the two PN junctions:

- The emitter-base junction (*forward* or *reverse* biased?)
- The base-collector junction (*forward* or *reverse* biased?)

One of these two junctions actually operates in the reverse-bias mode while the transistor is conducting. Explain how this is possible, as a simple PN junction (a diode) operating in reverse-bias mode conducts negligible current.

file 02040

Answer 93

The emitter-base junction is forward-biased, while the base-collector junction is reverse-biased. Collector current is made possible across the base-collector junction by the presence of *injected charge carriers* from the emitter.

Notes 93

This question is possible to answer only if one understands the energy levels inside a BJT. The most common explanations of BJT function I find in introductory (non-engineering) textbooks completely omit discussions of energy levels, making the subject very confusing to new students.

Question 94

Bipolar junction transistors are classified as *minority carrier* devices. Explain why.

file 01265

Answer 94

Conduction through a BJT depends on charge carriers being "injected" into the base layer of the transistor, and these charge carriers are always the "minority" type with respect to the doping of the base.

Notes 94

Note to your students that there is such a thing as a *majority carrier* type of transistor, but that it does not resemble the BJT in either construction or operational characteristics.

Question 95

A beginning electronics student is just learning about transistors, and reads in the textbook that a bipolar transistor (either NPN or PNP) can be thought of as two diodes connected back-to-back as such:

N P N   *equivalent to*   N P • P N

equivalent to
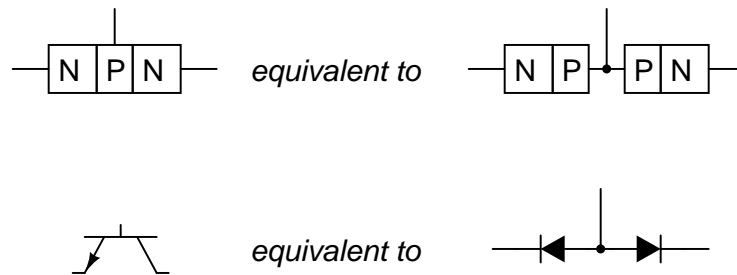
Acting on this idea, the student proceeds to connect two 1N4001 rectifying diodes back-to-back and try to use it as a transistor. This idea does not work: although the diode pair reads the same patterns of continuity as a transistor would, it does not amplify. Explain why.

Note: this is a fairly deep question, and may not be answered without an understanding of charge carrier energy levels and semiconductor junction behavior.

file 02033

Answer 95

This makeshift transistor will not work because the metal connection between the two "P"-type materials (the diode anodes) precludes the injection of minority carrier (conduction band level) electrons into the "P" material of the collector-side diode.

Follow-up question: what do you suppose is *really* meant by the textbook's statement of bipolar transistors being equivalent to back-to-back diodes, if two diodes connected back-to-back do not exhibit amplifying behavior? Is this a completely wrong statement, or is there some truth to it?

Notes 95

The idea for this question came from personal experience. I actually tried to build my own transistor out of two back-to-back diodes, and failed miserably. It took *many* years before I finally understood enough about semiconductor physics to realize why it would not work!

Question 96

Many digital multimeters have a "diode check" range that allows the user to measure the forward voltage drop of a PN junction:
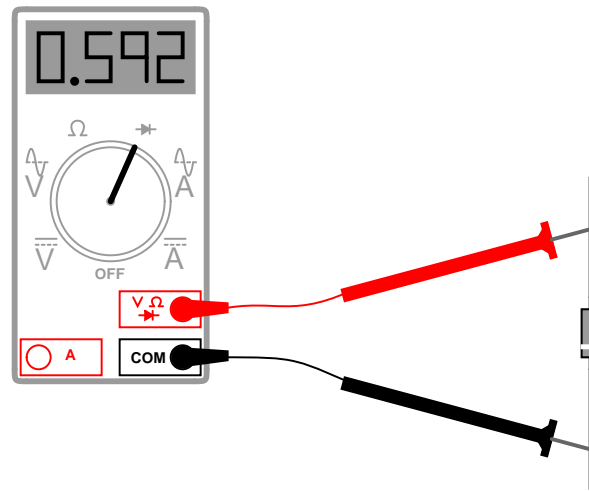
When using a multimeter with this feature to identify the terminals of a bipolar junction transistor, the forward voltage drop indication is necessary to distinguish the collector terminal from the emitter terminal. Explain how this distinction is made on the basis of the forward voltage measurement, and also explain why this is.

file 02041

Answer 96

The emitter-base junction has a slightly greater forward voltage drop than the base-collector junction. I'll let you explain why!

Notes 96

I am surprised how many textbooks do not explain how to identify BJT terminals using a multimeter (especially a multimeter with the "diode check" function). This is a very important skill for technicians to have, as they will often be faced with transistor terminal identification in the absence of datasheets or other graphical references to device terminals.

Question 97

A bipolar junction transistor parameter similar to β is "alpha," symbolized by the Greek letter α. It is defined as the ratio between collector current and emitter current:

$$\alpha = \frac{I_C}{I_E}$$

Apply algebraic substitution to this formula so that alpha is defined as a *function* of beta: $\alpha = f(\beta)$. In other words, substitute and manipulate this equation until you have alpha by itself on one side and no variable except beta on the other.

You may find the following equations helpful in your work:

$$\beta = \frac{I_C}{I_B} \qquad\qquad I_E = I_C + I_B$$

file 02064

Answer 97

$$\alpha = \frac{\beta}{\beta + 1}$$

Follow-up question: what range of values might you expect for α, with a typical transistor?

Notes 97

This question is nothing more than an exercise in algebraic manipulation.

Question 98

One of the most important parameters for semiconductor components is the *power rating*. Explain why power rating is such a critical parameter, especially compared with other types of electronic components (resistors, inductors, capacitors, etc.).

file 02039

Answer 98

Semiconductor devices tend to be especially sensitive to temperature. Thus, it is paramount to maintain power dissipation below maximum rated levels.

Challenge question: some semiconductor datasheets specify altitude values (height above sea level) along with the power ratings. Explain why altitude has anything to do with the power rating of an electronic component.

Notes 98

High temperature is the bane of most semiconductors. A classic example of this, though a bit dated, is the temperature sensitivity of the original germanium transistors. These devices were extremely sensitive to heat, and would fail rather quickly if allowed to overheat. Solid state design engineers had to be very careful in the techniques they used for transistor circuits to ensure their sensitive germanium transistors would not suffer from "thermal runaway" and destroy themselves.

Silicon is much more forgiving then germanium, but heat is still a problem with these devices. At the time of this writing (2004), there is promising developmental work on silicon carbide and gallium nitride transistor technology, which is able to function under *much* higher temperatures than silicon.

Question 99

A *stepper motor* is a special type of electric motor typically used for digital positioning systems. The motor shaft rotates by alternately energizing its coils in a specific sequence. These electromagnet coils draw a fair amount of DC current (several amperes is not uncommon for heavy-duty stepper motors), and as such are usually triggered by power transistors:
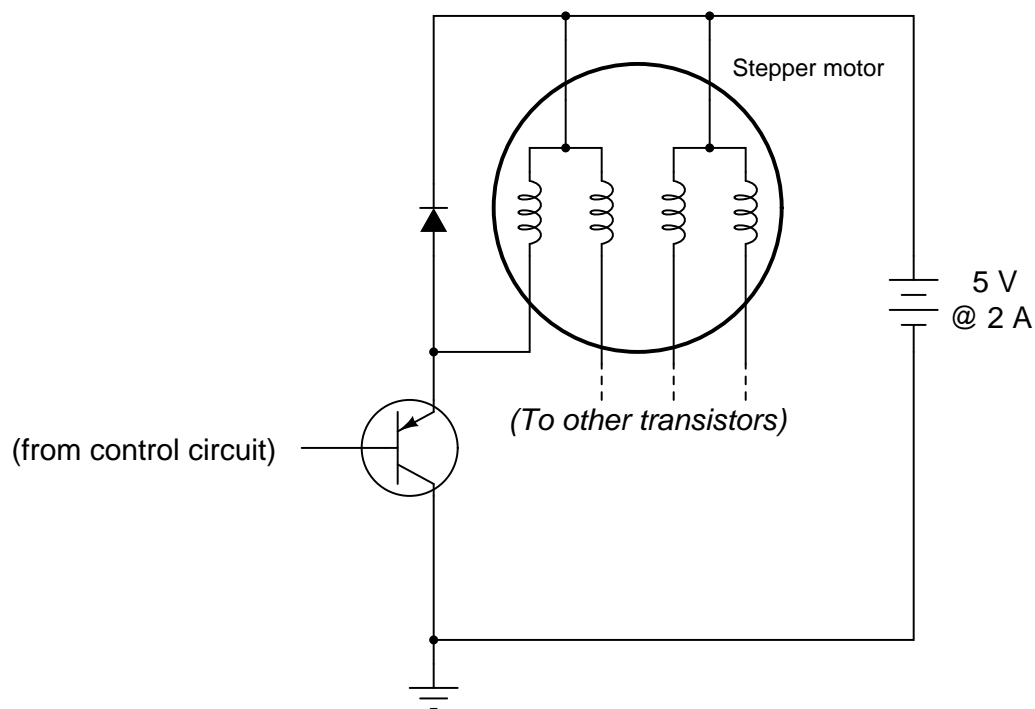
The control circuit that usually sends pulse signals to the base of the power transistors is not shown in this diagram, for simplicity. Your task is to draw a pushbutton switch in this schematic diagram showing how the first motor coil could be manually energized and de-energized. Be sure to note the directions of currents through the transistor, so that your switch is installed correctly!

Also, explain the purpose of the diode connected in parallel with the motor coil. Actually, there will be one of these diodes for each of the motor coils, but the other three are not shown for the sake of simplicity.

file 02046

136
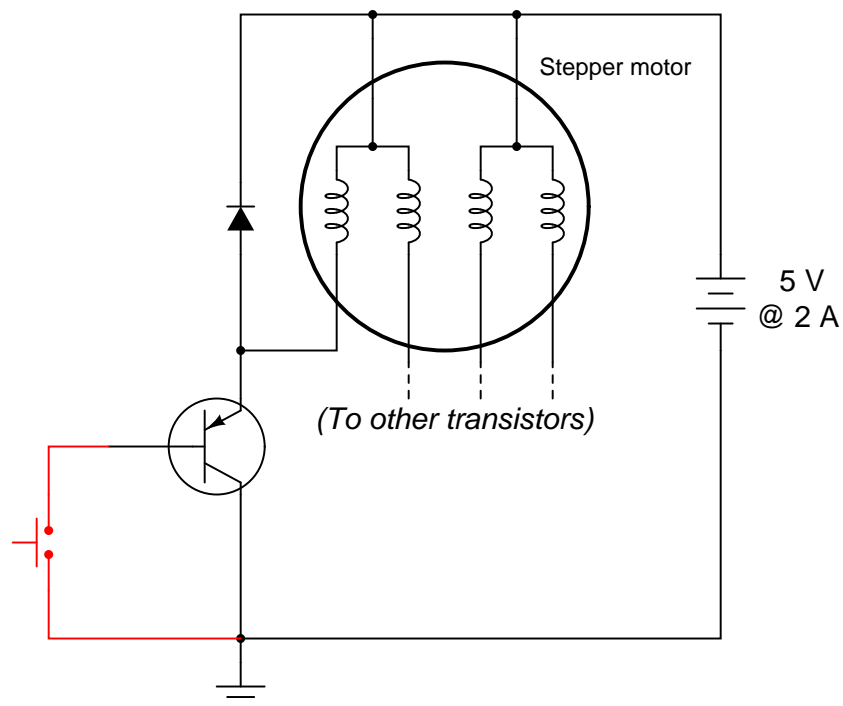
The diode prevents damage to the transistor resulting from inductive "kickback" each time the motor coil is de-energized.

Notes 99

It is very important for your students to learn how the base current controls the collector current in a BJT, and how to use this knowledge to properly set up switching circuits. This is not difficult to learn, but it takes time and practice for many students to master. Be sure to spend adequate time discussing this concept (and circuit design techniques) so they all understand.

Question 100

In this circuit, the electric motor is supposed to turn on whenever the cadmium sulfide photocell is darkened:
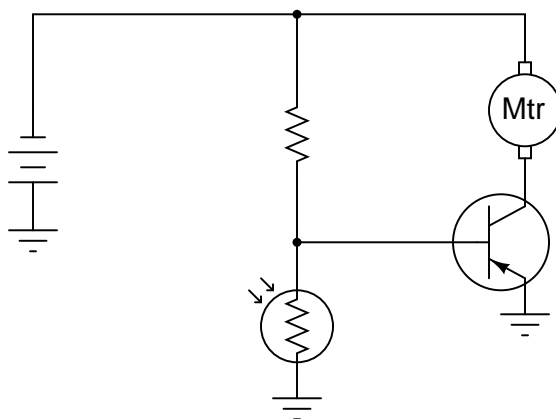
Unfortunately, though, the motor refuses to turn on no matter how little light strikes the photocell. In an attempt to troubleshoot the circuit, a technician measures voltage between the collector and emitter terminals of the transistor with the photocell covered by a piece of dark tape, and measures full battery voltage. The technician also measures voltage between the collector and base terminals of the transistor, and measures full battery voltage. At that point, the technician gives up and hands the problem to you.

Based on this information, what do you suspect is faulty in this circuit, and how might you determine the exact location of the fault? Also, identify what you know to be *not* faulted in the circuit, based on the information given here.

file 00501

Answer 100

The battery, and its connections to the rest of the circuit, are in good condition. Also, we know that the motor is not failed open. In all likelihood, the transistor is not being "told" to turn on.

Notes 100

It is just as important for your students to be able to identify what is *not* faulted in a system as it is for them to be able to identify what is faulted. Replacing components that are not faulted is expensive and wasteful!

An essential part of answering this question is what the photocell does when light strikes it. Obviously, it undergoes a change in electrical resistance, but which way? This is something your students will have to determine before they can successfully troubleshoot the system. If they do not understand what the system is *supposed* to do, they will be helpless in interpreting what it is presently doing.

Question 101

What is the significance of a transistor's *beta* (β) rating? What, exactly, does this figure mean? Explain how you might set up an experiment to calculate the beta of a given transistor.

Obtain a copy of a *datasheet* for a small-signal transistor such as the 2N2222 and see what it has to say about that transistor's beta. Note: the beta of a transistor may be represented by the Greek letter (β), or by a completely different symbolism known as a *hybrid parameter*: h_{FE}

file 00482

Answer 101

$$\beta_{DC} = \frac{I_C}{I_B}$$

$$\beta_{AC} = \frac{\Delta I_C}{\Delta I_B}$$

Notes 101

The "beta" rating of a transistor is a very important, yet very elusive parameter. Discuss the meaning of this specification with your students, and also their experimental setups for empirically determining beta. Then, compare the results of this discussion with the figures obtained from their datasheets. What do the datasheet figures indicate about the nature of beta as a parameter?

After sharing the datasheet results, re-discuss the experimental setups for measuring beta. Would a single test be sufficient, or would it be advisable to test beta more than once for a given transistor?

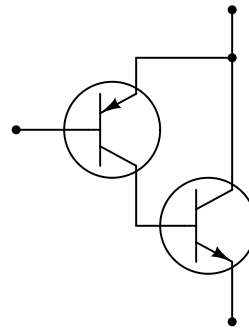Question 102

An alternative to the Darlington pair is the *Sziklai pair*, formed by a complementary pair of bipolar transistors:
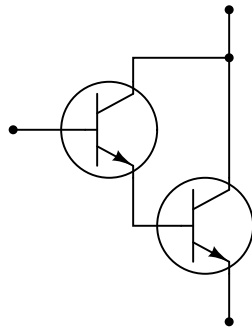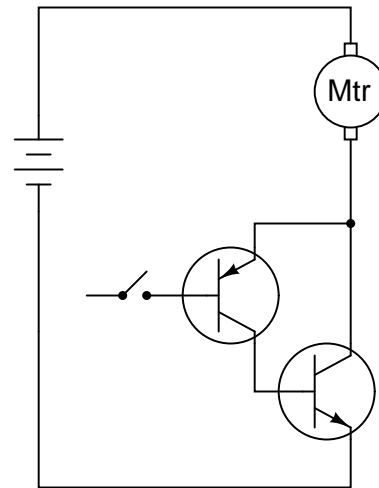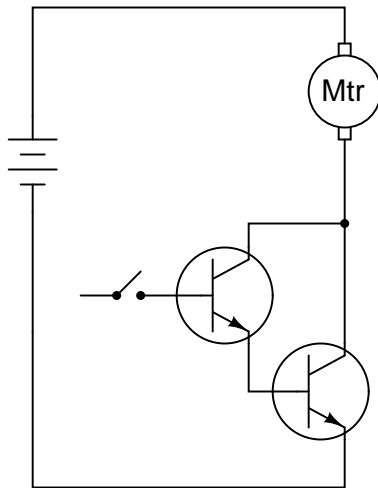
Darlington pair   Sziklai pair

Complete the following circuits, showing how a switch would be connected to each of the transistor pairs to exert control over the electric motor:

file 02049

Answer 102
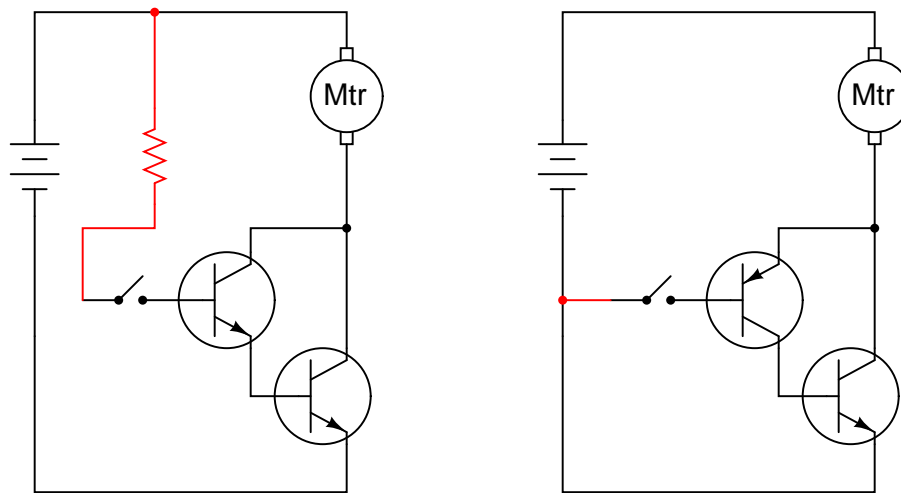
Follow-up question: why would anyone want to use either a Darlington or Sziklai pair when a single transistor is able to switch current on its own? What advantage do either of these transistor pair configurations give over a single transistor?

Notes 102

Sziklai pair circuits are often not discussed in electronics texts until the subject of audio power amplifiers, where the Sziklai pair is offered as an alternative to complementary power transistors in a push-pull circuit (where the final output transistors are both NPN instead of one being NPN and the other PNP). There is nothing wrong, however, with introducing the Sziklai pair configuration in the context of a simple switching circuit as it is done here.

Question 103

The circuit shown here is part of a digital *logic gate* circuit:
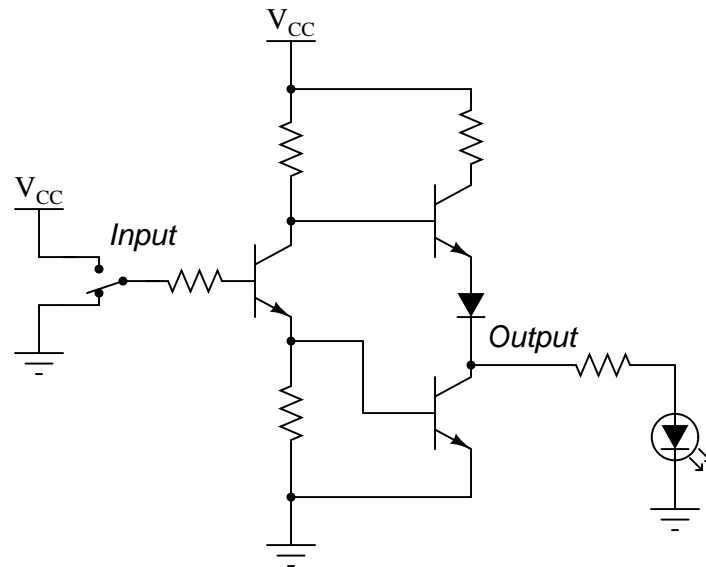
Logic circuits operate with their transistors either fully "on" or fully "off," never in-between. Determine what state the LED will be in (either on or off) for both switch positions. You may find it helpful to trace currents and label all voltage drops in this circuit for the two switch states:
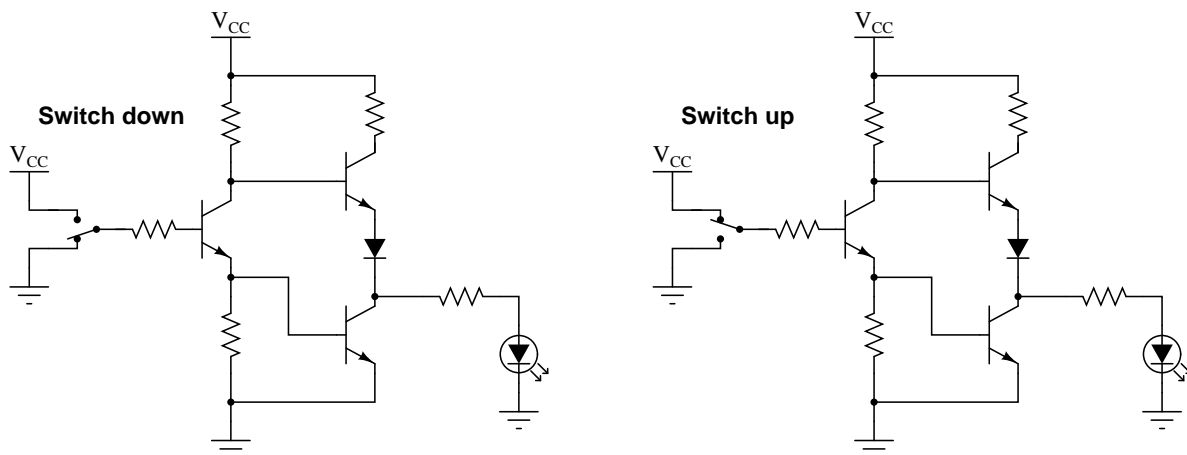
For your voltage drop calculations, assume the following parameters:

- $V_{CC} = 5$ volts
- V_{BE} (conducting) = 0.7 volts
- V_{CE} (conducting) = 0.3 volts
- V_f (regular diode conducting) = 0.7 volts
- V_f (LED conducting) = 1.6 volts

file 02051

142

Answer 103

Switch down, LED *on*; switch up, LED *off*.

Notes 103

The circuit shown in this question is a partial TTL inverter gate. I opted to simplify the circuit (omitting the "steering" diodes usually found at the input) for the sake of simplicity, so students could concentrate their attention on the two transistor stages following. Although this circuit may appear intimidating, it is not that difficult to trace currents and calculate voltage drops if one approaches it methodically.

Question 104

Field effect transistors are classified as *majority carrier* devices. Explain why.

file 01266

Answer 104

Conduction through a field-effect transistor depends on charge carriers present in the channel due to doping (the "majority" type of charge carrier).

Review question: in contrast, why are bipolar junction transistors considered *minority carrier* devices?

Notes 104

Ask your students what type of transistor operates on a *minority carrier* principle, as opposed to field-effect transistors.

Question 105

Junction Field-Effect Transistors (JFETs) differ in behavior from Bipolar Junction Transistors (BJTs) in several ways. Address each one of these behavioral aspects in your answer:

- Current gain
- Conduction with no input (gate/base) signal
- Polarization

file 00991

Answer 105

JFETs have much greater current gains than BJTs.

JFETs are normally-on devices. BJTs are normally-off devices.

JFETs can pass current from source to drain, or from drain to source with equal ease. BJTs can only pass current from emitter to collector in one direction.

Notes 105

For each one of these behavioral aspects, discuss with your students exactly *why* the two transistors types differ.

Question 106

When measuring the resistance of a JFET from source to drain, the ohmmeter reading may be seen to change simply by touching the gate terminal with your finger:

Touching the gate with your finger will cause the channel resistance to change!
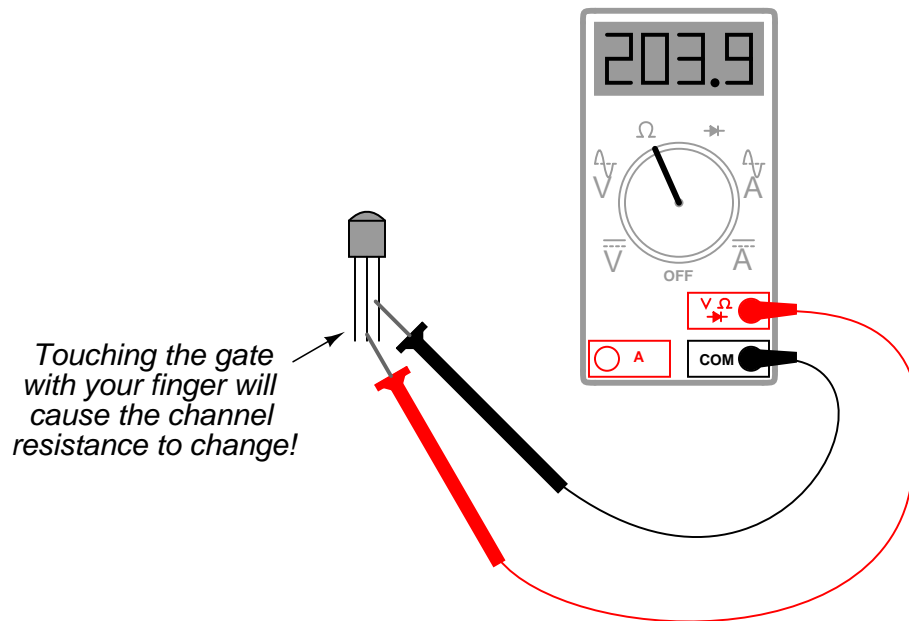
Such a degree of sensitivity is unheard of in bipolar junction transistors. Explain why the JFET is so sensitive, and comment on what advantages and disadvantages this gives the JFET as an electronic device.
file 02062

Answer 106

The gate-channel PN junction of a JFET normally operates in reverse-bias mode, whereas bipolar transistors require a forward current for emitter-collector conduction.

Notes 106

The stated answer is purposefully vague, to force students to think and to express the answer in their own words.

It is quite easy to demonstrate this sensitivity in the classroom with nothing more than an ohmmeter and a JFET, and so I encourage you to set this up as a demonstration for your students.

Question 107

What does the term *transconductance* mean, with reference to a field-effect transistor? Is the transconductance function for an FET a linear or a nonlinear relationship? Explain why, making reference to an equation if at all possible to explain your answer.

<u>file 00995</u>

Answer 107

"Transconductance" refers to the amount of change in drain current for a given amount of change in gate voltage ($\frac{\Delta I_D}{\Delta V_G}$). The transconductance function for an FET is definitely nonlinear.

Challenge question: what unit of measurement would be appropriate for expressing transconductance in?

Notes 107

Transconductance is not just a parameter for JFETs, but also MOSFETs (IGFETs) and vacuum tubes. Any voltage-controlled current-regulating device has a transconductance value (though it may change over the operating range of the device, just as β changes over the operating range of a BJT).

Question 108

What is the proper unit of measurement for the transconductance of a field-effect transistor (or an electron tube, which exhibits similar characteristics)? Explain why this unit makes sense, based on the mathematical definition of transconductance.

file 02061

Answer 108

Transconductance is measured in *Siemens* or *mhos*, the former unit being the official metric designation, and that latter being an older designation.

Notes 108

Although the physical meaning of transconductance (g_m) is significantly different from the physical meaning of conductance (G), they share the same unit of measurement due to their respective mathematical definitions. Discuss the concept of *dimensional analysis* with your students if they have not yet been exposed to it thus far through their use of physics formulae.

Question 109

Although field-effect transistors are not usually characterized in terms of current gain as bipolar junction transistors are, it would not be wrong to speak of FETs as having current gains. Compared to a BJT, how does the current gain of a FET compare? Explain your answer.

file 02060

Answer 109

Field-effect transistors have *enormous* current gains compared to bipolar junction transistors, due to their extremely high input impedances.

Notes 109

Ask your students to explain why a FET (JFET or MOSFET) has such a large current gain compared to a typical BJT. What is it about the function of a field-effect transistor that makes it such a powerful current-amplifying device?

149

Question 110

Explain the operation of this JFET audio signal switch circuit:
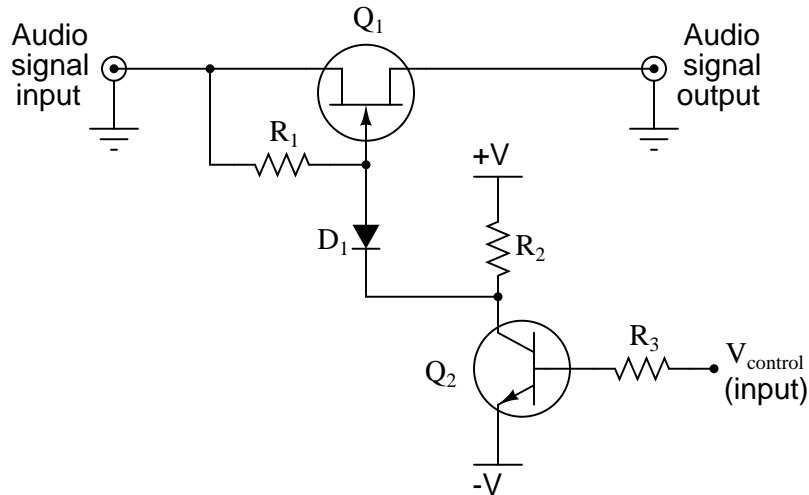
What sort of signal is necessary at pin $V_{control}$ to allow the audio signal to pass through the JFET, and what sort of signal turns the JFET off? Also, explain the purpose of each of these components in the audio switching circuit:

- Diode D_1
- Resistor R_1
- Resistor R_2
- Resistor R_3

Challenge question: what is the greatest peak audio signal voltage that this circuit will tolerate before misbehaving, in relation to the positive and negative DC supply voltages (+V and -V)?

file 02094

Answer 110

Diode D_1 prevents resistor R_2 from loading the audio signal source, and resistor R_1 provides a condition of $V_{GS} = 0$ volts whenever transistor Q_2 is in a state of cutoff. I'll let you determine the proper $V_{control}$ voltage levels for "on" and "off" control states.

Notes 110

This circuit was taken from the February 2004 edition of *Electronics World* magazine, in an article written by Douglas Self. The article's original circuit showed component values, but I show it here in generic form, and somewhat rearranged.

Question 111

If a junction field-effect transistor is subjected to several different gate-to-source voltages (V_{gs}), and the drain-to-source voltage (V_{ds}) "swept" through the full range for each of these gate voltage values, data for an entire "family" of characteristic curves may be obtained and graphed for the transistor:
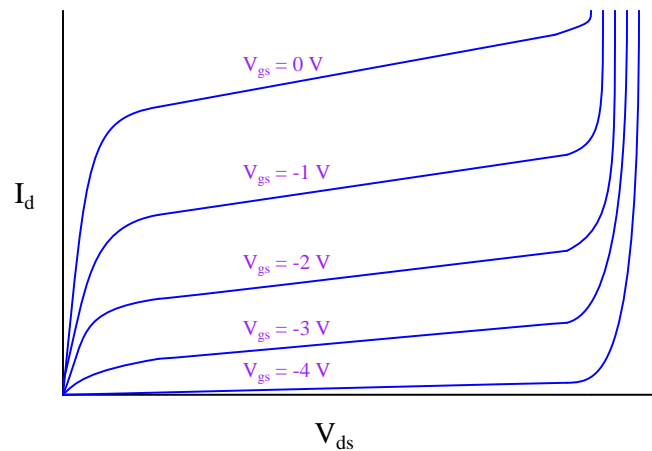
Identify the *saturation*, *active*, and *breakdown* regions on this graph.

What do these characteristic curves indicate about the gate voltage's control over drain current? How are the two signals related to each other?

file 00993

Answer 111

The *saturation*, *active*, and *breakdown* regions on this graph are equivalent to the same regions in bipolar junction transistor characteristic curves.

The drain current regulation point is established by the gate voltage while in the "active" region.

Notes 111

Ask your students what the characteristic curves would look like for a *perfect* transistor: one that was a perfect regulator of drain current over the full range of drain-source voltage.

Question 112

An important JFET parameter is $V_{GS(off)}$. Explain what this parameter means, and why it is important to us when selecting a JFET or designing a circuit around one.

file 00990

Answer 112

$V_{GS(off)}$ is called the *cutoff voltage*.

Challenge question: is $V_{GS(off)}$ approximately the same for all models of JFET, or does it vary from transistor to transistor? Explain your answer.

Notes 112

Ask your students what the "GS" subscript stands for in V_{GS}.

Question 113

What does the parameter I_{DSS} mean for a JFET? How can we use this figure, along with $V_{GS(off)}$, and V_{GS}, to calculate the amount of drain current (I_D) for a JFET operating in its active region? Write the equation for the relationship between these four variables.

file 00994

Answer 113

I_{DSS} is the amount of (regulated) current that will go through a JFET's drain when the gate terminal is shorted to the source terminal.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

Follow-up question: how could you empirically determine the I_{DSS} rating of a JFET? What sort of circuit would you have to set up in order to test and measure this transistor parameter?

Notes 113

Be sure to ask students where they found this equation! It should be available from most basic electronics textbooks. Also, discuss the experimental circuit that would have to be constructed in order to test the shorted-gate drain current of a JFET. You might want to plan on having your students build this very circuit during class time as an exercise in using JFETs.

Question 114

Calculate the amount of gate-to-source voltage necessary to regulate a JFET's drain current at a value of 2.5 mA, given the following transistor parameters:

- $V_{GS(off)} = 3$ volts
- $I_{DSS} = 17$ mA

Also, write the equation used for obtaining the value of V_{GS}.
file 00998

Answer 114

$V_{GS} = 1.85$ volts

$$V_{GS} = V_{GS(off)} \left(1 - \sqrt{\frac{I_D}{I_{DSS}}} \right)$$

Notes 114

Once students have found the standard drain current formula (transconductance equation), the rest is algebraic manipulation.

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Question 115

Cutoff voltage is not the same thing as *pinch-off* voltage, although the names seem quite similar. Give a concise definition for each of these field-effect transistor parameters, referencing them to a graph of characteristic curves if possible.

file 03180

Answer 115

Cutoff voltage is that gate-to-source voltage (V_{GS}) resulting in zero drain current. *Pinch-off* voltage is that drain-to-source voltage (V_{DS}) value where further increases do not yield significantly greater drain current values.

Follow-up question: which of these two parameters is more appropriate to consider when using an FET as a switch, and which is more appropriate when using an FET as a linear amplifier?

Notes 115

This contrast and comparison is probably best shown on a graph of characteristic curves, but I leave this to the student to research!
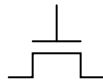
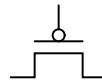Question 116

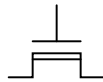Identify these schematic symbols:
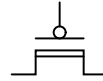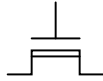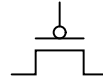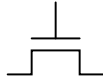
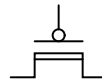Answer 116

N-channel E-type   P-channel E-type

N-channel D-type   P-channel D-type

Notes 116

The "bubble" symbol on the gate of the P-channel devices is reminiscent of inversion bubbles used on logic gate symbols. I'm assuming that your students will not have studied logic gates at this point, so this is a foreshadowing of things to come!

Question 117

Metal Oxide Field-Effect Transistors (MOSFETs) differ in behavior from Bipolar Junction Transistors (BJTs) in several ways. Address each one of these behavioral aspects in your answer:

- Current gain
- Conduction with no input (gate/base) signal
- Polarization

file 02073

Answer 117

MOSFETs have *much* greater current gains than BJTs.

BJTs are normally-off devices, whereas a MOSFET may either be normally-on or normally-off depending on its manufacture.

MOSFETs can pass current from source to drain, or from drain to source with equal ease. BJTs can only pass current from emitter to collector in one direction.

Notes 117

For each one of these behavioral aspects, discuss with your students exactly *why* the two transistors types differ.

Question 118

Bipolar junction transistors (BJTs) are considered "normally-off" devices, because their natural state with no signal applied to the base is no conduction between emitter and collector, like an open switch. Are insulate-gate field-effect transistors (IGFETs) considered the same? Why or why not?

file 02072

Answer 118

IGFETs may be manufactured *either* as "normally-on" or "normally-off" devices.

Notes 118

Ask your students to elaborate on the answer given. Do not accept a mindless recitation of the answer, that "it depends on how they're manufactured," but rather demand that some sort of explanation be given as to *why* an IGFET would be normally-on versus normally-off.

Question 119

Metal Oxide Field-Effect Transistors (MOSFETs) differ in some regards from Junction Field-Effect Transistors (JFETs). Explain in your own words what the difference(s) is/are.

file 02074

Answer 119

I'll let you do your own research here.

Notes 119

Despite their many similarities, MOSFETs and JFETs are not identical. Ask your students to explain *why* the two types of transistor behave differently, not just recite differences read from a textbook or other reference.

A technician is using a digital multimeter (with a "diode check" feature) to identify the terminals of a power MOSFET:
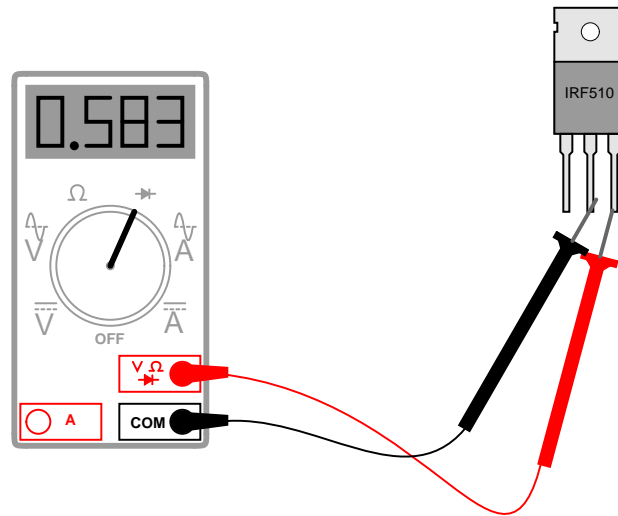
The technician obtains the following "diode check" voltage measurements, in this order:

1. Black lead on middle terminal, Red lead on right terminal = 0.583 volts (*shown in illustration*)
2. Red lead on middle terminal, Black lead on right terminal = O.L. (open)
3. Black lead on middle terminal, Red lead on left terminal = O.L. (open)
4. Black lead on middle terminal, Red lead on right terminal = 0.001 volts
5. Red lead on middle terminal, Black lead on right terminal = 0.001 volts

Explain why the fourth and fifth measurements are so different from the first and second, respectively, when they were taken between the same terminals on the MOSFET. Hint: this particular MOSFET is an N-channel, enhancement-type.

file 03451

Answer 120

The act of taking the third measurement enhanced the transistor into the on (saturated) state by means of the multimeter's output voltage in the diode test mode. The MOSFET then remained in its on state for the fourth and fifth measurements.

Follow-up question: where would the meter have to be connected in order to force the MOSFET into is off (cutoff) state?

Notes 120

Field-effect transistors, by their very nature being voltage-activated devices with extremely high input impedance, are more difficult to identify than bipolar junction transistors because the meter's output in the "diode check" mode is sufficient to activate and de-activate them. This question showcases a practical example of this (the values actually came from real-life testing of an IRF510 transistor!).
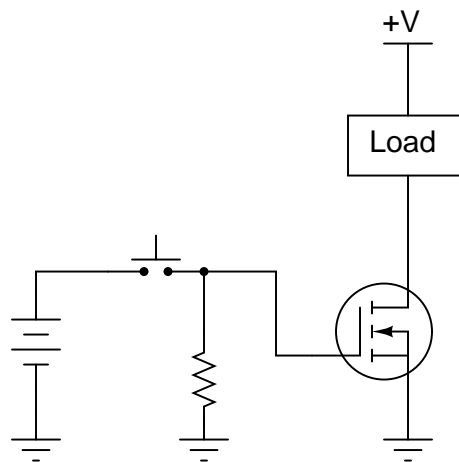
Question 121

Complete the circuit, showing how the pushbutton switch could be connected to the gate of the MOSFET in order to exert control over the load:
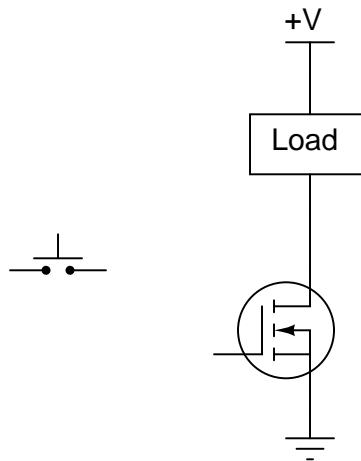
Answer 121

This solution, while workable, is not the most practical. Improve on this design!

Follow-up question: would you say this transistor *sources* current to the load, or *sinks* current from the load? Explain your answer.

Notes 121

Discuss with your students why the circuit shown in the answer would not necessarily be practical, and work together to develop a better design.

Question 122

Explain what will happen in this circuit when each pushbutton switch is individually actuated:
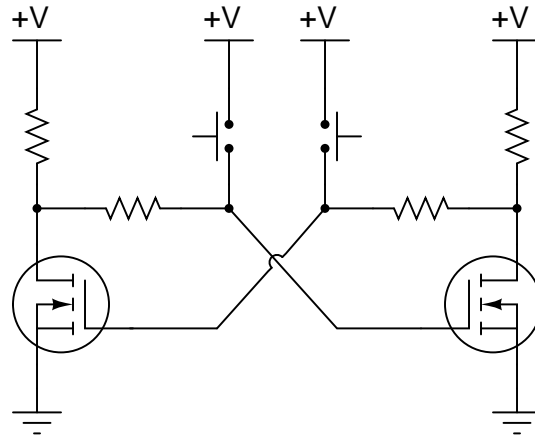
Can you think of any practical applications for a circuit like this?
file 02126

Answer 122

This circuit is commonly known as a *bistable* latch, since it is able to "latch" into two different stable states.

If you experience difficulty analyzing this circuit's operation, imagine that one of the transistors is in the "on" state and the other is in the "off" state immediately after power-up. Then ask yourself what will happen when each pushbutton is actuated.

Notes 122

Bistable latch, or multivibrator, circuits are quite useful and quite simple to implement with MOSFETs as this example demonstrates. Discuss some practical applications with your students, especially if they have not discovered a few applications of their own.
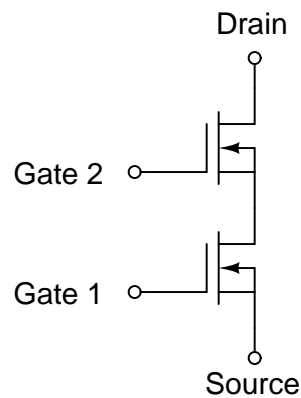
Question 123

A special type of insulated-gate field-effect transistor is the *dual gate MOSFET*, shown here:
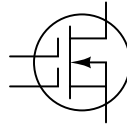
Draw a schematic diagram using normal (single-gate) MOSFETs, equivalent to this dual-gate MOSFET.

file 01134

Answer 123

Notes 123

A pretty simple answer to this question, but the real purpose is to challenge students to think of complex circuit elements in terms of *equivalent circuits* comprised of simple, idealized components.

Question 124

$\boxed{\int f(x)\,dx \quad \textit{Calculus alert!}}$

A potential problem for power MOSFETs is $\frac{dv}{dt}$ *induced turn-on*. Explain why a MOSFET may turn on when it's not supposed to, given an excessive $\frac{dv}{dt}$ condition.

file 01133

Answer 124

If the drain voltage rate-of-change over time $(\frac{dv}{dt})$ is excessive, the transistor may turn on due to the coupling effect of gate-to-drain capacitance (C_{GD}).
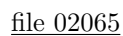
Challenge question: draw an equivalent schematic diagram showing the parasitic C_{GD} capacitance, and write the equation relating capacitive current to instantaneous voltage change over time.

Notes 124

This question is a good review of capacitor theory and calculus notation. Ask your students to explain exactly what $\frac{dv}{dt}$ means, and how it relates to current in a circuit containing capacitance.

The problem of dv/dt induced turn-on is not unique to power MOSFETs. Various thyristors, most notably SCRs and TRIACs, also exhibit this problem.

Question 125

Complete the schematic diagram showing an equivalent circuit for an N-channel IGBT, using an N-channel E-type MOSFET and a PNP bipolar transistor:
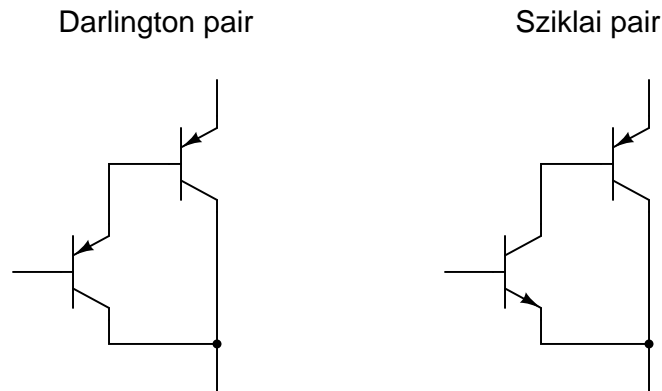
Answer 125

Notes 125

You should discuss with your students the fact that IGBT's are not actually made of two discrete transistors connected as shown. Instead, they are fabricated as monolithic devices, all on the same semiconductor substrate. The "model" of an IGBT consisting of a MOSFET coupled to a BJT is similar to the model commonly used to emulate an SCR: a circuit whose sole purpose it is to show the operation of a special device in terms of other, well-understood devices.

Question 126

The equivalent circuit for an IGBT – comprised of a MOSFET coupled to a BJT – bears resemblance to a couple of other BJT circuits you may have seen before:

Darlington pair   Sziklai pair

Which of these two paired-BJT circuits most resembles the IGBT equivalent circuit, in terms of what two terminals the control signal voltage must be applied between to turn the device on?

file 02066

Answer 126

The Sziklai pair most resembles the IGBT equivalent circuit.

Notes 126

It is important for students to realize what two terminals of the device the input (control) signal must be applied to in order to turn the device on. This is really the point of the question, not so much a review of Darlington versus Sziklai pairs.
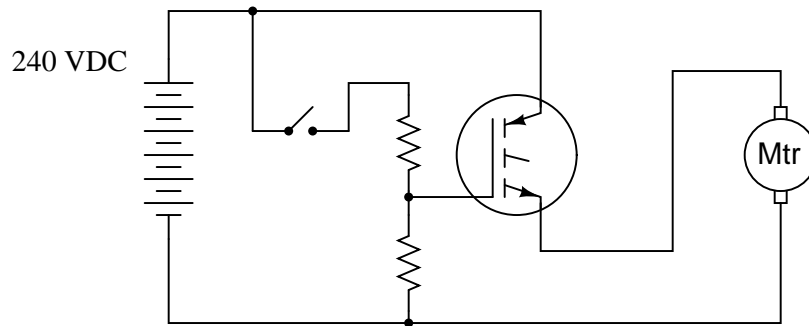
166

Question 127

Draw a complete schematic diagram showing how this IGBT can be used to control a DC motor, at the command of the toggle switch:

240 VDC

Mtr
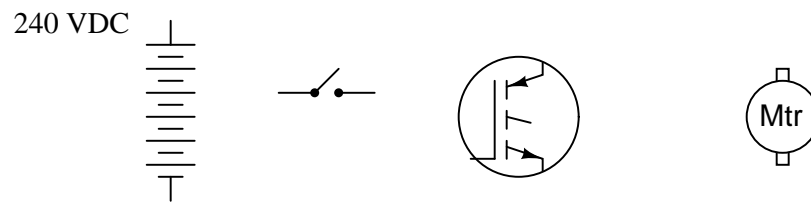
Note: the DC power supply voltage is 240 VDC, and the IGBT's maximum gate-to-emitter control voltage is 20 volts!

file 01192

Follow-up question: calculate the values necessary for the two resistors shown, to provide a gate-to-emitter voltage of 10 volts, using 1/2 watt resistors.

Challenge question: why might it be a good idea to include a diode in the circuit, like this?
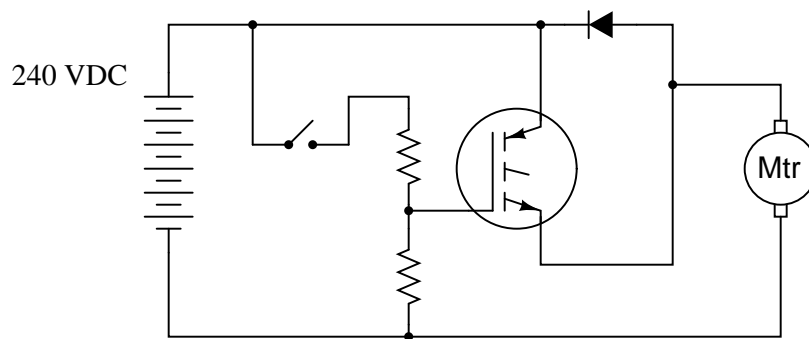

Notes 127

Ask your students what purpose the voltage divider serves. The first purpose should be obvious, as hinted in the "Note" at the end of the question. However, a second purpose is not so obvious. If the lower resistor were to fail open, the IGBT would turn on when the switch closes, but it would not turn off (at least not reliably) when the switch opens! Present this scenario to your students, and ask them to explain why this would happen.

Check your students' math when they present resistor values. Do not be surprised if some students specify the resistor values such that the actual power dissipation runs right at 1/2 watt each! Use this as an opportunity to discuss component reliability versus power dissipation, and good engineering practices.

Regarding the challenge question, the diode is *not* there to provide a path for inductive "free-wheeling" current. Some of your students may suggest this as its purpose, but a close examination of polarity will show otherwise. The true answer to this question, in the context of a DC motor control circuit, has to do with the behavior of DC motors.

Question 128

Examine the schematic diagram for this photographic strobe light control system:
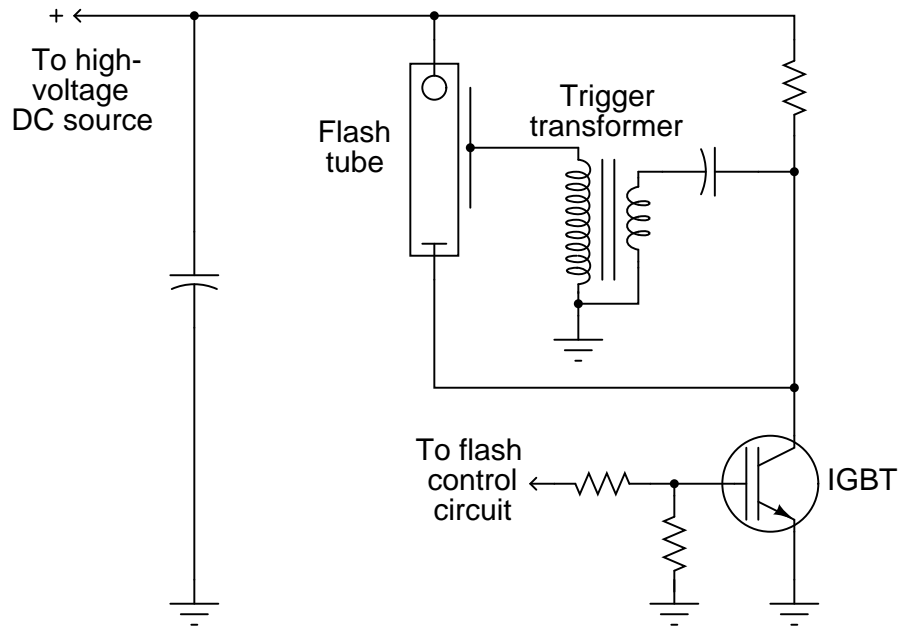
Explain its operation, and explain why an IGBT is a good transistor type for this application.
<u>file 02127</u>

Answer 128

When the IGBT is turned on, the "trigger" transformer develops a high voltage pulse on the flash tube's trigger wire, ionizing the xenon gas within and allowing a surge of current to pass between the tube's main electrodes. Since the IGBT handles the tube's main current as well, it is able to turn off the strobe as easily as it turned it on.

Notes 128

Even if students have never seen a strobe light circuit, they should at least be able to determine what happens when the transistor is immediately turned "on." The fact that professional flash tubes require currents in excess of a hundred amps is not obvious from this schematic, so you should mention this fact in the discussion.

This schematic was adapted (simplified) from one found in a Fairchild IGBT application note (AN9006 – "IGBT Application Note For Camera Strobe").