Summary

- There are two distinctly different types of signal generator: the linear oscillator, which utilizes some form of resonance, and the nonlinear oscillator or function generator, which employs a switching mechanism implemented with a multivibrator circuit.
- A linear oscillator can be realized by placing a frequency-selective network in the feedback path of an amplifier (an op amp or a transistor). The circuit will oscillate at the frequency at which the total phase shift around the loop is zero or 360°, provided the magnitude of loop gain at this frequency is equal to, or greater than, unity.
- If in an oscillator the magnitude of loop gain is greater than unity, the amplitude will increase until a nonlinear amplitude-control mechanism is activated.
- The Wien-bridge oscillator, the phase-shift oscillator, the quadrature oscillator, and the active-filter-tuned oscillator are popular configurations for frequencies up to about 1 MHz. These circuits employ RC networks together with op amps or transistors. For higher frequencies, LC-tuned or crystal-tuned oscillators are utilized. Popular configurations include the Colpitts circuit for discrete-circuit implementation and the cross-coupled circuit for IC implementation at frequencies as high as hundreds of gigahertz.
- Crystal oscillators provide the highest possible frequency accuracy and stability.
- There are three types of multivibrator: bistable, monostable, and astable. Op-amp circuit implementations of multivibrators are useful in analog-circuit applications that require high precision.
- The bistable multivibrator has two stable states and can remain in either state indefinitely. It changes state when triggered. A comparator with hysteresis is bistable.
- A monostable multivibrator, also known as a one-shot, has one stable state, in which it can remain indefinitely. When triggered, it goes into a quasi-stable state in which it remains for a predetermined interval, thus generating, at its output, a pulse of known width.
- An astable multivibrator has no stable state. It oscillates between two quasi-stable states, remaining in each for a predetermined interval. It thus generates a periodic waveform at the output.
- A feedback loop consisting of an integrator and a bistable multivibrator can be used to generate triangular and square waveforms.
- The 555 timer, a commercially available IC, can be used with external resistors and a capacitor to implement high-quality monostable and astable multivibrators.
- A sine waveform can be generated by feeding a triangular waveform to a sine-wave shaper. A sine-wave shaper can be implemented either by using diodes (or transistors) and resistors, or by using an amplifier having a nonlinear transfer characteristic that approximates the sine function.

PROBLEMS

Section 14.1: Basic Principles of Sinusoidal Oscillators

14.1 Consider a sinusoidal oscillator consisting of an amplifier having a frequency-independent gain A (where A is positive) and a second-order bandpass filter with a pole frequency ω_0, a pole Q denoted Q, and a positive center-frequency gain K. Find the frequency of oscillation, and the condition that A and K must satisfy for sustained oscillation.

14.2 For the oscillator circuit described in Problem 14.1:

(a) Derive an expression for $d\phi/d\omega$, evaluated at $\omega = \omega_0$.

(b) Use the result of (a) to find an expression for the per-unit change in frequency of oscillation resulting from a phase-angle change of $\Delta\phi$, in the amplifier transfer function.

$$Hint: \frac{d}{dx}\left(\tan^{-1} y\right) = \frac{1}{1+y^2}\frac{dy}{dx}$$

14.3 For the oscillator described in Problem 14.1, show that, independent of the value of A and K, the poles of the circuit lie at a radial distance of ω_0. Find the value of AK that results in poles appearing (a) on the $j\omega$ axis, and (b) in the right half

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem of the s plane, at a horizontal distance from the $j\omega$ axis of $\omega_0/(2Q)$.

14.4 An oscillator is formed by loading a transconductance amplifier having a positive gain with a parallel RLC circuit and connecting the output directly to the input (thus applying positive feedback with a factor $\beta = 1$). Let the transconductance amplifier have an input resistance of 5 kΩ and an output resistance of 5 kΩ. The LC resonator has $L = 1$ μH, $C = 100$ pF, and $Q = 50$. For what value of transconductance G_m will the circuit oscillate? At what frequency?

D 14.5 For the oscillator circuit in Fig. 14.3(a) find the percentage change in the oscillation frequency resulting from a change of +1% in the value of (a) L, (b) C, and (c) R.

14.6 An oscillator is designed by connecting in a loop three identical common-source amplifier stages of the type shown in Fig. P14.6. Note that the bias circuits are not shown, and assume that R and C include the transistor output resistance and capacitance, respectively. For the circuit to oscillate at a frequency ω_0, what must the phase angle provided by each amplifier stage be? Give an expression for ω_0. For sustained oscillations, what is the minimum g_m required of each transistor?

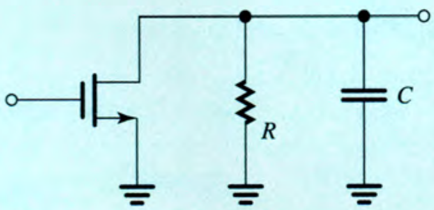

Figure P14.6

14.7 In a particular oscillator characterized by the structure of Fig. 14.1, the frequency-selective network exhibits a loss of 12 dB and a phase shift of 180° at ω_0. Give the phase shift and the minimum gain that the amplifier must have for oscillation to begin.

D 14.8 Consider the circuit of Fig. 14.4(a) with R_f removed to realize the comparator function. Find suitable values for all resistors so that the comparator output levels are ±3 V and the slope of the limiting characteristic is 0.05. Use power-supply voltages of ±5 V and assume the voltage drop of a conducting diode to be 0.7 V.

D 14.9 Consider the circuit of Fig. 14.4(a) with R_f removed to realize the comparator function. Sketch the transfer characteristic. Show that by connecting a dc source V_B to the virtual ground of the op amp through a resistor R_B, the transfer characteristic is shifted along the v_I axis to the point $v_I = -(R_1/R_B)V_B$. Utilizing available ±5-V dc supplies for $\pm V$ and for V_B, find suitable component values so that the limiting levels are ±3 V and the comparator threshold is at $v_I = +2$ V. Neglect the diode voltage drop (i.e., assume that $V_D = 0$). The input resistance of the comparator is to be 100 kΩ, and the slope in the limiting regions is to be ≤ 0.05 V/V. Use standard 5% resistors (see Appendix J).

Section 14.2: Op Amp–RC Oscillator Circuits

14.10 For the Wien-bridge oscillator circuit in Fig. 14.5, show that the transfer function of the feedback network $[V_a(s)/V_o(s)]$ is that of a bandpass filter. Find ω_0 and Q of the poles, and find the center-frequency gain.

14.11 For the Wien-bridge oscillator of Fig. 14.5, use the expression for loop gain in Eq. (14.10) to find the poles of the closed-loop system. Give the expression for the pole Q, and use it to show that to locate the poles in the right half of the s plane, R_2/R_1 must be selected to be greater than 2.

14.12 For the Wien-bridge oscillator of Fig. 14.5, let the closed-loop amplifier (formed by the op amp and the resistors R_1 and R_2) exhibit a phase shift of −3° in the neighborhood of $\omega = 1/CR$. Find the frequency at which oscillations can occur in this case in terms of CR. (*Hint:* Use Eq. 14.11.)

D 14.13 Reconsider Exercise 14.5 with R_3 and R_6 increased to reduce the output voltage. What values are required for a peak-to-peak output of 8 V? What results if R_3 and R_6 are open-circuited?

14.14 For the circuit in Fig. P14.14, find $L(s)$, $L(j\omega)$, the frequency for zero loop phase, and R_2/R_1 for oscillation. Assume the op amp to be ideal.

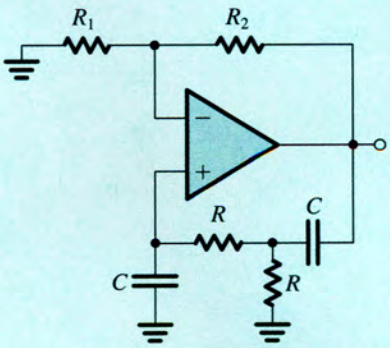

Figure P14.14

D **14.15 Design the circuit of Fig. 14.7 for operation at 10 kHz using $R = 10\ \text{k}\Omega$. If at 10 kHz the op amp provides an excess phase shift (lag) of 5.7°, what will be the frequency of oscillation? (Assume that the phase shift introduced by the op amp remains constant for frequencies around 10 kHz.) To restore operation to 10 kHz, what change must be made in the shunt resistor of the Wien bridge? Also, to what value must R_2/R_1 be changed?

***14.16** Consider the circuit of Fig. 14.7 with the 50-kΩ potentiometer replaced by two fixed resistors: 10 kΩ between the op amp's negative input and ground, and 15 kΩ. Modeling each diode as a 0.65-V battery in series with a 100-Ω resistance, find the peak-to-peak amplitude of the output sinusoid.

D 14.17 For the circuit in Fig. P14.17, break the loop at node X and find the loop gain (working backward for simplicity to find V_x in terms of V_o). For $R = 10\ \text{k}\Omega$, find C and R_f to obtain sinusoidal oscillations at 15 kHz.

***14.18** For the circuit of Fig. 14.9, connect an additional resistor ($R = 10\ \text{k}\Omega$) in series with the rightmost capacitor C. For this modification (and ignoring the amplitude stabilization circuitry), find the loop gain $A\beta$ by breaking the circuit at node X. Find R_f for oscillation to begin, and find f_0.

***14.19** Consider the quadrature-oscillator circuit of Fig. 14.10 without the limiter. Let the resistance R_f be equal to $2R/(1+\Delta)$, where $\Delta \ll 1$. Show that the poles of the characteristic equation are in the right-half s plane and given by $s \simeq (1/CR)[(\Delta/4) \pm j]$.

D 14.20 Using $C = 1.6$ nF, find the value of R such that the circuit of Fig. 14.12 produces 10-kHz sine waves. If the diode drop is 0.7 V, find the peak-to-peak amplitude of the output sine wave. How do you modify the circuit to double the output amplitude? (*Hint*: A square wave with peak-to-peak amplitude of V volts has a fundamental component with $4V/\pi$ volts peak-to-peak amplitude.)

***14.21** Assuming that the diode-clipped waveform in Exercise 14.9 is nearly an ideal square wave and that the resonator Q is 20, provide an estimate of the distortion in the output sine wave by calculating the magnitude (relative to the fundamental) of

(a) the second harmonic
(b) the third harmonic
(c) the fifth harmonic
(d) the rms of harmonics to the tenth

Note that a square wave of amplitude V and frequency ω is represented by the series

$$\frac{4V}{\pi}\left(\sin\omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t + \ldots\right)$$

Section 14.3: LC and Crystal Oscillators

14.22 For the Colpitts oscillator circuit in Fig. P14.22, derive an equation governing circuit operation and hence find the frequency of oscillation and the condition the gain $g_m R_L$ must satisfy for oscillations to start. Assume that R_L includes the MOSFET's r_o.

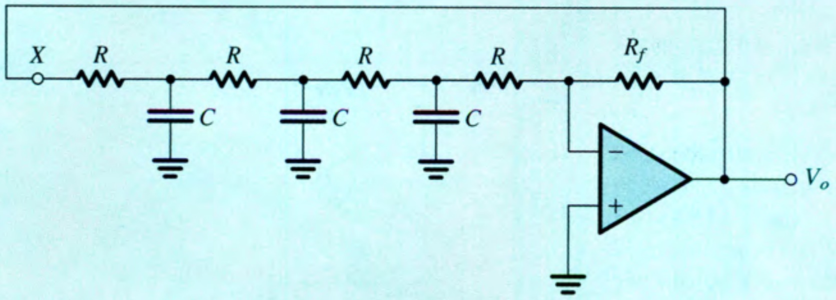

Figure P14.17

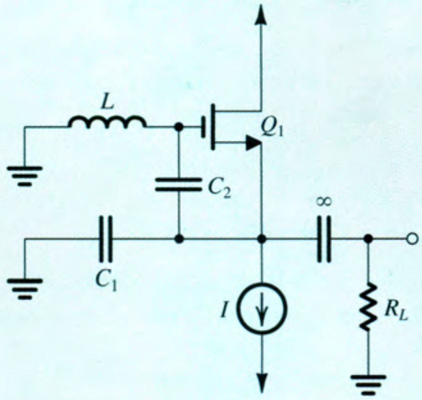

Figure P14.22

14.23 For the Colpitts oscillator circuit in Fig. P14.23, derive an equation governing circuit operation and hence find the frequency of oscillation and the condition on the gain $g_m R_L$ that ensures that oscillations will start. Assume that R_L includes r_o of Q_1. Simplify your final expressions by assuming r_π is large. Observe that this circuit is based on the configuration in Fig. 14.13(a) except that here the biasing circuit is included and the collector is placed at signal ground.

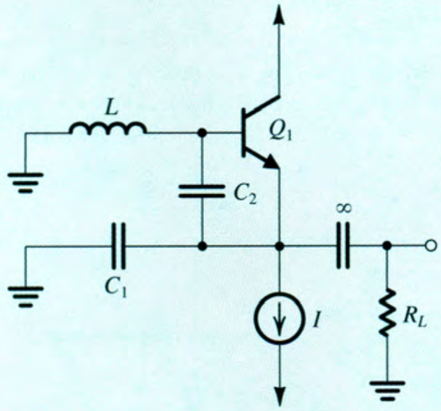

Figure P14.23

14.24 For the Colpitts oscillator circuit in Fig. P14.24, derive an equation governing circuit operation and hence find the frequency of oscillation and the condition the gain $g_m R_L$ must satisfy to ensure that oscillations will start. Neglect r_o of the BJT. Simplify your final expressions by assuming that r_π is large. Note that this circuit is based on the configuration of Fig. 14.13(a) but with the bias circuit included and the base grounded.

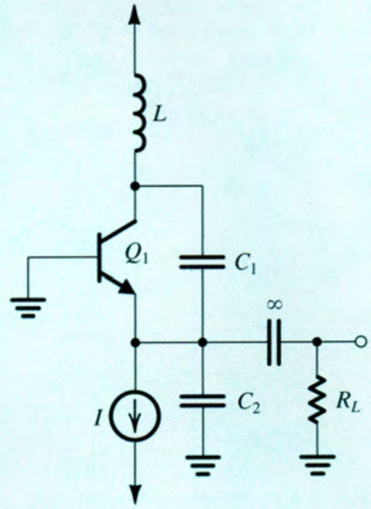

Figure P14.24

14.25 For the Colpitts oscillator circuit in Fig. P14.25, derive an equation governing circuit operation and hence find the frequency of oscillation and the condition the gain $g_m R_L$ must satisfy to ensure that oscillations will start. Assume that r_o of the BJT is included in R_L and neglect R_f (i.e., assume $R_f \gg \omega_0 L$). Simplify your final expressions by assuming r_π is large. Observe that this circuit is similar to that in Fig. 14.15 except for utilizing a different biasing scheme.

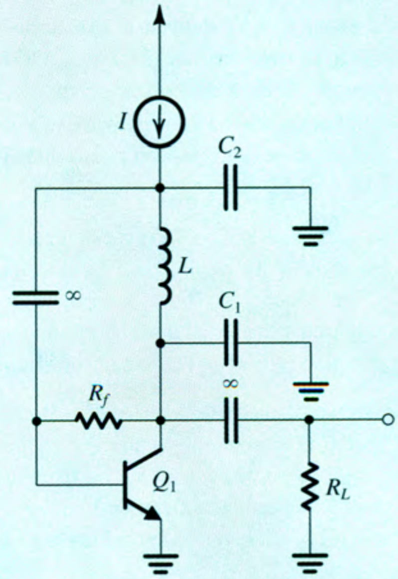

Figure P14.25

***14.26** The LC oscillator in Fig. P14.26 is based on connecting a positive-gain amplifier (formed by Q_1, Q_2, and R_C) with a bandpass RLC circuit in a feedback loop.

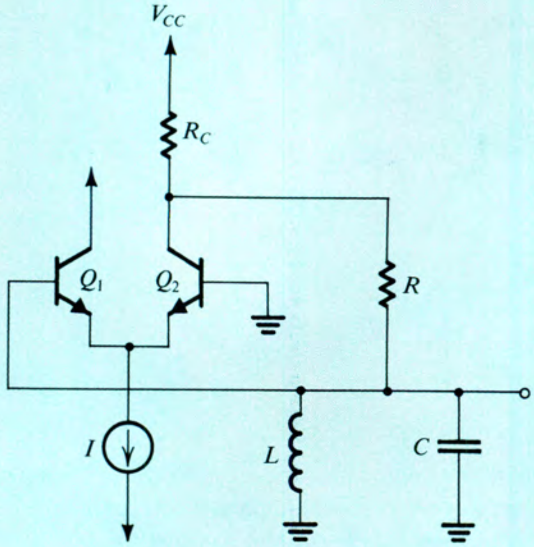

Figure P14.26

(a) Replace the BJTs with their small-signal models while neglecting r_π and r_o (to simplify matters).
(b) By inspection of the circuit found in (a), find the frequency of oscillation and the condition required for oscillations to start. Express the latter as the minimum required value of (IR_C).
(c) If IR_C is selected equal to 1 V, show that oscillations will start. If oscillations grow to the point that V_o is large enough to turn the BJTs on and off, show that the signal at the collector of Q_2 will be a square wave of 1 V peak-to-peak. Estimate the peak-to-peak amplitude of the output sine wave V_o.

D 14.27 Design the cross-coupled LC oscillator of Fig. 14.16(a) to operate at $\omega_0 = 20$ Grad/s. The IC inductors available have $L = 5$ nH and $Q = 10$. If the transistor $r_o = 5$ kΩ, find the required value of C and the minimum required value of g_m at which Q_1 and Q_2 are to be operated.

14.28 Consider the Pierce crystal oscillator of Fig. 14.18 with the crystal as specified in Exercise 14.13. Let C_1 be variable in the range 1 pF to 10 pF, and let C_2 be fixed at 10 pF. Find the range over which the oscillation frequency can be tuned. (*Hint:* Use the result in the statement leading to the expression in Eq. 14.29.)

Section 14.4: Bistable Multivibrators

D 14.29 Design the bistable circuit in Fig. 14.21(a) to obtain a hysteresis of 2-V width. The op amp saturates at ±5 V. Select $R_1 = 10$ kΩ and determine R_2.

14.30 Consider the bistable circuit of Fig. 14.21(a) with the op amp's positive input terminal connected to a positive-voltage source V through a resistor R_3.

(a) Derive expressions for the threshold voltages V_{TL} and V_{TH} in terms of the op amp's saturation levels L_+ and L_-, R_1, R_2, R_3, and V.
(b) Let $L_+ = -L_- = 10$ V, $V = 15$ V, and $R_1 = 10$ kΩ. Find the values of R_2 and R_3 that result in $V_{TL} = +4.9$ V and $V_{TH} = +5.1$ V.

14.31 Consider the bistable circuit of Fig. 14.22(a) with the op amp's negative-input terminal disconnected from ground and connected to a reference voltage V_R.

(a) Derive expressions for the threshold voltages V_{TL} and V_{TH} in terms of the op amp's saturation levels L_+ and L_-, R_1, R_2, and V_R.
(b) Let $L_+ = -L_- = V$ and $R_1 = 10$ kΩ. Find R_2 and V_R that result in threshold voltages of 0 and $V/10$.

14.32 For the circuit in Fig. P14.32, sketch and label the transfer characteristic v_O–v_I. The diodes are assumed to have a constant 0.7-V drop when conducting, and the op amp saturates at ±12 V. What is the maximum diode current?

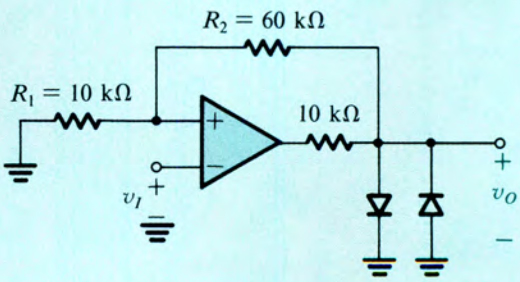

Figure P14.32

***14.33** Consider a bistable circuit having a noninverting transfer characteristic with $L_+ = -L_- = 12$ V, $V_{TL} = -1$ V, and $V_{TH} = +1$ V.

(a) For a 0.5-V-amplitude sine-wave input having zero average, what is the output?

(b) Describe the output if a sinusoid of frequency f and amplitude of 1.1 V is applied at the input. By how much can the average of this sinusoidal input shift before the output becomes a constant value?

D 14.34 Design the circuit of Fig. 14.25(a) to realize a transfer characteristic with ±7.5-V output levels and ±7.5-V threshold values. Design so that when $v_I = 0$ V a current of 0.5 mA flows in the feedback resistor and a current of 1 mA flows through the zener diodes. Assume that the output saturation levels of the op amp are ±10 V. Specify the voltages of the zener diodes and give the values of all resistors.

Section 14.5: Generation of Square and Triangular Waveforms Using Astable Multivibrators

14.35 Find the frequency of oscillation of the circuit in Fig. 14.26(b) for the case $R_1 = 10$ kΩ, $R_2 = 16$ kΩ, $C = 5$ nF, and $R = 62$ kΩ.

D 14.36 Augment the astable multivibrator circuit of Fig. 14.26(b) with an output limiter of the type shown in Fig. 14.25(b). Design the circuit to obtain an output square wave with 5-V amplitude and 1-kHz frequency using a 10-nF capacitor C. Use $\beta = 0.462$, and design for a current in the resistive divider approximately equal to the average current in the RC network over a half-cycle. Assuming ±13-V op-amp saturation voltages, arrange for the zener to operate at a minimum current of 1 mA. Specify the values of all resistors and the zener voltage.

D 14.37 Using the scheme of Fig. 14.27, design a circuit that provides square waves of 10 V peak to peak and triangular waves of 10 V peak to peak. The frequency is to be 1 kHz. Implement the bistable circuit with the circuit of Fig. 14.25(b). Use a 0.01-μF capacitor and specify the values of all resistors and the required zener voltage. Design for a minimum zener current of 1 mA and for a maximum current in the resistive divider of 0.2 mA. Assume that the output saturation levels of the op amps are ±12 V.

D *14.38 The circuit of Fig. P14.38 consists of an inverting bistable multivibrator with an output limiter and a noninverting integrator. Using equal values for all resistors except R_7 and a 0.5-nF capacitor, design the circuit to obtain a square wave at the output of the bistable multivibrator of 15-V peak-to-peak amplitude and 10-kHz frequency. Sketch and label the waveform at the integrator output. Assuming ±13-V op-amp saturation levels, design for a minimum zener current of 1 mA. Specify the zener voltage required, and give the values of all resistors.

Section 14.6: Generation of a Standardized Pulse—The Monostable Multivibrator

D 14.39 For the monostable circuit considered in Exercise 14.22, calculate the recovery time.

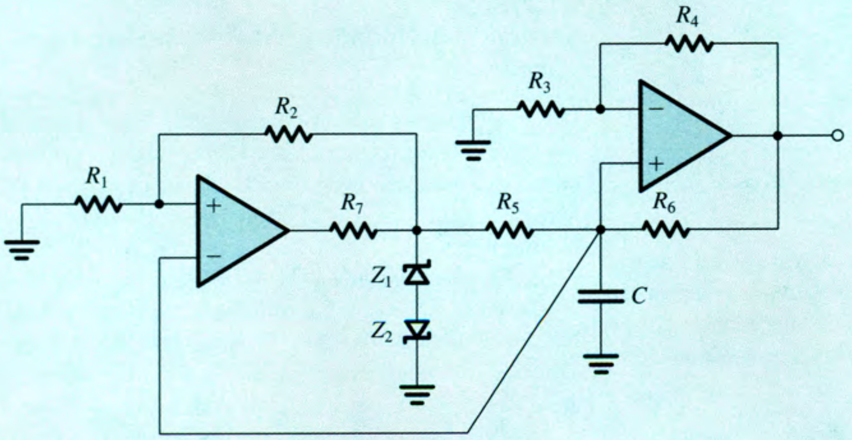

Figure P14.38

D *14.40 Using the circuit of Fig. 14.28(a), with a nearly ideal op amp for which the saturation levels are ± 13 V, design a monostable multivibrator to provide a negative output pulse of 100-μs duration. Use capacitors of 0.1 nF and 1 nF. Wherever possible, choose resistors of 100 kΩ in your design. Diodes have a drop of 0.7 V. What is the minimum input step size that will ensure triggering? How long does the circuit take to recover to a state in which retriggering is possible with a normal output?

***14.41** Figure P14.41 shows a monostable multivibrator circuit. In the stable state, $v_O = L_+$, $v_A = 0$, and $v_B = -V_{ref}$. The circuit can be triggered by applying a positive input pulse of height greater than V_{ref}. For normal operation, $C_1R_1 \ll CR$. Show the resulting waveforms of v_O and v_A. Also, show that the pulse generated at the output will have a width T given by

$$T = CR\ln\left(\frac{L_+ - L_-}{V_{ref}}\right)$$

Note that this circuit has the interesting property that the pulse width can be controlled by changing V_{ref}.

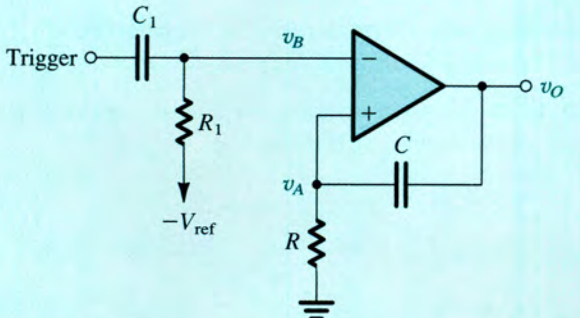

Figure P14.41

Section 14.7: Integrated-Circuit Timers

14.42 Consider the 555 circuit of Fig. 14.29 when the Threshold and the Trigger input terminals are joined together and connected to an input voltage v_I. Verify that the transfer characteristic v_O–v_I is that of an inverting bistable circuit with thresholds $V_{TL} = \frac{1}{3}V_{CC}$ and $V_{TH} = \frac{2}{3}V_{CC}$ and output levels of 0 and V_{CC}.

D 14.43 Using a 680-pF capacitor, design the astable circuit of Fig. 14.31(a) to obtain a square wave with a 20-kHz frequency and an 80% duty cycle. Specify the values of R_A and R_B.

D 14.44 (a) Using a 0.5-nF capacitor C in the circuit of Fig. 14.30(a), find the value of R that results in an output pulse of 10-μs duration.
(b) If the 555 timer used in (a) is powered with $V_{CC} = 12$ V, and assuming that V_{TH} can be varied externally (i.e., it need not remain equal to $\frac{2}{3}V_{CC}$), find its required value so that the pulse width is increased to 20 μs, with other conditions the same as in (a).

***14.45** The node in the 555 timer at which the voltage is V_{TH} (i.e., the inverting input terminal of comparator 1) is usually connected to an external terminal. This allows the user to change V_{TH} externally (i.e., V_{TH} no longer remains at $\frac{2}{3}V_{CC}$). Note, however, that whatever the value of V_{TH} becomes, V_{TL} always remains $\frac{1}{2}V_{TH}$.

(a) For the astable circuit of Fig. 14.31(a), rederive the expressions for T_H and T_L, expressing them in terms of V_{TH} and V_{TL}.
(b) For the case $C = 1$ nF, $R_A = 7.2$ kΩ, $R_B = 3.6$ kΩ, and $V_{CC} = 5$ V, find the frequency of oscillation and the duty cycle of the resulting square wave when no external voltage is applied to the terminal V_{TH}.
(c) For the design in (b), let a sine-wave signal of a much lower frequency than that found in (b) and of 1-V peak amplitude be capacitively coupled to the circuit node V_{TH}. This signal will cause V_{TH} to change around its quiescent value of $\frac{2}{3}V_{CC}$, and thus T_H will change correspondingly—a modulation process. Find T_H, and find the frequency of oscillation and the duty cycle at the two extreme values of V_{TH}.

Section 14.8: Nonlinear Waveform-Shaping Circuits

D *14.46 The two-diode circuit shown in Fig. P14.46 can provide a crude approximation to a sine-wave output when driven by a triangular waveform. To obtain a good approximation, we select the peak of the triangular waveform, V, so that the slope of the desired sine wave at the zero crossings is equal to that of the triangular wave. Also, the value of R is selected so that when v_I is at its peak, the output voltage is equal to the desired peak of the sine wave. If the diodes exhibit a voltage drop of 0.7 V at 1-mA current, changing at the rate of 0.1 V per decade, find the values of V and R that will yield an approximation to a sine waveform of 0.7-V peak amplitude. Then find the angles θ (where $\theta = 90°$ when v_I is at its peak) at which the output of the circuit, in volts, is 0.7, 0.65, 0.6, 0.55, 0.5, 0.4, 0.3, 0.2, 0.1, and 0. Use the angle values obtained to determine the values of the exact sine wave (i.e., 0.7 sin θ), and thus find the percentage error of this circuit as a sine shaper. Provide your results in tabular form.

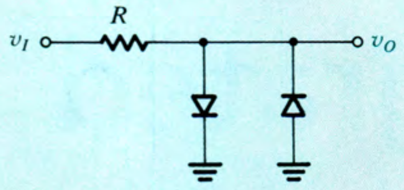

Figure P14.46

D 14.47 Design a two-segment sine-wave shaper using a 6.8-kΩ-input resistor, two diodes, and two clamping voltages. The circuit, fed by an 8-V peak-to-peak triangular wave, should limit the amplitude of the output signal via a 0.7-V diode to a value corresponding to that of a sine wave whose zero-crossing slope matches that of the triangle. What are the clamping voltages you have chosen?

14.48 Show that the output voltage of the circuit in Fig. P14.48 is given by

$$v_O = -V_T \ln\left(\frac{v_I}{I_S R}\right), \quad v_I > 0$$

where I_S is the saturation current of the diode and V_T is the thermal voltage. Since the output voltage is proportional to the logarithm of the input voltage, the circuit is known as a **logarithmic amplifier**. Such amplifiers find application in situations where it is desired to compress the signal range.

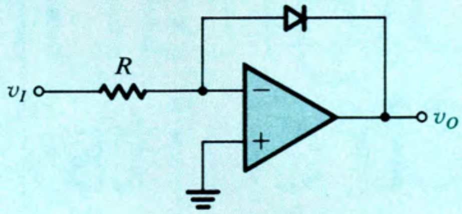

Figure P14.48

14.49 Verify that the circuit in Fig. P14.49 implements the transfer characteristic $v_O = -v_1 v_2$ for v_1, $v_2 > 0$. Such a circuit is known as an analog multiplier. Check the circuit's performance for various combinations of input voltage of values, say, 0.5 V, 1 V, 2 V, and 3 V. Assume all diodes to be identical, with 700-mV drop at 1-mA current. Note that a *squarer* can easily be produced using a single input (e.g., v_1) connected via a 0.5-kΩ resistor (rather than the 1-kΩ resistor shown).

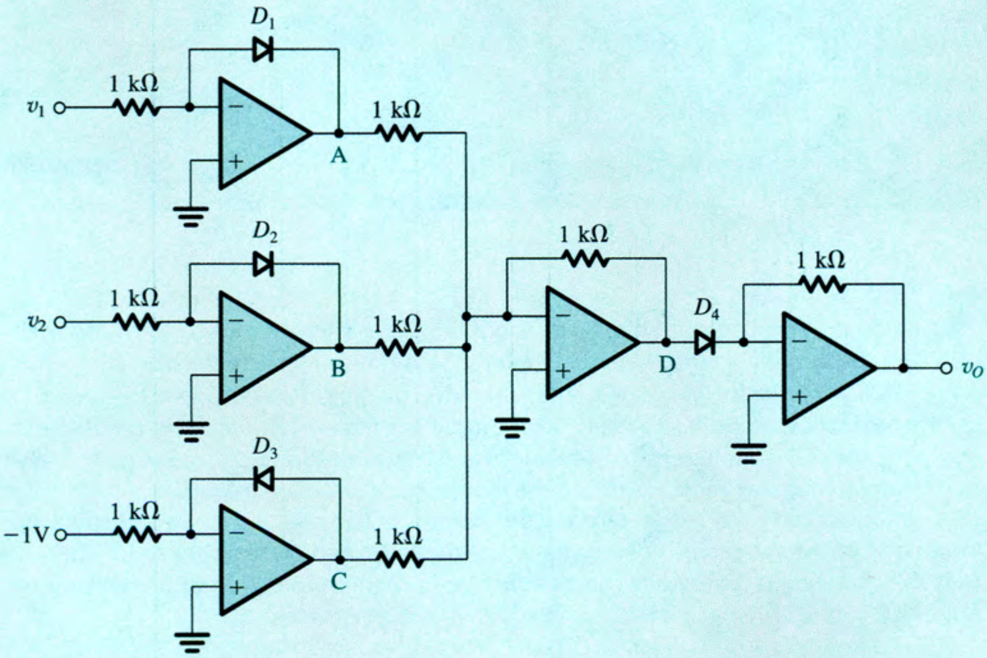

Figure P14.49