

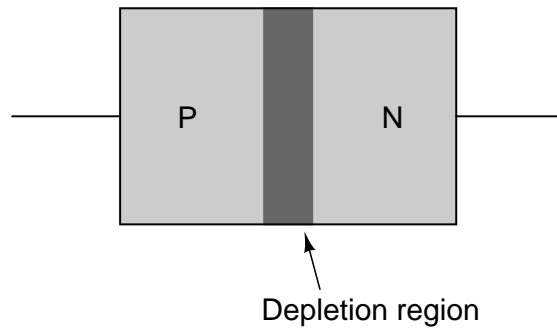
Junction field-effect transistors

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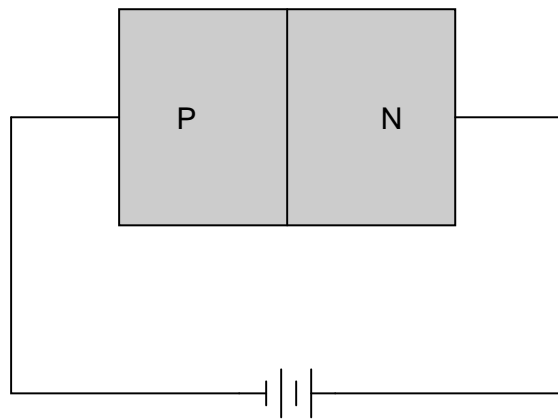
Resources and methods for learning about these subjects (list a few here, in preparation for your research):

Question 1

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

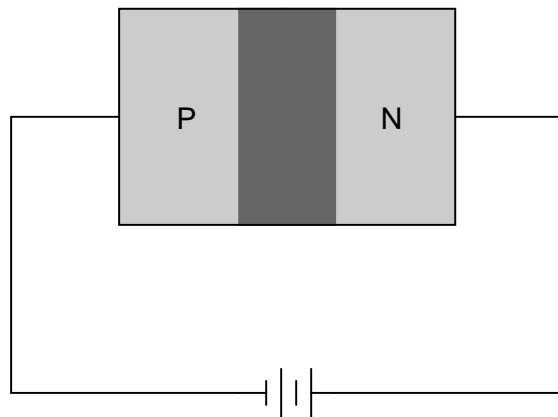


Re-draw the depletion region when the PN junction is subjected to a reverse-bias voltage:



file 02053

Answer 1



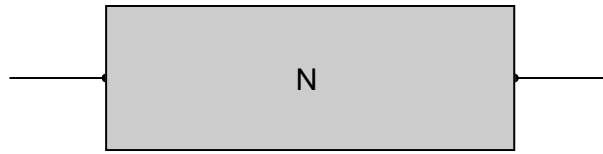
Follow-up questions: describe the conductivity of the depletion region: is it high or low? What exactly does the word "depletion" refer to, anyway?

Notes 1

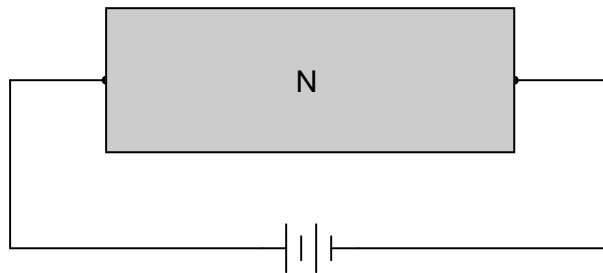
This question makes a good lead-in to a discussion of JFET operation, where the channel conductivity is modulated by the width of the gate-channel depletion region.

Question 2

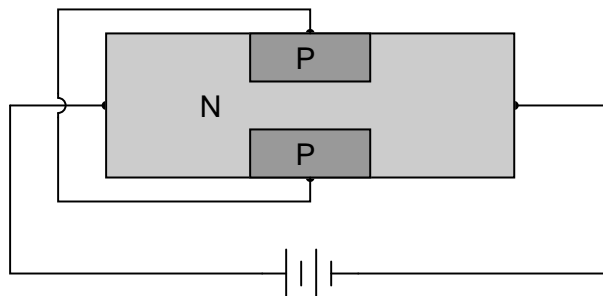
A *field-effect transistor* is made from a continuous "channel" of doped semiconductor material, either N or P type. In the illustration shown below, the channel is N-type:



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:

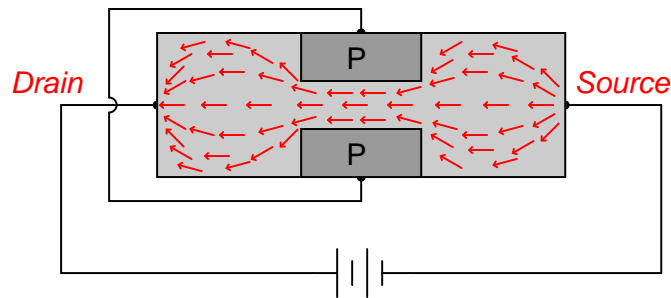


Show how the presence of these "gate" regions in the channel influence the flow of charge carriers. Use small arrows if necessary to show how the charge carriers move through the channel and past the gate regions of the transistor. Finally, label which terminal of the transistor is the *source* and which 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 2

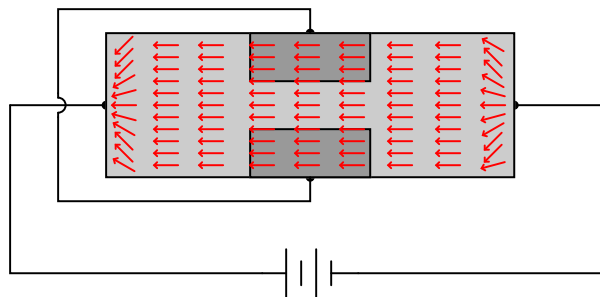
The majority charge carriers in this transistor's channel are electrons, not holes. Thus, the arrows drawn in the following diagrams point in the direction of electron flow:



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:

Why not this?

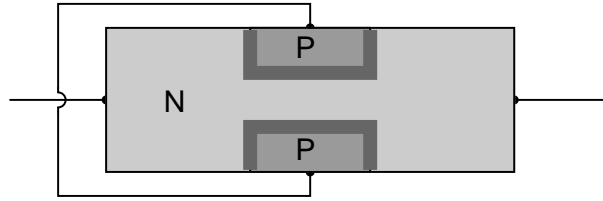


Notes 2

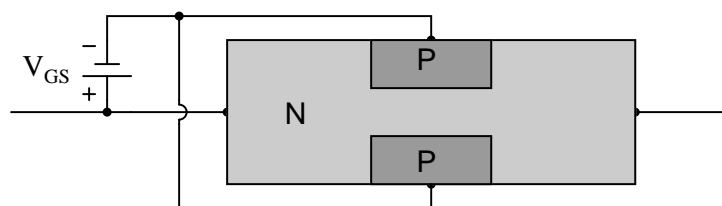
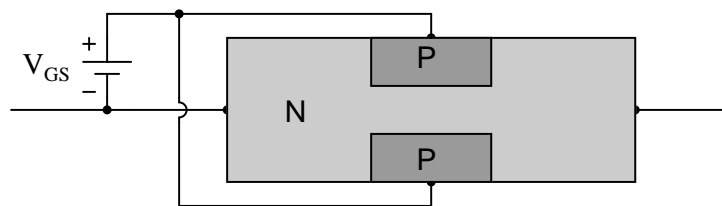
Students typically find junction field-effect transistors much easier to understand than bipolar junction transistors, because there is less understanding of energy levels required to grasp the operation of JFETs than what is required to comprehend the operation of BJTs. Still, students need to understand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

Question 3

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:

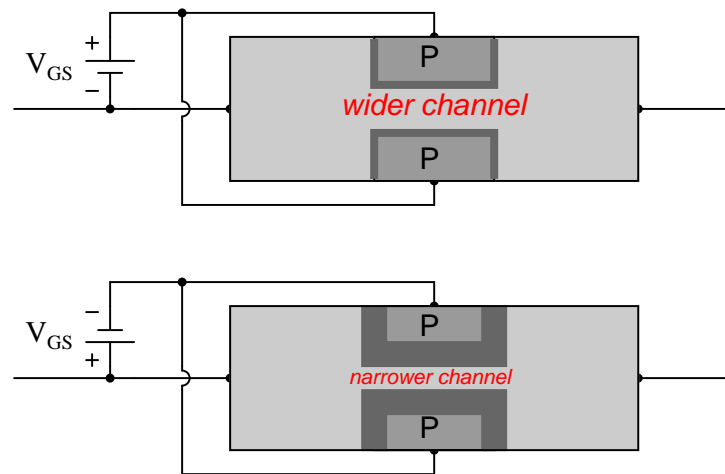


Re-draw the depletion regions for the following scenarios, where an external voltage (V_{GS}) is applied between the gate and channel:



Note how the different depletion region sizes affect the conductivity of the transistor's channel.
[file 02055](#)

Answer 3



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 3

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 4

Field effect transistors are classified as *majority carrier* devices. Explain why.
file 01266

Answer 4

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

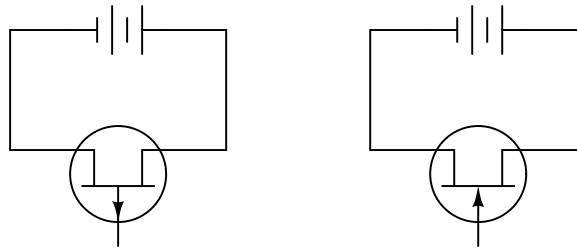
Review question: in contrast, why are bipolar junction transistors considered *minority carrier* devices?

Notes 4

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

Question 5

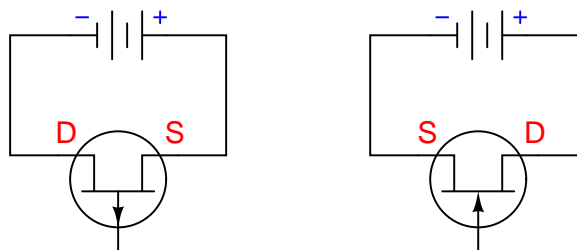
Identify which transistor terminal functions as the *source* and which transistor terminal functions as the *drain* in both of these JFET circuits:



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 5



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

Notes 5

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 6

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 6

JFETs are "normally-on" devices.

Notes 6

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 7

The typical amount of current through a JFET 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 JFET that limits the input current to almost nothing during normal operation.

file 02322

Answer 7

The gate-source PN junction is reverse-biased.

Notes 7

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

Question 8

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 8

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

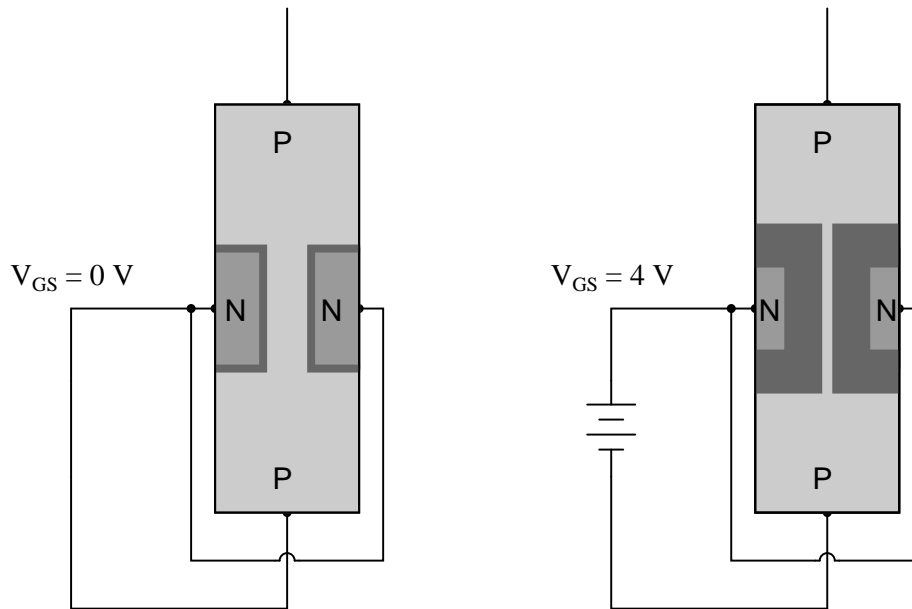
Follow-up question: based on your research of these datasheets, how constant is $V_{GS(off)}$ between different transistors? In other words, is this a parameter you can accurately predict from the datasheet before purchasing a transistor, or does it vary significantly from transistor to transistor (of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

Notes 8

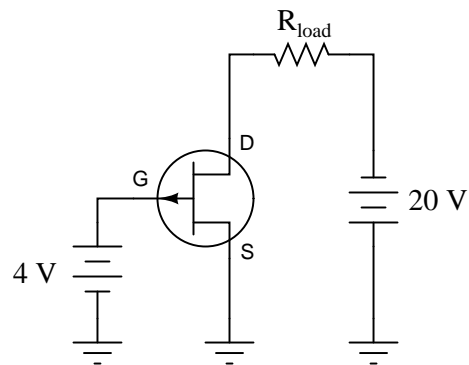
Discuss with your students the significance of $V_{GS(off)}$, especially its stability (or instability, as the case may be) between transistors. How does this impact the design of FET circuits?

Question 9

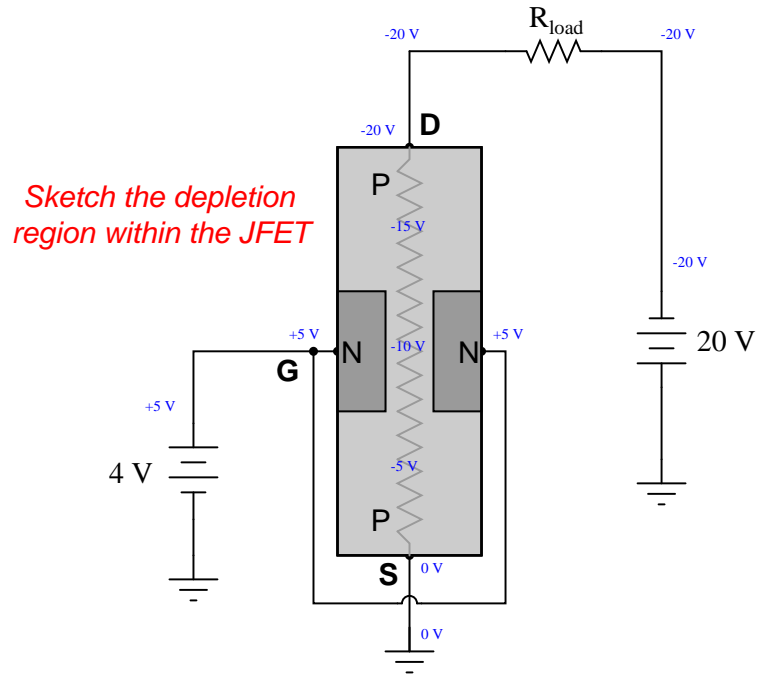
When a reverse-bias voltage is applied between the gate and channel of a JFET, the depletion region within expands. The greater the reverse-bias voltage, the wider the depletion region becomes. With enough applied V_{GS} , this expansion will cut off the JFET's channel, preventing drain-source current:



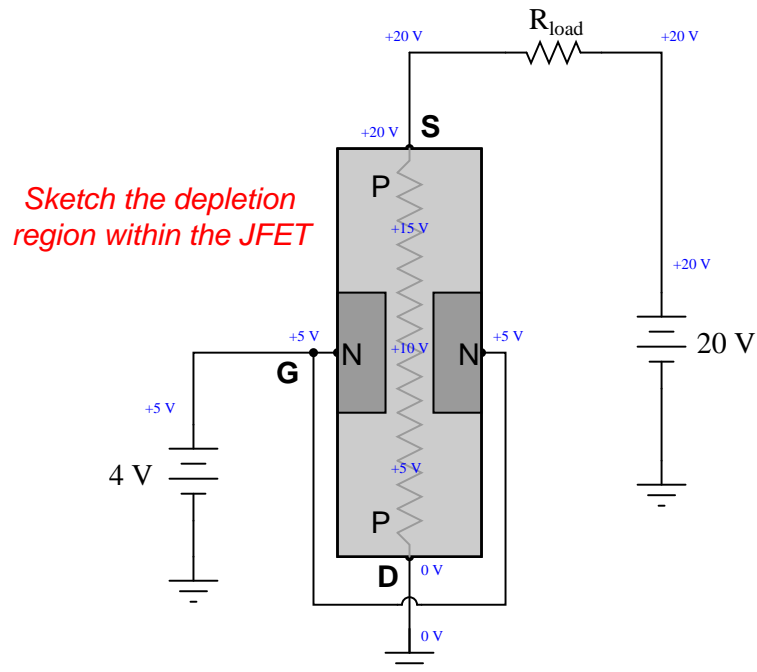
Something not immediately apparent about this effect is that the formation of a wide depletion region necessary for cut-off of a field-effect transistor is *also* affected by the drain-to-source voltage drop (V_{DS}).



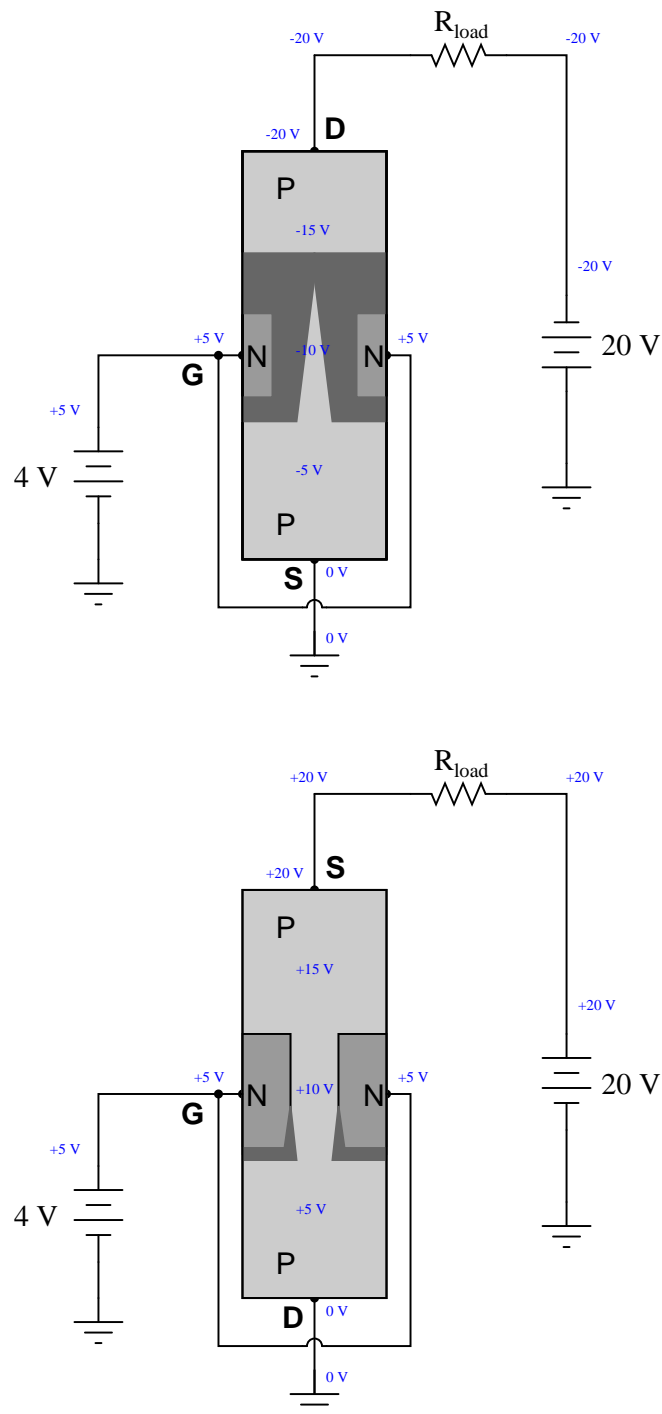
If we connect a gate-to-source voltage (V_{GS}) large enough to force the transistor into cutoff mode, the JFET channel will act as a huge resistance. If we look carefully at the voltages measured with reference to ground, we will see that the width of the depletion region must vary within the JFET's channel. Sketch this varying width, given the voltages shown in the illustration:



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:



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?

Notes 9

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 10

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 10

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 10

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

Question 11

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 11

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.

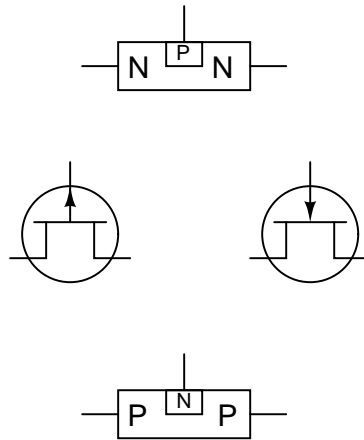
Follow-up question: is any gate *current* required to drive a JFET into the cutoff state? Why or why not?

Notes 11

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.

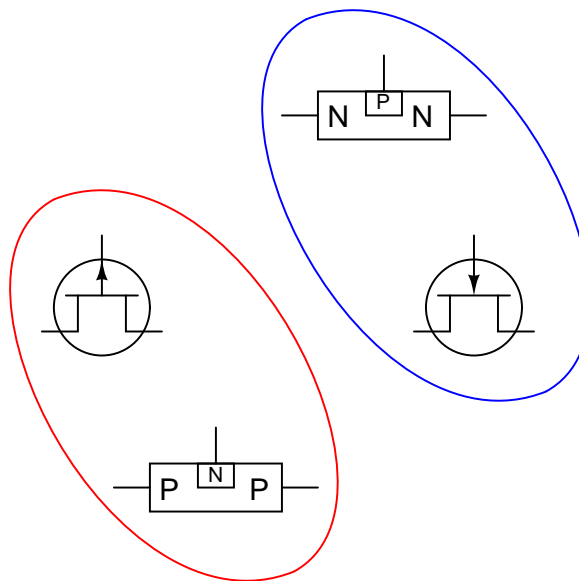
Question 12

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



file 00986

Answer 12



Notes 12

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 13

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 13

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

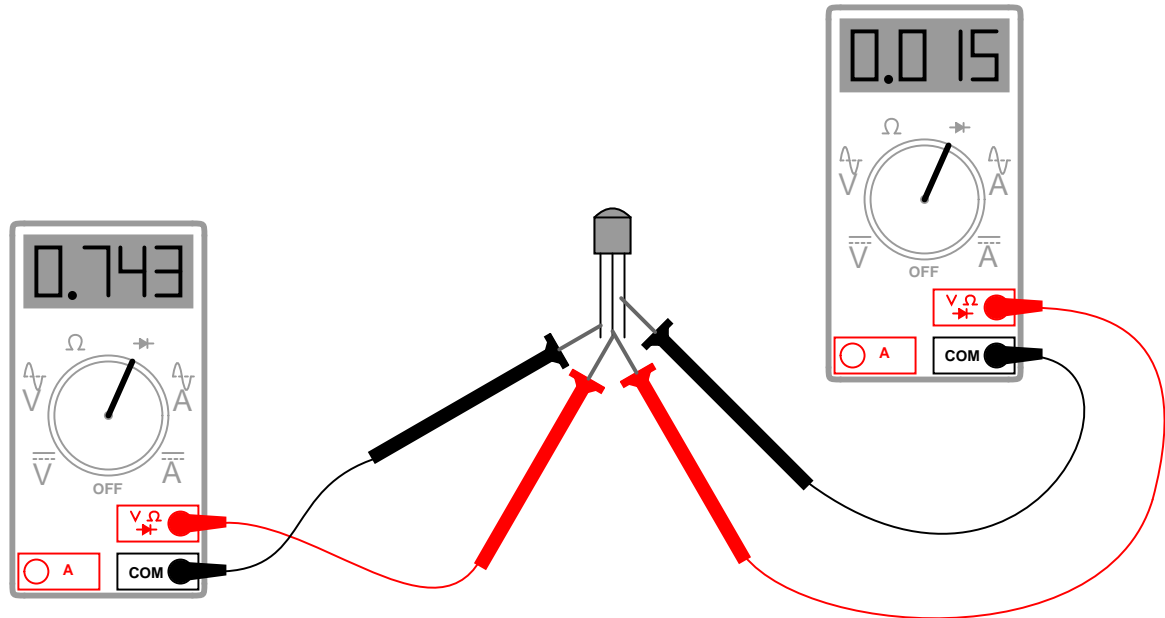
Notes 13

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 14

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 14

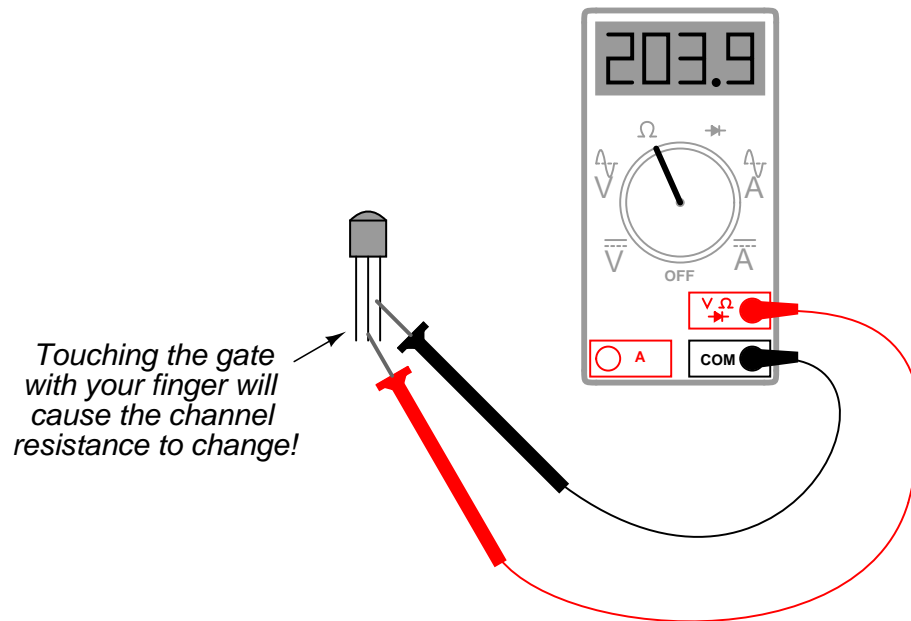
The left-most terminal on this JFET is the gate, and the other two are source and drain. This is a P-channel JFET.

Notes 14

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 15

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:



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 15

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 15

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 16

The "transconductance" ratio (g_m) of a field-effect transistor 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 02059](#)

Answer 16

Transconductance is defined as the ratio between drain current and gate voltage. I'll let you research some typical values. Here are some transistor part numbers you could research datasheets for:

- J110
- J308
- J309
- J310
- MPF 102

Challenge question: the "beta" ratio for a BJT (β) may be defined as the direct ratio of collector current to base current, or as the ratio between *change* in collector current and *change* in base current, as the following equations show.

$$\beta_{DC} = \frac{I_C}{I_B} \quad (\text{DC current gain for a BJT})$$

$$\beta_{AC} = \frac{\Delta I_C}{\Delta I_B} \quad (\text{AC current gain for a BJT})$$

By contrast, the transconductance of a FET is always defined in terms of change, and never in terms of a direct ratio:

$$g_m = \frac{\Delta I_D}{\Delta V_G}$$

$$g_m \neq \frac{I_D}{V_G}$$

Explain why this is.

Notes 16

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!

Discuss with your students why transconductance is measured in units of *Siemens*. Where else have they seen this unit of measurement? Why would it be an appropriate unit of measurement in this context?

Question 17

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 17

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

Notes 17

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 18

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 18

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

Notes 18

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 19

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 19

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

Notes 19

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?

Question 20

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 20

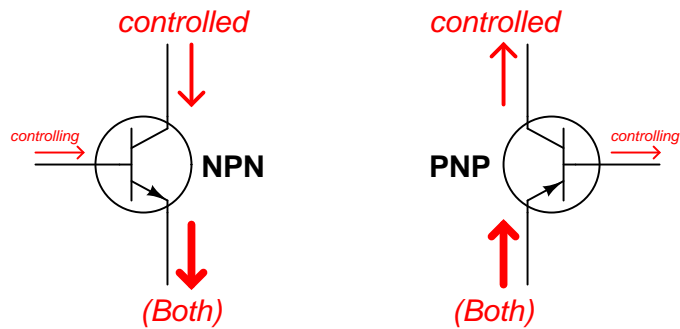
I_G is zero for all practical purposes.

Notes 20

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.

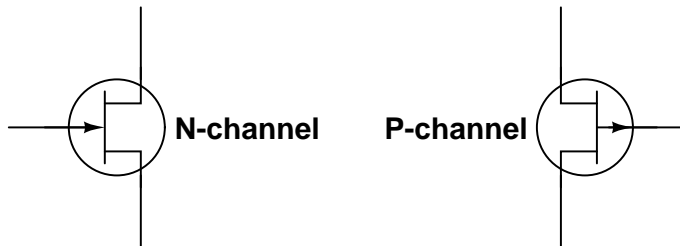
Question 21

Bipolar junction transistors are definitely unidirectional ("polarized") devices, able to handle electric currents in one particular direction through each terminal:



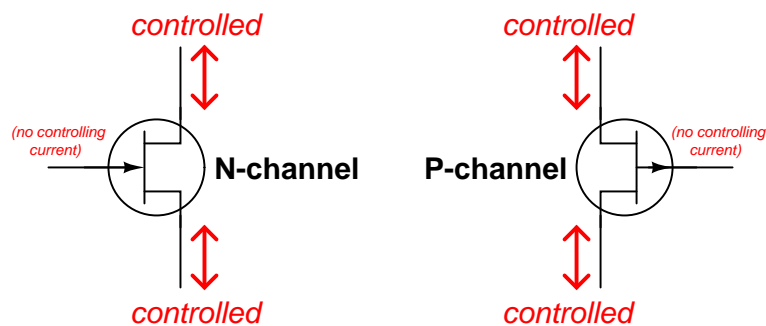
All currents shown using conventional flow notation

What about JFETs? Are they polarized just like BJTs? Explain your answer, complete with arrows showing proper directions of current through these two JFETs:



file 02414

Answer 21



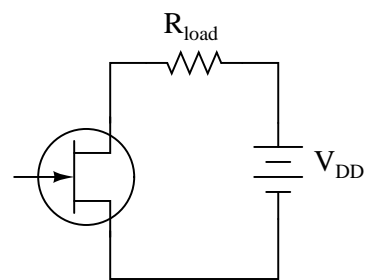
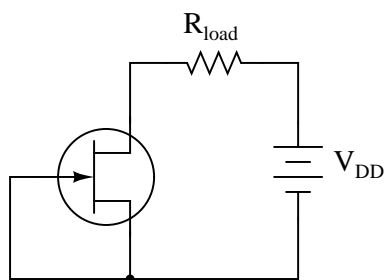
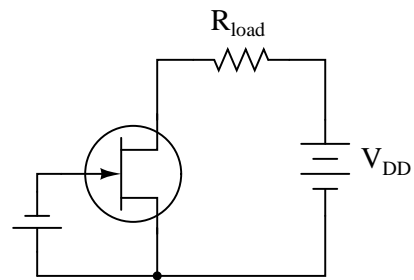
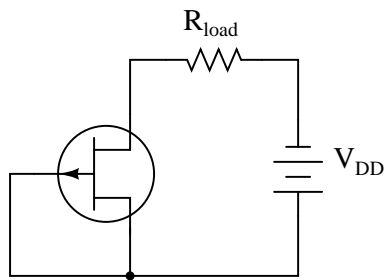
All currents shown using conventional flow notation

Follow-up question: explain why there is no "controlling" current (ideally) in a JFET.

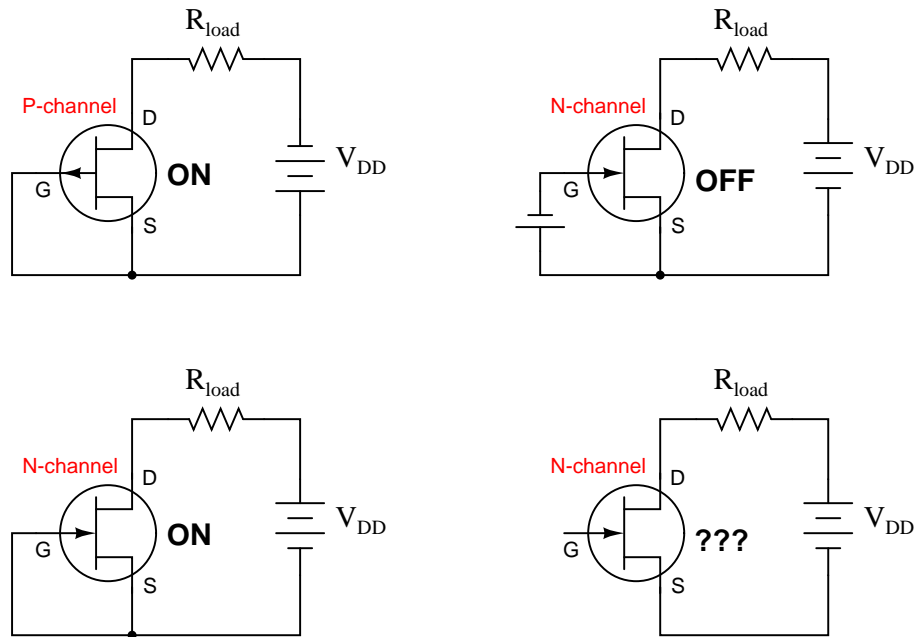
The fact that JFETs are *bilateral* devices rather than unilateral as bipolar junction transistors leads to some interesting applications whereby AC currents may be controlled! JFETs are often used in this capacity as AC signal switches, allowing a DC voltage to control passage or blocking of a low-amplitude AC signal such as an audio or RF signal prior to power amplification.

Question 22

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



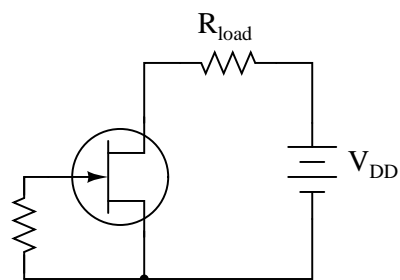
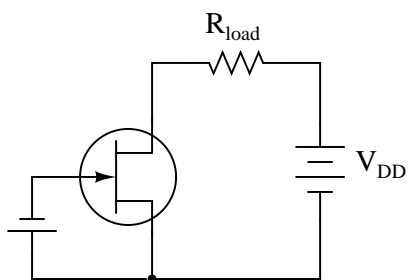
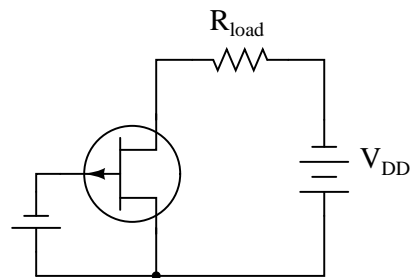
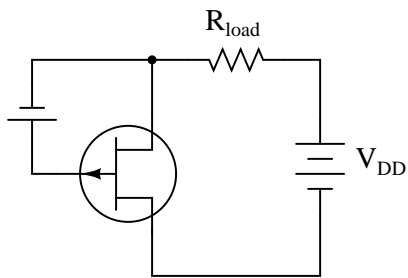
Follow-up question: explain why the lower-right circuit has question-marks next to the transistor. Why is the JFET's state uncertain?

Notes 22

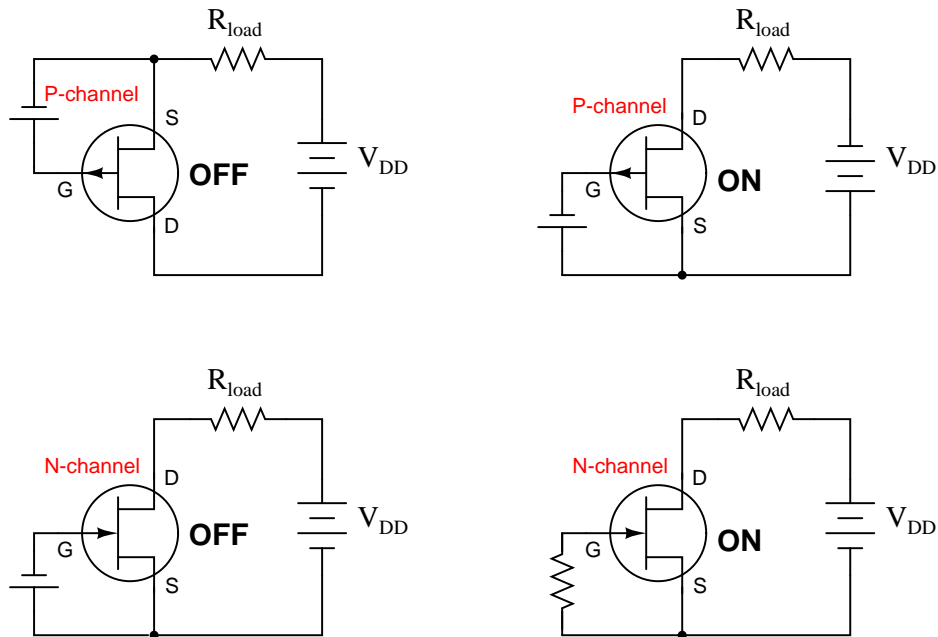
It is very important for your students to understand what factor(s) in a circuit force a JFET to turn on or off. Be sure to ask your students to explain their reasoning for each transistor's status. What factor, or combination of factors, is necessary to turn a JFET on, versus off? One point of this 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 23

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



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

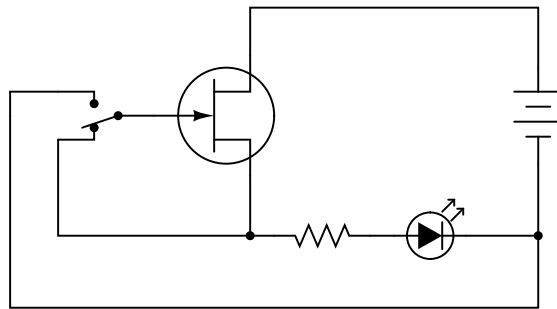
Notes 23

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 24

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



file 02093

Answer 24

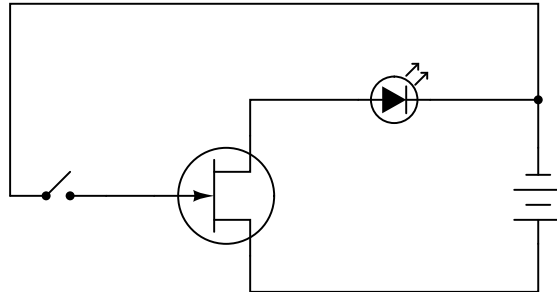
The switch is shown in the "LED on" position.

Notes 24

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

Question 25

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 25

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.

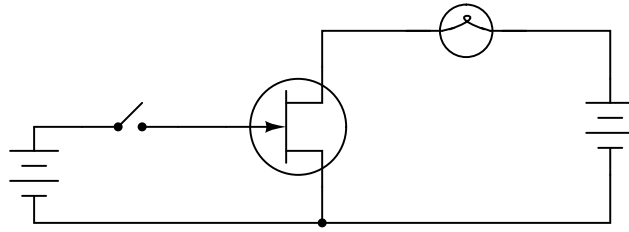
Notes 25

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 26

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



file 00989

Answer 26

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

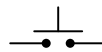
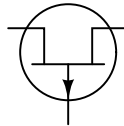
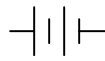
Notes 26

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.

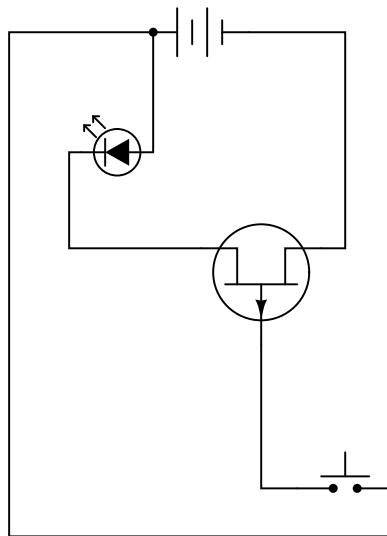
Question 27

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



file 00987

Answer 27



Notes 27

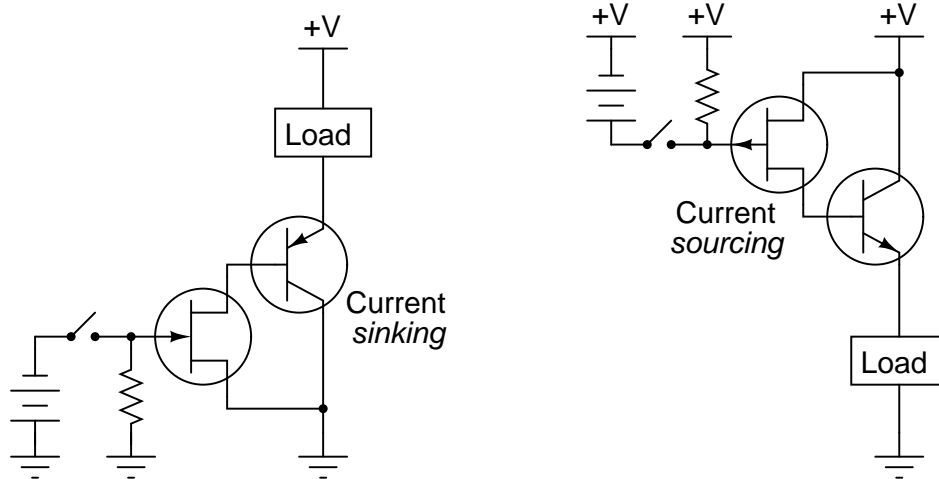
Ask your students to describe the biasing of the gate-channel junction inside the transistor when the switch is closed. Is this PN junction forward-biased, or reverse-biased? What does this biasing do inside the transistor to interrupt current to the LED?

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.

Question 28

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 28

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

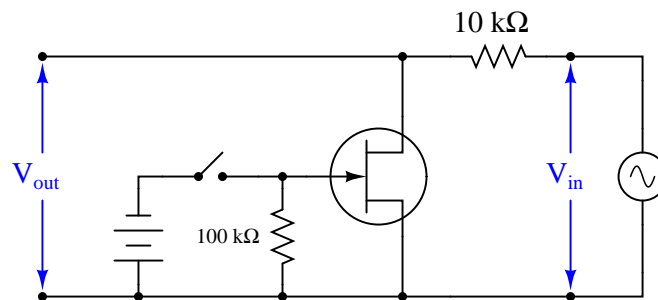
Follow-up question: explain the purpose of the resistor in each circuit. What might happen if it were not there?

Notes 28

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 29

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 29

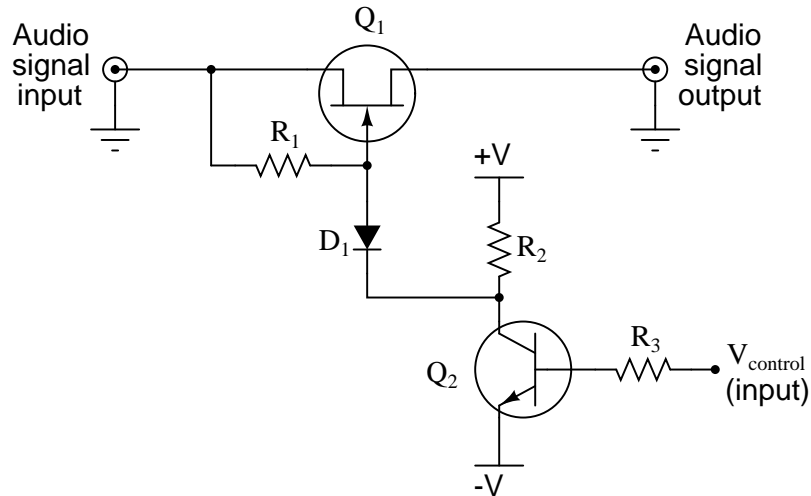
When the toggle switch is open, the output signal will fall to (nearly) 0 volts AC. When the toggle switch is closed, the output signal will be (nearly) the same as V_{in} .

Notes 29

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 30

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 30

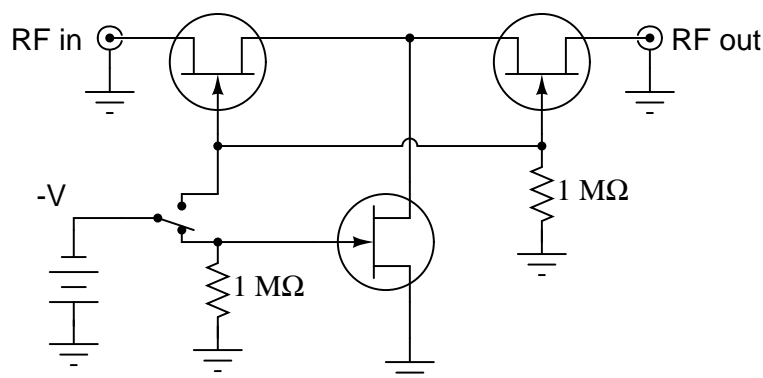
Diode D_1 prevents resistor R_2 from loading the audio signal source, and resistor R_1 provides a condition of $V_{GS} = 0$ volts whenever transistor Q_2 is in a state of cutoff. I'll let you determine the proper $V_{control}$ voltage levels for "on" and "off" control states.

Notes 30

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 31

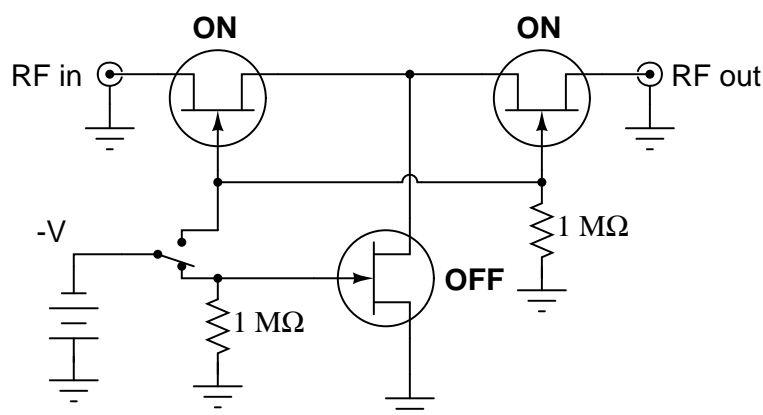
This is a switching circuit for video signals, or any other radio-frequency (RF), low-amplitude AC signals that one might need to switch on and off for a variety of different applications:



Identify the "on" and "off" states of the three JFETs in this circuit with the switch in the position shown in the schematic, and also determine whether the switch position shown in the diagram is for "passing" or "blocking" the RF signal from input to output.

[file 02336](#)

Answer 31



With the switch in the position shown, the circuit will *pass* the RF signal from input to output.

Notes 31

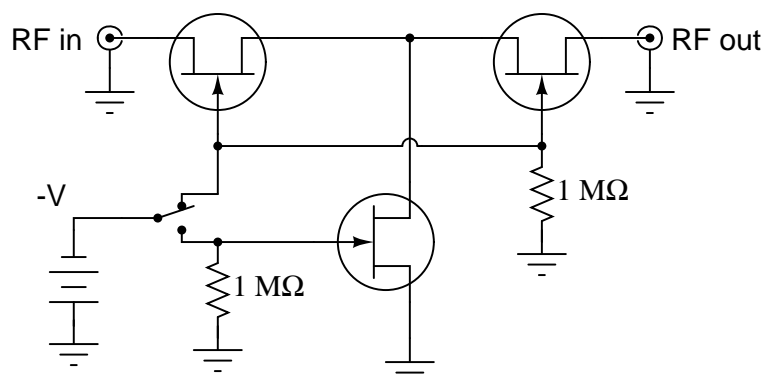
Ask your students to explain the problem-solving strategy(ies) they used to derive the correct answer for this question. How were they able to tell whether the transistors would be on or off? Ask them to explain the purpose of the 1 MΩ resistors. What might happen without them?

If time permits, discuss with your students the design of this circuit: why two "pass" transistors and one "shunt" transistor? How critical is the magnitude of the -V switching control voltage?

The idea for this circuit came from a National Semiconductor application note on JFET circuits: *Application Note 32, February 1970, page 13.*

Question 32

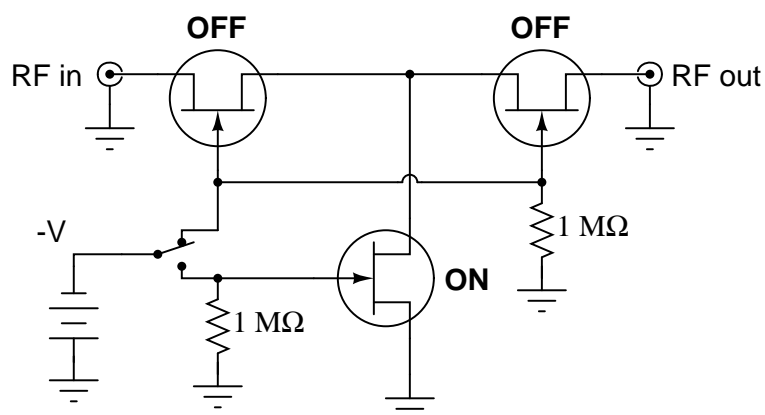
This is a switching circuit for video signals, or any other radio-frequency (RF), low-amplitude AC signals that one might need to switch on and off for a variety of different applications:



Identify the "on" and "off" states of the three JFETs in this circuit with the switch in the position shown in the schematic, and also determine whether the switch position shown in the diagram is for "passing" or "blocking" the RF signal from input to output.

file 02337

Answer 32



With the switch in the position shown, the circuit will *block* the RF signal from getting to the output.

Notes 32

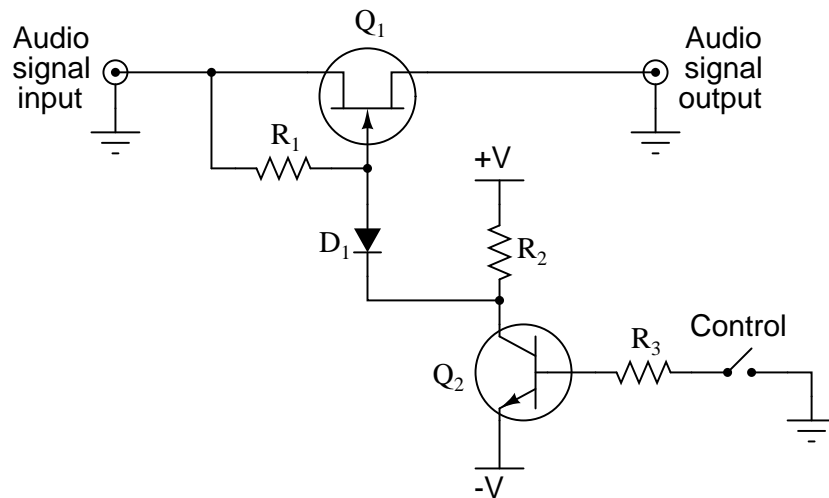
Ask your students to explain the problem-solving strategy(ies) they used to derive the correct answer for this question. How were they able to tell whether the transistors would be on or off? Ask them to explain the purpose of the 1 MΩ resistors. What might happen without them?

If time permits, discuss with your students the design of this circuit: why two "pass" transistors and one "shunt" transistor? How critical is the magnitude of the -V switching control voltage?

The idea for this circuit came from a National Semiconductor application note on JFET circuits: *Application Note 32, February 1970, page 13.*

Question 33

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 33

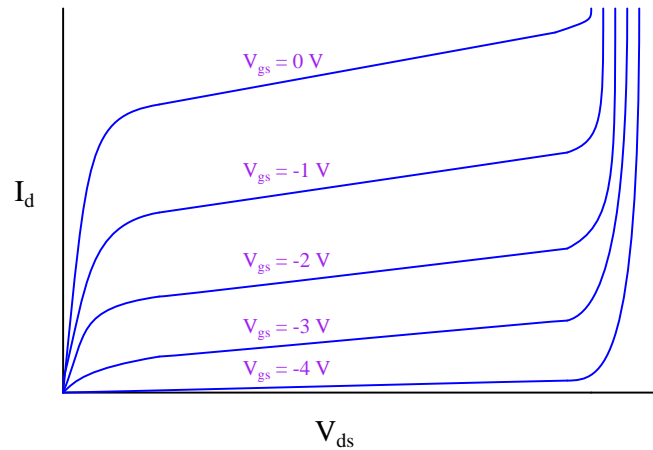
- Diode D_1 fails open: *Audio signal always passes through and cannot be turned off.*
- Transistor Q_1 fails shorted (drain-to-source): *Audio signal always passes through and cannot be turned off.*
- Transistor Q_1 fails open (drain-to-source): *Audio signal never passes through and cannot be turned on.*
- Transistor Q_2 fails shorted (collector-to-emitter): *Audio signal never passes through and cannot be turned on.*

Notes 33

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 34

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 34

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 34

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 35

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 35

$V_{GS(off)}$ 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 35

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

Question 36

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 36

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 36

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 37

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 37

$V_{GS} = 1.85$ volts

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

Notes 37

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

Question 38

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 38

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 38

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

Question 39

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.

file 00995

Answer 39

"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.

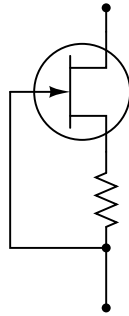
Challenge question: what unit of measurement would be appropriate for expressing transconductance in?

Notes 39

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 40

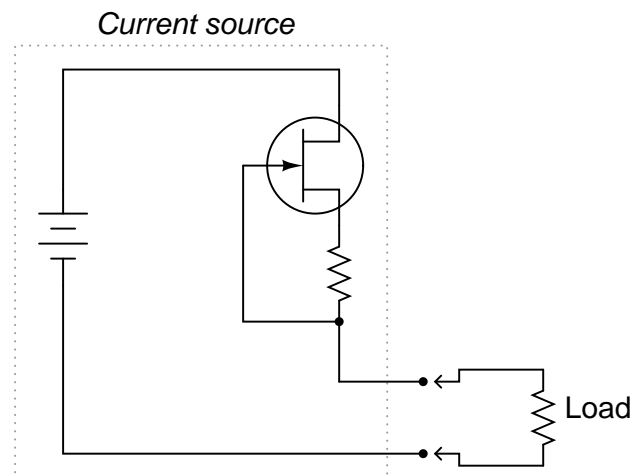
A very simple circuit that may be used as a *current regulator* in a DC circuit is this:



Draw a battery symbol and any necessary connecting wires to form a complete *DC current source*, that will attempt to supply a regulated amount of DC current through any given load.

file 00997

Answer 40



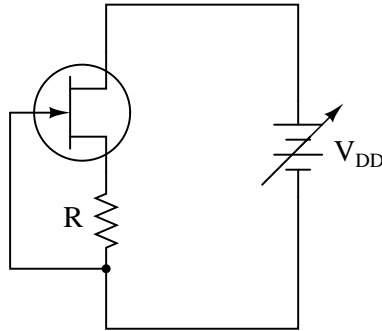
Notes 40

The direction of current through the JFET, when used as a current regulator in this fashion, is very important. Not so much for the JFET's sake, as for the sake of establishing the correct type of feedback (negative) to make the circuit self-regulating.

Discuss this circuit's operation with your students, asking them to determine the polarity of the resistor's voltage drop, and how that relates to the "pinching off" of the JFET.

Question 41

The following circuit is useful as a *current regulator*, the regulated current setpoint being established by the value of the resistor and the JFET's $V_{GS(off)}$ parameter:



Despite wide variations in V_{DD} , the current in this circuit will remain relatively constant. The reason this circuit works as it does is *negative feedback*. Explain what causes negative feedback to occur in this circuit, and why it has a stabilizing effect on the current.

file 02251

Answer 41

The resistor creates a voltage drop that tries to pinch off the JFET as current increases. To put it in colloquial terms, "when the current *zigs*, the JFET *zags*."

Notes 41

This is a simple example of negative feedback in action: one that does not require any AC analysis and all its associated considerations. Here it is just DC at work, and the students must determine what it is the JFET/resistor combination does in response to attempted changes in current that makes the current so stable.

Question 42

Find one or two real junction field-effect transistors and bring them with you to class for discussion. Identify as much information as you can about your transistors prior to discussion:

- Terminal identification (which terminal is gate, source, drain)
- Continuous power rating
- Typical transconductance

[file 01165](#)

Answer 42

If possible, find a manufacturer's datasheet for your components (or at least a datasheet for a similar component) to discuss with your classmates. Be prepared to *prove* the terminal identifications of your transistors in class, by using a multimeter!

Notes 42

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

Don't just sit there! Build something!!

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

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

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

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

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

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

[file 00505](#)

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

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

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

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

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

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

What is the purpose of students taking your course?

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

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

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