

Recommended schedule

Day 1

Topics: *Basic oscillator theory and relaxation oscillator circuits*

Questions: *1 through 10*

Lab Exercise: *BJT multivibrator circuit, astable (question 51)*

Day 2

Topics: *Phase-shift and resonant oscillator circuits*

Questions: *11 through 20*

Lab Exercise: *Wien bridge oscillator, BJT (question 52)*

Day 3

Topics: *Harmonics*

Questions: *21 through 30*

Lab Exercise: *Colpitts oscillator, BJT (question 53)*

Demo: Use graphing calculator to synthesize square wave from sinusoidal harmonics

Demo: Show harmonics using a spectrum analyzer and function generator

Demo: Show harmonics in power-line signal using a spectrum analyzer and transformer

Demo: Show example of spectrum plot from an amplifier datasheet

Day 4

Topics: *Fundamentals of radio, amplitude modulation, and frequency modulation (optional)*

Questions: *31 through 50*

Lab Exercise: *Troubleshooting practice (oscillator/amplifier circuit – question 55)*

Just for fun (not required): *AM radio transmitter (question 54)*

Demo: Use signal generator with AM function to broadcast audio tone to radio

Day 5

Exam 3: *includes Oscillator Circuit performance assessment*

Troubleshooting Assessment due: *oscillator/amplifier circuit (question 55)*

Question 56: Troubleshooting log

Question 57: Sample troubleshooting assessment grading criteria

Troubleshooting practice problems

Questions: *58 through 67*

General concept practice and challenge problems

Questions: *68 through the end of the worksheet*

Skill standards addressed by this course section

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

C Technical Skills – AC circuits

- C.02** Demonstrate an understanding of the properties of an AC signal.
- C.03** Demonstrate an understanding of the principles of operation and characteristics of sinusoidal and non-sinusoidal wave forms.

E Technical Skills – Analog Circuits

- E.20** Understand principles and operations of sinusoidal and non-sinusoidal oscillator circuits.
- E.21** Troubleshoot and repair sinusoidal and non-sinusoidal oscillator circuits.
- E.27** Understand principles and operations of signal modulation systems (AM, FM, stereo). *Partially met – basic AM and FM only.*

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: *Calculating phase shift of RC network.*

The only real difficulty here is the lapse in time between when most students study RC circuit analysis and the time they study phase-shift oscillator circuits. Calculating the phase shift of a series RC circuit is as simple as drawing its impedance triangle, and then properly identifying which two sides represent the input (total) and output voltages in order to identify which angle you must calculate.

Difficult concept: *Fourier analysis.*

No doubt about it, Fourier analysis is a strange concept to understand. Strange, but incredibly useful! While it is relatively easy to grasp the principle that we may create a square-shaped wave (or any other symmetrical waveshape) by mixing together the right combinations of sine waves at different frequencies and amplitudes, it is far from obvious that *any* periodic waveform may be decomposed into a series of sinusoidal waves the same way. The practical upshot of this is that it is possible to consider very complex waveshapes as being nothing more than a bunch of sine waves added together. Since sine waves are easy to analyze in the context of electric circuits, this means we have a way of simplifying what would otherwise be a dauntingly complex problem: analyzing how circuits respond to non-sinusoidal waveforms.

The actual "nuts and bolts" of Fourier analysis is highly mathematical and well beyond the scope of this course. Right now all I want you to grasp is the concept and significance of equivalence between arbitrary waveshapes and series of sine waves.

A great way to experience this equivalence is to play with a digital oscilloscope with a built-in spectrum analyzer. By introducing different wave-shape signals to the input and switching back and forth between the time-domain (scope) and frequency-domain (spectrum) displays, you may begin to see patterns that will enlighten your understanding.

Question 1

Define what an *oscillator* circuit is, using your own words. Give a few examples of oscillators at work in common devices and systems.

file 01075

Answer 1

Here is a sample definition:

An "oscillator" is a device that produces oscillations (back-and-forth) changes – usually an electronic circuit that produces AC – from a steady (DC) source of power.

I'll let you determine some practical oscillator applications on your own!

Notes 1

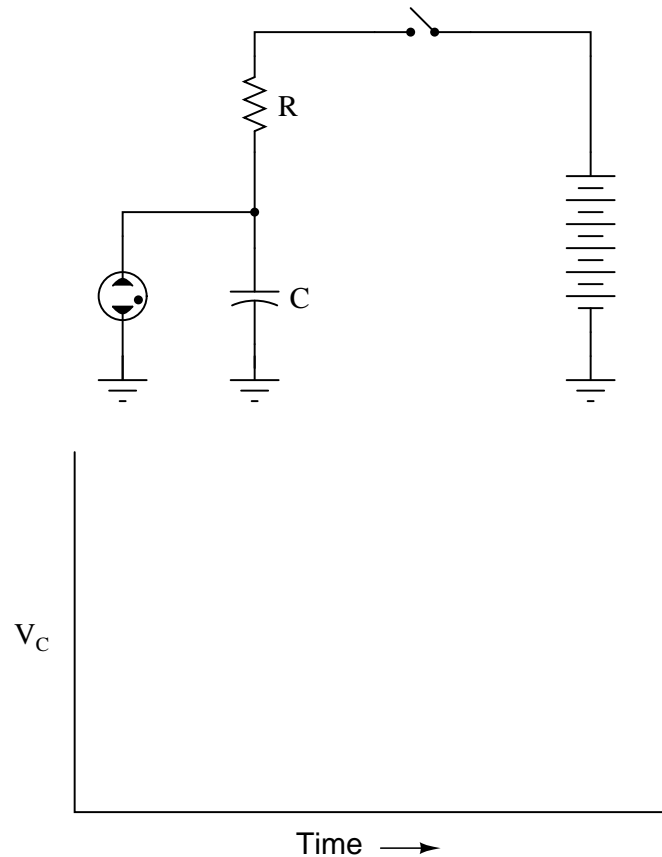
Oscillators are nearly ubiquitous in a modern society. If your students' only examples are electronic in nature, you may want to mention these mechanical devices:

- Pendulum clock mechanism
- Shaker (for sifting granular materials or mixing liquids such as paint)
- Whistle
- Violin string

Question 2

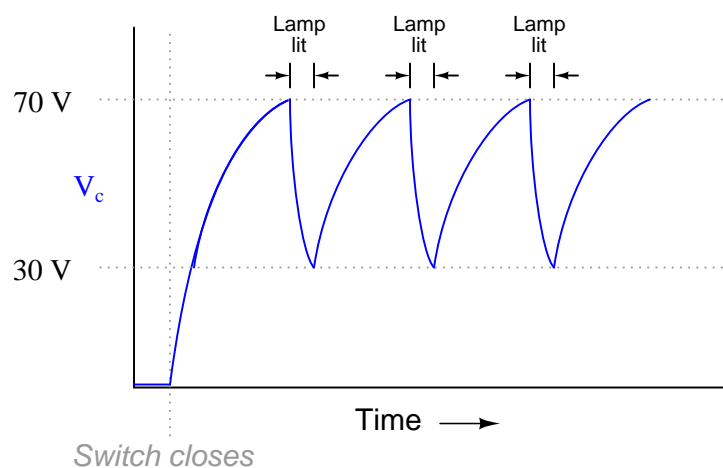
The circuit shown here is called a *relaxation oscillator*. It works on the principles of capacitor charging over time (an RC circuit), and of the *hysteresis* of a gas-discharge bulb: the fact that the voltage required to initiate conduction through the bulb is significantly greater than the voltage below which the bulb ceases to conduct current.

In this circuit, the neon bulb ionizes at a voltage of 70 volts, and stops conducting when the voltage falls below 30 volts:



Graph the capacitor's voltage over time as this circuit is energized by the DC source. Note on your graph at what times the neon bulb is lit:

file 00430



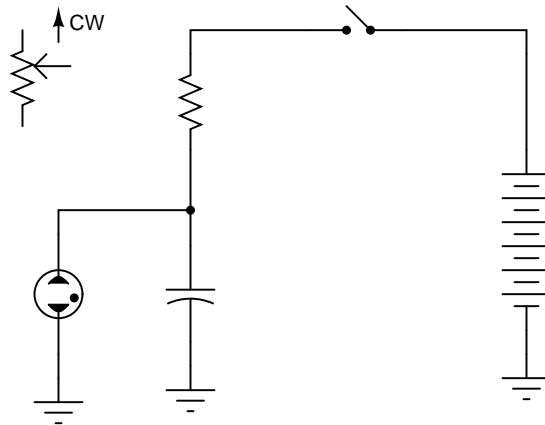
Follow-up question: assuming a source voltage of 100 volts, a resistor value of $27\text{ k}\Omega$, and a capacitor value of $22\text{ }\mu\text{F}$, calculate the amount of time it takes for the capacitor to charge from 30 volts to 70 volts (assuming the neon bulb draws negligible current during the charging phase).

 Notes 2

What we have here is a very simple strobe light circuit. This circuit may be constructed in the classroom with minimal safety hazard if the DC voltage source is a hand-crank generator instead of a battery bank or line-powered supply. I've demonstrated this in my own classroom before, using a hand-crank "Megger" (high-range, high-voltage ohmmeter) as the power source.

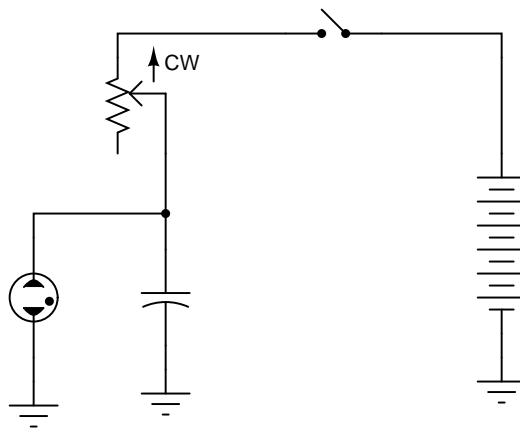
Question 3

Replace the fixed-value resistor with a potentiometer to adjust the blinking rate of the neon lamp, in this *relaxation oscillator* circuit. Connect the potentiometer in such a way that clockwise rotation of the knob makes the lamp blink faster:



file 00431

Answer 3

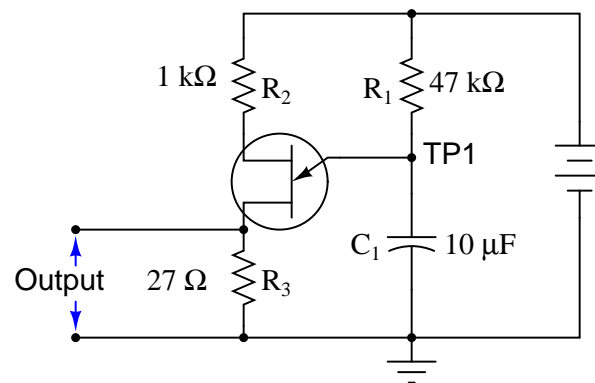


Notes 3

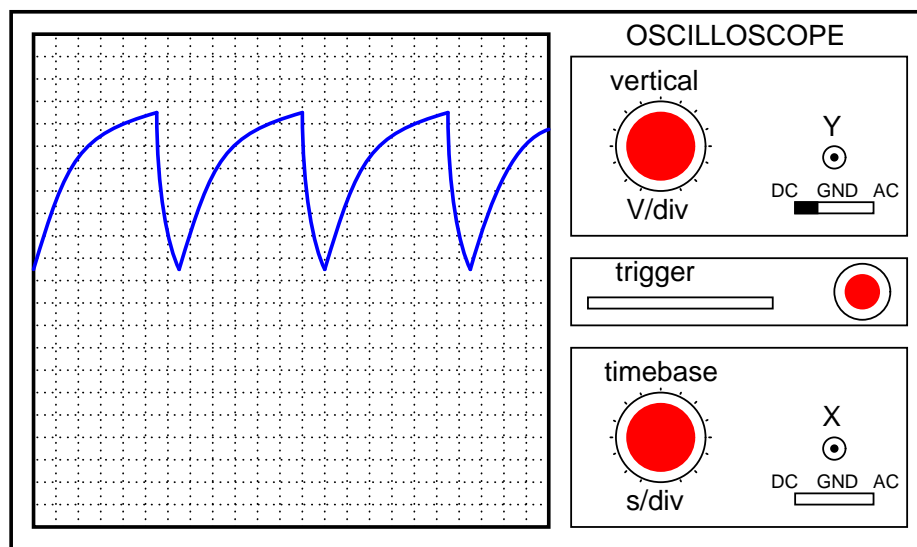
Ask your students to explain *why* the potentiometer has the speed-changing effect it does on the circuit's flash rate. Would there be any other way to change this circuit's flash rate, without using a potentiometer?

Question 4

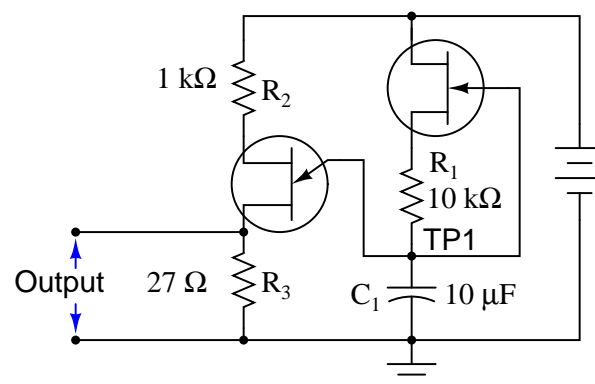
This relaxation oscillator circuit uses a resistor-capacitor combination ($R_1 - C_1$) to establish the time delay between output pulses:



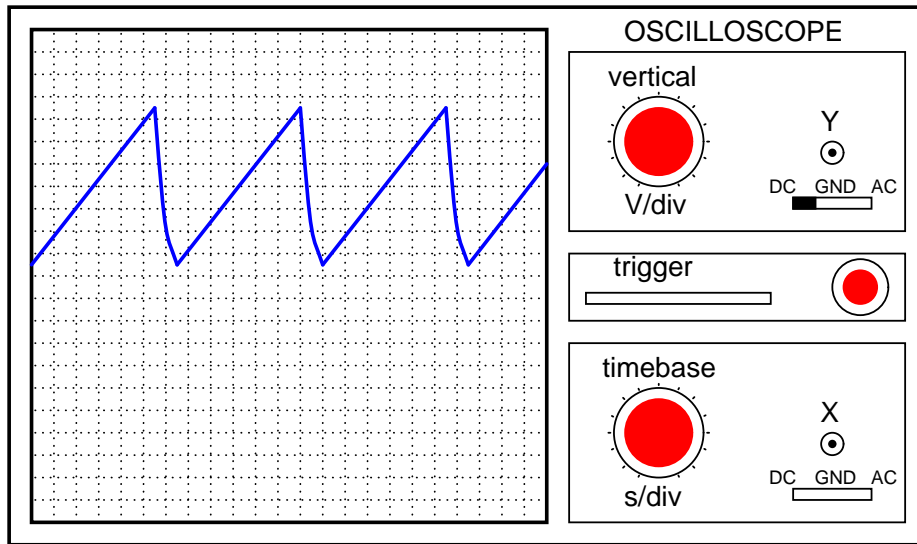
The voltage measured between TP1 and ground looks like this on the oscilloscope display:



A slightly different version of this circuit adds a JFET to the capacitor's charge current path:



Now, the voltage at TP1 looks like this:



What function does the JFET perform in this circuit, based on your analysis of the new TP1 signal waveform? The straight-line charging voltage pattern shown on the second oscilloscope display indicates what the JFET is doing in this circuit.

Hint: you don't need to know anything about the function of the unijunction transistor (at the circuit's output) other than it acts as an on/off switch to periodically discharge the capacitor when the TP1 voltage reaches a certain threshold level.

Challenge question: write a formula predicting the *slope* of the ramping voltage waveform measured at TP1.

[file 01186](#)

Answer 4

The JFET in this circuit functions as a constant current regulator.

Answer to challenge question: $\text{Slope} = \frac{dv}{dt} = \frac{I_D}{C}$

Notes 4

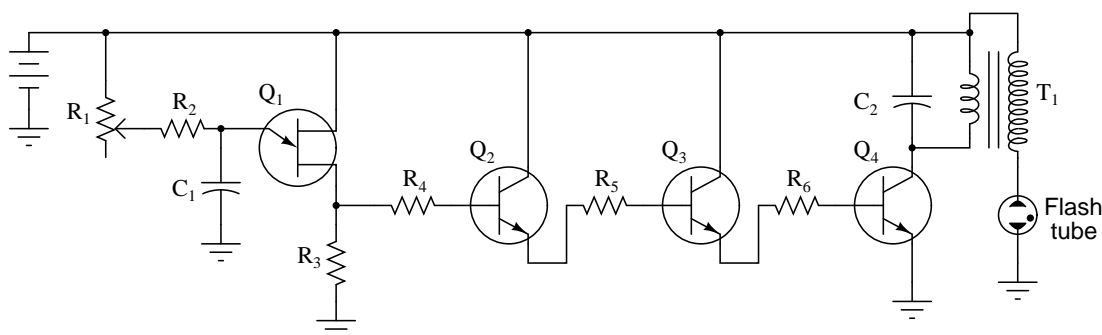
Ask your students how they would know to relate "constant current" to the peculiar charging action of this capacitor. Ask them to explain this mathematically.

Then, ask them to explain exactly how the JFET works to regulate charging current.

Note: the schematic diagram for this circuit was derived from one found on page 958 of John Markus' [Guidebook of Electronic Circuits](#), first edition. Apparently, the design originated from a Motorola publication on using unijunction transistors ("Unijunction Transistor Timers and Oscillators," AN-294, 1972).

Question 5

This circuit shown here is for a *timing light*: a device that uses a pulsed strobe lamp to "freeze" the motion of a rotating object.



Which component(s) in this circuit form the oscillator section? What type of oscillator is used in this circuit? Which component values have a direct influence on the frequency of the flash tube's output?

file 01078

Answer 5

The heart of the oscillator circuit is unijunction transistor Q_1 . Together with some other components (I'll let you figure out which!), this transistor forms a *relaxation oscillator* circuit. R_1 , R_2 , and C_1 have direct influence over the oscillation frequency.

Challenge question: what purpose does resistor R_2 serve? It would seem at first glance that it serves no useful purpose, as potentiometer R_1 is capable of providing any desired amount of resistance for the RC time constant circuit on its own – R_2 's resistance is simply added to it. However, there is an important, practical reason for including R_2 in the circuit. Explain what that reason is.

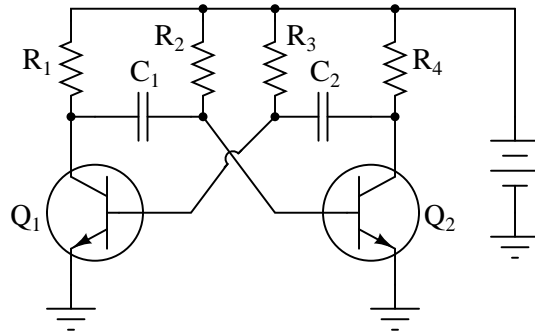
Notes 5

Ask your students to explain what the other transistors do in this circuit. If time permits, explore the operation of the entire circuit with your students, asking them to explain the purpose and function of all components in it.

After they identify which components control the frequency of oscillation, ask them to specifically identify which direction each of those component values would need to be changed in order to increase (or decrease) the flash rate.

Question 6

Explain the principle of operation in this *astable multivibrator* circuit:



Also, identify where you would connect to this circuit to obtain an output signal. What type of signal would it be (sine wave, square wave, ramp or triangle wave, etc.)?

[file 01079](#)

Answer 6

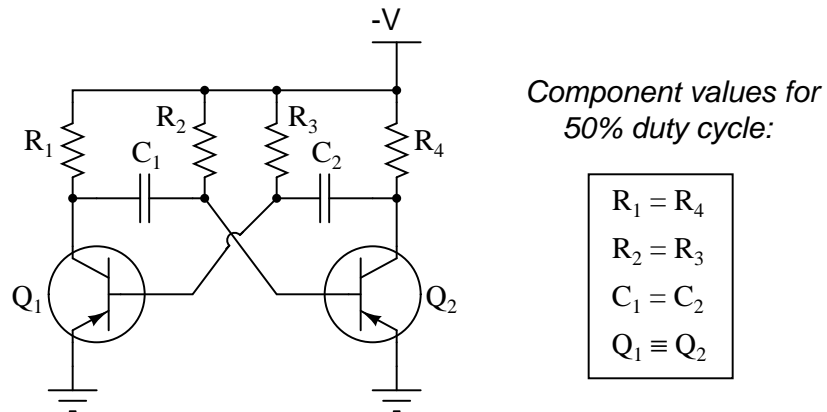
A square-wave output signal may be obtained at the collector of either transistor. I'll let you research this circuit's principle of operation.

Notes 6

Ask your students to explain how the frequency of this circuit could be altered. After that, ask them what they would have to do to alter the *duty cycle* of this circuit's oscillation.

Question 7

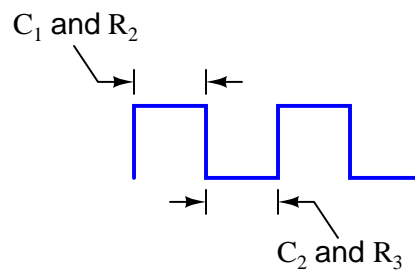
This astable multivibrator circuit will oscillate with a 50% duty cycle if the components are symmetrically sized:



Determine which component(s) would have to be re-sized to produce a duty cycle other than 50%.
file 02254

Answer 7

I won't answer this question directly, but I will give a large hint: C_1 and R_2 determine the pulse width of one-half of the square wave, while C_2 and R_3 control the pulse width of the other half:



Challenge question: re-draw the schematic diagram to show how a potentiometer could be used to make the duty cycle adjustable over a wide range.

Notes 7

Astable multivibrator circuits are simple and versatile, making them good subjects of study and discussion for your students.

Question 8

If you have ever used a public address ("PA") amplifier, where sounds detected by a microphone are amplified and reproduced by speakers, you know how these systems can create "screeching" or "howling" sounds if the microphone is held too close to one of the speakers.

The noise created by a system like this is an example of *oscillation*: where the amplifier circuit spontaneously outputs an AC voltage, with no external source of AC signal to "drive" it. Explain what necessary condition(s) allow an amplifier to act as an *oscillator*, using a "howling" PA system as the example. In other words, what exactly is going on in this scenario, that makes an amplifier generate its own AC output signal?

file 01074

Answer 8

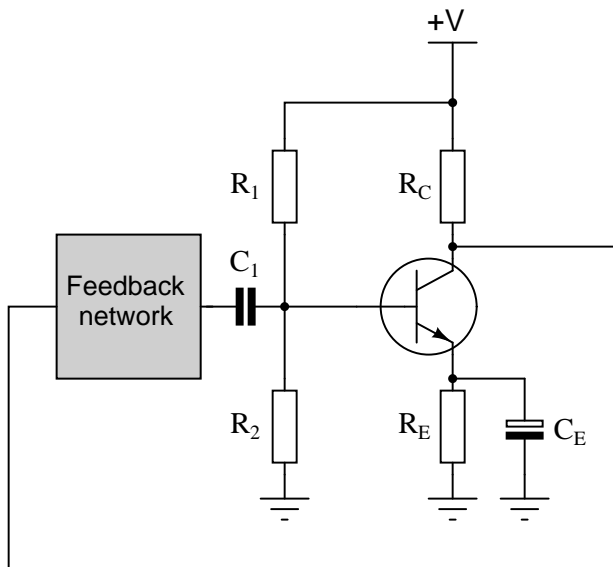
The amplifier receives *positive feedback* from the output (speaker) to the input (microphone).

Notes 8

Ask your students to define what "positive feedback" is. In what way is the feedback in this system "positive," and how does this feedback differ from the "negative" variety commonly seen within amplifier circuitry?

Question 9

How many degrees of phase shift must the feedback circuit (the box in this schematic) introduce to the signal in order for this common-emitter amplifier circuit to oscillate?



We know that oscillator circuits require "regenerative" feedback in order to continuously sustain oscillation. Explain how the correct amount of phase shift is *always* provided in the feedback circuit to ensure that the nature of the feedback is always regenerative, not degenerative. In other words, explain why it is not possible to incorrectly choose feedback network component values and thus fail to achieve the proper amount of phase shift.

[file 01080](#)

Answer 9

The feedback network in this circuit must provide 180 degrees of phase shift, in order to sustain oscillations.

So long as the feedback network contains the correct *types* of components (resistors, capacitors, and/or inductors) in a working configuration, the components' values will not alter the amount of phase shift, only the frequency of the oscillation.

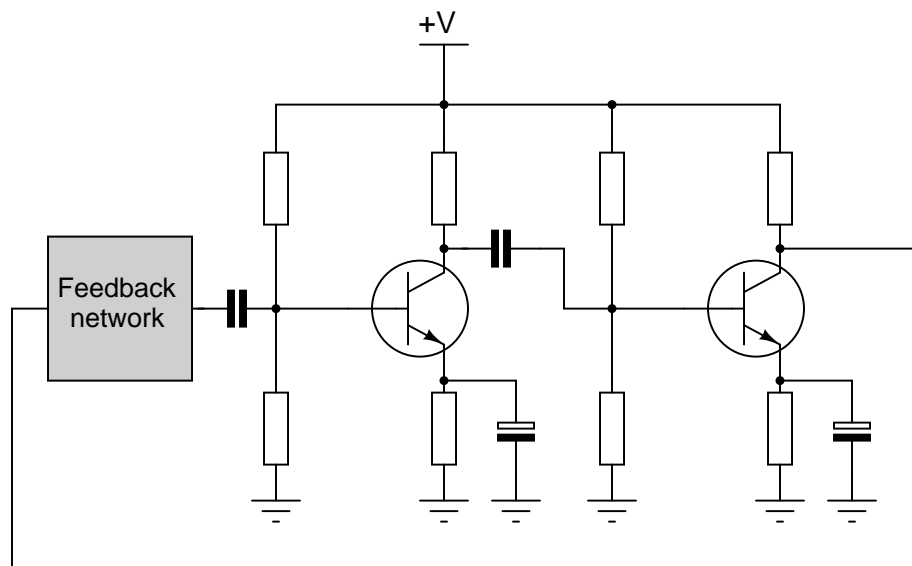
Notes 9

Ask your students to explain why the feedback network must provide 180 degrees of phase shift to the signal. Ask them to explain how this requirement relates to the need for *regenerative* feedback in an oscillator circuit.

The question and answer concerning feedback component selection is a large conceptual leap for some students. It may baffle some that the phase shift of a reactive circuit will always be the proper amount to ensure regenerative feedback, for any arbitrary combination of component values, because they should know the phase shift of a reactive circuit depends on the values of its constituent components. However, once they realize that the phase shift of a reactive circuit is *also* dependent on the signal frequency, the resolution to this paradox is much easier to understand.

Question 10

How many degrees of phase shift must the feedback circuit (the box in this schematic) introduce to the signal in order for this two-stage common-emitter amplifier circuit to oscillate?



Why is this amount of phase shift different from that of a single-transistor oscillator?
[file 01212](#)

Answer 10

The feedback network in this circuit must provide 0 degrees of phase shift, in order to sustain oscillations.

Notes 10

Ask your students to explain why the feedback network must provide 180 degrees of phase shift to the signal. Ask them to explain how this requirement relates to the need for *regenerative* feedback in an oscillator circuit.

The question and answer concerning feedback component selection is a large conceptual leap for some students. It may baffle some that the phase shift of a reactive circuit will always be the proper amount to ensure regenerative feedback, for any arbitrary combination of component values, because they should know the phase shift of a reactive circuit depends on the values of its constituent components. However, once they realize that the phase shift of a reactive circuit is *also* dependent on the signal frequency, the resolution to this paradox is much easier to understand.

Question 11

Explain what the *Barkhausen criterion* is for an oscillator circuit. How will the oscillator circuit's performance be affected if the Barkhausen criterion falls below 1, or goes much above 1?

file 01211

Answer 11

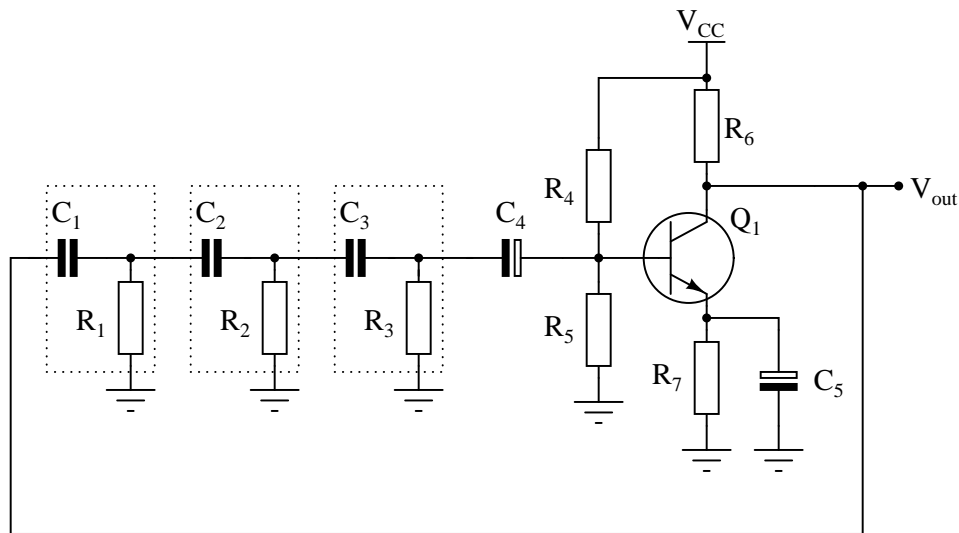
I'll let you determine exactly what the "Barkhausen" criterion is. If its value is less than 1, the oscillator's output will diminish in amplitude over time. If its value is greater than 1, the oscillator's output will not be sinusoidal!

Notes 11

The question of "What is the Barkhausen criterion" could be answered with a short sentence, memorized verbatim from a textbook. But what I'm looking for here is real comprehension of the subject. Have your students explain to you the reason why oscillation amplitude depends on this factor.

Question 12

One way to achieve the phase shift necessary for regenerative feedback in an oscillator circuit is to use multiple RC phase-shifting networks:



What must the voltage gain be for the common-emitter amplifier if the total voltage attenuation for the three phase-shifting RC networks is -29.25 dB?

file 02263

Answer 12

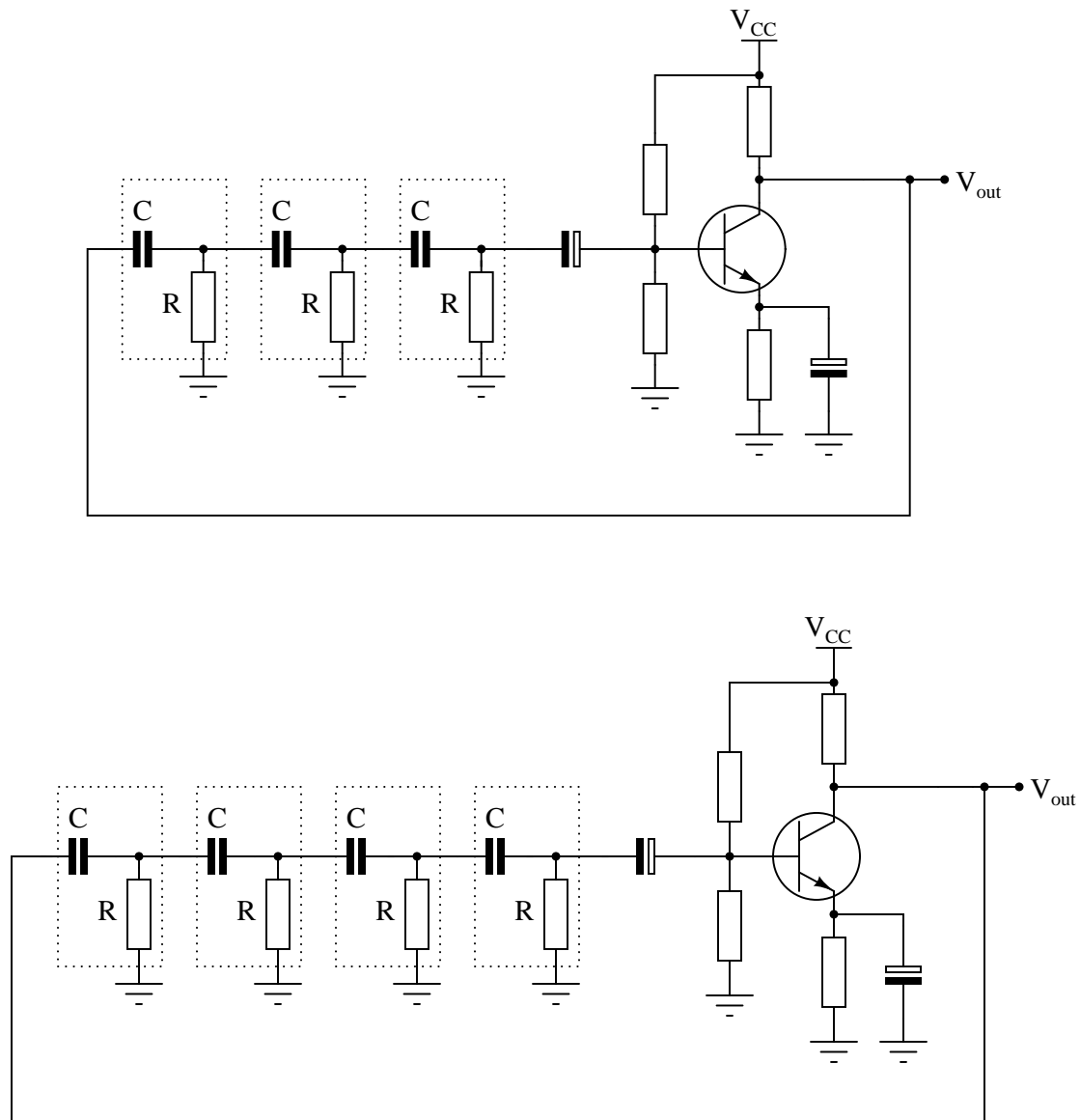
The amplifier's voltage gain must be (at least) +29.25 dB.

Notes 12

This question probes students' comprehension of the Barkhausen criterion: that total loop gain must be equal or greater than unity in order for sustained oscillations to occur.

Question 13

RC phase-shift oscillator circuits may be constructed with different numbers of RC sections. Shown here are schematic diagrams for three- and four-section RC oscillators:



What difference will the number of sections in the oscillator circuit make? Be as specific as you can in your answer.

file 02264

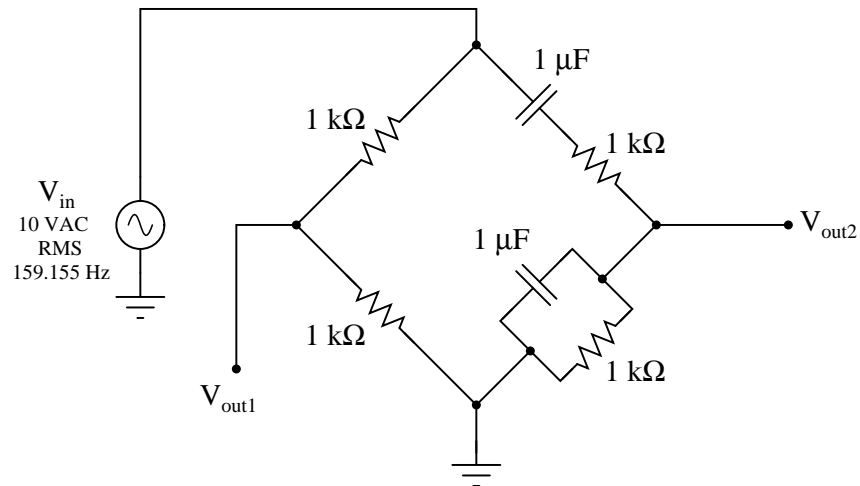
Answer 13

The amount of phase shift per RC section will be different in each circuit, as well as the operating frequency (given the same R and C component values).

In either case, the point of the RC stages is to phase-shift the feedback signal by 180° . It is an oversimplification, though, to say that each stage in the three-section circuit shifts the signal by 60° , and/or that each stage in the four-section circuit shifts the signal by 45° . The amount of phase-shift in each section will not be equal (with equal R and C values) due to the loading of each section by the previous section(s).

Question 14

Calculate the output voltages of this Wien bridge circuit, if the input voltage is 10 volts RMS at a frequency of 159.155 Hz:



file 01213

Answer 14

$$V_{out1} = 5.00 \text{ VAC RMS } \angle 0^\circ$$

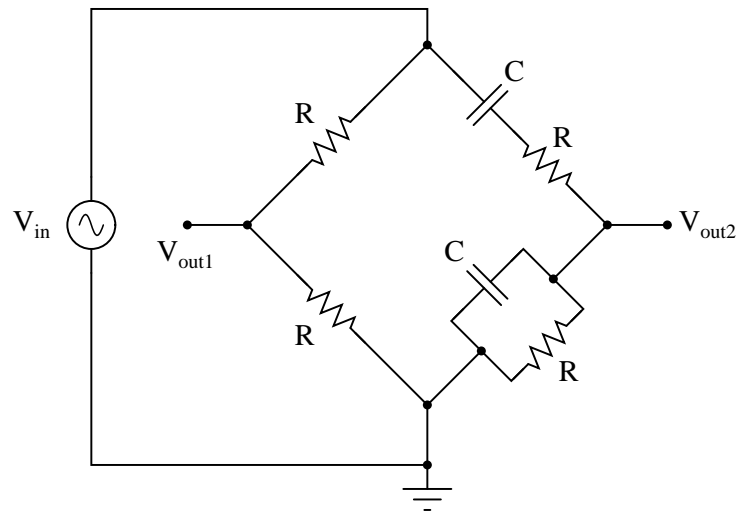
$$V_{out2} = 3.33 \text{ VAC RMS } \angle 0^\circ$$

Notes 14

This question provides an excellent opportunity for your students to review AC circuit analysis, as well as pave the way for questions regarding Wien bridge oscillator circuits!

Question 15

In this Wien bridge circuit (with equal-value components all around), both output voltages will have the same phase angle only at one frequency:



At this same frequency, V_{out2} will be exactly one-third the amplitude of V_{in} . Write an equation in terms of R and C to solve for this frequency.

file 02262

It's your luck day! Here, I show one method of solution:

$$\begin{aligned}
 R - j\frac{1}{\omega C} &= 2 \left(\frac{1}{\frac{1}{R} + j\omega C} \right) \\
 R - j\frac{1}{\omega C} &= \frac{2}{\frac{1}{R} + j\omega C} \\
 \left(R - j\frac{1}{\omega C} \right) \left(\frac{1}{R} + j\omega C \right) &= 2 \\
 \frac{R}{R} + j\omega RC - j\frac{1}{\omega RC} - j^2\frac{\omega C}{\omega C} &= 2 \\
 1 + j\omega RC - j\frac{1}{\omega RC} + 1 &= 2 \\
 j\omega RC - j\frac{1}{\omega RC} &= 0 \\
 j\omega RC &= j\frac{1}{\omega RC} \\
 \omega RC &= \frac{1}{\omega RC} \\
 \omega^2 &= \frac{1}{R^2 C^2} \\
 \omega &= \frac{1}{RC} \\
 2\pi f &= \frac{1}{RC} \\
 f &= \frac{1}{2\pi RC}
 \end{aligned}$$

I chose to show the method of solution here because I find many of my students weak in manipulating imaginary algebraic terms (anything with a j in it). The answer is not exactly a give-away, as students still have to figure out how I arrived at the first equation. This involves both an understanding of the voltage divider formula as well as the algebraic expression of series impedances and parallel admittances.

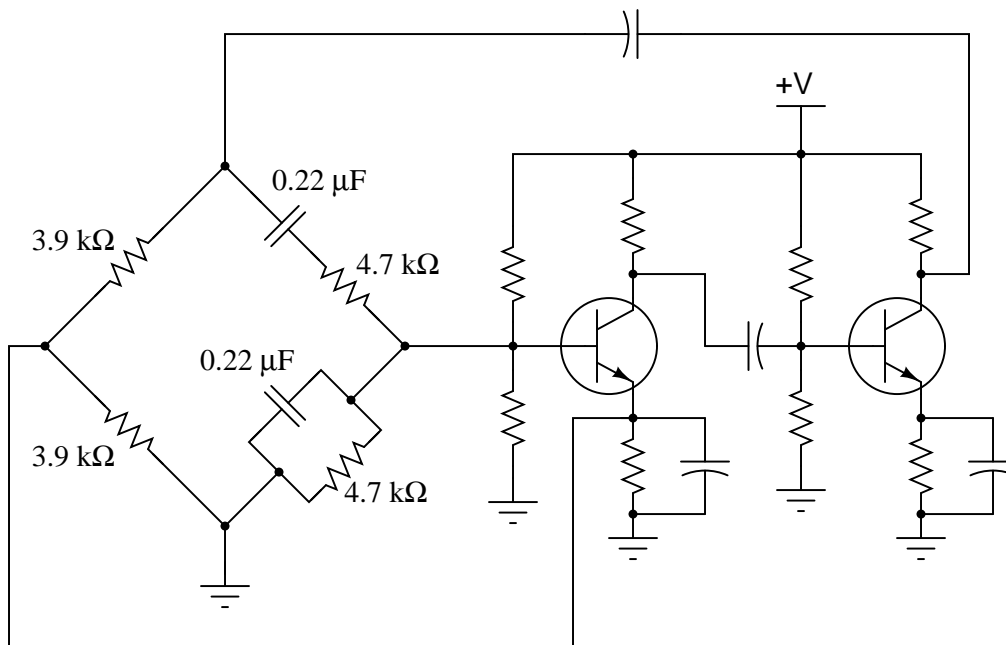
It is also possible to solve for the frequency by only considering phase angles and not amplitudes. Since the only way V_{out2} can have a phase angle of zero degrees in relation to the excitation voltage is for the upper and lower arms of that side of the bridge to have equal impedance phase angles, one might approach the problem in this fashion:

$$\begin{aligned}
 \theta &= \tan^{-1} \left(\frac{X_{series}}{R_{series}} \right) \\
 \theta &= \tan^{-1} \left(\frac{B_{parallel}}{G_{parallel}} \right) \\
 \frac{X_{series}}{R_{series}} &= \frac{B_{parallel}}{G_{parallel}}
 \end{aligned}$$

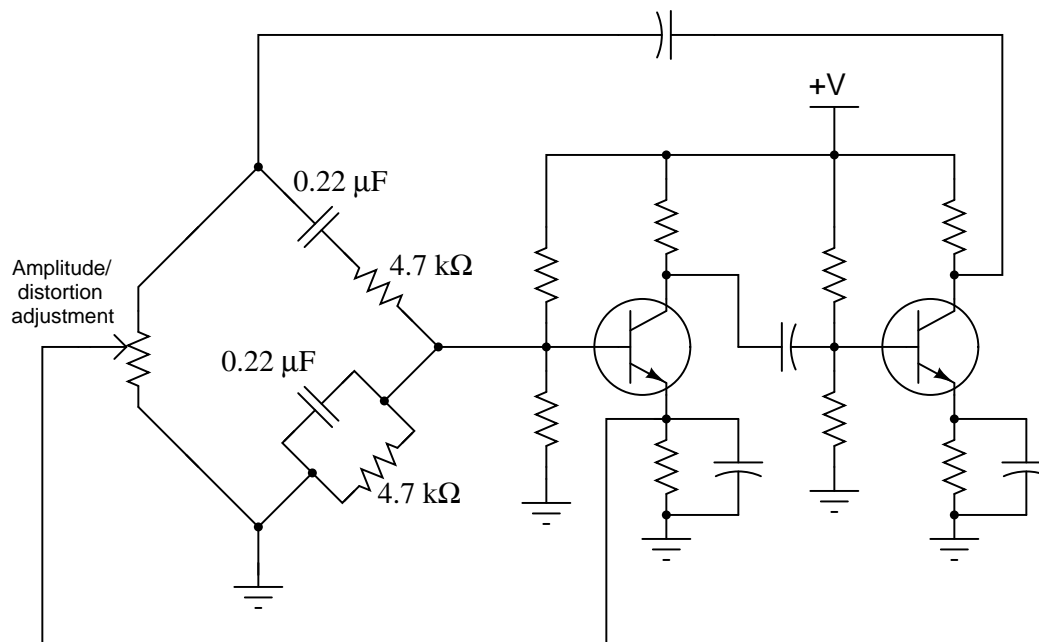
You might try presenting this solution to your students if imaginary algebra is too much for them at this point.

Question 16

The circuit shown here is a *Wien-bridge oscillator*:



If one side of the Wien bridge is made from a potentiometer instead of two fixed-value resistors, this adjustment will affect both the *amplitude* and the *distortion* of the oscillator's output signal:



Explain why this adjustment has the effect that it does. What, exactly, does moving the potentiometer do to the circuit to alter the output signal? Also, calculate the operating frequency of this oscillator circuit, and explain how you would make that frequency adjustable as well.

Answer 16

The potentiometer adjusts the Barkhausen criterion of the oscillator. I'll let you figure out how to make the frequency adjustable.

$$f = 153.9 \text{ Hz}$$

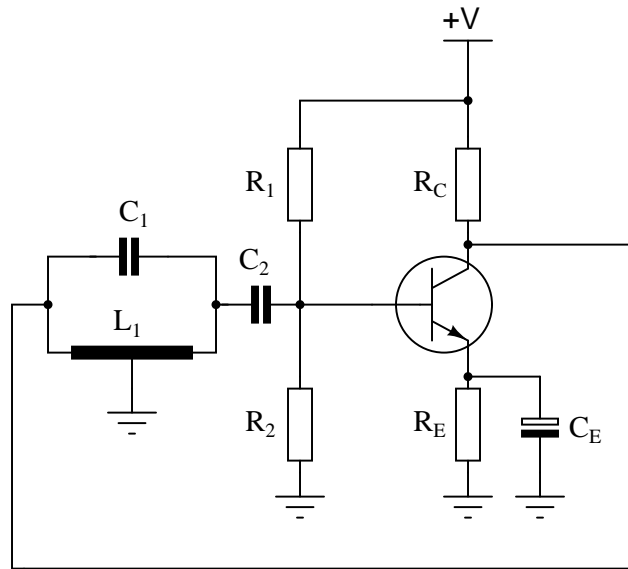
Follow-up question: identify the paths of positive and negative feedback from the Wien bridge to the first amplifier stage.

Notes 16

One of the advantages of the Wien bridge circuit is its ease of adjustment in this manner. Using high-quality capacitors and resistors in the other side of the bridge, its output frequency will be very stable.

Question 17

Identify the type of oscillator circuit shown in this schematic diagram, and explain the purpose of the tank circuit (L_1 and C_1):



Also, write the equation describing the operating frequency of this type of oscillator circuit.
[file 01082](#)

Answer 17

This is a *Hartley* oscillator circuit, and the tank circuit establishes its frequency of operation.

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

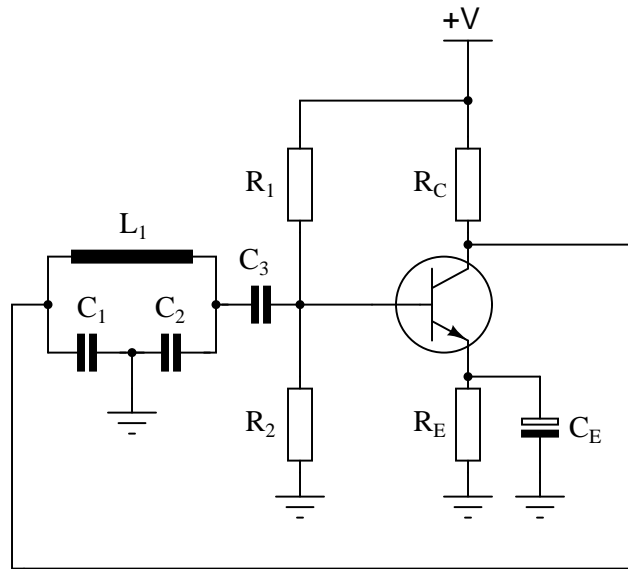
Follow-up question: calculate the operating frequency of this oscillator circuit if $L_1 = 330 \text{ mH}$ and $C_1 = 0.15 \text{ }\mu\text{F}$.

Notes 17

Ask your students to describe the amount of phase shift the tank circuit provides to the feedback signal. Also, ask them to explain how the oscillator circuit's natural frequency may be altered.

Question 18

Identify the type of oscillator circuit shown in this schematic diagram, and explain the purpose of the tank circuit (L_1 , C_1 , and C_2):



Also, write the equation describing the operating frequency of this type of oscillator circuit.
[file 01081](#)

Answer 18

This is a *Colpitts* oscillator circuit, and the tank circuit establishes its frequency of operation.

$$f = \frac{1}{2\pi\sqrt{L_1 \frac{C_1 C_2}{C_1 + C_2}}}$$

Follow-up question: calculate the operating frequency of this oscillator circuit if $L_1 = 270 \text{ mH}$, $C_1 = 0.047 \text{ }\mu\text{F}$, and $C_2 = 0.047 \text{ }\mu\text{F}$.

Notes 18

Ask your students to describe the amount of phase shift the tank circuit provides to the feedback signal. Also, ask them to explain how the oscillator circuit's natural frequency may be altered.

Question 19

Describe the purpose and operation of a *crystal* in an oscillator circuit. What physical principle does the crystal exploit, and what other components could be substituted in place of a crystal in an oscillator circuit?

file 01077

Answer 19

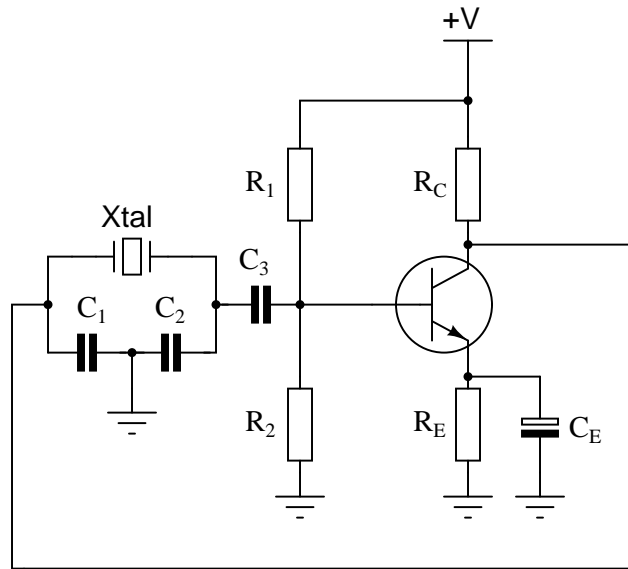
A "crystal" is a chip of *piezoelectric* material that acts as an electromechanical tank circuit.

Notes 19

Ask your students to describe the phenomenon of piezoelectricity, and how this principle works inside an oscillator crystal. Also, ask them why crystals are used instead of tank circuits in so many precision oscillator circuits.

Question 20

Identify the type of oscillator circuit shown in this schematic diagram, and explain the purpose of the crystal:



Challenge question: this type of oscillator circuit is usually limited to lower power outputs than either Hartley or Colpitts designs. Explain why.

[file 01083](#)

Answer 20

This is a *Pierce* oscillator circuit, and the crystal plays the same role that a tank circuit would in a Hartley or Colpitts oscillator.

Notes 20

Ask your students to explain how the oscillator circuit's natural frequency may be altered. How does this differ from frequency control in either the Hartley or Colpitts designs?

Question 21

What is a *harmonic* frequency? If an oscillator circuit outputs a fundamental frequency of 12 kHz, calculate the frequencies of the following harmonics:

- 1st harmonic =
- 2nd harmonic =
- 3rd harmonic =
- 4th harmonic =
- 5th harmonic =
- 6th harmonic =

[file 02255](#)

Answer 21

- 1st harmonic = 12 kHz
- 2nd harmonic = 24 kHz
- 3rd harmonic = 36 kHz
- 4th harmonic = 48 kHz
- 5th harmonic = 60 kHz
- 6th harmonic = 72 kHz

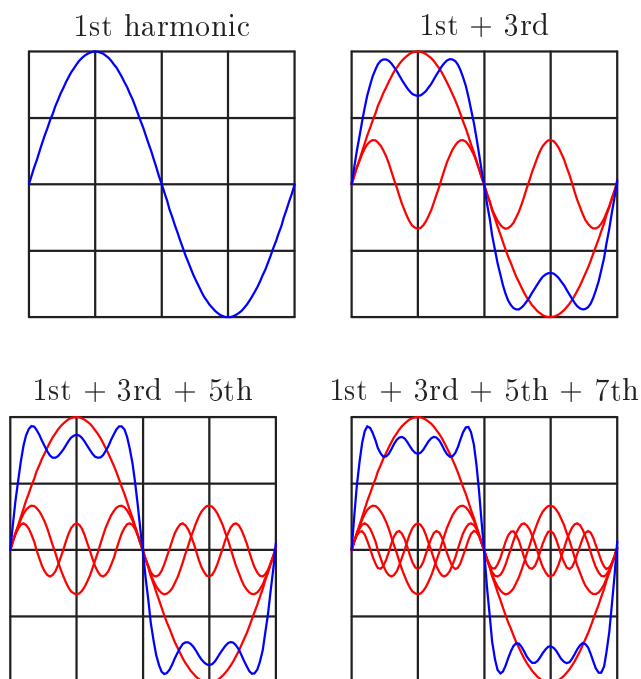
Notes 21

Ask your students to determine the mathematical relationship between harmonic number, harmonic frequency, and fundamental frequency. It isn't difficult to figure out!

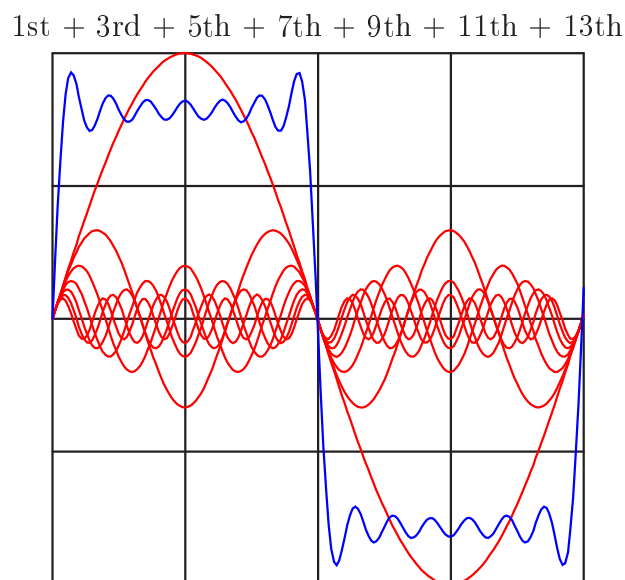
Question 22

An interesting thing happens if we take the odd-numbered harmonics of a given frequency and add them together at certain diminishing ratios of the fundamental's amplitude. For instance, consider the following harmonic series:

$$(1 \text{ volt at } 100 \text{ Hz}) + (1/3 \text{ volt at } 300 \text{ Hz}) + (1/5 \text{ volt at } 500 \text{ Hz}) + (1/7 \text{ volt at } 700 \text{ Hz}) + \dots$$

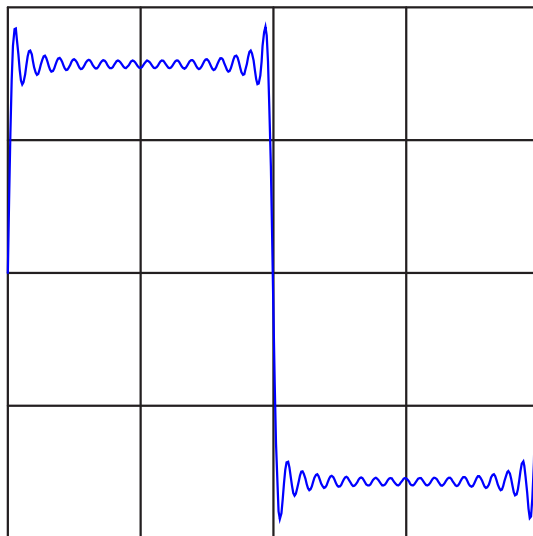


Here is what the composite wave would look like if we added all odd-numbered harmonics up to the 13th together, following the same pattern of diminishing amplitudes:



If we take this progression even further, you can see that the sum of these harmonics begins to appear more like a square wave:

All odd-numbered harmonics up to the 35th



This mathematical equivalence between a square wave and the weighted sum of all odd-numbered harmonics is very useful in analyzing AC circuits where square-wave signals are present. From the perspective of AC circuit analysis based on sinusoidal waveforms, how would you describe the way an AC circuit "views" a square wave?

file 01597

Answer 22

Though it may seem strange to speak of it in such terms, an AC circuit "views" a square wave as an infinite series of sinusoidal harmonics.

Follow-up question: explain how this equivalence between a square wave and a particular series of sine waves is a practical example of the *Superposition Theorem* at work.

Notes 22

If you have access to a graphing calculator or a computer with graphing software installed, and a projector capable of showing the resulting graph(s), you may demonstrate this square-wave synthesis in front of the whole class. It makes an excellent illustration of the concept.

Discuss this with your students: that the relatively simple rules of AC circuit analysis (calculating reactance by ωL and $\frac{1}{\omega C}$, calculating impedance by the trigonometric sum of reactance and resistance, etc.) can be applied to the analysis of a square wave's effects if we repeat that analysis for every harmonic component of the wave.

This is truly a remarkable principle, that the effects of a complex waveform on a circuit may be determined by considering each of that waveform's harmonics separately, then those effects added together (superimposed) just as the harmonics themselves are superimposed to form the complex wave. Explain to your students how this superposition principle is not limited to the analysis of square waves, either. *Any* complex waveform whose harmonic constituents are known may be analyzed in this fashion.

Question 23

In the early 1800's, French mathematician Jean Fourier discovered an important principle of waves that allows us to more easily analyze non-sinusoidal signals in AC circuits. Describe the principle of the *Fourier series*, in your own words.

[file 00650](#)

Answer 23

“*Any periodic waveform*, no matter how complex, is equivalent to a series of sinusoidal waveforms added together at different amplitudes and different frequencies, plus a DC component.”

Follow-up question: what does this equation represent?

$$f(t) = A_0 + (A_1 \sin \omega t) + (B_1 \cos \omega t) + (A_2 \sin 2\omega t) + (B_2 \cos 2\omega t) + \dots$$

Notes 23

So far, all the “tools” students have learned about reactance, impedance, Ohm’s Law, and such in AC circuits assume sinusoidal waveforms. Being able to equate any non-sinusoidal waveform to a series of sinusoidal waveforms allows us to apply these “sinusoidal-only” tools to *any* waveform, theoretically.

An important caveat of Fourier’s theorem is that the waveform in question must be *periodic*. That is, it must repeat itself on some fixed period of time. Non-repetitive waveforms do not reduce to a definite series of sinusoidal terms. Fortunately for us, a great many waveforms encountered in electronic circuits are periodic and therefore may be represented by, and analyzed in terms of, definite Fourier series.

It would be good to mention the so-called *FFT* algorithm in this discussion while you’re on this topic: the digital algorithm that computers use to separate any sampled waveform into multiple constituent sinusoidal frequencies. Modern computer hardware is able to easily implement the FFT algorithm, and it finds extensive use in analytical and test equipment.

Question 24

Identify the type of electronic instrument that displays the relative amplitudes of a range of signal frequencies on a graph, with amplitude on the vertical axis and frequency on the horizontal.

file 00649

Answer 24

A *spectrum analyzer*.

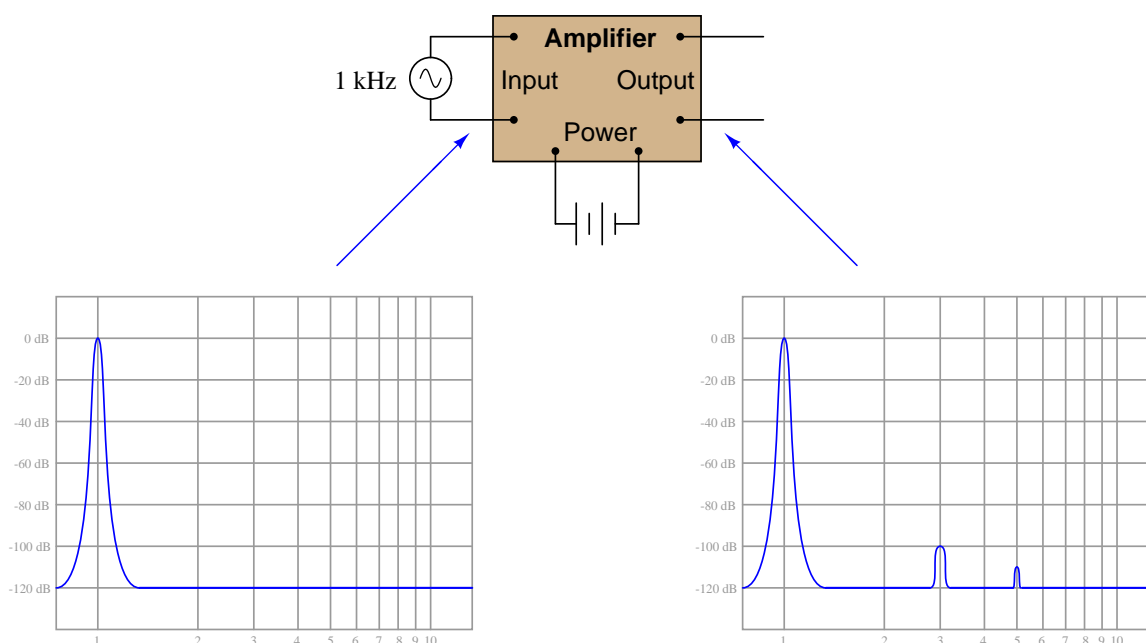
Challenge questions: two similar instruments are the *wave analyzer* and the *Fourier analyzer*. Explain how both these instruments are similar in function to a spectrum analyzer, and also how both differ.

Notes 24

Spectrum analyzers capable of analyzing radio-frequency signals are very expensive, but low-cost personal computer hardware and software does a good job of analyzing complex audio signals. It would be a benefit to your class to have a low-frequency spectrum analyzer setup available for student use, and possible demonstration during discussion.

Question 25

Suppose an amplifier circuit is connected to a sine-wave signal generator, and a spectrum analyzer used to measure both the input and the output signals of the amplifier:



Interpret the two graphical displays and explain why the output signal has more "peaks" than the input. What is this difference telling us about the amplifier's performance?

file 03307

Answer 25

The input signal is clean: a single peak at the 1 kHz mark. The amplifier's output, on the other hand, is a bit distorted (i.e. no longer a perfect sine-wave shape as the input is).

Notes 25

The purpose of this question is to get students to realize the presence of harmonics means a departure from a once-perfect sinusoidal wave-shape. What used to be free of harmonics now contains harmonics, and this indicates distortion of the sine wave somewhere within the amplifier.

By the way, the perfectly flat "noise floor" at -120 dB is highly unusual. There will always be a "rough" floor shown on the display of a spectrum analyzer, but this is not pertinent to the question at hand so I omitted it for simplicity's sake.

Question 26

What causes harmonics to form in the output of a transistor amplifier circuit, if the input waveform is perfectly sinusoidal (free from harmonics)? Be as specific as you can in your answer.

file 03746

Answer 26

Any feature (or fault) of the circuit causing imperfect signal reproduction will necessarily create harmonics, for it will turn a perfectly sinusoidal input signal into a distorted (non-perfect-sinusoidal) signal.

Notes 26

Discuss with your students the nature of harmonics: how *multiple* sinusoidal waveforms are necessarily contained in any periodic waveform that is not perfectly sinusoidal itself.

Question 27

What causes harmonics to form in the output of a transistor oscillator circuit such as a Colpitts or a Hartley, which is designed to produce a sinusoidal signal? Be as specific as you can in your answer.
file 03747

Answer 27

Any feature (or fault) of the amplifier portion of the oscillator circuit causing imperfect signal reproduction will necessarily create harmonics, for it will turn a perfectly sinusoidal input signal (from the LC network) into a distorted (non-perfect-sinusoidal) output signal.

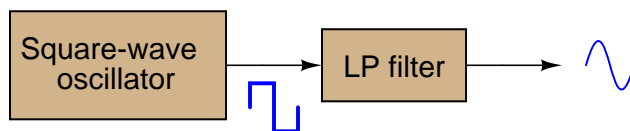
Challenge question: Colpitts oscillators tend to produce "purer" sine-wave outputs than Hartley oscillators, all other factors being equal. Explain why.

Notes 27

Discuss with your students the nature of harmonics: how *multiple* sinusoidal waveforms are necessarily contained in any periodic waveform that is not perfectly sinusoidal itself.

Question 28

A clever way to produce sine waves is to pass the output of a square-wave oscillator through a low-pass filter circuit:



Explain how this principle works, based on your knowledge of Fourier's theorem.

file 03754

Answer 28

The LP filter blocks all harmonics of the square wave except the fundamental (1st harmonic), resulting in a sinusoidal output.

Notes 28

Ask your students what they think about the *rolloff* requirement for this LP filter. Will any LP filter work, or do we need something special?

Question 29

What causes harmonics to form in AC electric power systems?

file 00653

Answer 29

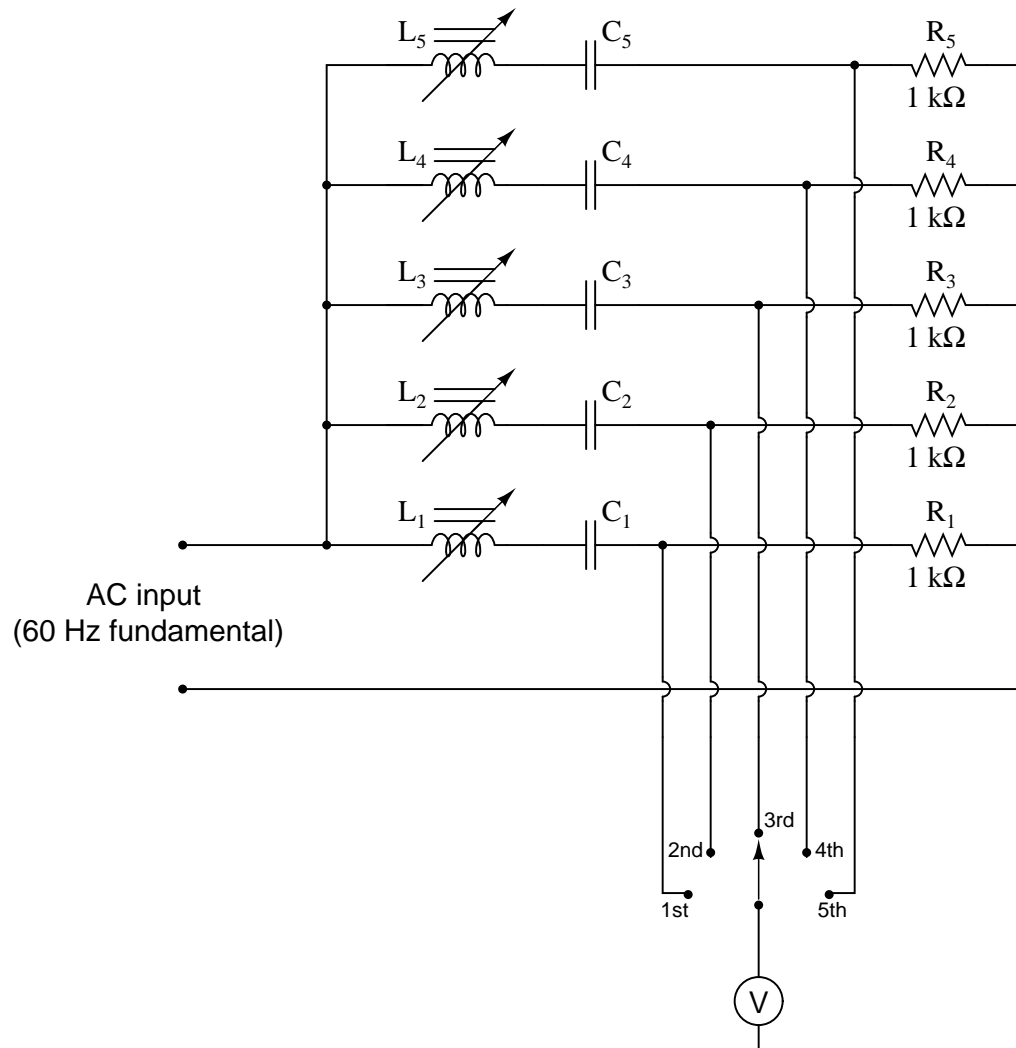
Nonlinear loads.

Notes 29

My answer to this question is intentionally vague. It is correct, but does not reveal anything about the real nature of the cause, or more importantly, *why* a "nonlinear" load would cause harmonics. Discuss with your students what a "nonlinear" device is, and what it does to a sinusoidal signal to generate harmonics.

Question 30

Explain how the following power-line harmonic analyzer circuit works:



| Harmonic # | $L_{\#}$ value | $C_{\#}$ value |
|------------|----------------|--------------------|
| 1st | 20 to 22 H | $0.33 \mu\text{F}$ |
| 2nd | 11 to 12 H | $0.15 \mu\text{F}$ |
| 3rd | 5 to 6 H | $0.15 \mu\text{F}$ |
| 4th | 1.5 to 2.5 H | $0.22 \mu\text{F}$ |
| 5th | 1 to 1.5 H | $0.27 \mu\text{F}$ |

file 03694

Answer 30

Each series LC section is a resonant band-pass filter, tuned to successive harmonics of a 60 Hz sine wave. The selector switch enables a single voltmeter to measure the RMS amplitude of each harmonic.

Follow-up question: calculate the *exact* inductance values necessary for precise tuning of the five LC filters, for the first five harmonics of a 60 Hz waveform.

Challenge question: the voltmeter in this circuit would not have to be a true-RMS meter. It could simply be an average-responding (RMS-calibrated) voltmeter and it would work the same. Explain why.

Notes 30

This question provides students with some review of passive filter circuit theory, as well as insight into a practical circuit they could conceivably build as a project.

A very important design feature of this circuit is the narrow bandwidth of each harmonic "channel." The filter pass-bands must *not* come close to overlapping, or else the meter response will not be exclusively indicative of the harmonic it is switched to. High Q values for each filter section ensure that the meter will *only* register the particular harmonic that is selected for measurement.

Question 31

What does the acronym *RF* stand for, in reference to radio-related electronics?
file 03459

Answer 31

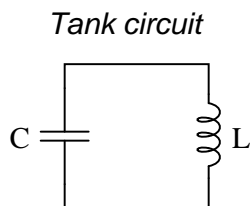
"RF" means *Radio Frequency*, implying a frequency of alternating current (AC) much greater than that encountered in AC power or audio circuitry.

Notes 31

Ask your students to list the frequencies of their favorite broadcast radio stations as an example of some radio frequencies. Show them a typical benchtop signal generator (non-RF) for comparison of frequency range, and they should begin to understand the concept.

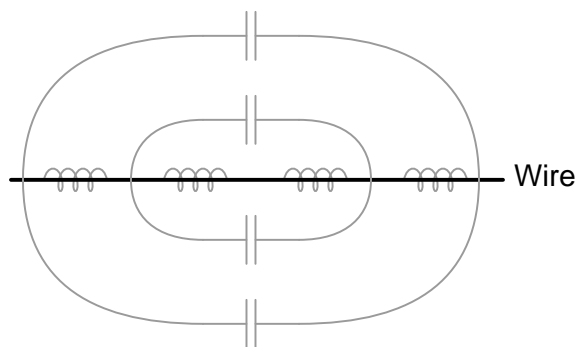
Question 32

We know at this point that any circuit comprised of inductance (L) and capacitance (C) is capable of *resonating*: attaining large values of AC voltage and current if "excited" at the proper frequency. The so-called *tank circuit* is the simplest example of this:



The less resistance (R) such a circuit has, the better its ability to resonate.

We also know that any piece of wire contains both inductance and capacitance, distributed along its length. These properties are not necessarily intentional – they exist whether we would want them to or not:



Given that the electrical resistance of a continuous piece of metal wire is usually quite low, describe what these natural properties of inductance and capacitance mean with regard to that wire's function as an electrical element.

[file 03461](#)

Answer 32

The fact that an piece of wire contains both inductance and capacitance means that it has the ability to resonate just like any tank circuit!

Follow-up question: qualitatively estimate the frequency you suppose a length of wire would resonate at. Do you think f_r would be a very low value (tens of hertz), a very high value (thousands, millions, or billions of hertz), or somewhere in between? Keep in mind the equation for resonant frequency:

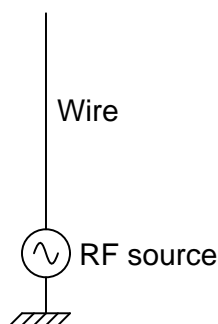
$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Notes 32

If your students have difficulty knowing where to start with the follow-up question, ask them to qualitatively estimate the distributed L and C for a piece of wire, say, 10 feet long. Given the lack of any high-permeability core material and the lack of any high-permittivity dielectric (just air), the answers for both should be "very small." Then, ask them again how they would qualitatively rate the wire's resonant frequency.

Question 33

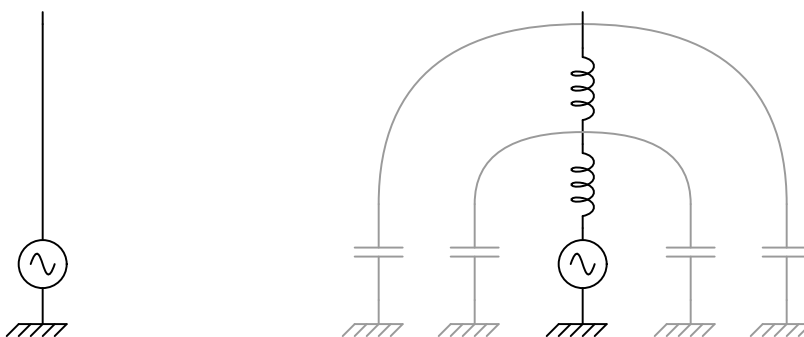
Shown here is a simple *quarter-wave* antenna, comprised of a single wire projecting vertically from one terminal of an RF voltage source, the other terminal connected to earth ground:



Re-draw this illustration, showing the equivalent inductance and capacitance exhibited by this antenna. Show these properties using actual inductor and capacitor symbols.

[file 03460](#)

Answer 33

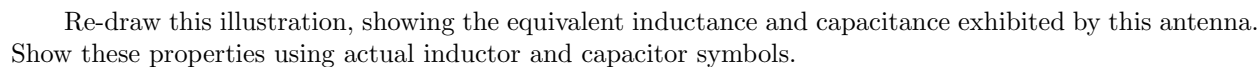


Follow-up question: how would you expect the inductance and capacitance of this antenna to relate to its physical length? In other words, as you increase the length of an antenna, would its inductance increase or decrease? As the length increases, would its capacitance increase or decrease? Explain your reasoning.

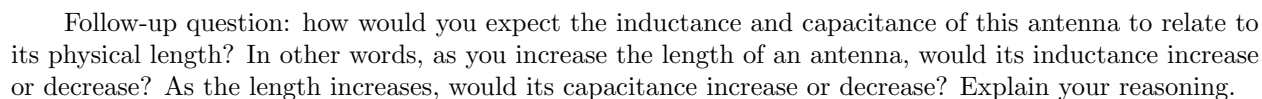
Notes 33

Do not be surprised if some of your students ask whether or not an antenna is capable of resonating, since it possesses both inductance and capacitance. In fact, this is the subversive point of this question: to get students to realize that even a simple pair of wires may be considered a resonant system, and then to beg the question of what happens at resonance! The follow-up question suggests a relationship between physical size and resonant frequency, by asking what happens to both L and C as length changes. Explore these ideas with your students, and watch them gain a surprisingly deep understanding of how an antenna works based on their knowledge of LC resonant circuits.

Shown here is a simple *dipole* antenna, comprised of two equal-length wires projecting from the terminals of an RF voltage source:



Answer 34



Do not be surprised if some of your students ask whether or not an antenna is capable of resonating, since it possesses both inductance and capacitance. In fact, this is the subversive point of this question: to get students to realize that even a simple pair of wires may be considered a resonant system, and then to beg the question of what happens at resonance! The follow-up question suggests a relationship between physical size and resonant frequency, by asking what happens to both L and C as length changes. Explore these ideas with your students, and watch them gain a surprisingly deep understanding of how an antenna works based on their knowledge of LC resonant circuits.

Question 35

A Scottish physicist named James Clerk Maxwell made an astonishing theoretical prediction in the nineteenth century, which he expressed with these two equations:

$$\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt}$$
$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

The first equation states that an electric field (\mathbf{E}) will be produced in open space by a changing magnetic flux ($\frac{d\Phi_B}{dt}$). The second equation states that a magnetic field (\mathbf{B}) will be produced in open space either by an electric current (I) or by a changing electric flux ($\frac{d\Phi_E}{dt}$). Given this complementary relationship, Maxwell reasoned, it was possible for a changing electric field to create a changing magnetic field which would then create another changing electric field, and so on. This cause-and-effect cycle could continue, ad infinitum, with fast-changing electric and magnetic fields radiating off into open space without needing wires to carry or guide them. In other words, the complementary fields would be self-sustaining as they traveled.

Explain the significance of Maxwell's prediction, especially as it relates to electronics.

[file 03462](#)

Answer 35

What James Clerk Maxwell predicted was the existence of *electromagnetic waves*, the lowest-frequency type we commonly refer to as *radio waves*.

Follow-up question: name the scientist who first experimentally confirmed Maxwell's prediction of electromagnetic waves.

Notes 35

Not only does this question relate the concept of radio waves to concepts your students should already be familiar with (electric and magnetic fields), but it also introduces a piece of amazing scientific history. That radio waves were first predicted mathematically rather than discovered accidentally by experiment is both astonishing and enlightening.

You may find that one or more of your brighter students notice Maxwell's prediction relates a change in one type of field to a static magnitude of the other (i.e. $E \propto \frac{d\Phi_B}{dt}$ and $B \propto \frac{d\Phi_E}{dt}$), and that this makes it difficult to see how one changing field could create another *changing* field. If anyone asks this question, point out to them that there is a set of similar mathematical functions related to one another by derivatives, and they are:

$$\sin t = -\frac{d}{dt} \cos t \qquad \cos t = \frac{d}{dt} \sin t$$

Does anything look familiar (omitting the $\mu_0 I$ term from the second equation)?

$$\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt} \qquad \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

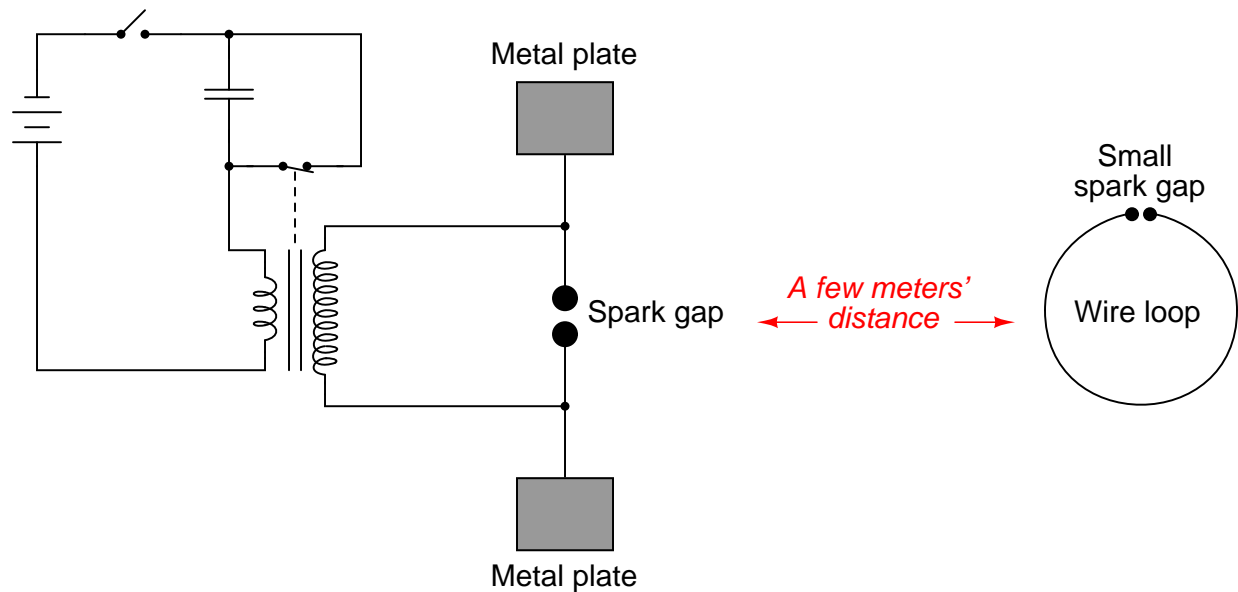
Since we know electric flux is related to electric field by geometry ($\Phi_E = \int \mathbf{E} \cdot d\mathbf{A}$) and magnetic flux is related to magnetic field by geometry as well ($\Phi_B = \int \mathbf{B} \cdot d\mathbf{A}$), we may write the following proportionalities:

$$\Phi_E \propto -\frac{d\Phi_B}{dt} \qquad \Phi_B \propto \frac{d\Phi_E}{dt}$$

Now do things look similar to the sine/cosine derivative relationship? Thus, if the electric flux Φ_E oscillates as a sine wave, the magnetic flux Φ_B will oscillate as a cosine wave, and so on.

Question 36

In 1887, a German physicist named Heinrich Hertz successfully demonstrated the existence of *electromagnetic waves*. Examine the following schematic of the apparatus he used to do this, and explain what significance Hertz's discovery has to do with your study of electronics:



file 02278

Answer 36

Hertz's experiment empirically demonstrated the theoretical discovery of James Clerk Maxwell, who concluded years before that "electromagnetic waves" comprised of electric and magnetic fields oscillating perpendicular to one another must be capable of radiating through empty space. This is the basis of radio communication: generating these electromagnetic waves for the purpose of communicating information over long distances without wires.

Notes 36

An experiment such as this is not difficult to set up. Be sure to provide the appropriate safety precautions against electric shock, as such spark-gap transmitters (as they came to be called) require substantially high voltages to operate.

Question 37

Given James Clerk Maxwell's prediction of electromagnetic *waves* arising from the self-sustenance of changing electric and magnetic fields in open space, what sort of a device or collection of devices do you think we would need to create electromagnetic waves oscillating at a frequency within the range attainable by an electric circuit? In other words, what kind of component(s) would we attach to a source of high-frequency AC to radiate these waves?

file 03463

Answer 37

Ideally you will need a device that produces both electric and magnetic fields in space: something that possesses both capacitance and inductance in an unshielded form where the electric and magnetic fields would be open to space. In other words, you will need an *antenna*.

Notes 37

The purpose of this question is to relate the concept of distributed capacitance and inductance along a plain piece of wire to the very nature of electromagnetic waves (oscillating electric and magnetic fields). If students suggest using capacitors and inductors, they are quite close to the mark. Unfortunately, these devices are usually designed to contain their respective fields to *prevent* radiation into space. Here, we *want* the fields to radiate away from the device, and so we use an open wire (or an array of open wires).

Question 38

Although radio transmitter antennae ideally possesses only inductance and capacitance (no resistance), in practice they are found to be very dissipative. In other words, they tend to act as large *resistors* to the transmitters they are connected to. Explain why this is. In what form is the dissipated energy manifest (heat, light, or something else)?

file 02280

Answer 38

Ideally, 100% of the energy input to an antenna leaves in the form of electromagnetic radiation.

Notes 38

Although students may have some to associate the concept of "dissipation" exclusively with resistors, this is not entirely correct. All that is meant by "dissipation" is the dispersal of energy; that is, energy leaving an electric circuit and not returning. With resistors, this occurs in the form of heat, but this is not the only kind of dissipation! In electric motors, most of the energy is dissipated in the form of mechanical energy, which goes into doing *work* (and some heat, of course). Light bulbs dissipate energy in the form of light, not just heat.

Question 39

A crystal goblet may be shattered if exposed to high-intensity sound. Less volume is required to shatter the goblet if the sound is at such a frequency that it *resonates* with the goblet's natural frequency. That is, there will be maximum transfer of energy to the goblet if the sound waves are transmitted at precisely the goblet's resonant frequency.

How does this phenomenon relate to the reception of radio waves, since we know that a radio antenna effectively acts as a resonant LC (inductance/capacitance) network?

file 02282

Answer 39

A radio antenna will receive electromagnetic energy most efficiently if it is sized (tuned) to the exact frequency of the desired radio waves.

Notes 39

The analogy of a goblet shattered by sound waves helps students readily identify with a concept that is otherwise abstract: the reception of *electromagnetic* waves by an antenna. Ask your students to relate the matching of frequencies to the transmission of radio waves as well as the reception of them.

Question 40

Radio waves are comprised of oscillating electric and magnetic fields, which radiate away from sources of high-frequency AC at (nearly) the speed of light. An important measure of a radio wave is its *wavelength*, defined as the distance the wave travels in one complete cycle.

Suppose a radio transmitter operates at a fixed frequency of 950 kHz. Calculate the approximate wavelength (λ) of the radio waves emanating from the transmitter tower, in the metric distance unit of meters. Also, write the equation you used to solve for λ .

file 01819

Answer 40

$$\lambda \approx 316 \text{ meters}$$

I'll let you find the equation on your own!

Notes 40

I purposely omit the velocity of light, as well as the time/distance/velocity equation, so that students will have to do some simple research this calculate this value. Neither of these concepts is beyond high-school level science students, and should pose no difficulty at all for college-level students to find on their own.

Question 41

A very important concept in electronics is *modulation*. Explain what "modulation" means, and give one or two examples of it.

file 02266

Answer 41

Modulation is the act of impressing information onto an otherwise featureless stream of matter or energy, usually for the sake of communicating that information over a long distance. Radio is a very common example of modulation, but I'll let you research a few more on your own!

Notes 41

There are many examples of modulation that students can find for presentation, and not all of them are electronic. Challenge them to think of scenarios other than modern electronic and/or optical communication schemes where modulation of some kind is employed.

Question 42

A primitive form of communication long ago was the use of *smoke signals*: interrupting the rising stream of smoke from a fire by waving a blanket over it so that specific sequences of smoke "puffs" could be seen some distance away. Explain how this is an example of *modulation*, albeit in a non-electronic form.

file 02265

Answer 42

Modulation is the impression of information onto an otherwise featureless stream of matter or energy. In this case, the modulation of a smoke stream by blanket motions should be rather evident.

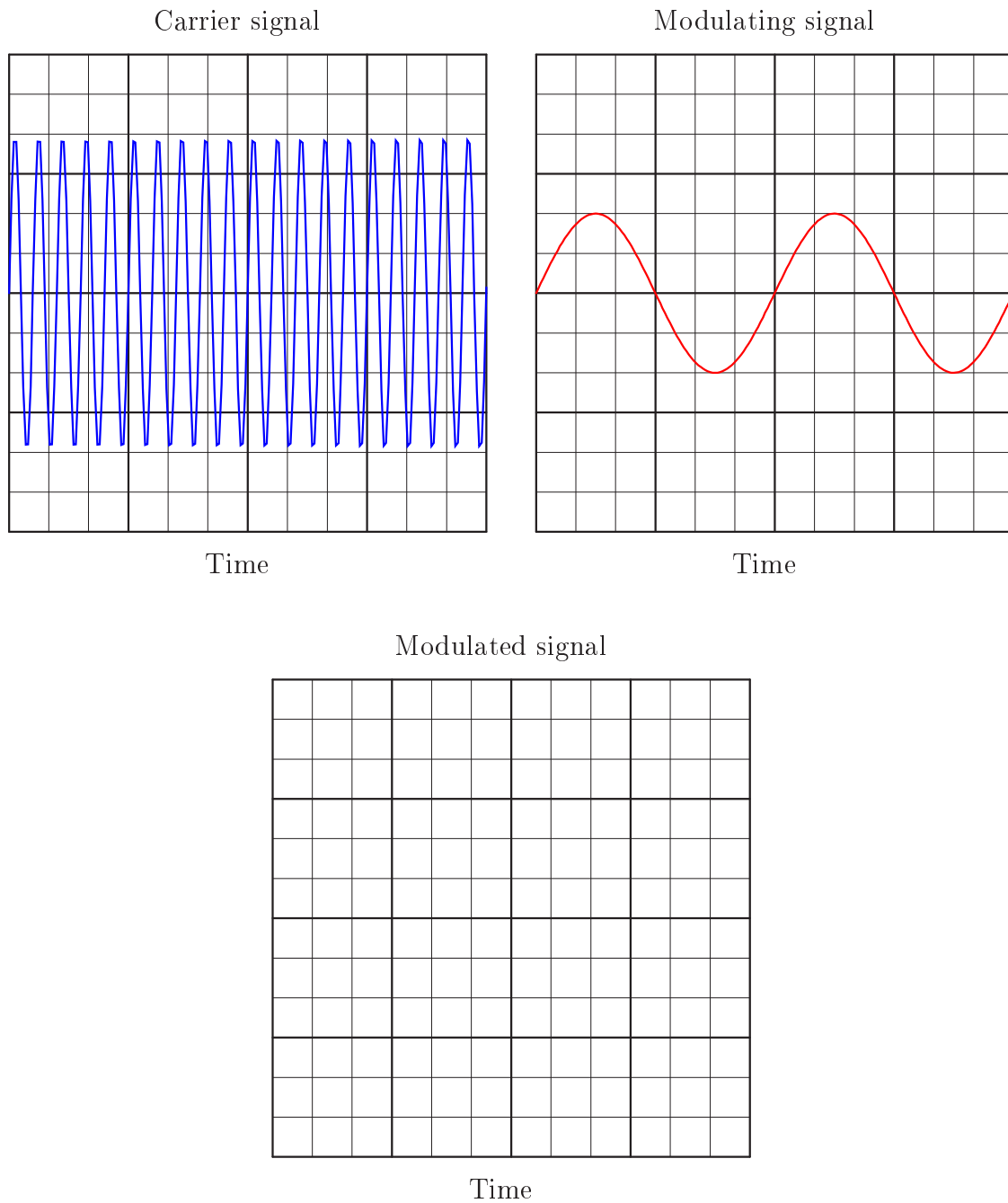
Notes 42

It is important for students to understand that modulation is not limited to electronic media. Stranger examples than this may be cited as proof. I once spoke with an engineer specializing in vibration measurement who told me of a very odd application of modulation for data communication. He worked on the design of a vibration sensor that would be embedded in the head of an oil well drill bit. This sensor was supposed to transmit information to the surface, thousands of feet up, but could not use radio or any other "normal" data media because of the distances involved and the harsh environment. The solution taken to this unique problem was to have the sensor activate a valve at the drill head which would modulate the flow of drilling mud up to the surface: a byproduct of the drilling process that had to be pumped up to the surface anyway. By pulsing the normally steady mud flow, digital data could be communicated to pressure sensors at the surface, and then converted into binary data for a computer to archive and translate. Granted, the bit rate was very slow, but the system worked.

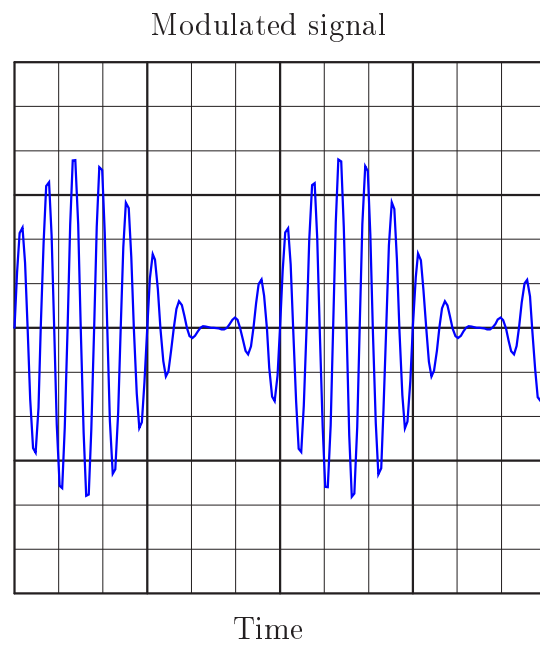
An application like this shows how important it is for students to exercise creativity. The really interesting problems in life do not yield to "tried and true" solutions, but can only be overcome through the exercise of creativity and skill. Do everything you can to expose your students to such creative thinking within their discipline(s), and this will help them to become the problem-solvers of tomorrow!

Question 43

One of the simplest electronic methods of modulation is *amplitude modulation*, or *AM*. Explain how a high-frequency *carrier* signal would be modulated by a lower-frequency signal such as in the case of the two signals shown here in the time domain:



file 02273

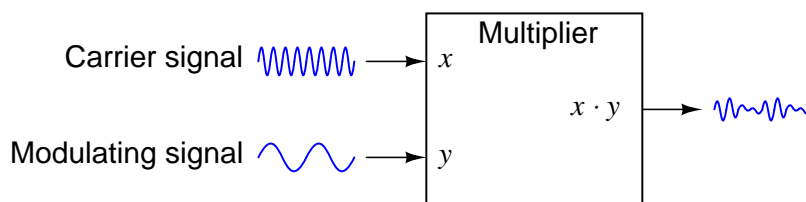


Notes 43

I do not expect that students will be able to precisely sketch the modulated waveform, especially when the period of the carrier is so short. However, they should be able to express the general idea of amplitude modulation in some form of drawing or sketch, and that's all I'm interested in seeing from them in response to this question.

Question 44

A circuit often used to amplitude-modulate a carrier signal is a *multiplier*:



Explain how the instantaneous multiplication of two sine waves results in amplitude modulation. If possible, graph this on a graphing calculator or other computer plotting device.

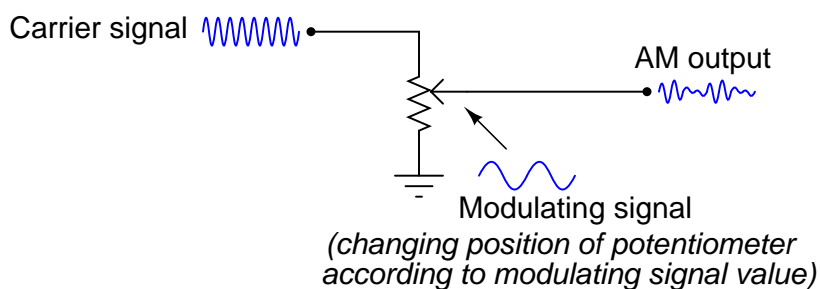
[file 02284](#)

Answer 44

I'll let you figure this one out on your own!

Notes 44

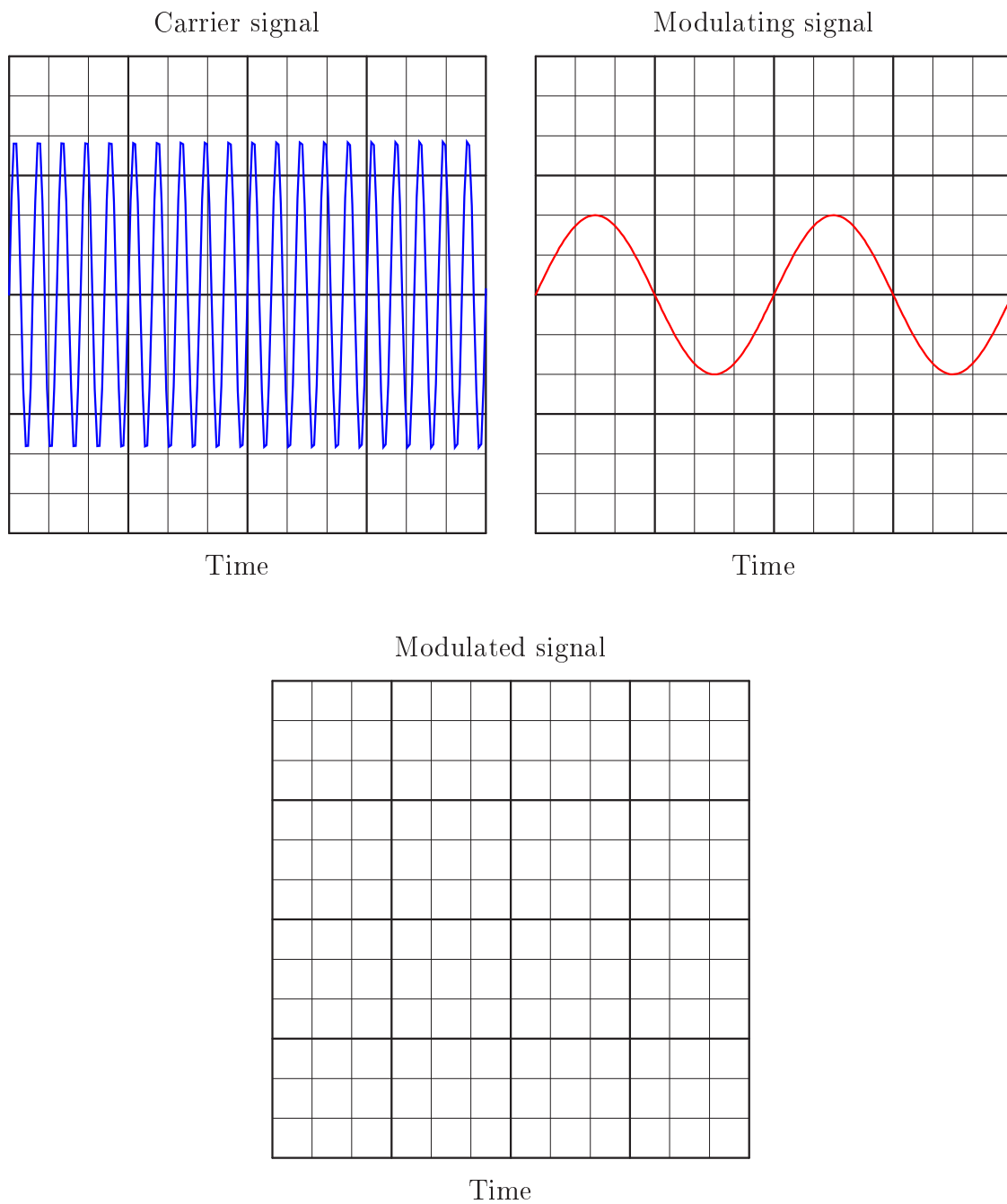
Multiplier circuits are quite useful, and not just for amplitude modulation. The fact that they can be used as amplitude modulators, though, is a concept some students find hard to understand. One illustration that might clear things up is an adjustable voltage divider (since multiplication and division are very closely related):



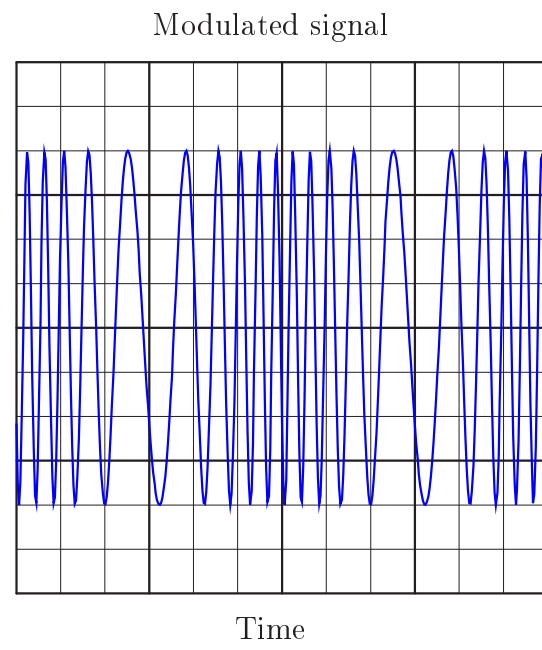
Now, such a potentiometer circuit would be totally impractical for any modulating signal frequency measured in Hertz, as the potentiometer would wear out very rapidly from all the motion. It is the *principle* of modulated voltage division that this circuit helps to communicate, though. Multiplier circuits do the same thing, only multiplying the amplitude of the carrier signal rather than dividing it.

Question 45

A common modulation technique employed in radio broadcasting is *frequency modulation*, or *FM*. Explain how a high-frequency *carrier* signal would be modulated by a lower-frequency signal such as in the case of the two signals shown here in the time domain:



file 02274



Notes 45

I do not expect that students will be able to precisely sketch the modulated waveform, especially when the period of the carrier is so short. However, they should be able to express the general idea of frequency modulation in some form of drawing or sketch, and that's all I'm interested in seeing from them in response to this question.

Question 46

At the heart of an FM transmitter is a circuit called a *voltage-controlled oscillator*, or *VCO*. Explain what the purpose of a VCO is, and how this directly relates to frequency modulation.

file 02276

Answer 46

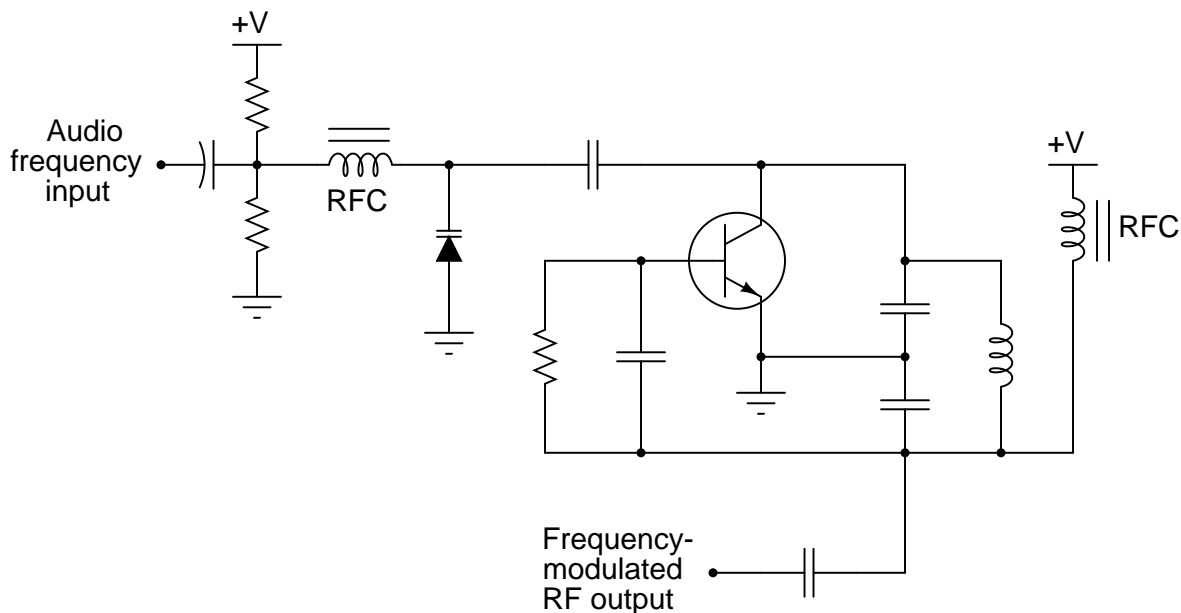
A VCO generates an AC output signal whose frequency is proportional to an externally-supplied input voltage.

Notes 46

Note to your students that VCO circuits are not just used in FM radio transmission. They are also essential to the function of *phase-locked loops*.

Question 47

This is a schematic for a very simple VCO:



The oscillator is of the "Colpitts" design. The key to understanding this circuit's operation is knowing how the *varactor* diode responds to different amounts of DC bias voltage. Explain how this circuit works, especially how the diode exerts control over the oscillation frequency. Why does the output frequency vary as the control voltage varies? Does the output frequency increase or decrease as the control voltage input receives a more positive voltage?

Note: "RFC" is an acronym standing for *Radio-Frequency Choke*, an iron-core inductor whose purpose it is to block radio frequency current from passing through.

[file 02283](#)

Answer 47

As voltage across the varactor diode changes, its capacitance changes.

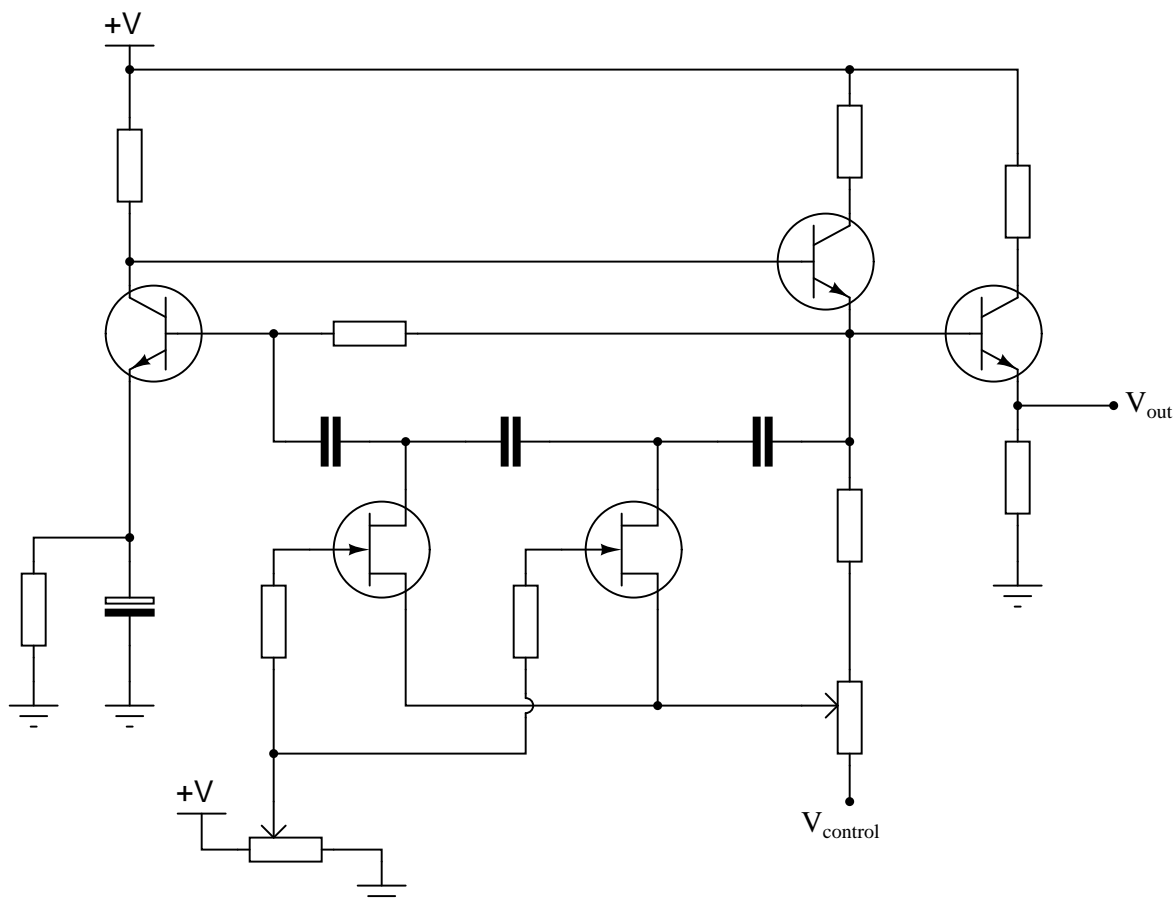
The output frequency *increases* as the control voltage becomes more positive.

Notes 47

This question is a good review of varactor diode function, as well as frequency modulation theory.

Question 48

This is a schematic for a simple VCO:



The oscillator is of the RC "phase shift" design. Explain how this circuit works. Why does the output frequency vary as the control voltage varies? Does the output frequency increase or decrease as the control voltage input receives a more positive voltage?

Hint: the JFETs in this circuit are not functioning as amplifiers!

file 01187

Answer 48

To understand how the JFETs are functioning in this VCO design, closely examine the "saturation" regions of a JFET's characteristic curves. Note that these regions appear as nearly straight-line sections. This indicates something about the behavior of a saturated JFET that is exploited in this VCO circuit.

The output frequency *decreases* as the control voltage becomes more positive.

Notes 48

Not only does this question allow students to examine the workings of a VCO, but it also provides a good review of JFET theory, as well as a practical example of a special application of junction field-effect transistors.

Note: the schematic diagram for this circuit was derived from one found on page 997 of John Markus' Guidebook of Electronic Circuits, first edition. Apparently, the design originated from a Motorola publication on using field effect transistors ("Low Frequency Applications of Field-Effect Transistors," AN-511, 1971).

Question 49

FM tends to be a far more noise-resistant means of signal modulation than AM. For instance, the "crackling" form of radio interference caused by natural lightning or the "buzzing" noise produced by high-voltage power lines are both easy to hear on an AM radio, but absent on an FM radio. Explain why.

file 02275

Answer 49

Radio interference manifests itself as additional peaks on the "envelope" of a modulated carrier wave. AM reception is based on the extraction of that envelope from the modulated carrier, and so AM receivers will "pick up" unwanted noise. FM reception is based on the extraction of information from changes in *frequency*, which is largely unaffected by noise.

Notes 49

Ask students to explain this principle in their own words, and not just repeat the given answer.

Question 50

When transmitting audio information (such as music and speech) in the form of radio waves, why bother modulating a high-frequency carrier signal? Why not just connect a powerful audio amplifier straight to an antenna and broadcast the audio frequencies directly?

file 02277

Answer 50

There are several reasons you would *not* want to try to broadcast electromagnetic (radio) waves at audio frequencies. A few of the most important are listed here:

- The necessary size of the antenna.
- Low transmission efficiency from inability to match antenna length to (changing) audio frequency.
- Interference from other (similar) radio transmitters.

Be prepared to explain *why* each of these factors effectively prohibits radio broadcasts at audio frequencies.

Notes 50

The purpose of this question is to have students relate their understanding of basic RF and antenna theory to a very practical problem of broadcasting low-frequency (in this case, audio) information. A fun exercise to do along with this question is to calculate the necessary physical dimensions of a quarter-wave ($\frac{\lambda}{4}$) antenna at a frequency of 2 kHz, keeping in mind that $\lambda = \frac{v}{f}$ and $v \approx 3 \times 10^8$ meters per second.

| | | | | | | | | | | |
|--|-----------|----------|---|-----------|----------|---------|------------------------------------|---------|---------|---|
| Competency: BJT multivibrator circuit, astable | | Version: | | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Schematic</div> <div style="text-align: center; margin-top: 20px;"> </div> | | | | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Given conditions</div> <table style="width: 100%; margin-top: 10px;"> <tr> <td style="width: 25%;">$V_{CC} =$</td> <td style="width: 25%;">$R_1 =$</td> <td style="width: 25%;">$R_2 =$</td> <td style="width: 25%;">$C_1 =$</td> </tr> <tr> <td></td> <td>$R_4 =$</td> <td>$R_3 =$</td> <td>$C_2 =$</td> </tr> </table> | | | $V_{CC} =$ | $R_1 =$ | $R_2 =$ | $C_1 =$ | | $R_4 =$ | $R_3 =$ | $C_2 =$ |
| $V_{CC} =$ | $R_1 =$ | $R_2 =$ | $C_1 =$ | | | | | | | |
| | $R_4 =$ | $R_3 =$ | $C_2 =$ | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Parameters</div> <table style="width: 100%; margin-top: 10px;"> <tr> <td style="width: 30%;"></td> <td style="width: 15%; text-align: center;">Predicted</td> <td style="width: 15%; text-align: center;">Measured</td> <td style="width: 40%;"></td> </tr> <tr> <td>Duty Cycle (at Q_1 collector)</td> <td style="border: 1px solid black; height: 20px;"></td> <td style="border: 1px solid black; height: 20px;"></td> <td>Potentiometer turned fully clockwise</td> </tr> </table> | | | | Predicted | Measured | | Duty Cycle (at Q_1 collector) | | | Potentiometer turned fully clockwise |
| | Predicted | Measured | | | | | | | | |
| Duty Cycle (at Q_1 collector) | | | Potentiometer turned fully clockwise | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Fault analysis</div> <p style="margin-top: 10px;">Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____</p> <p style="margin-left: 10px;"><input type="checkbox"/> shorted</p> <p style="margin-left: 10px;"><i>What will happen in the circuit?</i></p> <div style="height: 150px; border: 1px solid black; margin-top: 10px;"></div> | | | | | | | | | | |

file 01939

Answer 51

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

Notes 51

Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 k Ω and 100 k Ω (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

This circuit produces nice, sharp-edged square wave signals at the transistor collector terminals when resistors R_1 and R_4 are substantially smaller than resistors R_2 and R_3 . This way, R_2 and R_3 dominate the capacitors' charging times, making calculation of duty cycle much more accurate. Component values I've used with success are 1 k Ω for R_1 and R_4 , 100 k Ω for R_2 and R_3 , and 0.1 μ F for C_1 and C_2 .

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: Wien bridge oscillator, BJT | | Version: | |
|---|---------------|-------------|---------|
| Schematic | | | |
| | | | |
| Given conditions | | | |
| $V_{CC} =$ | $C_1 = C_2 =$ | $C_3 =$ | $C_4 =$ |
| $R_1 = R_2 =$ | $R_3 =$ | $R_4 =$ | $R_5 =$ |
| $R_6 =$ | $R_7 =$ | $R_{pot} =$ | |
| Parameters | | | |
| | Predicted | Measured | |
| f_{out} | | | |
| Fault analysis | | | |
| Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted | | | |
| <i>What will happen in the circuit?</i> | | | |

file 01975

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

Notes 52

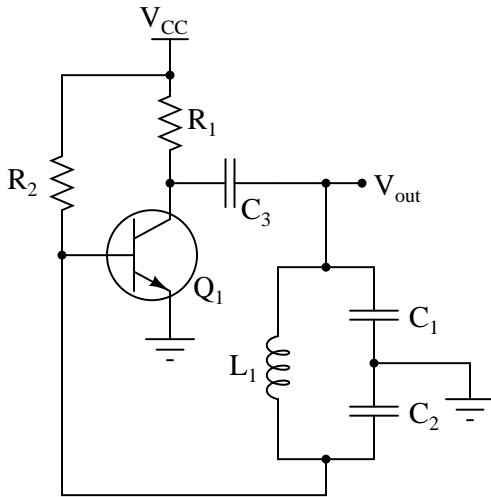
Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 k Ω and 100 k Ω (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

R_{pot} serves the purpose of providing variable AC gain in the first amplifier stage to meet the Barkhausen criterion.

I have had good success with the following values:

- $V_{CC} = 12$ volts
- C_1 and $C_2 = 0.001$ μ F
- $C_3 = 47$ μ F
- $C_4 = 0.47$ μ F
- R_1 and $R_2 = 4.7$ k Ω
- $R_3 = 4.7$ k Ω
- $R_4 = 39$ k Ω
- $R_5 = 22$ k Ω
- $R_6 = 27$ k Ω
- $R_7 = 3.3$ k Ω
- $R_{pot} = 10$ k Ω , linear
- Q_1 and $Q_2 =$ part number 2N2222

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: Colpitts oscillator, BJT | | Version: | | | | | | |
|--|-----------|----------|--|-----------|----------|-----------|--|--|
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Schematic</div>  | | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Given conditions</div> <div style="display: flex; justify-content: space-around; margin-top: 10px;"> <div>$V_{CC} =$</div> <div>$C_1 = C_2 =$</div> <div>$L_1 =$</div> <div>$C_3 =$</div> </div> <div style="display: flex; justify-content: space-around; margin-top: 10px;"> <div>$R_1 =$</div> <div>$R_2 =$</div> </div> | | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Parameters</div> <table style="width: 100%; border-collapse: collapse; margin-top: 10px;"> <thead> <tr> <th style="width: 10%;"></th> <th style="width: 20%; text-align: center;">Predicted</th> <th style="width: 20%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td>f_{out}</td> <td style="border: 1px solid black; height: 30px;"></td> <td style="border: 1px solid black; height: 30px;"></td> </tr> </tbody> </table> | | | | Predicted | Measured | f_{out} | | |
| | Predicted | Measured | | | | | | |
| f_{out} | | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Fault analysis</div> <p style="margin-top: 10px;">Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____</p> <p style="margin-left: 10px;"><input type="checkbox"/> shorted</p> <p style="margin-top: 10px;"><i>What will happen in the circuit?</i></p> <div style="border: 1px solid black; height: 150px; margin-top: 10px;"></div> | | | | | | | | |

file 01952

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

Notes 53

I have had great success with the following values:

- $V_{CC} = 7$ to 24 volts
- C_1 and $C_2 = 0.22 \mu\text{F}$
- $C_3 = 0.47 \mu\text{F}$
- $L_1 = 100 \mu\text{H}$ (ferrite core RF choke)
- $R_1 = 22 \text{ k}\Omega$
- $R_2 = 1.5 \text{ M}\Omega$
- $Q_1 =$ part number 2N3403

With these component values, the output waveform was quite clean and the frequency was very close to predicted:

$$f_{out} = \frac{1}{2\pi\sqrt{\frac{LC_1C_2}{C_1+C_2}}}$$

You might want to quiz your students on the purpose of resistor R_2 , since it usually only has to be present at power-up to initiate oscillation!

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: AM radio transmitter | | Version: |
|---|---------------|----------|
| Schematic | | |
| | | |
| Given conditions | | |
| $+V =$ | $C_1 = C_2 =$ | $L_1 =$ |
| $V_{\text{signal}} =$ | $R_1 =$ | $R_2 =$ |
| $f_{\text{signal}} =$ | $R_3 =$ | $R_4 =$ |
| Parameters | | |
| Predicted | Measured | |
| f_{out} | | |
| Audio signal can be heard on AM radio <input style="width: 30px; height: 20px;" type="checkbox"/> | | |
| Oscilloscope display of modulation | | |

file 01953

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

I have had great success with the following values:

- $+V = 7$ to 24 volts
- C_1 and $C_2 = 0.001 \mu\text{F}$
- C_3 , C_4 , and $C_5 = 0.47 \mu\text{F}$
- $L_1 = 100 \mu\text{H}$ (ferrite core RF choke)
- $R_1 = 22 \text{ k}\Omega$
- $R_2 = 1.5 \text{ M}\Omega$
- $R_3 = 6.8 \text{ k}\Omega$
- $R_4 = 100 \text{ k}\Omega$
- $Q_1 =$ part number 2N3403
- $Q_2 =$ part number MPF 102

With these component values, the carrier waveform was quite clean and the frequency was almost exactly 700 kHz:

$$f_{out} = \frac{1}{2\pi\sqrt{\frac{LC_1C_2}{C_1+C_2}}}$$

Modulation isn't that great, due to the crude nature of the circuit, but it is certainly good enough to hear over an appropriately tuned AM radio. Setting V_{signal} and f_{signal} is a matter of experimentation, to achieve the desired degree of modulation and tone pitch.

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: Oscillator/waveshaper/amplifier circuit | | Version: | | | | | | | | | | | | | | | | | | | | | | | | | | |
|--|---|---|----------------------|---|----------------------|---------------------|----------------------|---------------------|-------------|---|---|----------|---|-------------|---|---|----------|---|----------|---|---|-----------|---|--|---------|-------------|--|--|
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Schematic</div> | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Given conditions</div> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 15%;">$-V =$</td> <td style="width: 15%;">$R_1 =$</td> <td style="width: 15%;">$R_6 =$</td> <td style="width: 15%;">$C_1 =$</td> <td style="width: 15%;">$C_5 =$</td> </tr> <tr> <td></td> <td>$R_2 =$</td> <td>$R_7 =$</td> <td>$C_2 =$</td> <td>$C_6 =$</td> </tr> <tr> <td></td> <td>$R_3 =$</td> <td>$R_8 =$</td> <td>$C_3 =$</td> <td>$C_7 =$</td> </tr> <tr> <td></td> <td>$R_4 =$</td> <td>$R_9 =$</td> <td>$C_4 =$</td> <td></td> </tr> <tr> <td></td> <td>$R_5 =$</td> <td>$R_{pot} =$</td> <td></td> <td></td> </tr> </table> | | | | $-V =$ | $R_1 =$ | $R_6 =$ | $C_1 =$ | $C_5 =$ | | $R_2 =$ | $R_7 =$ | $C_2 =$ | $C_6 =$ | | $R_3 =$ | $R_8 =$ | $C_3 =$ | $C_7 =$ | | $R_4 =$ | $R_9 =$ | $C_4 =$ | | | $R_5 =$ | $R_{pot} =$ | | |
| $-V =$ | $R_1 =$ | $R_6 =$ | $C_1 =$ | $C_5 =$ | | | | | | | | | | | | | | | | | | | | | | | | |
| | $R_2 =$ | $R_7 =$ | $C_2 =$ | $C_6 =$ | | | | | | | | | | | | | | | | | | | | | | | | |
| | $R_3 =$ | $R_8 =$ | $C_3 =$ | $C_7 =$ | | | | | | | | | | | | | | | | | | | | | | | | |
| | $R_4 =$ | $R_9 =$ | $C_4 =$ | | | | | | | | | | | | | | | | | | | | | | | | | |
| | $R_5 =$ | $R_{pot} =$ | | | | | | | | | | | | | | | | | | | | | | | | | | |
| <div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Parameters</div> <table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 15%;">Predicted weshape</th> <th style="width: 15%;">Measured weshape</th> <th style="width: 15%;">Predicted weshape</th> <th style="width: 15%;">Measured weshape</th> </tr> </thead> <tbody> <tr> <td>$V_{C(Q2)}$</td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> <td>V_{C4}</td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> </tr> <tr> <td>$V_{B(Q2)}$</td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> <td>V_{R7}</td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> </tr> <tr> <td>V_{C3}</td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> <td>V_{out}</td> <td><div style="border: 1px solid black; width: 80px; height: 20px;"></div></td> </tr> </tbody> </table> | | | | | Predicted weshape | Measured weshape | Predicted weshape | Measured weshape | $V_{C(Q2)}$ | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | V_{C4} | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | $V_{B(Q2)}$ | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | V_{R7} | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | V_{C3} | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | V_{out} | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | | | | | |
| | Predicted weshape | Measured weshape | Predicted weshape | Measured weshape | | | | | | | | | | | | | | | | | | | | | | | | |
| $V_{C(Q2)}$ | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | V_{C4} | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | | | | | | | | | | | | | | | | | | | | | | | | |
| $V_{B(Q2)}$ | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | V_{R7} | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | | | | | | | | | | | | | | | | | | | | | | | | |
| V_{C3} | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | V_{out} | <div style="border: 1px solid black; width: 80px; height: 20px;"></div> | | | | | | | | | | | | | | | | | | | | | | | | |

file 02507

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

Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 k Ω and 100 k Ω (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

This circuit demonstrates the use of passive integrators to convert a square wave into a pseudo-sine wave output. The multivibrator portion produces nice, sharp-edged square wave signals at the transistor collector terminals when resistors R_1 and R_4 are substantially smaller than resistors R_2 and R_3 . Component values I've used with success are 1 k Ω for R_1 and R_4 , 100 k Ω for R_2 and R_3 , and 0.001 μ F for C_1 and C_2 .

Resistors R_5 and R_6 , along with capacitors C_3 and C_4 , form a dual passive integrator network to re-shape the square-wave output of the multivibrator into a pseudo-sine wave. These components' values must be chosen according to the multivibrator frequency, so that the integration is realistic without the attenuation being excessive. Integrator component values that have worked well for the multivibrator components previously specified are 10 k Ω for R_5 and R_6 , and 0.1 μ F for C_3 and C_4 .

Transistor Q_3 is just an emitter follower, placed there to give the amplifier section a high input impedance. Q_3 's emitter resistor value is not critical. I have used a 1 k Ω resistor for R_7 with good success.

The last transistor (Q_4) is for voltage amplification. A "trimmer" style potentiometer (10 k Ω recommended for R_{pot}) provides easy adjustment of biasing for different supply voltages. Using the potentiometer, I have operated this circuit on supply voltages ranging from -6 volts to -27 volts. Use a bypass capacitor (C_7) large enough that its reactance at the operating frequency is negligible (less than 1 ohm is good), such as 33 μ F. Resistor values I've used with success are 10 k Ω for R_8 and 4.7 k Ω for R_9 . Coupling capacitor values are not terribly important, so long as they present minimal reactance at the operating frequency. I have used 0.47 μ F for both C_5 and C_6 with good success.

You may find that the relatively high operating frequency of this circuit complicates matters with regard to parasitic capacitances. The fast rise and fall times of the strong square wave tend to couple easily to the sine-wave portions of the circuit, especially when the sine wave signal is so severely attenuated by the double integrators. One solution to this dilemma is to lower the operating frequency of the circuit, allowing a lower cutoff frequency for the double integrator (two-pole lowpass filter) section which in turn will improve the signal-to-noise ratio throughout. If you wish to try this, you may use these suggested component values:

- $R_1 = 1 \text{ k}\Omega$
- $R_2 = 100 \text{ k}\Omega$
- $R_3 = 100 \text{ k}\Omega$
- $R_4 = 1 \text{ k}\Omega$
- $R_5 = 100 \text{ k}\Omega$
- $R_6 = 100 \text{ k}\Omega$
- $R_7 = 1 \text{ k}\Omega$
- $R_8 = 10 \text{ k}\Omega$
- $R_9 = 4.7 \text{ k}\Omega$
- $R_{pot} = 10 \text{ k}\Omega$
- $C_1 = 0.047 \text{ }\mu\text{F}$
- $C_2 = 0.047 \text{ }\mu\text{F}$
- $C_3 = 0.1 \text{ }\mu\text{F}$
- $C_4 = 0.047 \text{ }\mu\text{F}$
- $C_5 = 1 \text{ }\mu\text{F}$
- $C_6 = 1 \text{ }\mu\text{F}$
- $C_7 = 33 \text{ }\mu\text{F}$

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.

Troubleshooting log

| Actions / Measurements / Observations (i.e. <i>What I did and/or noticed . . .</i>) | Conclusions (i.e. <i>What this tells me . . .</i>) |
|--|---|
| | |
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file 03933

I do not provide a grading rubric here, but elsewhere.

The idea of a troubleshooting log is three-fold. First, it gets students in the habit of documenting their troubleshooting procedure and thought process. This is a valuable habit to get into, as it translates to more efficient (and easier-followed) troubleshooting on the job. Second, it provides a way to document student steps for the assessment process, making your job as an instructor easier. Third, it reinforces the notion that each and every measurement or action should be followed by reflection (conclusion), making the troubleshooting process more efficient.

Question 57

NAME: _____

Troubleshooting Grading Criteria

You will receive the highest score for which *all* criteria are met.

100 % (*Must meet or exceed all criteria listed*)

- A. Absolutely flawless procedure
- B. No unnecessary actions or measurements taken

90 % (*Must meet or exceed these criteria in addition to all criteria for 85% and below*)

- A. No reversals in procedure (i.e. changing mind without sufficient evidence)
- B. Every single action, measurement, and relevant observation properly documented

80 % (*Must meet or exceed these criteria in addition to all criteria for 75% and below*)

- A. No more than one unnecessary action or measurement
- B. No false conclusions or conceptual errors
- C. No missing conclusions (i.e. at least one documented conclusion for action / measurement / observation)

70 % (*Must meet or exceed these criteria in addition to all criteria for 65%*)

- A. No more than one false conclusion or conceptual error
- B. No more than one conclusion missing (i.e. an action, measurement, or relevant observation without a corresponding conclusion)

65 % (*Must meet or exceed these criteria in addition to all criteria for 60%*)

- A. No more than two false conclusions or conceptual errors
- B. No more than two unnecessary actions or measurements
- C. No more than one undocumented action, measurement, or relevant observation
- D. Proper use of all test equipment

60 % (*Must meet or exceed these criteria*)

- A. Fault accurately identified
- B. Safe procedures used at all times

50 % (*Only applicable where students performed significant development/design work – i.e. not a proven circuit provided with all component values*)

- A. Working prototype circuit built and demonstrated

0 % (*If any of the following conditions are true*)

- A. Unsafe procedure(s) used at any point

file 03932

Answer 57

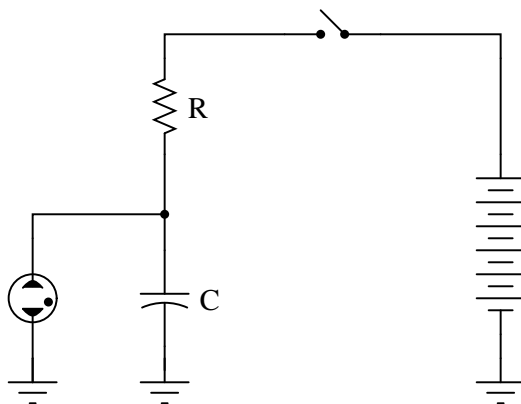
Be sure to document all steps taken and conclusions made in your troubleshooting!

Notes 57

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 58

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



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

For each of these conditions, explain *why* the resulting effects will occur.
[file 03749](#)

Answer 58

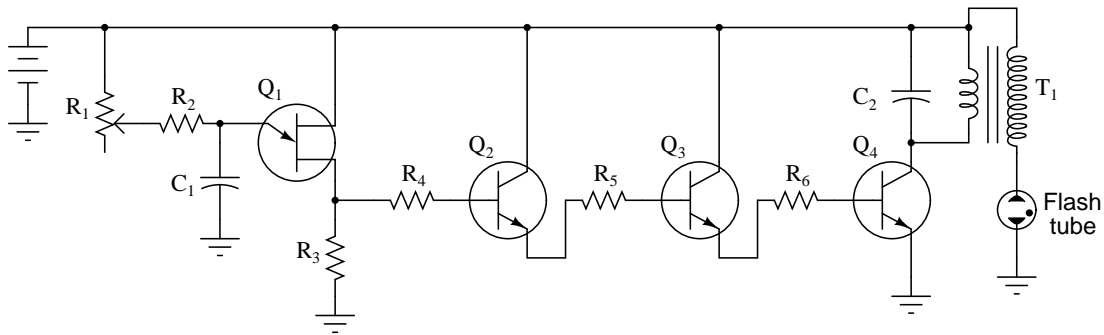
- Capacitor C_1 fails open: *Constant (unblinking) light from the neon bulb.*
- Capacitor C_1 fails shorted: *No light from the bulb at all.*
- Resistor R_1 fails open: *No light from the bulb at all.*
- Solder bridge (short) past resistor R_1 : *Very bright, constant (unblinking) light from the bulb, possible bulb failure resulting from excessive current.*

Notes 58

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 59

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



- Capacitor C_1 fails open:
- Capacitor C_1 fails shorted:
- Resistor R_2 fails open:
- Solder bridge (short) past resistor R_2 :
- Resistor R_4 fails open:
- Transistor Q_4 fails open (collector-to-emitter):
- Capacitor C_2 fails open:
- Capacitor C_2 fails shorted:

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

file 03750

Answer 59

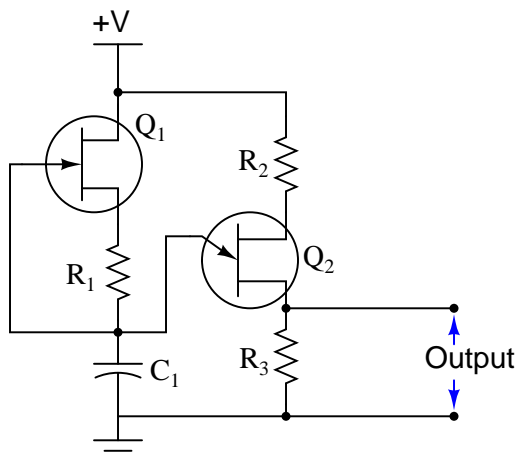
- Capacitor C_1 fails open: *No light from flash tube, possible failure of transformer primary winding and/or transistor Q_4 due to overheating.*
- Capacitor C_1 fails shorted: *No light from flash tube.*
- Resistor R_2 fails open: *No light from flash tube.*
- Solder bridge (short) past resistor R_2 : *Faster strobe rate for any given position of potentiometer R_1 , possibility of adjusting the strobe rate too high where the flash tube just refuses to flash.*
- Resistor R_4 fails open: *No light from flash tube.*
- Transistor Q_4 fails open (collector-to-emitter): *No light from flash tube.*
- Capacitor C_2 fails open: *Possible damage to transistor Q_4 from excessive transient voltages.*
- Capacitor C_2 fails shorted: *No light from flash tube, Q_4 will almost certainly fail due to overheating.*

Notes 59

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 60

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



- Capacitor C_1 fails shorted:
- Resistor R_1 fails open:
- JFET fails shorted (drain-to-source):
- Resistor R_3 fails open:

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

file 03756

Answer 60

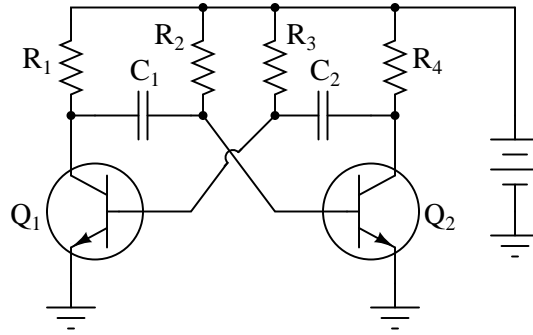
- Capacitor C_1 fails shorted: *No oscillation, low DC voltage output.*
- Resistor R_1 fails open: *No oscillation, low DC voltage output.*
- JFET fails shorted (drain-to-source): *Oscillation waveform looks "rounded" instead of having a straight leading edge, frequency is higher than normal.*
- Resistor R_3 fails open: *No oscillation, high DC voltage output.*

Notes 60

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 61

Predict how the operation of this astable multivibrator circuit will be affected as a result of the following faults. Specifically, identify the final states of the transistors (on or off) resulting from each fault. Consider each fault independently (i.e. one at a time, no multiple faults):



- Capacitor C_1 fails open:
- Capacitor C_2 fails open:
- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Resistor R_3 fails open:
- Resistor R_4 fails open:

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

file 03751

Answer 61

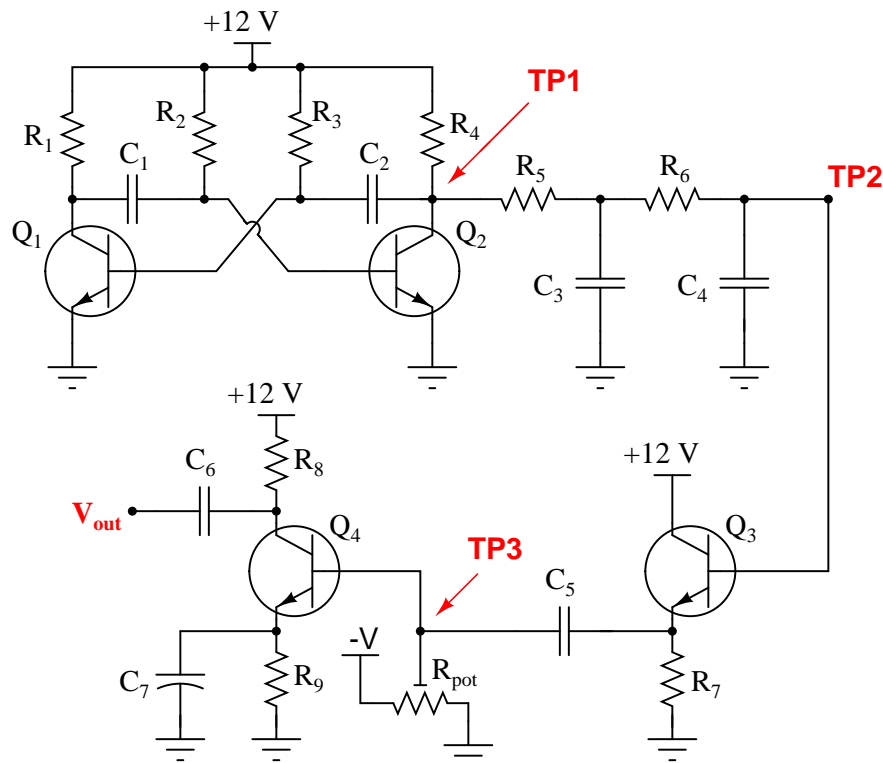
- Capacitor C_1 fails open: Q_2 immediately on, Q_1 on after short time delay.
- Capacitor C_2 fails open: Q_1 immediately on, Q_2 on after short time delay.
- Resistor R_1 fails open: Q_2 on, Q_1 will have base current but no collector current.
- Resistor R_2 fails open: Q_1 on, Q_2 off.
- Resistor R_3 fails open: Q_2 on, Q_1 off.
- Resistor R_4 fails open: Q_1 on, Q_2 will have base current but no collector current.

Notes 61

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 62

Predict how the operation of this astable multivibrator circuit will be affected as a result of the following faults. Specifically, identify the signals found at test points TP1, TP2, TP3, and V_{out} resulting from each fault. Consider each fault independently (i.e. one at a time, no multiple faults):



- Resistor R_4 fails open:
- Resistor R_5 fails open:
- Resistor R_7 fails open:
- Resistor R_9 fails open:
- Capacitor C_7 fails shorted:
- Capacitor C_4 fails shorted:
- Capacitor C_5 fails open:
- Transistor Q_3 fails open (collector-to-emitter):

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

file 03753

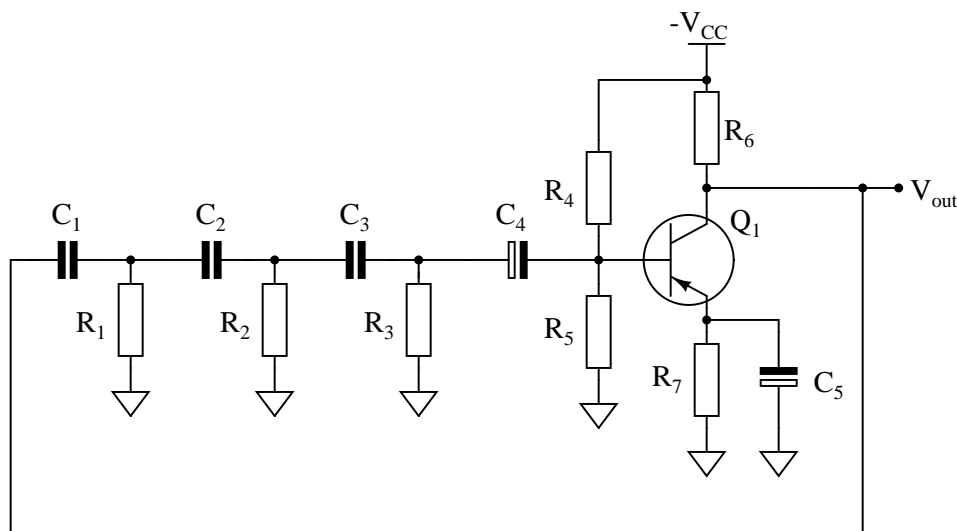
- Resistor R_4 fails open: *Zero volts DC and AC at all four test points except for TP3 where there will be normal DC bias voltage.*
- Resistor R_5 fails open: *Normal signal at TP1, zero volts AC and DC at all other test points except for TP3 where there will be normal DC bias voltage.*
- Resistor R_7 fails open: *Normal signals at TP1 and at TP2, zero volts AC and DC at all other test points except for TP3 where there will be normal DC bias voltage.*
- Resistor R_9 fails open: *Normal signals at TP1, at TP2, and at TP3, but zero volts AC and DC at V_{out} .*
- Capacitor C_7 fails shorted: *Normal AC signals at TP1, at TP2, and at TP3, badly distorted waveform at V_{out} , only about 0.7 volts DC bias at TP3.*
- Capacitor C_4 fails shorted: *Normal signal at TP1, zero volts AC and DC at all other test points except for TP3 where there will be normal DC bias voltage.*
- Capacitor C_5 fails open: *Normal signals at TP1 and at TP2, zero volts AC and DC at all other test points except for TP3 where there will be normal DC bias voltage.*
- Transistor Q_3 fails open (collector-to-emitter): *Normal signals at TP1 and at TP2, zero volts AC and DC at all other test points except for TP3 where there will be normal DC bias voltage.*

Notes 62

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 63

Identify some realistic component failures that would definitely prevent this oscillator circuit from oscillating:



For each of the faults you propose, explain *why* the oscillations will cease.

file 03755

Answer 63

Note: The fault list shown here is not comprehensive.

- Solder bridge shorting across any of the phase-shift resistors (R_1 through R_3).
- Resistor R_4 failing open.
- Transistor Q_1 failing in any mode.

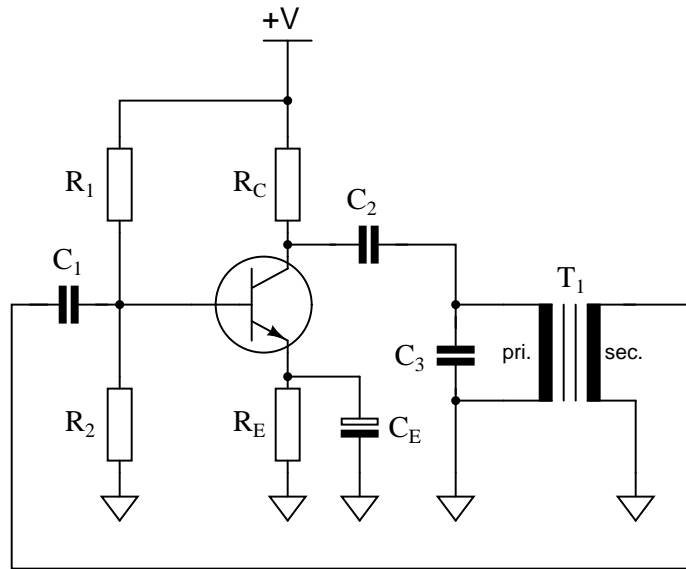
Follow-up question: how would you rank the listed faults in order of probability? In other words, which of these faults do you suppose would be more likely than the others, least likely than the others, etc.?

Notes 63

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of assessing probable faults given very limited information about the circuit's behavior. An important part of troubleshooting is being able to decide what faults are more likely than others, and questions such as this help develop that skill.

Question 64

Suppose some of the turns of wire (but not all) in the primary winding of the transformer were to fail shorted in this Armstrong oscillator circuit:



How would this effective decreasing of the primary winding turns affect the operation of this circuit? What if it were the secondary winding of the transformer to suffer this fault instead of the primary?
[file 03757](#)

Answer 64

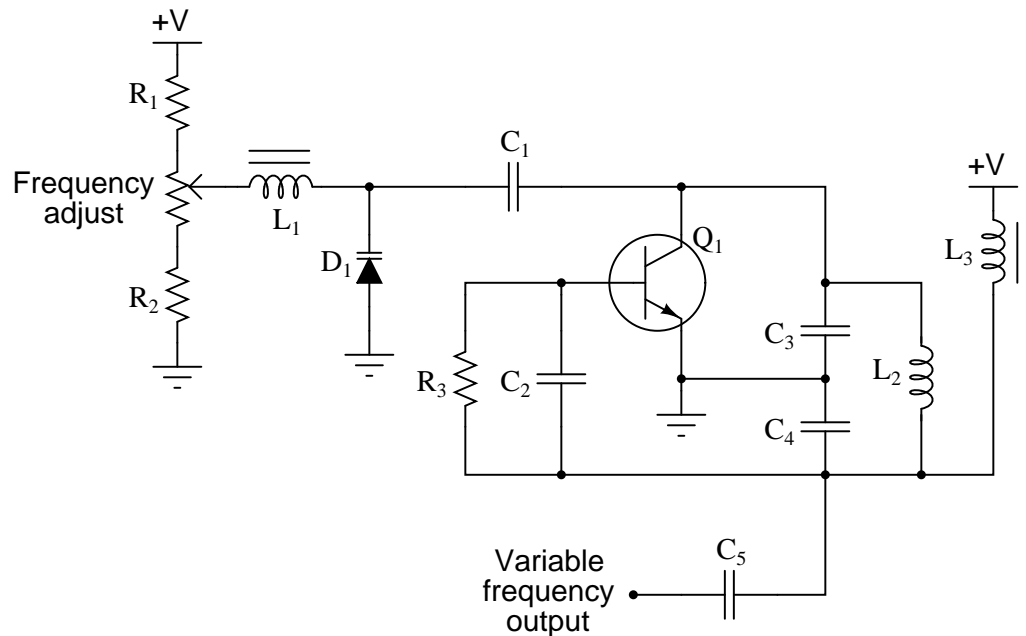
A partially shorted primary winding will result in increased frequency and (possibly) increased distortion in the output signal. A partially shorted secondary winding may result in oscillations ceasing altogether!

Notes 64

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 65

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



- Capacitor C_1 fails open:
- Inductor L_1 fails open:
- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Inductor L_2 fails partially shorted:

For each of these conditions, explain *why* the resulting effects will occur. Note: the voltage-dependent capacitance of a *varactor* diode is given by the following equation:

$$C_j = \frac{C_o}{\sqrt{2V + 1}}$$

Where,

C_j = Junction capacitance

C_o = Junction capacitance with no applied voltage

V = Applied reverse junction voltage

file 03758

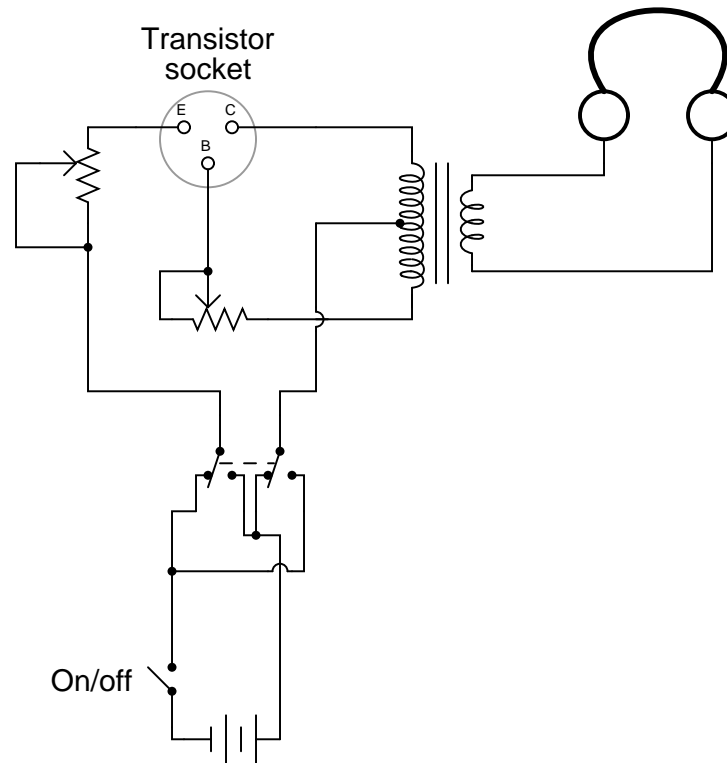
- Capacitor C_1 fails open: *Output frequency increases.*
- Inductor L_1 fails open: *Output frequency decreases.*
- Resistor R_1 fails open: *Output frequency decreases.*
- Resistor R_2 fails open: *Output frequency increases.*
- Inductor L_2 fails partially shorted: *Output frequency increases.*

Notes 65

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 66

A technician is given a transistor testing circuit to repair. This simple circuit is an audio-frequency oscillator, and has the following schematic diagram:



After repairing a broken solder joint, the technician notices that the DPDT switch has lost its label. The purpose of this switch is to allow polarity to be reversed so as to test both PNP and NPN transistor types. However, the label showing which direction is for NPN and which direction is for PNP has fallen off. And, to make matters worse, the schematic diagram does not indicate which position is which.

Determine what the proper DPDT switch label should be for this transistor tester, and explain how you know it is correct. Note: you do not even have to understand how the oscillator circuit works to be able to determine the proper switch label. All you need to know is the proper voltage polarities for NPN and PNP transistor types.

[file 01528](#)

Answer 66

Left is NPN, and right is PNP.

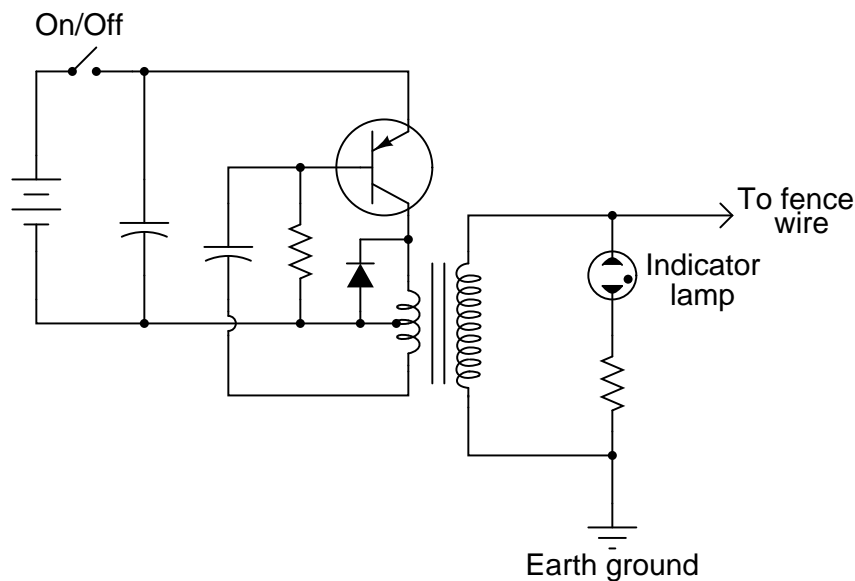
Notes 66

This is a very realistic problem for a technician to solve. Of course, one could determine the proper switch labeling experimentally (by trying a known NPN or PNP transistor and seeing which position makes the oscillator work), but students need to figure this problem out without resorting to trial and error. It is very important that they learn how to properly bias transistors!

Be sure to ask your students to explain *how* they arrived at their conclusion. It is not good enough for them to simply repeat the given answer!

Question 67

This electric fence-charging circuit, which is designed to produce short, high-voltage pulses on its output, has failed. Now, it produces no output voltage at all:



A technician does some troubleshooting and determines that the transistor is defective. She replaces the transistor, and the circuit begins to work again, its rhythmic output pulses indicated by the neon lamp.

But after producing only a few pulses, the circuit stops working. Puzzled, the technician troubleshoots it again and finds that the transistor has failed (again). Both the original and the replacement transistor were of the correct part number for this circuit, so the failure is not due to an incorrect component being used. Something is causing the transistor to fail prematurely. What do you suppose it is?

[file 01189](#)

Answer 67

I strongly suspect a bad diode. Explain why a defective diode would cause the transistor to fail prematurely, and specifically what type of diode failure (open or shorted) would be necessary to cause the transistor to fail in this manner.

Notes 67

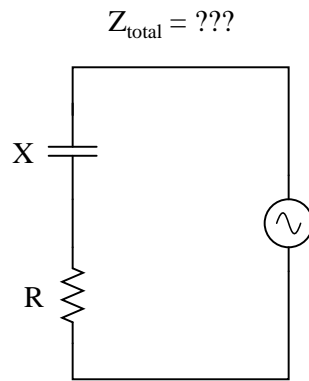
There are many things in this circuit that could prevent it from generating output voltage pulses, but a failed diode (subsequently causing the transistor to fail) is the only problem I can think of which would allow the circuit to briefly function properly after replacing the transistor, and yet fail once more after only a few pulses. Students will likely suggest other possibilities, so be prepared to explore the consequences of each, determining whether or not the suggested failure(s) would account for *all* observed effects.

While your students are giving their reasoning for the diode as a cause of the problem, take some time and analyze the operation of the circuit with them. How does this circuit use positive feedback to support oscillations? How could the output pulse rate be altered? What is the function of each and every component in the circuit?

This circuit provides not only an opportunity to analyze a particular type of amplifier, but it also provides a good review of capacitor, transformer, diode, and transistor theory.

Question 68

Write an equation that solves for the impedance of this series circuit. The equation need not solve for the phase angle between voltage and current, but merely provide a scalar figure for impedance (in ohms):



file 01844

Answer 68

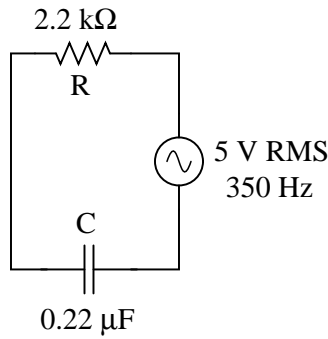
$$Z_{\text{total}} = \sqrt{R^2 + X^2}$$

Notes 68

Ask your students if this equation looks similar to any other mathematical equations they've seen before. If not, square both sides of the equation so it looks like $Z^2 = R^2 + X^2$ and ask them again.

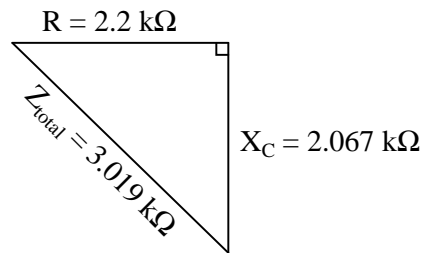
Question 69

Draw a phasor diagram showing the trigonometric relationship between resistance, reactance, and impedance in this series circuit:



Show mathematically how the resistance and reactance combine in series to produce a total impedance (scalar quantities, all). Then, show how to analyze this same circuit using complex numbers: regarding each of the component as having its own impedance, demonstrating mathematically how these impedances add up to comprise the total impedance (in both polar and rectangular forms).

[file 01828](#)

Answer 69**Scalar calculations**

$$R = 2.2\text{ k}\Omega \quad X_C = 2.067\text{ k}\Omega$$

$$Z_{series} = \sqrt{R^2 + X_C^2}$$

$$Z_{series} = \sqrt{2200^2 + 2067^2} = 3019\text{ }\Omega$$

Complex number calculations

$$\mathbf{Z}_R = 2.2\text{ k}\Omega \angle 0^\circ \quad \mathbf{Z}_C = 2.067\text{ k}\Omega \angle -90^\circ \quad (\text{Polar form})$$

$$\mathbf{Z}_R = 2.2\text{ k}\Omega + j0\text{ }\Omega \quad \mathbf{Z}_C = 0\text{ }\Omega - j2.067\text{ k}\Omega \quad (\text{Rectangular form})$$

$$\mathbf{Z}_{series} = \mathbf{Z}_1 + \mathbf{Z}_2 + \cdots \mathbf{Z}_n \quad (\text{General rule of series impedances})$$

$$\mathbf{Z}_{series} = \mathbf{Z}_R + \mathbf{Z}_C \quad (\text{Specific application to this circuit})$$

$$\mathbf{Z}_{series} = 2.2\text{ k}\Omega \angle 0^\circ + 2.067\text{ k}\Omega \angle -90^\circ = 3.019\text{ k}\Omega \angle -43.2^\circ$$

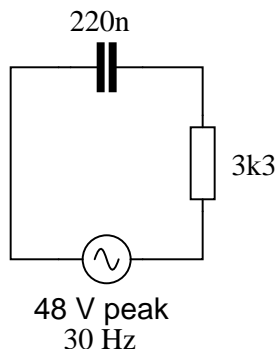
$$\mathbf{Z}_{series} = (2.2\text{ k}\Omega + j0\text{ }\Omega) + (0\text{ }\Omega - j2.067\text{ k}\Omega) = 2.2\text{ k}\Omega - j2.067\text{ k}\Omega$$

I want students to see that there are two different ways of approaching a problem such as this: with *scalar* math and with *complex number* math. If students have access to calculators that can do complex-number arithmetic, the "complex" approach is actually simpler for series-parallel combination circuits, and it yields richer (more informative) results.

Ask your students to determine which of the approaches most resembles DC circuit calculations. Incidentally, this is why I tend to prefer complex-number AC circuit calculations over scalar calculations: because of the conceptual continuity between AC and DC. When you use complex numbers to represent AC voltages, currents, and impedances, almost all the rules of DC circuits still apply. The big exception, of course, is calculations involving *power*.

Question 70

Solve for all voltages and currents in this series RC circuit, and also calculate the phase angle of the total impedance:



file 01849

Answer 70

$$\begin{aligned}V_C &= 47.56 \text{ volts peak} \\V_R &= 6.508 \text{ volts peak} \\I &= 1.972 \text{ milliamps peak} \\\Theta_Z &= -82.21^\circ\end{aligned}$$

Follow-up question: what would we have to do to get these answers in units RMS instead of units "peak"?

Notes 70

Bring to your students' attention the fact that total voltage in this circuit is given in "peak" units rather than RMS, and what effect this has on our answers.

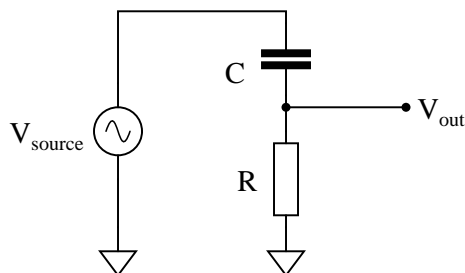
Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them. The following is a sample of a written problem-solving strategy for analyzing a series resistive-reactive AC circuit:

- Step 1:** Calculate all reactances (X).
- Step 2:** Draw an impedance triangle (Z ; R ; X), solving for Z
- Step 3:** Calculate circuit current using Ohm's Law: $I = \frac{V}{Z}$
- Step 4:** Calculate series voltage drops using Ohm's Law: $V = IZ$
- Step 5:** Check work by drawing a voltage triangle (V_{total} ; V_1 ; V_2), solving for V_{total}

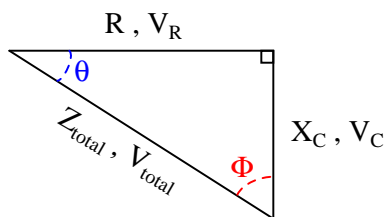
By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 71

A student is asked to calculate the phase shift for the following circuit's output voltage, relative to the phase of the source voltage:



He recognizes this as a series circuit, and therefore realizes that a right triangle would be appropriate for representing component impedances and component voltage drops (because both impedance and voltage are quantities that add in series, and the triangle represents phasor addition):



The problem now is, which angle does the student solve for in order to find the phase shift of V_{out} ? The triangle contains two angles besides the 90° angle, θ and Φ . Which one represents the output phase shift, and more importantly, *why*?

[file 03748](#)

Answer 71

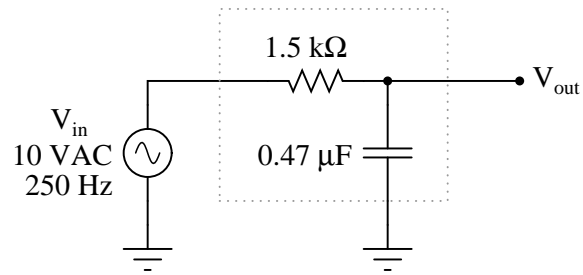
The proper angle in this circuit is θ , and it will be a positive (leading) quantity.

Notes 71

Too many students blindly use impedance and voltage triangles without really understand what they are and why they work. These same students will have no idea how to approach a problem like this. Work with them to help them understand!

Question 72

Calculate the output voltage of this phase-shifting circuit, expressing it in polar form (magnitude and phase angle relative to the source voltage):



file 02620

Answer 72

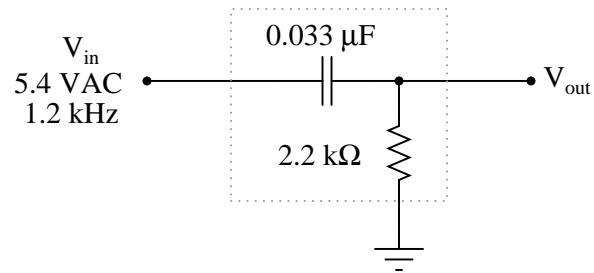
$$V_{out} = 6.7\text{ V} \angle -47.9^\circ$$

Notes 72

This is a very practical application of resistor-capacitor (RC) circuits: to introduce a phase shift to an AC signal. Examples of where a circuit such as this may be used include oscillators (to introduce phase shift into a feedback network for a total phase shift of 360°) and thyristor firing control circuits (phase-shifting the triggering voltage in relation to the source voltage).

Question 73

Calculate the output voltage of this phase-shifting circuit, expressing it in polar form (magnitude and phase angle relative to the source voltage):



file 02621

Answer 73

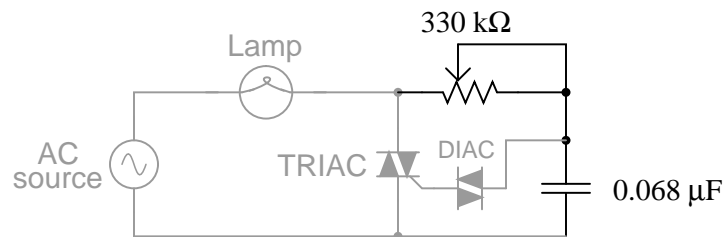
$$V_{out} = 2.593 \text{ V} \angle 61.3^\circ$$

Notes 73

This is a very practical application of resistor-capacitor (RC) circuits: to introduce a phase shift to an AC signal. Examples of where a circuit such as this may be used include oscillators (to introduce phase shift into a feedback network for a total phase shift of 360°) and thyristor firing control circuits (phase-shifting the triggering voltage in relation to the source voltage).

Question 74

In this circuit, a series resistor-capacitor network creates a phase-shifted voltage for the "gate" terminal of a power-control device known as a *TRIAC*. All portions of the circuit except for the RC network are "shaded" for de-emphasis:



Calculate how many degrees of phase shift the capacitor's voltage is, compared to the total voltage across the series RC network, assuming a frequency of 60 Hz, and a 50% potentiometer setting.

[file 00637](#)

Answer 74

$$E_C \text{ phase shift} = -76.7^\circ$$

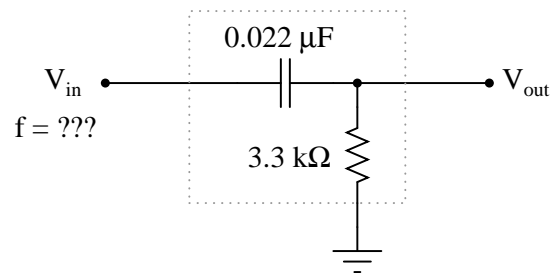
Challenge question: what effect will a change in potentiometer setting have on this phase angle? Specifically, will increasing the resistance make the phase shift approach -90° or approach 0° ?

Notes 74

In this question, I purposely omitted any reference to voltage levels, so the students would have to set up part of the problem themselves. The goal here is to build problem-solving skills.

Question 75

Determine the input frequency necessary to give the output voltage a phase shift of 70° :



file 02623

Answer 75

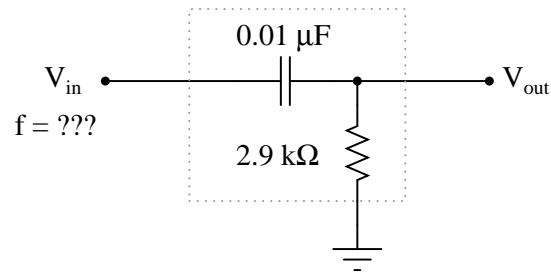
$$f = 798 \text{ Hz}$$

Notes 75

Phase-shifting circuits are very useful, and important to understand. They are particularly important in some types of oscillator circuits, which rely on RC networks such as this to provide certain phase shifts to sustain oscillation.

Question 76

Determine the input frequency necessary to give the output voltage a phase shift of 40° :



file 02622

Answer 76

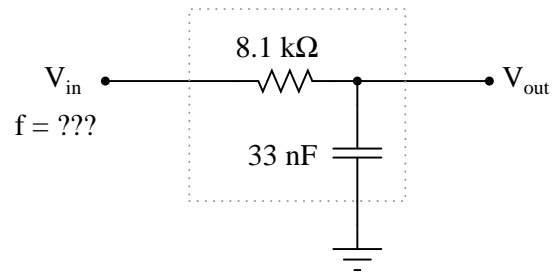
$$f = 6.54 \text{ kHz}$$

Notes 76

Phase-shifting circuits are very useful, and important to understand. They are particularly important in some types of oscillator circuits, which rely on RC networks such as this to provide certain phase shifts to sustain oscillation.

Question 77

Determine the input frequency necessary to give the output voltage a phase shift of -38° :



file 02626

Answer 77

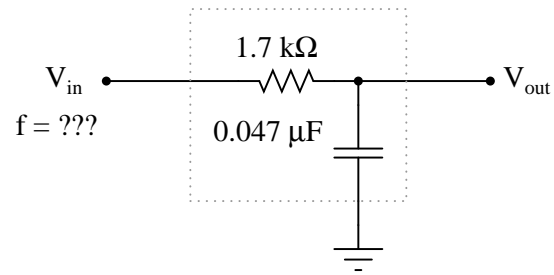
$$f = 465\text{ Hz}$$

Notes 77

Phase-shifting circuits are very useful, and important to understand. They are particularly important in some types of oscillator circuits, which rely on RC networks such as this to provide certain phase shifts to sustain oscillation.

Question 78

Determine the input frequency necessary to give the output voltage a phase shift of -25° :



file 02625

Answer 78

$$f = 929\text{ Hz}$$

Notes 78

Phase-shifting circuits are very useful, and important to understand. They are particularly important in some types of oscillator circuits, which rely on RC networks such as this to provide certain phase shifts to sustain oscillation.

Question 79

Spring- and weight-driven clock mechanisms always use a *pendulum* as an integral part of their workings. What function does a pendulum serve in a clock? What would a mechanical clock mechanism do if the pendulum were removed?

Describe what the electrical equivalent of a mechanical pendulum is, and what purpose it might serve in an oscillator circuit.

file 01076

Answer 79

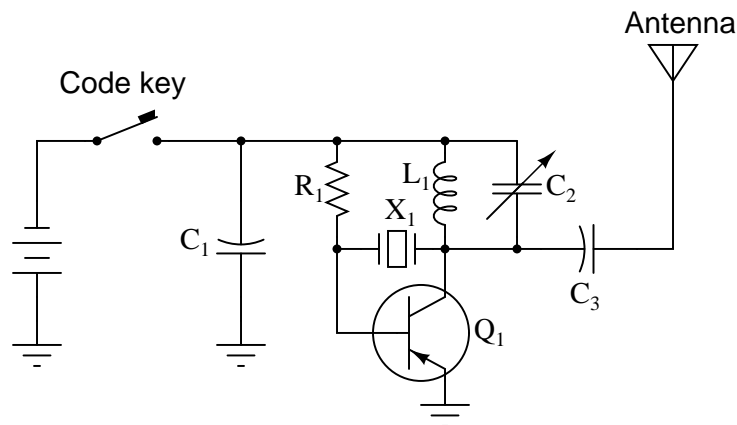
The pendulum in a mechanical clock serves to regulate the frequency of the clock's ticking. The electrical equivalent of a pendulum is a *tank circuit*.

Notes 79

Ask your students to brainstorm possible applications for electrical oscillator circuits, and why frequency regulation might be an important feature.

Question 80

Two technicians are arguing over the function of a component in this oscillator circuit. Capacitor C_1 has failed, and they are debating over the proper value of its replacement.



One technician argues that the value of capacitor C_1 helps set the oscillation frequency of the circuit, and that the value of the replacement capacitor therefore must be precisely matched to the value of the original. The other technician thinks its value is not critical at all, arguing that all it does is help to provide a stable DC power supply voltage. What do you think?

Also, describe the purpose of this circuit: what is it?

[file 01486](#)

Answer 80

This circuit is a simple "CW" radio transmitter, used to broadcast information using Morse code.

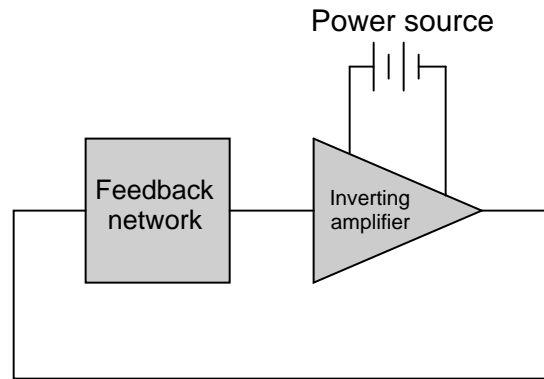
The second technician is closer to the truth than the first, with regard to the capacitor. C_1 is not part of the oscillator's resonant network, and so does not set the oscillation frequency. However, if the replacement capacitor's value is too far from the original's value, this circuit will not start and stop oscillating as "crisply" as it did before, when the code key switch is repeatedly actuated.

Notes 80

Ask your students how they can tell that C_1 is not part of the oscillator's resonant network.

Question 81

How many degrees of phase shift must the feedback circuit (the square box in this schematic) introduce to the signal in order for this inverting amplifier circuit to oscillate?



file 02669

Answer 81

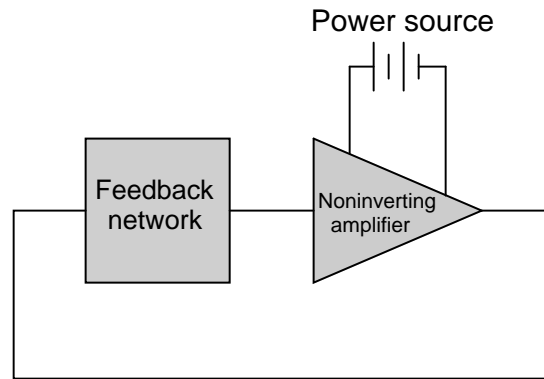
The feedback network in this circuit must provide 180 degrees of phase shift, in order to sustain oscillations.

Notes 81

Ask your students to explain why the feedback network must provide 180 degrees of phase shift to the signal. Ask them to explain how this requirement relates to the need for *regenerative* feedback in an oscillator circuit.

Question 82

How many degrees of phase shift must the feedback circuit (the square box in this schematic) introduce to the signal in order for this noninverting amplifier circuit to oscillate?



file 02670

Answer 82

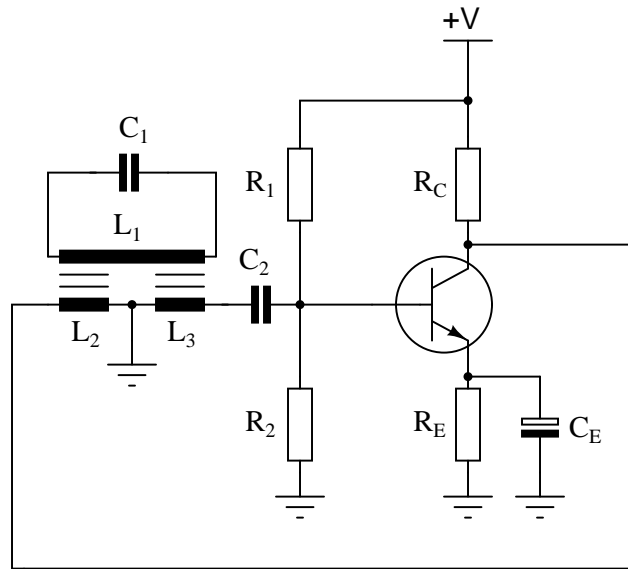
The feedback network in this circuit must provide 360 degrees of phase shift, in order to sustain oscillations.

Notes 82

Ask your students to explain why the feedback network must provide 180 degrees of phase shift to the signal. Ask them to explain how this requirement relates to the need for *regenerative* feedback in an oscillator circuit.

Question 83

Identify the type of oscillator circuit shown in this schematic diagram, and explain the purpose of the tank circuit (L_1 and C_1):



Also, write the equation describing the operating frequency of this type of oscillator circuit.
[file 02632](#)

Answer 83

This is a *Meissner* oscillator circuit, and the tank circuit establishes its frequency of operation.

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

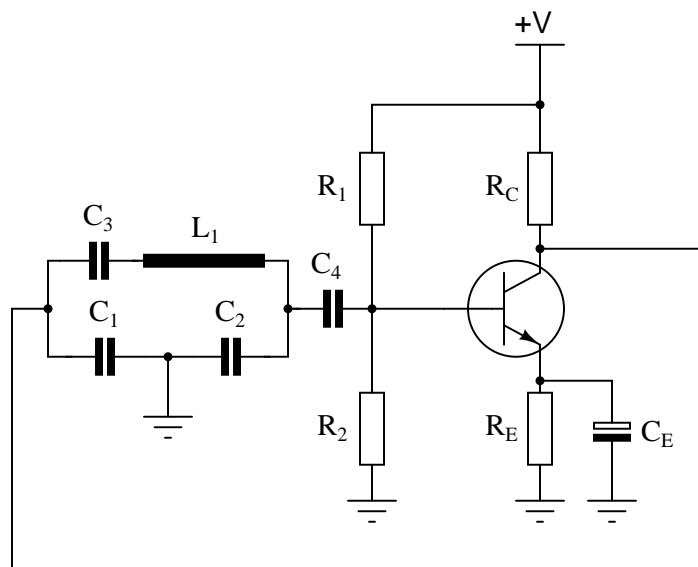
Notes 83

Ask your students to describe the amount of phase shift the tank circuit provides to the feedback signal. Also, ask them to explain how the oscillator circuit's natural frequency may be altered.

This circuit is unusual, as inductors L_2 and L_3 are not coupled to each other, but each is coupled to tank circuit inductor L_1 .

Question 84

Identify the type of oscillator circuit shown in this schematic diagram:



Also, write the equation describing the operating frequency of this type of oscillator circuit.
[file 02634](#)

Answer 84

This is a *Clapp* oscillator circuit, and the tank circuit establishes its frequency of operation.

$$f = \frac{1}{2\pi\sqrt{L_1\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)}}$$

Follow-up question: you may notice that the Clapp oscillator is just a variation of the Colpitts oscillator design. If C_3 is much smaller than either C_1 or C_2 , the frequency stability of the oscillator circuit will be relatively unchanged by variations in parasitic capacitance throughout the circuit (especially transistor junction "Miller effect" capacitances). Explain why, and how the following equation provides an approximation of operating frequency under these conditions:

$$f \approx \frac{1}{2\pi\sqrt{L_1 C_3}}$$

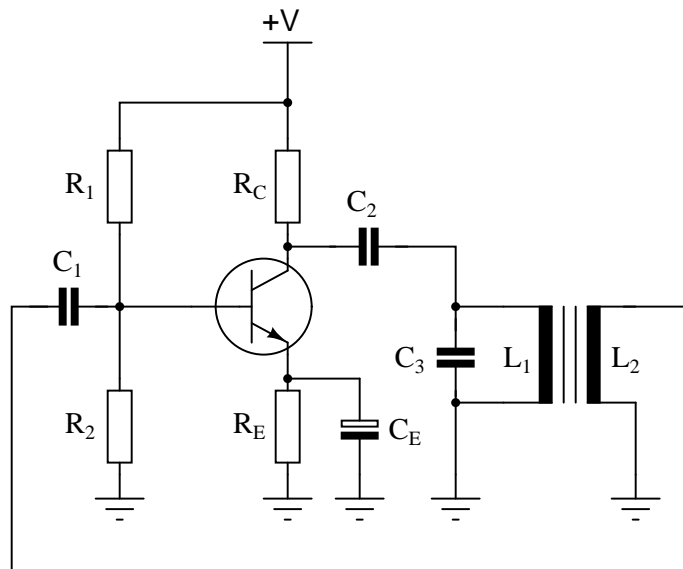
Notes 84

Ask your students to describe the amount of phase shift the tank circuit provides to the feedback signal. Also, ask them to explain how the oscillator circuit's natural frequency may be altered.

The only "trick" to figuring out the answer here is successfully identifying which capacitors are part of the tank circuit and which are not. Remind your students if necessary that tank circuits require direct (galvanic) connections between inductance and capacitance to oscillate – components isolated by an amplifier stage or a significant resistance cannot be part of a proper tank circuit. The identity of the constituent components may be determined by tracing the path of oscillating current between inductance(s) and capacitance(s).

Question 85

Identify the type of oscillator circuit shown in this schematic diagram, and draw the transformer phasing dots in the right places to ensure regenerative feedback:

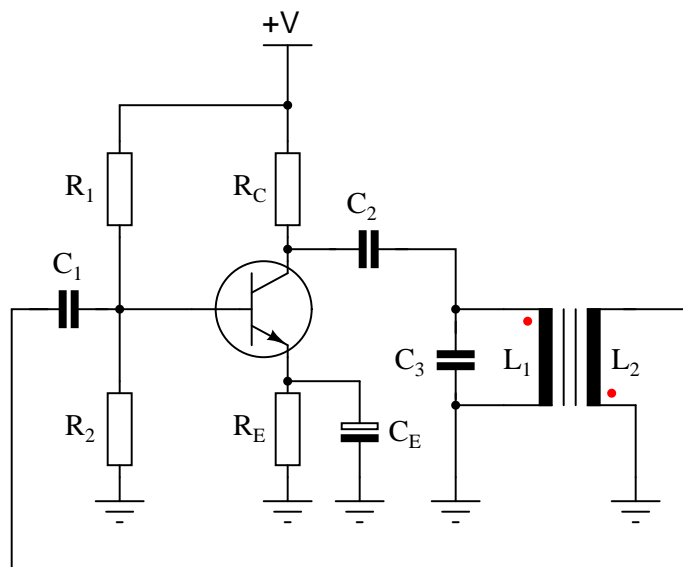


Also, write the equation describing the operating frequency of this type of oscillator circuit.
[file 02633](#)

Answer 85

This is an *Armstrong* oscillator circuit, and the combination of capacitor C_3 and primary transformer winding inductance L_1 establishes its frequency of operation.

$$f = \frac{1}{2\pi\sqrt{L_1 C_3}}$$



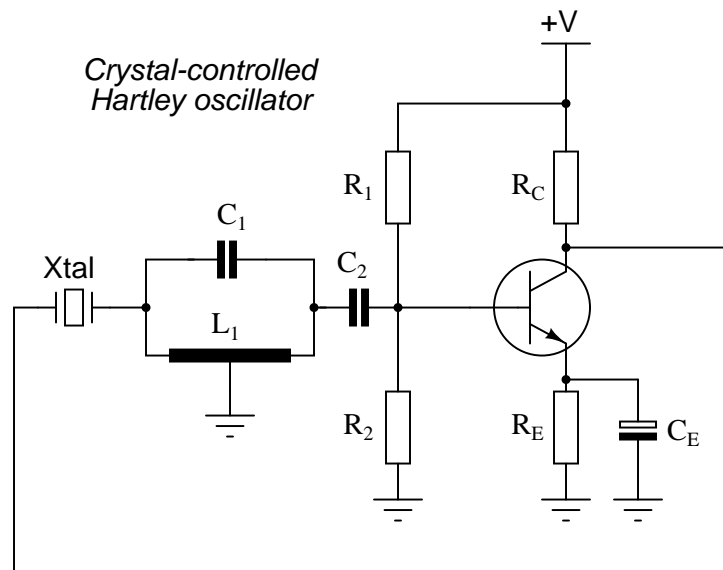
Ask your students to describe the amount of phase shift the transformer-based tank circuit provides to the feedback signal. Having them place phasing dots near the transformer windings is a great review of this topic, and a practical context for winding "polarity". Also, ask them to explain how the oscillator circuit's natural frequency may be altered.

Question 86

Modify the schematic diagram for a Hartley oscillator to include a *crystal*. What advantage(s) does a crystal-controlled Hartley oscillator exhibit over a regular Hartley oscillator?

file 01084

Answer 86



Follow-up question: does the resonant frequency of the tank circuit have to match the crystal's resonant frequency? Why or why not?

Notes 86

Ask your students to explain what purpose a crystal serves in an oscillator circuit that already contains a tank circuit for tuning.

Question 87

How does the *quality factor* (Q) of a typical quartz crystal compare to that of a regular LC tank circuit, and what does this indicate about the frequency stability of crystal-controlled oscillators?

file 02635

Answer 87

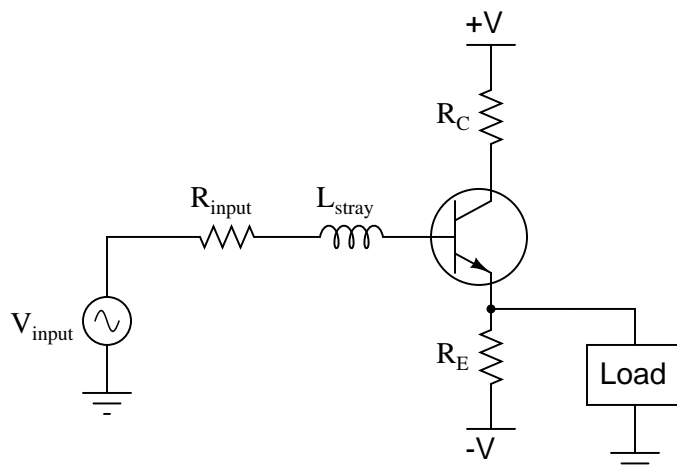
Q values of several *thousand* are commonplace with crystals, while Q values in excess of 10 are considered good for LC tank circuits!

Notes 87

Note that I did not answer the frequency stability question, but left that for the students to figure out.

Question 88

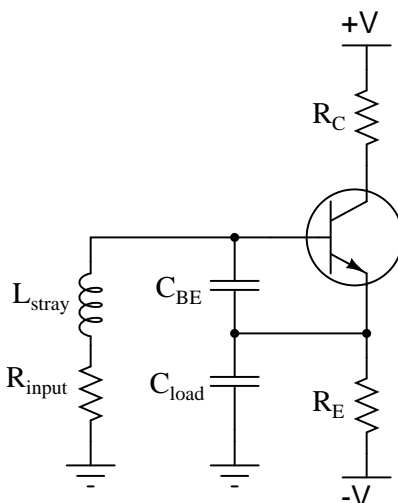
Under certain conditions (especially with certain types of loads) it is possible for a simple one-transistor voltage amplifier circuit to oscillate:



Explain how this is possible. What parasitic effects could possibly turn an amplifier into an oscillator?
[file 01085](#)

Answer 88

Here is a re-drawn representation of the amplifier circuit, with the base-emitter capacitance shown:



Follow-up question: what type of oscillator circuit does this resemble?

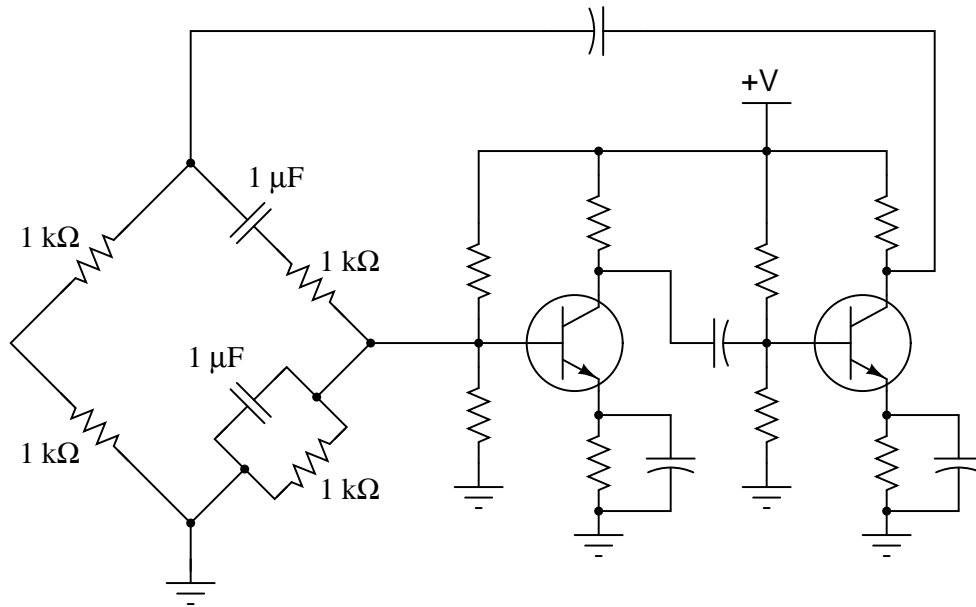
Challenge question: what type(s) of load would tend to make this circuit oscillate more readily than others?

Notes 88

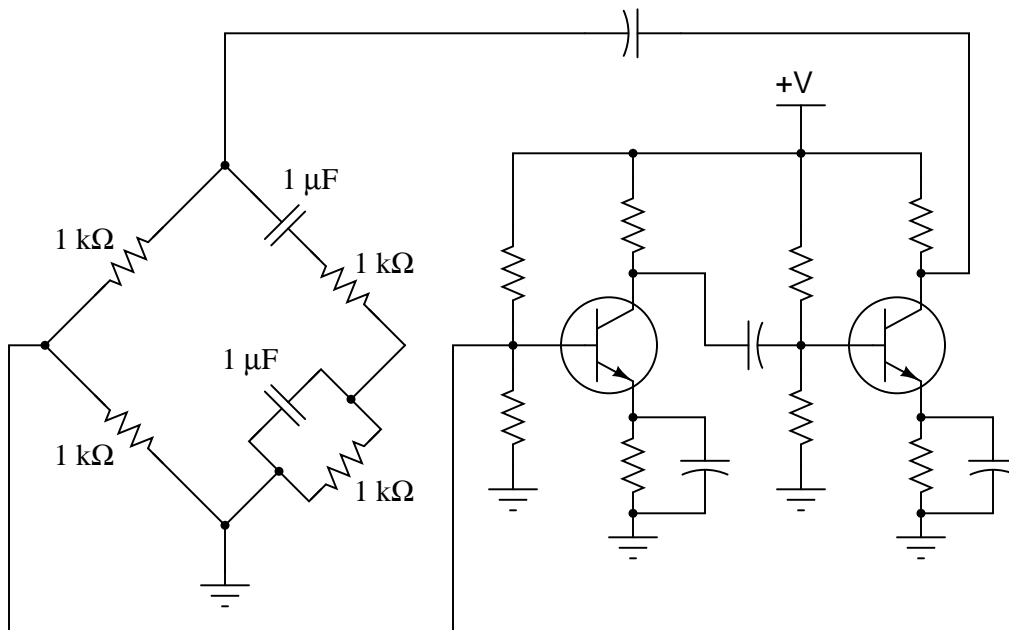
This question reinforces a very important lesson in electronic circuit design: parasitic effects may produce some *very* unexpected consequences! Just because you didn't intend for your amplifier circuit to oscillate does not mean that it won't.

Question 89

Calculate the operating frequency of this oscillator circuit:



Explain why the operating frequency will not be the same if the transistor receives its feedback signal from the other side of the bridge, like this:



file 01214

Answer 89

$$f = 159.155 \text{ Hz}$$

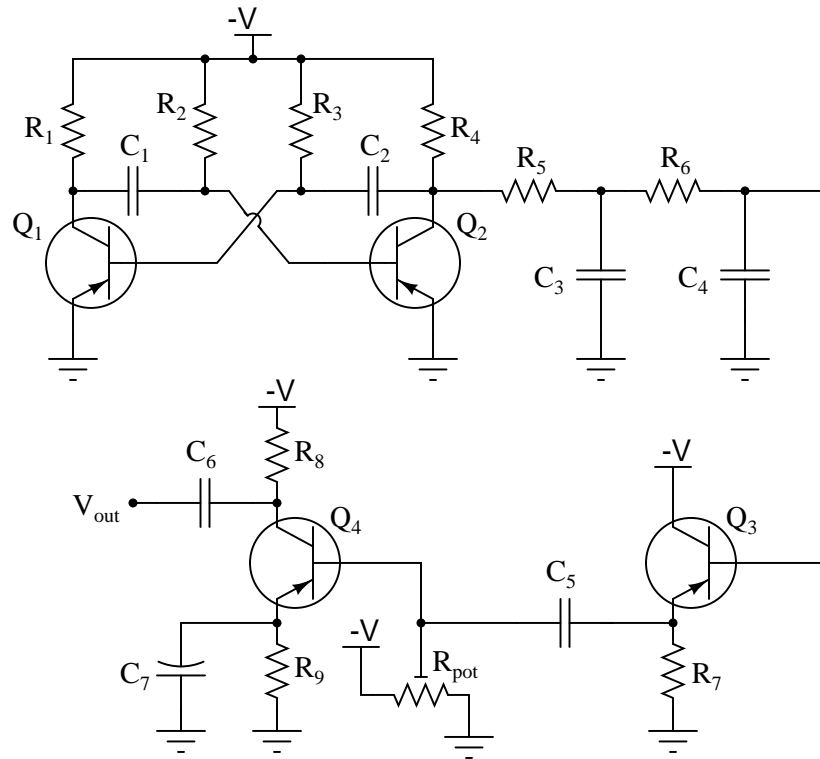
If the feedback signal comes from the other side of the bridge, the feedback signal's phase shift will be determined by a different set of components (primarily, the coupling capacitors and bias network resistances) rather than the reactive arms of the bridge.

Notes 89

Given the phase shift requirements of a two-stage oscillator circuit such as this, some students may wonder why the circuit won't act the same in the second configuration. If such confusion exists, clarify the concept with a question: "What is the phase relationship between input and output voltages for the bridge in these two configurations, over a wide range of frequencies?" From this observation, your students should be able to tell that only one of these configurations will be stable at 159.155 Hz.

Question 90

This circuit generates quasi-sine waves at its output. It does so by first generating square waves, integrating those square waves (twice) with respect to time, then amplifying the double-integrated signal:



Identify the sections of this circuit performing the following functions:

- Square wave oscillator:
- First integrator stage:
- Second integrator stage:
- Buffer stage (current amplification):
- Final gain stage (voltage amplification):

[file 03752](#)

Answer 90

- Square wave oscillator: R_1 through R_4 , C_1 and C_2 , Q_1 and Q_2
- First integrator stage: R_5 and C_3
- Second integrator stage: R_6 and C_4
- Buffer stage (current amplification): Q_3 and R_7
- Final gain stage (voltage amplification): R_8 and R_9 , R_{pot} , Q_4 , and C_7

Notes 90

The purpose of this question is to have students identify familiar sub-circuits within a larger, practical circuit. This is a very important skill for troubleshooting, as it allows technicians to divide a malfunctioning system into easier-to-understand sections.

Question 91

What is a *harmonic* frequency? If a particular electronic system (such as an AC power system) has a fundamental frequency of 60 Hz, calculate the frequencies of the following harmonics:

- 1st harmonic =
- 2nd harmonic =
- 3rd harmonic =
- 4th harmonic =
- 5th harmonic =
- 6th harmonic =

file 01890

Answer 91

- 1st harmonic = 60 Hz
- 2nd harmonic = 120 Hz
- 3rd harmonic = 180 Hz
- 4th harmonic = 240 Hz
- 5th harmonic = 300 Hz
- 6th harmonic = 360 Hz

Notes 91

Ask your students to determine the mathematical relationship between harmonic number, harmonic frequency, and fundamental frequency. It isn't difficult to figure out!

Question 92

An *octave* is a type of harmonic frequency. Suppose an electronic circuit operates at a fundamental frequency of 1 kHz. Calculate the frequencies of the following octaves:

- 1 octave greater than the fundamental =
- 2 octaves greater than the fundamental =
- 3 octaves greater than the fundamental =
- 4 octaves greater than the fundamental =
- 5 octaves greater than the fundamental =
- 6 octaves greater than the fundamental =

file 01891

Answer 92

- 1 octave greater than the fundamental = 2 kHz
 - 2 octaves greater than the fundamental = 4 kHz
 - 3 octaves greater than the fundamental = 8 kHz
 - 4 octaves greater than the fundamental = 16 kHz
 - 5 octaves greater than the fundamental = 32 kHz
 - 6 octaves greater than the fundamental = 64 kHz
-

Notes 92

Ask your students if they can determine the mathematical relationship between octave number, octave frequency, and fundamental frequency. This is a bit more difficult to do than for integer harmonics, but not beyond reason if students are familiar with exponents.

Clarify for your students the fact that "octave" is not just a musical term. In electronic circuit analysis (especially filter circuits), the word "octave" is often used to represent multiples of a given frequency, usually in reference to a bandwidth (i.e. "This filter's passband response is essentially flat over two octaves!").

Question 93

The Fourier series for a square wave is as follows:

$$v_{square} = \frac{4}{\pi} V_m \left(\sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t + \frac{1}{7} \sin 7\omega t + \cdots + \frac{1}{n} \sin n\omega t \right)$$

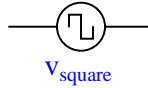
Where,

V_m = Peak amplitude of square wave

ω = Angular velocity of square wave (equal to $2\pi f$, where f is the fundamental frequency)

n = An odd integer

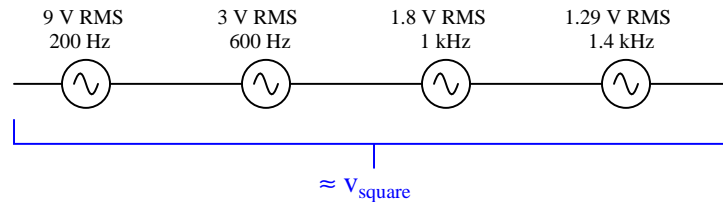
Electrically, we might represent a square-wave voltage source as a circle with a square-wave symbol inside, like this:



Knowing the Fourier series of this voltage, however, allows us to represent the same voltage source as a set of series-connected voltage sources, each with its own (sinusoidal) frequency. Draw the equivalent schematic for a 10 volt (peak), 200 Hz square-wave source in this manner showing only the first four harmonics, labeling each sinusoidal voltage source with its own RMS voltage value and frequency:

Hint: $\omega = 2\pi f$

[file 02260](#)

Answer 93

Notes 93

To be honest, the four-harmonic equivalent circuit is a rather poor approximation for a square wave. The real purpose of this question, though, is to have students relate the sinusoidal terms of a common Fourier series (for a square wave) to a schematic diagram, translating between angular velocity and frequency, peak values and RMS values.

Please note that the voltage magnitudes shown in the answer are *RMS* and not peak! If you were to calculate peak sinusoid source values, you would obtain these results:

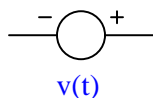
- 1st harmonic: $\frac{40}{\pi}$ volts peak = 12.73 volts peak
- 3rd harmonic: $\frac{40}{3\pi}$ volts peak = 4.244 volts peak
- 5th harmonic: $\frac{40}{5\pi}$ volts peak = 2.546 volts peak
- 7th harmonic: $\frac{40}{7\pi}$ volts peak = 1.819 volts peak

Question 94

Suppose a non-sinusoidal voltage source is represented by the following Fourier series:

$$v(t) = 23.2 + 30 \sin(377t) + 15.5 \sin(1131t + 90) + 2.7 \sin(1508t - 40)$$

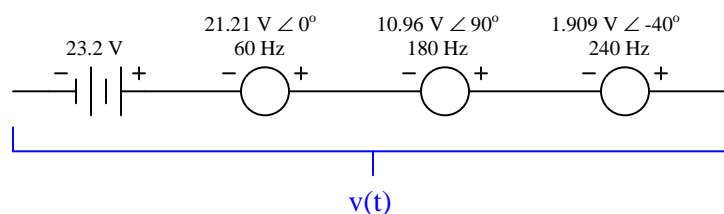
Electrically, we might represent this non-sinusoidal voltage source as a circle, like this:



Knowing the Fourier series of this voltage, however, allows us to represent the same voltage source as a set of series-connected voltage sources, each with its own (sinusoidal) frequency. Draw the equivalent schematic in this manner, labeling each voltage source with its RMS voltage value, frequency (in Hz), and phase angle:

Hint: $\omega = 2\pi f$

[file 02259](#)

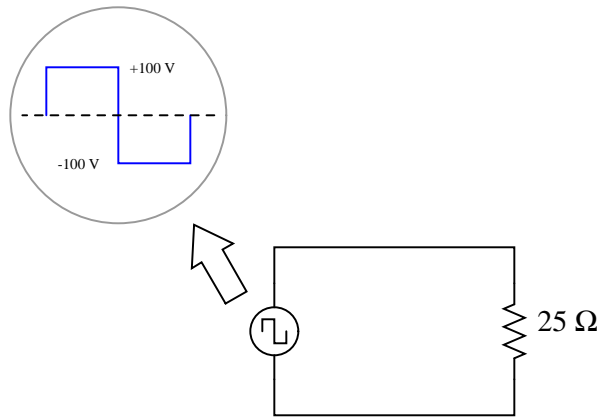
Answer 94

Notes 94

The purpose of this question is to have students relate the sinusoidal terms of a particular Fourier series to a schematic diagram, translating between angular velocity and frequency, peak values and RMS values.

Question 95

Calculate the power dissipated by a $25\ \Omega$ resistor, when powered by a square-wave with a symmetrical amplitude of 100 volts and a frequency of 2 kHz:



file 00651

Answer 95

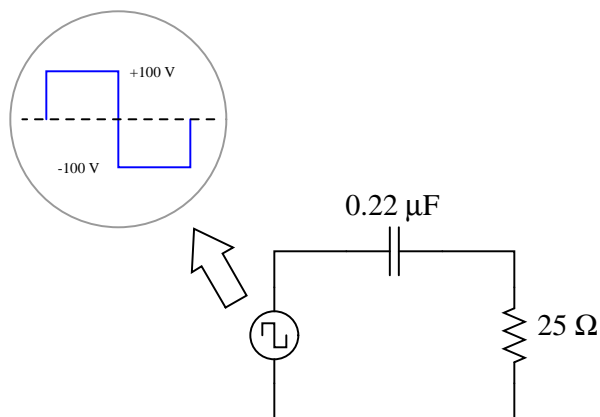
$$P_R = 400 \text{ watts}$$

Notes 95

To calculate this power figure, students have to determine the RMS value of the square wave. Thankfully, this is not difficult.

Question 96

Calculate the power dissipated by a $25\ \Omega$ resistor, when powered by a square-wave with a symmetrical amplitude of 100 volts and a frequency of 2 kHz, through a $0.22\ \mu\text{F}$ capacitor:



No, I'm not asking you to calculate an infinite number of terms in the Fourier series – that would be cruel and unusual. Just calculate the power dissipated in the resistor by the 1st, 3rd, 5th, and 7th harmonics only.

[file 00652](#)

Answer 96

$$P_{R(1st)} = 1.541\ \text{watts}$$

$$P_{R(3rd)} = 1.485\ \text{watts}$$

$$P_{R(5th)} = 1.384\ \text{watts}$$

$$P_{R(7th)} = 1.255\ \text{watts}$$

$$P_{R(1+3+5+7)} = 5.665\ \text{watts}$$

Notes 96

To calculate this power figure, students have to research the Fourier series for a square wave. Many textbooks use square waves to introduce the subject of Fourier series, so this should not be difficult for students to find.

Ask your students how the real power dissipated by this resistor compares with the final figure of 5.665 watts. Is the real power dissipation more, less, or equal to this figure? If not equal, what would we have to do to arrive at a more precise figure?

Question 97

Ideally, a sinusoidal oscillator will output a signal consisting of a single (fundamental) frequency, with no harmonics. Realistically, though, sine-wave oscillators always exhibit some degree of distortion, and are therefore never completely harmonic-free.

Describe what the display of a spectrum analyzer would look like when connected to the output of a *perfect* sinusoidal oscillator. Then, describe what the same instrument's display would look like if the oscillator exhibited substantial distortion.

file 02258

Answer 97

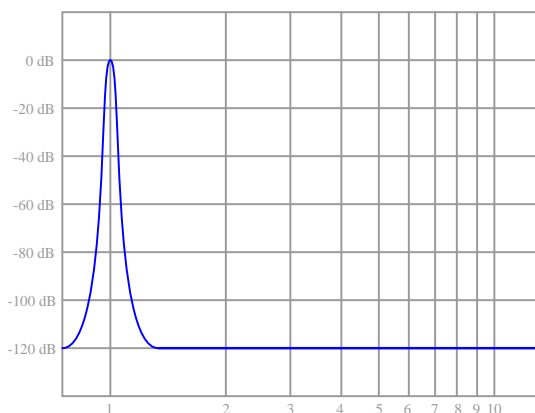
I'll let you figure out the answer to this question on your own.

Notes 97

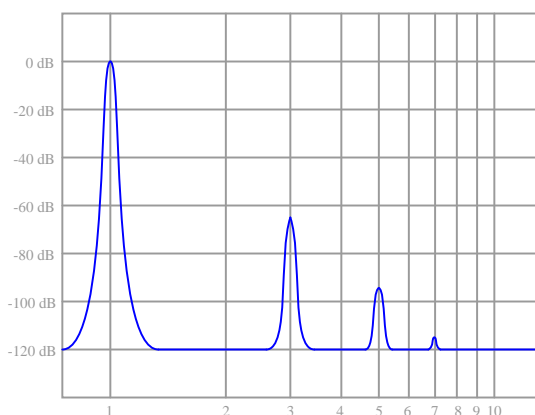
The purpose of this question is to get students to think about how a spectrum analyzer would be used in a practical scenario, and what the spectrum would look like for a couple of different scenarios. Really, it focuses more on the harmonic analysis instrument (the spectrum analyzer) more than the oscillator circuit.

Question 98

An electronics technician connects the input of a spectrum analyzer to the secondary winding of an AC power transformer, plugged into a power receptacle. He sets the spectrum analyzer to show 60 Hz as the fundamental frequency, expecting to see the following display:



Instead, however, the spectrum analyzer shows more than just a single peak at the fundamental:



Explain what this pattern means, in practical terms. Why is this power system's harmonic signature different from what the technician expected to see?

[file 03695](#)

Answer 98

What this pattern means is the power-line voltage waveform is distorted from what should be a perfect sine-wave shape.

Notes 98

Note to your students that this is quite typical for modern power systems, due to the prevalence of switching power supply circuits and other "non-linear" electrical loads. The presence of harmonic frequencies in significant quantity can cause severe problems for power systems, including transformer overheating, motor overheating, overloaded neutral conductors (especially in three-phase, four-wire "Wye" systems), and excessive currents through power-factor correction capacitors.

Question 99

Ideally, an amplifier circuit increases the amplitude of a signal without altering the signal's wave-shape in the least. Realistically, though, amplifiers always exhibit some degree of distortion.

Describe how harmonic analysis – either with a spectrum analyzer or some other piece of test equipment capable of measuring harmonics in a signal – is used to quantify the distortion of an amplifier circuit.

file 02257

Answer 99

A pure sine wave is input to the amplifier under test, and a spectrum analyzer is connected to the amplifier's output.

Notes 99

The answer given is purposefully vague. All I did is describe what gets connected to the amplifier, not how to interpret the measurements. Ask your students to explain *why* a pure sine wave is chosen as the test signal, and what sort of response would be considered ideal to see on the spectrum analyzer.

Question 100

Under certain conditions, harmonics may be produced in AC power systems by inductors and transformers. How is this possible, as these devices are normally considered to be linear?

[file 00655](#)

Answer 100

I'll answer this question with another question: is the "B-H" plot for a ferromagnetic material typically linear or nonlinear? This is the key to understanding how an electromagnetic device can produce harmonics from a "pure" sinusoidal power source.

Notes 100

Ask your students what it means for an electrical or electronic device to be "linear." How many devices qualify as linear? And of those devices, are they *always* linear, or are they capable of nonlinear behavior under special conditions?

Use the discussion time to review B-H curves for ferromagnetic materials with your students, asking them to draw the curves and point out where along those curves inductors and transformers normally operate. What conditions, specifically, would make an iron-core device act nonlinearly?

On a similar note, the (slightly) nonlinear nature of ferromagnetic core transformers is known to permit signals to *modulate* each other in certain audio amplifier designs, to produce a specific kind of audio signal distortion known as *intermodulation distortion*. Normally, modulation is a function possible only in nonlinear systems, so the fact that modulation occurs in a transformer is proof positive of (at least some degree of) nonlinearity.

Question 101

Identify some ways in which harmonics may be mitigated in AC power systems, since they tend to cause trouble for a variety of electrical components.

file 02261

Answer 101

Filter circuits may be employed to block harmonic frequencies from reaching certain sensitive components.

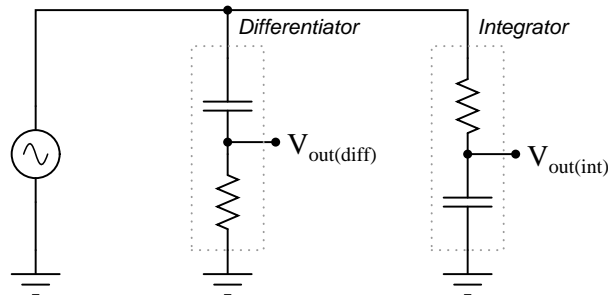
Notes 101

The answer given here is correct, but vague. I did not specify the type of filter or exactly how it might be connected to a load. These are questions to ask your students during discussion.

Question 102

$\int f(x) dx$ *Calculus alert!*

If both these circuits are energized by an AC sine-wave source providing a perfectly undistorted signal, the resulting output waveforms will differ in phase and possibly in amplitude, but not in shape:



If, however, the excitation voltage is slightly distorted, one of the outputs will be more sinusoidal than the other. Explain whether it is the differentiator or the integrator that produces the signal most resembling a pure sine wave, and why.

Hint: I recommend building this circuit and powering it with a triangle wave, to simulate a mildly distorted sine wave.

[file 01600](#)

Answer 102

The *differentiator* circuit will output a much more distorted waveshape, because differentiation magnifies harmonics:

$$\frac{d}{dt}(\sin t) = \cos t$$

$$\frac{d}{dt}(\sin 2t) = 2 \cos 2t$$

$$\frac{d}{dt}(\sin 3t) = 3 \cos 3t$$

$$\frac{d}{dt}(\sin 4t) = 4 \cos 4t$$

...

$$\frac{d}{dt}(\sin nt) = n \cos nt$$

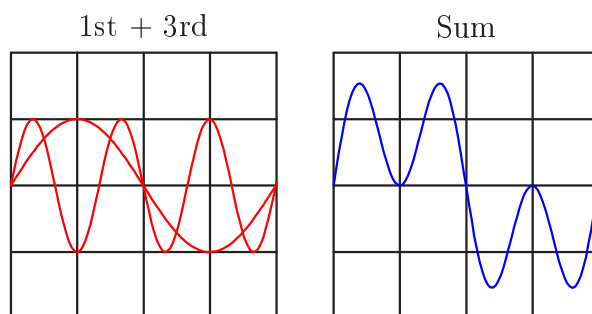
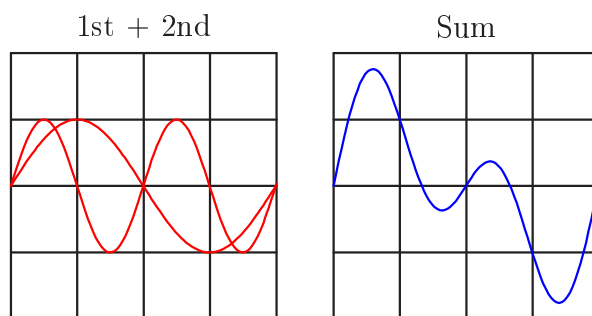
Notes 102

As an interesting footnote, this is precisely why differentiation is rarely performed on real-world signals. Since the frequency of noise often exceeds the frequency of the signal, differentiating a "noisy" signal will only lead to a decreased signal-to-noise ratio.

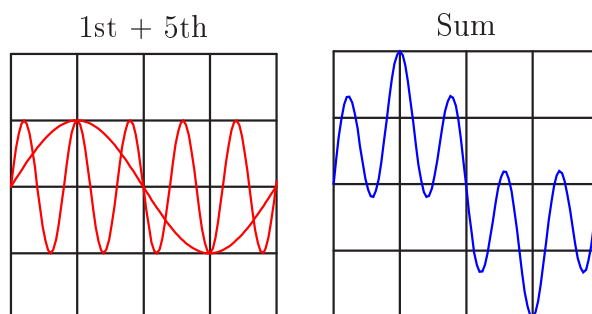
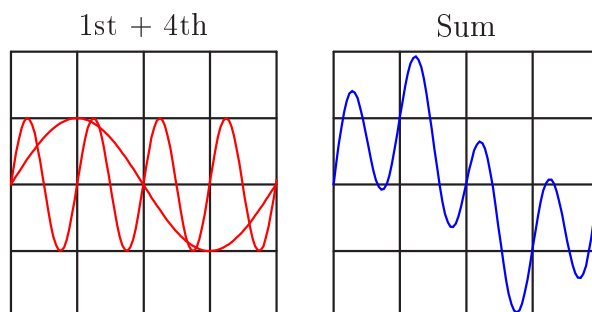
For a practical example of this, tell your students about vibration measurement, where it is more common to calculate velocity based on time-integration of an acceleration signal than it is to calculate acceleration based on time-differentiation of a velocity signal.

Question 103

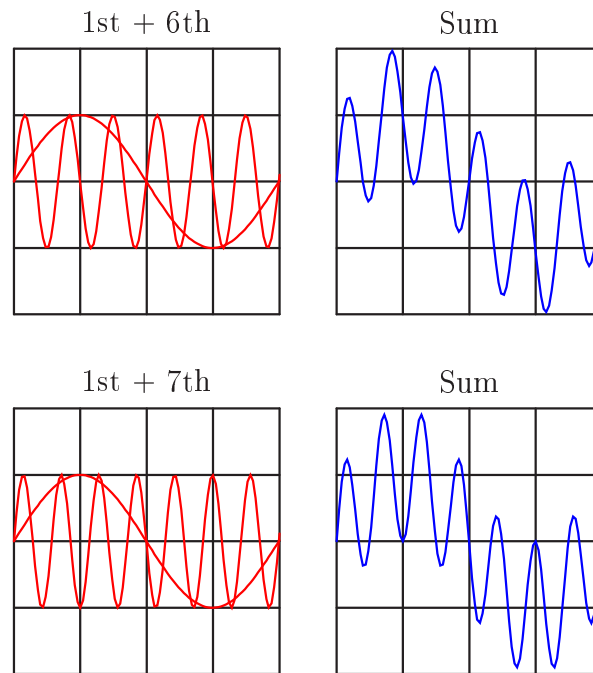
Note the effect of adding the second harmonic of a waveform to the fundamental, and compare that effect with adding the *third* harmonic of a waveform to the fundamental:



Now compare the sums of a fundamental with its fourth harmonic, versus with its fifth harmonic:



And again for the 1st + 6th, versus the 1st + 7th harmonics:



Examine these sets of harmonic sums, and indicate the trend you see with regard to harmonic number and symmetry of the final (Sum) waveforms. Specifically, how does the addition of an *even* harmonic compare to the addition of an *odd* harmonic, in terms of final waveshape?

[file 01892](#)

Answer 103

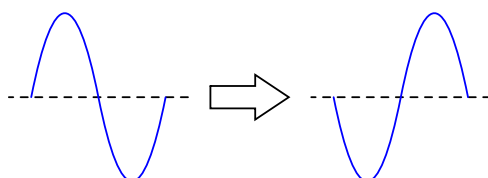
The addition of an even harmonic introduces asymmetry about the horizontal axis. The addition of odd harmonics does not.

Challenge question: explain *why* this is the case, any way you can.

Although the sequence of images presented in the question by no means constitutes a formal proof, it should lead students to observe a trend: that odd harmonics do not make a waveform unsymmetrical about the horizontal axis, whereas even harmonics do. Given these two facts, we may make qualitative judgments about the harmonic content of a waveform simply by visually checking for symmetry about the horizontal axis.

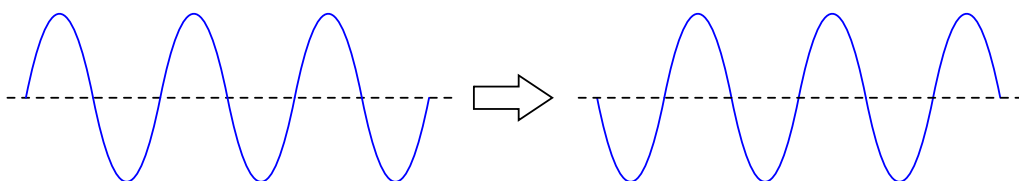
Incidentally, some students have a difficult time grasping the concept of symmetry about the horizontal axis of a waveform. Take this simple example, which *is* symmetrical about its horizontal centerline:

(Flipping waveform about the axis)



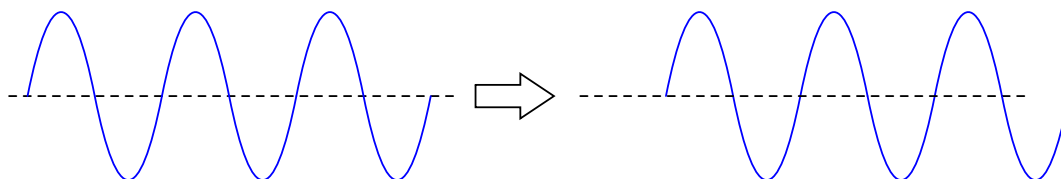
Some students will protest that this waveform is *not* symmetrical about its centerline, because it does not look exactly the same as before after flipping. They must bear in mind, though, that this is just one cycle of a continuous waveform. In reality, the waveform looks like this before and after flipping:

(Flipping waveform about the axis)



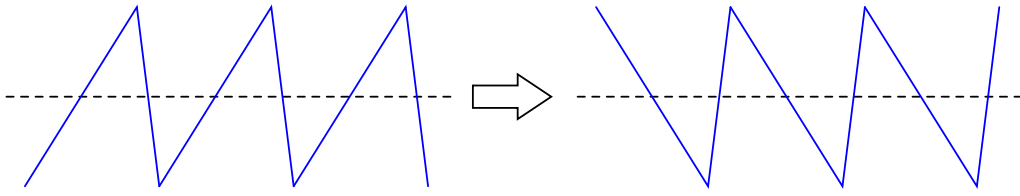
All one needs to do to see that these two waveforms are indeed identical is to do a 180 degree phase shift (shifting either to the left or to the right):

(After the phase shift)



By contrast, a waveform without symmetry about the horizontal axis cannot be made to look the same after flipping, no matter what subsequent phase shift is given to it:

(Flipping waveform about the axis)



Another way to describe this asymmetry is in terms of the waveform's departure from the centerline, compared to its return to the centerline. Is the rate-of-change ($\frac{dv}{dt}$ for a voltage waveform) equal in magnitude and opposite in sign at each of these points, or is there a difference in magnitude as well? Discuss ways to identify this type of asymmetry, and what it means in terms of harmonic content.

Mathematically, this symmetry is defined as such:

$$f(t) = -f\left(t + \frac{T}{2}\right)$$

Where,

$f(t)$ = Function of waveform with time as the independent variable

t = Time

T = Period of waveform, in same units of time as t

Question 104

When technicians and engineers consider harmonics in AC power systems, they usually only consider *odd-numbered* harmonic frequencies. Explain why this is.

[file 01893](#)

Answer 104

Nonlinear loads are usually (but not always!) symmetrical in their distortion.

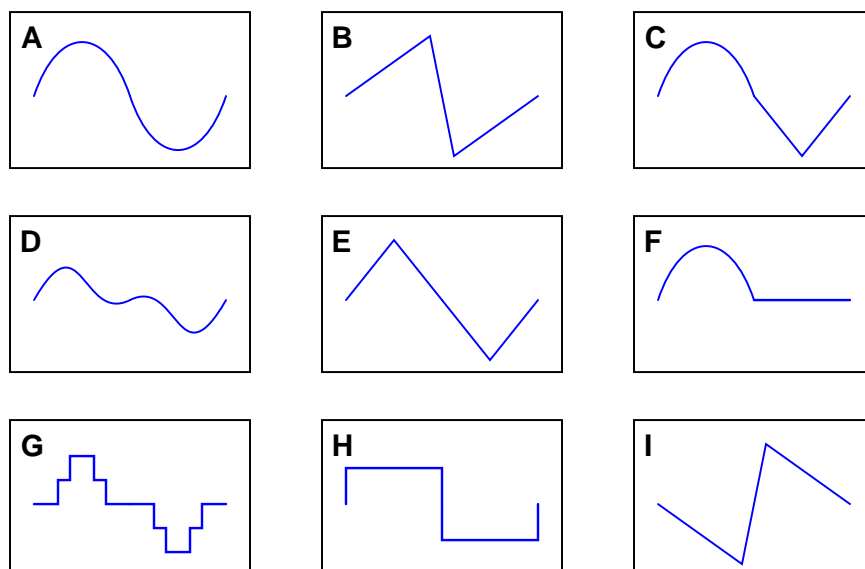
Notes 104

I've had electrical power system experts confidently tell me that even-numbered harmonics *cannot* exist in AC power systems, due to some deep mathematical principle mysteriously beyond their ability to describe or explain. Rubbish! Even-numbered harmonics can and do appear in AC power systems, although they are typically much lower in amplitude than the odd-numbered harmonics due to the nature of most nonlinear loads.

If you ever wish to prove the existence of even-numbered harmonics in a power system, all you have to do is analyze the input current waveform of a half-wave rectifier!

Question 105

By visual inspection, determine which of the following waveforms contain even-numbered harmonics:



Note that only one cycle is shown for each waveform. Remember that we're dealing with continuous waveforms, endlessly repeating, and not single cycles as you see here.

[file 01894](#)

Answer 105

The following waveforms contain even-numbered harmonics: **B, C, D, F, and I**. The rest only contain odd harmonics of the fundamental.

Notes 105

Ask your students how they were able to discern the presence of even-numbered harmonics by visual inspection. This typically proves difficult for some of my students whose spatial-relations skills are weak. These students need some sort of algorithmic (step-by-step) procedure to see what other students see immediately, and discussion time is a great opportunity for students to share technique.

Mathematically, this symmetry is defined as such:

$$f(t) = -f\left(t + \frac{T}{2}\right)$$

Where,

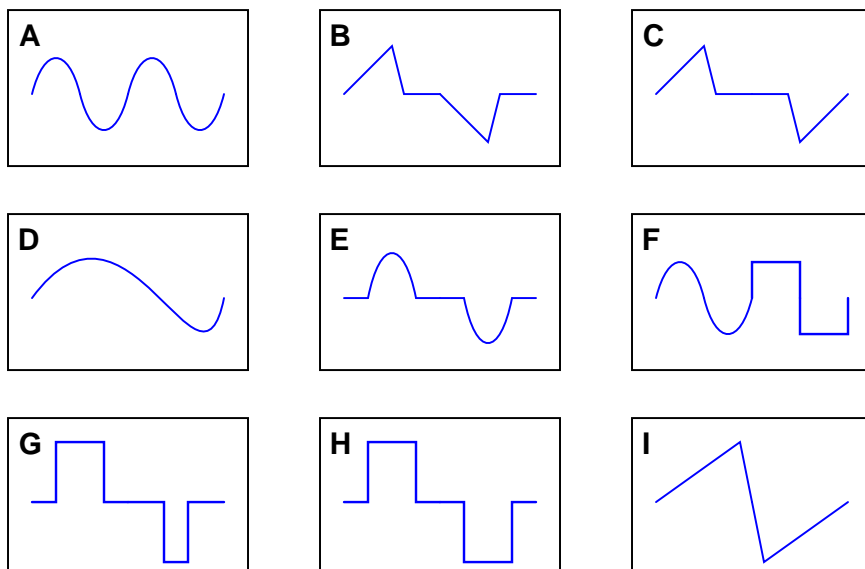
$f(t)$ = Function of waveform with time as the independent variable

t = Time

T = Period of waveform, in same units of time as t

Question 106

By visual inspection, determine which of the following waveforms contain even-numbered harmonics:



Note that only one cycle is shown for each waveform. Remember that we're dealing with continuous waveforms, endlessly repeating, and not single cycles as you see here.

file 03306

Answer 106

The following waveforms contain even-numbered harmonics: **C, D, G, and I**. The rest only contain odd harmonics of the fundamental.

Notes 106

Ask your students how they were able to discern the presence of even-numbered harmonics by visual inspection. This typically proves difficult for some of my students whose spatial-relations skills are weak. These students need some sort of algorithmic (step-by-step) procedure to see what other students see immediately, and discussion time is a great opportunity for students to share technique.

Mathematically, this symmetry is defined as such:

$$f(t) = -f\left(t + \frac{T}{2}\right)$$

Where,

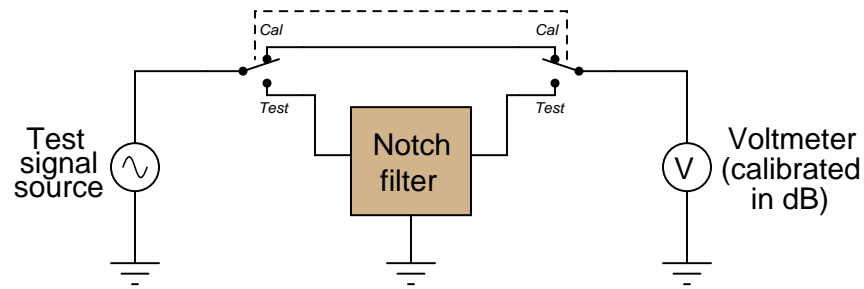
$f(t)$ = Function of waveform with time as the independent variable

t = Time

T = Period of waveform, in same units of time as t

Question 107

A crude measurement circuit for harmonic content of a signal uses a notch filter tuned to the fundamental frequency of the signal being measured. Examine the following circuit and then explain how you think it would work:



file 03455

Answer 107

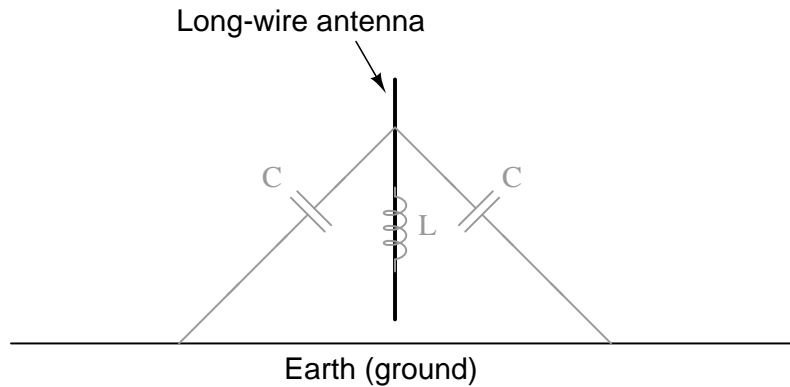
If the signal source is pure (no harmonics), the voltmeter will register nothing (negative infinite decibels) when the switch is flipped to the "test" position.

Notes 107

This test circuit relies on the assumption that the notch filter is perfect (i.e. that its attenuation in the stop-band is complete). Since no filter is perfect, it would be a good idea to ask your students what effect they think an imperfect notch filter would have on the validity of the test. In other words, what will a notch filter that lets a little bit of the fundamental frequency through do to the "test" measurement?

Question 108

A radio antenna possesses both parasitic capacitance and distributed inductance, distributed along its entire length:



Ideally, an antenna *only* exhibits these electrical properties, with no resistance. What does this suggest about the electrical behavior of an antenna, especially compared to the behavior of other LC circuits you are familiar with?

[file 02279](#)

Answer 108

A radio antenna has a *resonant frequency*, just like an LC circuit.

Follow-up question: what physical variable(s) determines the resonant frequency of an antenna?

Notes 108

It is important for students to be able to relate new information to that which they already understand. By likening an antenna to an LC (resonant) circuit, students should be able to predict something about the behavior of antennae, and why it is important to match an antenna to the frequency of transmission.

Question 109

When performing tests on a radio transmitter, it is often necessary to do so without actually broadcasting a signal through an antenna. In such scenarios, an equivalent *resistor* is connected to the output of the transmitter instead of an actual antenna. If chosen properly, the resistor "looks" the same as an antenna from the perspective of the transmitter.

Explain how this is possible, since real antennae are built to have as little resistance as possible. How can a *resistor* adequately substitute for an antenna, which is nothing like a resistor in either construction or purpose?

file 03457

Answer 109

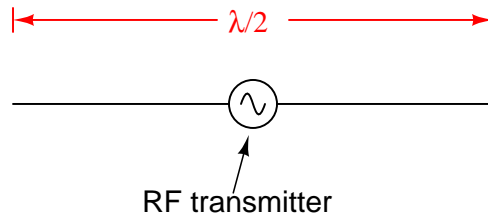
Although an antenna has little actual resistance, it does radiate energy into space, just like a resistor dissipates energy in the form of heat. The only significant difference is that an antenna's radiation is in the form of electromagnetic waves at the same frequency as the transmitter output.

Notes 109

Ask your students what criteria they think a resistor needs to meet in order to properly serve as a "dummy" antenna. Discuss impedance, Q factor, power rating, etc.

Question 110

Calculate the theoretical length for a "half-wave" antenna, assuming a transmitter "carrier" frequency of 105.3 MHz:



Also, calculate the practical antenna length considering the "end effect," which makes the antenna's *electrical length* slightly different from its *physical length* (assume a K factor of 0.95).

file 02281

Answer 110

$$\left(\frac{\lambda}{2}\right)_{\text{theoretical}} = 1.425 \text{ meters}$$

$$\left(\frac{\lambda}{2}\right)_{\text{practical}} = 1.353 \text{ meters}$$

Notes 110

Here, students must understand the mathematical relationship between antenna length and operating frequency, both theoretical and practical.

Question 111

Radio communication functions on the general principle of high-frequency AC power being *modulated* by low-frequency data. Two common forms of modulation are *Amplitude Modulation* (AM) and *Frequency Modulation* (FM). In both cases, the modulation of a high frequency waveform by a lower-frequency waveform produces something called *sidebands*.

Describe what "sidebands" are, to the best of your ability.

file 00654

Answer 111

"Sidebands" are sinusoidal frequencies just above and just below the carrier frequency, produced as a result of the modulation process. On a spectrum analyzer, they show up as peaks to either side of the main (carrier) peak. Their quantity, frequencies, and amplitudes are all a function of the data signals modulating the carrier.

Notes 111

Be sure to ask your students what "AM" and "FM" mean, before they present their answers on sidebands.

The answer makes frequent use of the word *carrier* without defining it. This is another intentional "omission" designed to make students do their research. If they have taken the time to find information on sidebands, they will surely discover what the word "carrier" means. Ask them to define this word, in addition to their description of sidebands.