16 OSCILLATORS

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Describe the operating principles of an oscillator
- Discuss the principle on which feedback oscillators is based
- Describe and analyze the operation of *RC* feedback oscillators
- Describe and analyze the operation of *LC* feedback oscillators
- Describe and analyze the operation of relaxation oscillators
- Discuss and analyze the 555 timer and use it in oscillator applications

KEY TERMS

- Oscillator
- Positive feedback
- Voltage-controlled oscillator (VCO)
- Astable

APPLICATION ACTIVITY PREVIEW

The application in this chapter is a circuit that produces an ASK signal for testing the RFID reader developed in the last chapter. The ASK test generator uses an oscillator, a 555 timer, and a JFET analog switch to produce a 125 kHz carrier signal modulated at 10 kHz by a digital signal. The output amplitude is adjustable down to a low level to simulate the RFID tag signal.

VISIT THE COMPANION WEBSITE

Study aids and Multisim files for this chapter are available at http://www.pearsonhighered.com/electronics

INTRODUCTION

Oscillators are electronic circuits that generate an output signal without the necessity of an input signal. They are used as signal sources in all sorts of applications. Different types of oscillators produce various types of outputs including sine waves, square waves, triangular waves, and sawtooth waves. In this chapter, several types of basic oscillator circuits using both discrete transistors and op-amps as the gain element are introduced. Also, a popular integrated circuit, the 555 timer, is discussed in relation to its oscillator applications.

Sinusoidal oscillator operation is based on the principle of positive feedback, where a portion of the output signal is fed back to the input in a way that causes it to reinforce itself and thus sustain a continuous output signal. Oscillators are widely used in most communications systems as well as in digital systems, including computers, to generate required frequencies and timing signals. Also, oscillators are found in many types of test instruments like those used in the laboratory.

16–1 THE OSCILLATOR

An **oscillator** is a circuit that produces a periodic waveform on its output with only the dc supply voltage as an input. A repetitive input signal is not required except to synchronize oscillations in some applications. The output voltage can be either sinusoidal or nonsinusoidal, depending on the type of oscillator. Two major classifications for oscillators are feedback oscillators and relaxation oscillators.

After completing this section, you should be able to

- **Describe the operating principles of an oscillator**
- Discuss feedback oscillators
  - List the basic elements of a feedback oscillator
  - Show a test setup
- Briefly describe a relaxation oscillator
  - State the difference between a feedback oscillator and a relaxation oscillator

Essentially, an oscillator converts electrical energy from the dc power supply to periodic waveforms. A basic oscillator is shown in Figure 16–1.

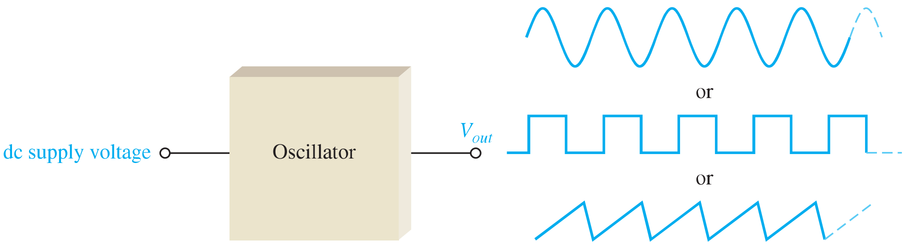


FIGURE 16–1
The basic oscillator concept showing three common types of output waveforms: sine wave, square wave, and sawtooth.

Feedback Oscillators One type of oscillator is the **feedback oscillator**, which returns a fraction of the output signal to the input with no net phase shift, resulting in a reinforcement of the output signal. After oscillations are started, the loop gain is maintained at 1.0 to maintain oscillations. A feedback oscillator consists of an amplifier for gain (either a discrete transistor or an op-amp) and a positive feedback circuit that produces phase shift and provides attenuation, as shown in Figure 16–2.

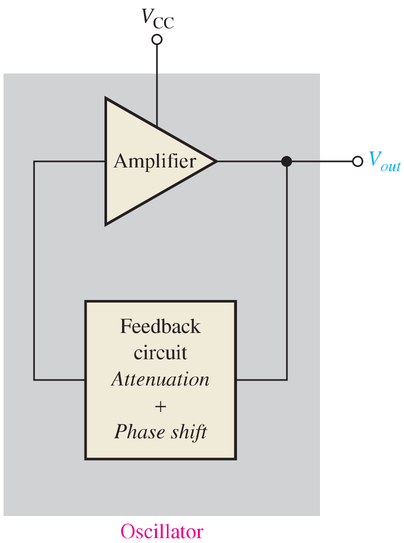


FIGURE 16–2
Basic elements of a feedback oscillator.

Relaxation Oscillators A second type of oscillator is the **relaxation oscillator**. Instead of feedback, a relaxation oscillator uses an *RC* timing circuit to generate a waveform that is generally a square wave or other nonsinusoidal waveform. Typically, a relaxation oscillator uses a Schmitt trigger or other device that changes states to alternately charge and discharge a capacitor through a resistor. Relaxation oscillators are discussed in Section 16–5.

SECTION 16–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. What is an oscillator?
2. What type of feedback does a feedback oscillator require?
3. What is the purpose of the feedback circuit?
4. Name the two types of oscillators.

16–2 FEEDBACK OSCILLATORS

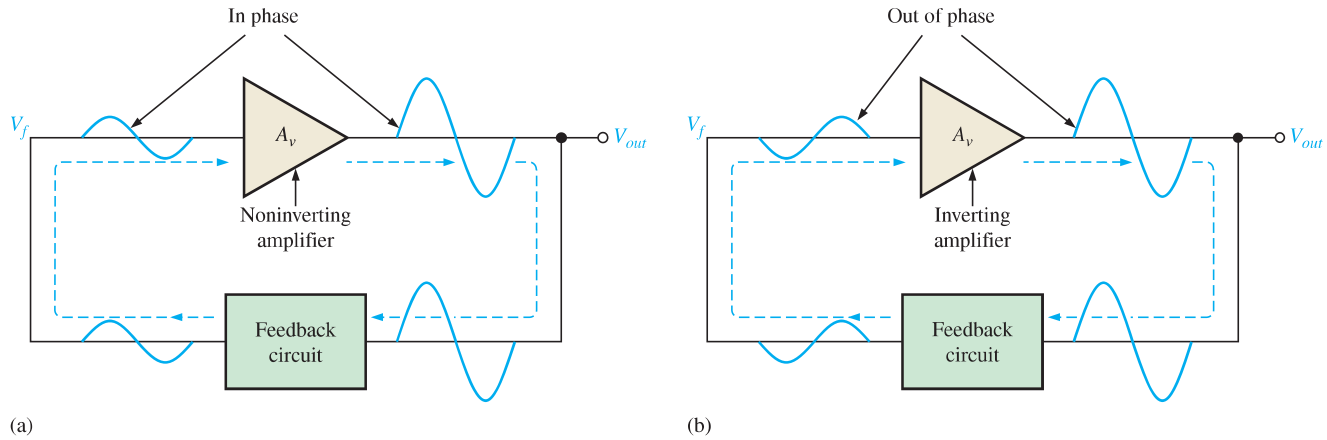
Feedback oscillator operation is based on the principle of positive feedback. In this section, we will examine this concept and look at the general conditions required for oscillation to occur. Feedback oscillators are widely used to generate sinusoidal waveforms.

After completing this section, you should be able to

- **Discuss the principle on which feedback oscillators is based**
- Explain positive feedback
  - Define *oscillation*
- Describe the conditions for oscillation
  - Define *closed loop gain*
- Discuss the conditions required for oscillator start-up

Positive Feedback

Positive feedback is characterized by the condition wherein a portion of the output voltage of an amplifier is fed back to the input with no net phase shift, resulting in a reinforcement of the output signal. This basic idea is illustrated in Figure 16–3(a). As you can see, the in-phase feedback voltage, V_f, is amplified to produce the output voltage, which in turn produces the feedback voltage. That is, a loop is created in which the signal sustains itself and



▲ FIGURE 16–3

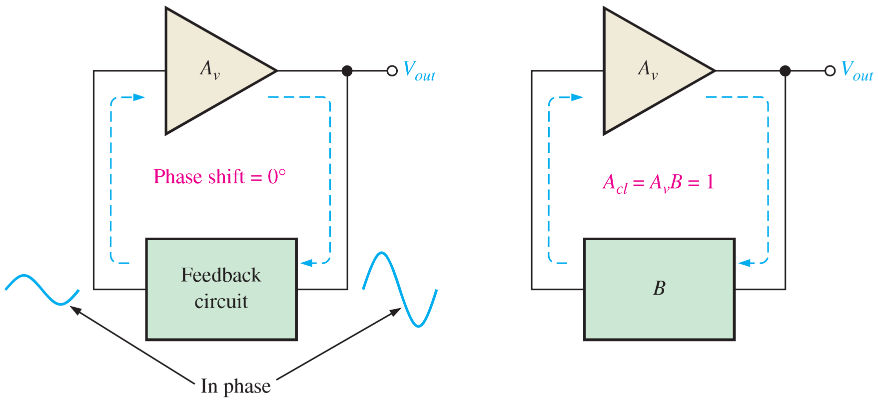
Positive feedback produces oscillation.

a continuous sinusoidal output is produced. This phenomenon is called *oscillation.* In some types of amplifiers, the feedback circuit shifts the phase 180° and an inverting amplifier is required to provide another 180° phase shift so that there is no net phase shift. This is illustrated in Figure 16–3(b).

Conditions for Oscillation

Two conditions, illustrated in Figure 16–4, are required for a sustained state of oscillation:

1. The phase shift around the feedback loop must be effectively 0°.
2. The voltage gain, A_{cl}, around the closed feedback loop (loop gain) must equal 1 (unity).



(a) The phase shift around the loop is 0°.

(b) The closed loop gain is 1.

◀ FIGURE 16–4

General conditions to sustain oscillation.

The voltage gain around the closed feedback loop, A_{cl}, is the product of the amplifier gain, A_v, and the attenuation, B, of the feedback circuit.

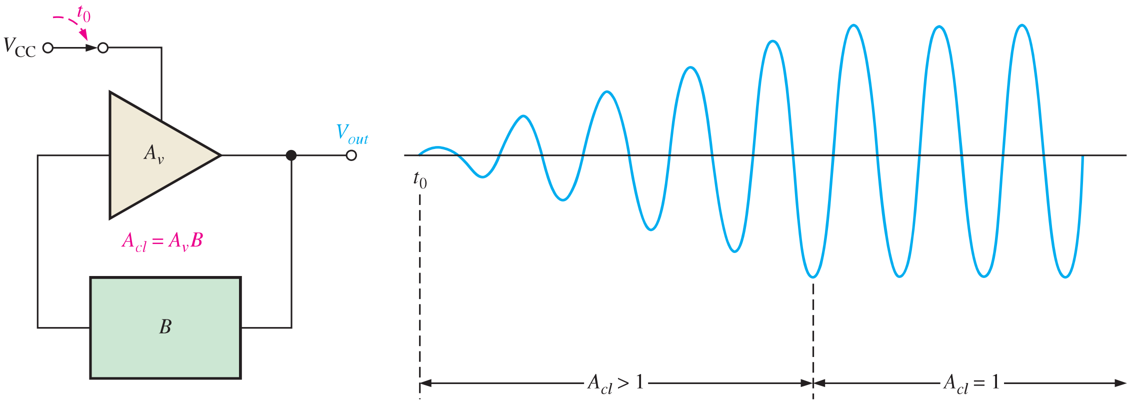
$$A_{cl} = A_v B$$

If a sinusoidal wave is the desired output, a loop gain greater than 1 will rapidly cause the output to saturate at both peaks of the waveform, producing unacceptable distortion. To avoid this, some form of gain control must be used to keep the loop gain at exactly 1 once oscillations have started. For example, if the attenuation of the feedback circuit is 0.01, the amplifier must have a gain of exactly 100 to overcome this attenuation and not create unacceptable distortion ($0.01 \times 100 = 1$). An amplifier gain of greater than 100 will cause the oscillator to limit both peaks of the waveform.

Start-Up Conditions

So far, you have seen what it takes for an oscillator to produce a continuous sinusoidal output. Now let's examine the requirements for the oscillation to start when the dc supply voltage is first turned on. As you know, the unity-gain condition must be met for oscillation to be sustained. For oscillation to *begin,* the voltage gain around the positive feedback loop must be greater than 1 so that the amplitude of the output can build up to a desired level. The gain must then decrease to 1 so that the output stays at the desired level and oscillation is sustained. Ways that certain amplifiers achieve this reduction in gain after start-up are discussed in later sections of this chapter. The voltage gain conditions for both starting and sustaining oscillation are illustrated in Figure 16–5.

A question that normally arises is this: If the oscillator is initially off and there is no output voltage, how does a feedback signal originate to start the positive feedback buildup process? Initially, a small positive feedback voltage develops from thermally produced broad-band noise in the resistors or other components or from power supply turn-on transients. The feedback circuit permits only a voltage with a frequency equal to the selected oscillation frequency to appear in phase on the amplifier's input. This initial feedback



▲ FIGURE 16–5

When oscillation starts at t_0, the condition $A_{cl} > 1$ causes the sinusoidal output voltage amplitude to build up to a desired level. Then A_{cl} decreases to 1 and maintains the desired amplitude.

voltage is amplified and continually reinforced, resulting in a buildup of the output voltage as previously discussed.

SECTION 16–2 CHECKUP

1. What are the conditions required for a circuit to oscillate?
2. Define *positive feedback.*
3. What is the voltage gain condition for oscillator start-up?

16–3 OSCILLATORS WITH *RC* FEEDBACK CIRCUITS

Three types of feedback oscillators that use *RC* circuits to produce sinusoidal outputs are the Wien-bridge oscillator, the phase-shift oscillator, and the twin-T oscillator. Generally, *RC* feedback oscillators are used for frequencies up to about 1 MHz. The Wien-bridge is by far the most widely used type of *RC* feedback oscillator for this range of frequencies.

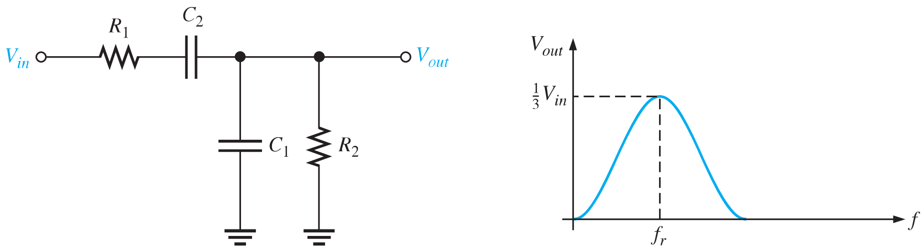
After completing this section, you should be able to

- **Describe and analyze the operation of *RC* feedback oscillators**
- Identify and describe the Wien-bridge oscillator
  ◆ Discuss the response of a lead-lag circuit ◆ Discuss the attenuation of the lead-lag circuit ◆ Calculate the resonant frequency ◆ Discuss the positive feedback conditions for oscillation ◆ Describe the start-up conditions ◆ Discuss a JFET stabilized Wien-bridge oscillator
- Describe and analyze the phase-shift oscillator
  ◆ Discuss the required value of feedback attenuation ◆ Calculate the resonant frequency
- Discuss the twin-T oscillator

The Wien-Bridge Oscillator

One type of sinusoidal feedback oscillator is the **Wien-bridge oscillator**. A fundamental part of the Wien-bridge oscillator is a lead-lag circuit like that shown in Figure 16–6(a).

R_1 and C_1 together form the lag portion of the circuit; R_2 and C_2 form the lead portion. The operation of this lead-lag circuit is as follows. At lower frequencies, the lead circuit dominates due to the high reactance of C_2. As the frequency increases, X_{C2} decreases, thus allowing the output voltage to increase. At some specified frequency, the response of the lag circuit takes over, and the decreasing value of X_{C1} causes the output voltage to decrease.



(a) Circuit (b) Response curve

FIGURE 16–6
A lead-lag circuit and its response curve.

The response curve for the lead-lag circuit shown in Figure 16–6(b) indicates that the output voltage peaks at a frequency called the resonant frequency, f_r. At this point, the attenuation (V_{out}/V_{in}) of the circuit is 1/3 if $R_1 = R_2$ and $X_{C1} = X_{C2}$ as stated by the following equation (derived in "Derivations of Selected Equations" at www.pearsonhighered.com/floyd):

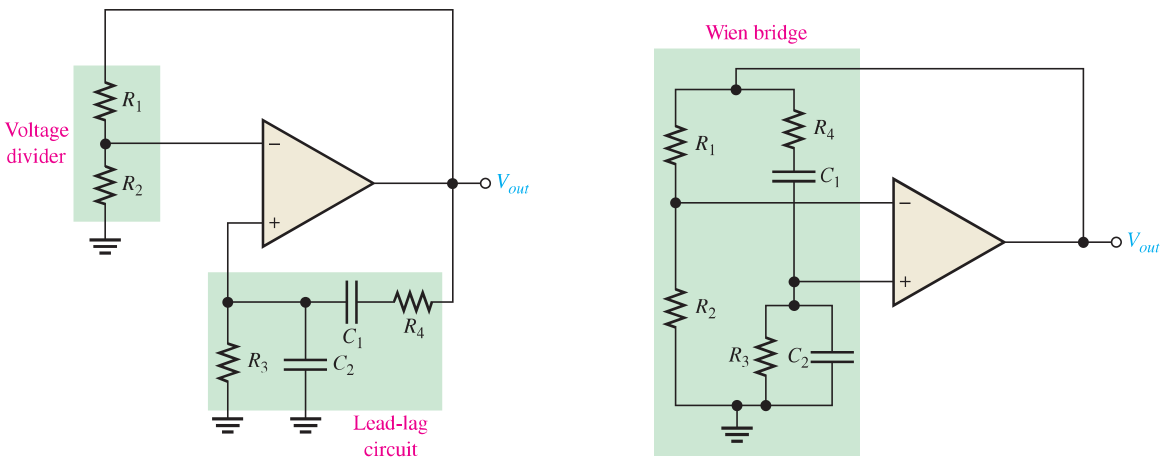
$$\frac{V_{out}}{V_{in}} = \frac{1}{3} \qquad \text{Equation 16–1}$$

The formula for the resonant frequency (also derived on the companion website) is

$$f_r = \frac{1}{2\pi RC} \qquad \text{Equation 16–2}$$

To summarize, the lead-lag circuit in the Wien-bridge oscillator has a resonant frequency, f_r, at which the phase shift through the circuit is 0° and the attenuation is 1/3. Below f_r, the lead circuit dominates and the output leads the input. Above f_r, the lag circuit dominates and the output lags the input.

The Basic Circuit The lead-lag circuit is used in the positive feedback loop of an op-amp, as shown in Figure 16–7(a). A voltage divider is used in the negative feedback loop.



(a) (b) Wien bridge circuit combines a voltage divider and a lead-lag circuit.

FIGURE 16–7
The Wien-bridge oscillator schematic drawn in two different but equivalent ways.

The Wien-bridge oscillator circuit can be viewed as a noninverting amplifier configuration with the input signal fed back from the output through the lead-lag circuit. Recall that the voltage divider determines the closed-loop gain of the amplifier.

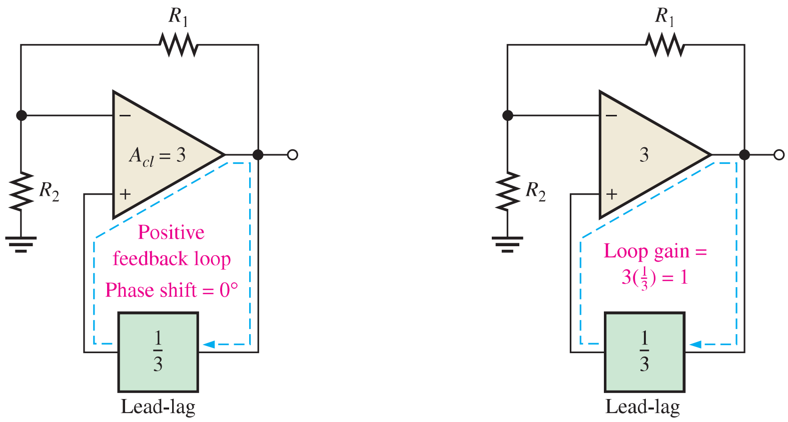
$$A_{cl} = \frac{1}{B} = \frac{1}{R_2/(R_1 + R_2)} = \frac{R_1 + R_2}{R_2}$$

The circuit is redrawn in Figure 16–7(b) to show that the op-amp is connected across the bridge circuit. One leg of the bridge is the lead-lag circuit, and the other is the voltage divider.

Positive Feedback Conditions for Oscillation As you know, for the circuit to produce a sustained sinusoidal output (oscillate), the phase shift around the positive feedback loop must be 0° and the gain around the loop must equal unity (1). The 0° phase-shift condition is met when the frequency is f_r because the phase shift through the lead-lag circuit is 0° and there is no inversion from the noninverting (+) input of the op-amp to the output. This is shown in Figure 16–8(a).

▶ FIGURE 16–8

Conditions for sustained oscillation.



(a) The phase shift around the loop is 0°.

(b) The voltage gain around the loop is 1.

The unity-gain condition in the feedback loop is met when

$$A_{cl} = 3$$

This offsets the 1/3 attenuation of the lead-lag circuit, thus making the total gain around the positive feedback loop equal to 1, as depicted in Figure 16–8(b). To achieve a closed-loop gain of 3,

$$R_1 = 2R_2$$

Then

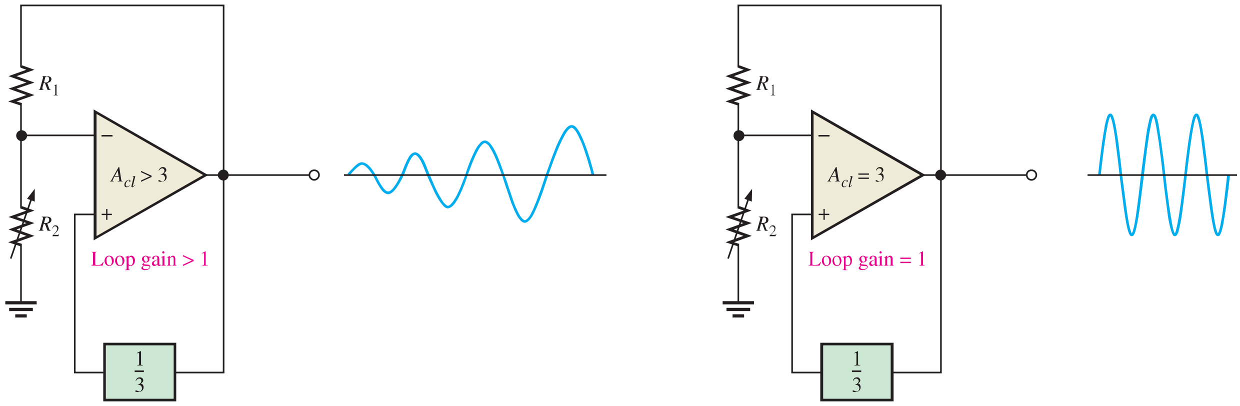
$$A_{cl} = \frac{R_1 + R_2}{R_2} = \frac{2R_2 + R_2}{R_2} = \frac{3R_2}{R_2} = 3$$

Start-Up Conditions Initially, the closed-loop gain of the amplifier itself must be more than 3 ($A_{cl} > 3$) until the output signal builds up to a desired level. Ideally, the gain of the amplifier must then decrease to 3 so that the total gain around the loop is 1 and the output signal stays at the desired level, thus sustaining oscillation. This is illustrated in Figure 16–9.

The circuit in Figure 16–10 illustrates a method for achieving sustained oscillations. Notice that the voltage-divider circuit has been modified to include an additional resistor R_3 in parallel with a back-to-back zener diode arrangement. When dc power is first applied,

HISTORY NOTE

Max Wien (1866–1938) was a German physicist. He theoretically developed the concept of the Wien-bridge oscillator in 1891. At that time, Wien did not have a means of developing electronic gain, so a workable oscillator could not be achieved. Based on Wien's work, William Hewlett, co-founder of Hewlett-Packard, was successful in building a practical Wien-bridge oscillator in 1939.

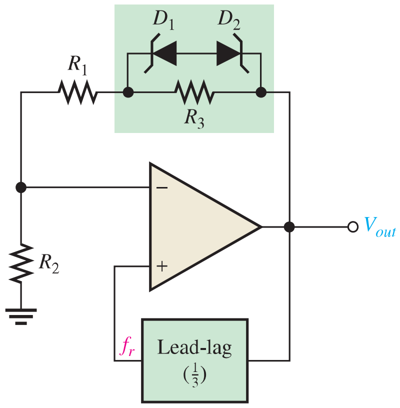


(a) Loop gain greater than 1 causes output to build up.

(b) Loop gain of 1 causes a sustained constant output.

▲ **FIGURE 16–9**

Conditions for start-up and sustained oscillations.



◀ **FIGURE 16–10**

Self-starting Wien-bridge oscillator using back-to-back zener diodes.

both zener diodes appear as opens. This places R_3 in series with R_1, thus increasing the closed-loop gain of the amplifier as follows ($R_1 = 2R_2$):

$$A_{cl} = \frac{R_1 + R_2 + R_3}{R_2} = \frac{3R_2 + R_3}{R_2} = 3 + \frac{R_3}{R_2}$$

Initially, a small positive feedback signal develops from noise or turn-on transients. The lead-lag circuit permits only a signal with a frequency equal to f_r to appear in phase on the noninverting input. This feedback signal is amplified and continually reinforced, resulting in a buildup of the output voltage. When the output signal reaches the zener breakdown voltage, the zeners conduct and effectively short out R_3. This lowers the amplifier's closed-loop gain to 3. At this point, the total loop gain is 1 and the output signal levels off and the oscillation is sustained.

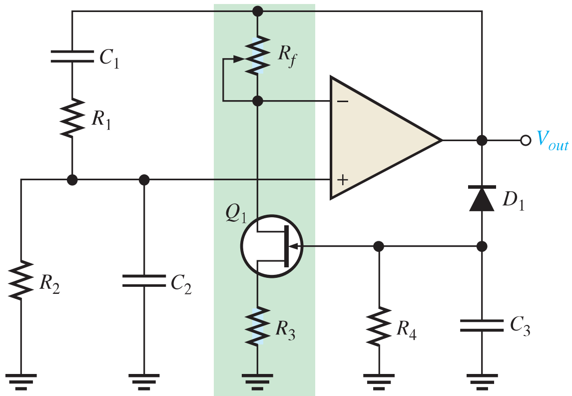
All practical methods to achieve stability for feedback oscillators require the gain to be self-adjusting. This requirement is a form of automatic gain control (AGC). The zener diodes in Figure 16–10 limit the gain at the onset of nonlinearity, in this case, zener conduction. Although the zener feedback is simple, it suffers from the nonlinearity of the zener diodes that occurs in order to control gain. It is difficult to achieve an undistorted sinusoidal output waveform. In some older designs, a tungsten lamp was used in the feedback circuit to achieve stability.

A better method to control the gain uses a JFET as a voltage-controlled resistor in a negative feedback path. This method can produce an excellent sinusoidal waveform that is stable. A JFET operating with a small or zero V_{DS} is operating in the ohmic region. As the gate voltage increases, the drain-source resistance increases. If the JFET is placed in the negative feedback path, automatic gain control can be achieved because of this voltage-controlled resistance.

A JFET stabilized Wien bridge is shown in Figure 16–11. The gain of the op-amp is controlled by the components shown in the green box, which include the JFET. The JFET's drain-source resistance depends on the gate voltage. With no output signal, the gate is at zero volts, causing the drain-source resistance to be at the minimum. With this condition, the loop gain is greater than 1. Oscillations begin and rapidly build to a large output signal. Negative excursions of the output signal forward-bias D_1, causing capacitor C_3 to charge to a negative voltage. This voltage increases the drain-source resistance of the JFET and reduces the gain (and hence the output). This is classic negative feedback at work. With the proper selection of components, the gain can be stabilized at the required level. Example 16–1 illustrates a JFET stabilized Wien-bridge oscillator.

▶ **FIGURE 16–11**

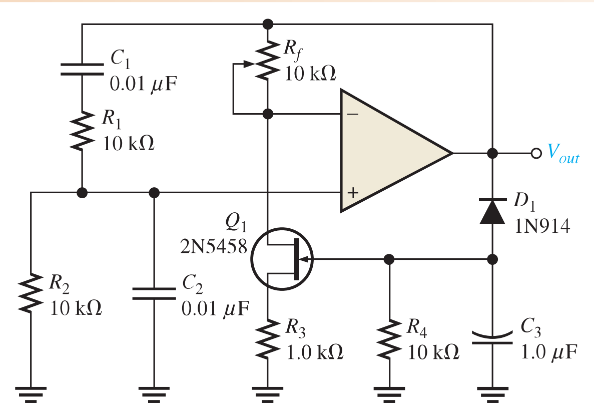
Self-starting Wien-bridge oscillator using a JFET in the negative feedback loop.



EXAMPLE 16–1

Determine the resonant frequency for the Wien-bridge oscillator in Figure 16–12. Also, calculate the setting for R_f assuming the internal drain-source resistance, r'_{ds}, of the JFET is 500 Ω when oscillations are stable.

▶ **FIGURE 16–12**



Solution For the lead-lag circuit, $R_1 = R_2 = R = 10\text{ k}\Omega$ and $C_1 = C_2 = C = 0.01\ \mu\text{F}$. The frequency is

$$f_r = \frac{1}{2\pi RC} = \frac{1}{2\pi(10\text{ k}\Omega)(0.01\ \mu\text{F})} = \mathbf{1.59\ kHz}$$

The closed-loop gain must be 3.0 for oscillations to be sustained. For an inverting amplifier, the gain expression is the same as for a noninverting amplifier.

$$A_v = \frac{R_f}{R_i} + 1$$

R_i is composed of R_3 (the source resistor) and r'_{ds}. Substituting,

$$A_v = \frac{R_f}{R_3 + r'_{ds}} + 1$$

Rearranging and solving for R_f,

$$R_f = (A_v - 1)(R_3 + r'_{ds}) = (3 - 1)(1.0\text{ k}\Omega + 500\ \Omega) = \mathbf{3.0\ k\Omega}$$

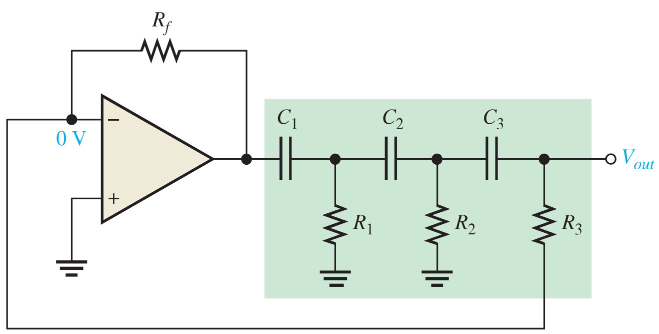
Related Problem[*] What happens to the oscillations if the setting of R_f is too high? What happens if the setting is too low?

[*] **Answers can be found at www.pearsonhighered.com/floyd.**

Open the Multisim file E16-01 in the Examples folder on the companion website. Determine the frequency of oscillation and compare with the calculated value.

The Phase-Shift Oscillator

Figure 16–13 shows a sinusoidal feedback oscillator called the **phase-shift oscillator**. Each of the three *RC* circuits in the feedback loop can provide a *maximum* phase shift approaching 90°. Oscillation occurs at the frequency where the total phase shift through the three *RC* circuits is 180°. The inversion of the op-amp itself provides the additional 180° to meet the requirement for oscillation of a 360° (or 0°) phase shift around the feedback loop.



◀ **FIGURE 16–13**

Phase-shift oscillator.

The attenuation, B, of the three-section *RC* feedback circuit is

$$B = \frac{1}{29} \qquad \text{Equation 16–3}$$

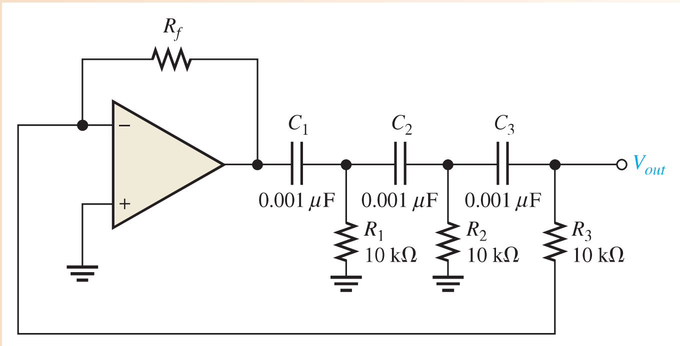
where $B = R_3/R_f$. The derivation of this unusual result is given in “Derivations of Selected Equations” at www.pearsonhighered.com/floyd. To meet the greater-than-unity loop gain requirement, the closed-loop voltage gain of the op-amp must be greater than 29 (set by R_f and R_3). The frequency of oscillation (f_r) is also derived on the companion website and is stated in the following equation, where $R_1 = R_2 = R_3 = R$ and $C_1 = C_2 = C_3 = C$.

$$f_r = \frac{1}{2\pi\sqrt{6}RC} \qquad \text{Equation 16–4}$$

EXAMPLE 16–2

(a) Determine the value of R_f necessary for the circuit in Figure 16–14 to operate as an oscillator.

(b) Determine the frequency of oscillation.



▲ FIGURE 16–14

Solution **(a)** $A_{cl} = 29$, and $B = 1/29 = R_3/R_f$. Therefore,

$$\frac{R_f}{R_3} = 29$$

$$R_f = 29R_3 = 29(10\text{ k}\Omega) = \mathbf{290\text{ k}\Omega}$$

(b) $R_1 = R_2 = R_3 = R$ and $C_1 = C_2 = C_3 = C$. Therefore,

$$f_r = \frac{1}{2\pi\sqrt{6}RC} = \frac{1}{2\pi\sqrt{6}(10\text{ k}\Omega)(0.001\ \mu\text{F})} \cong \mathbf{6.5\text{ kHz}}$$

Related Problem **(a)** If R_1, R_2, and R_3 in Figure 16–14 are changed to 8.2 kΩ, what value must R_f be for oscillation?

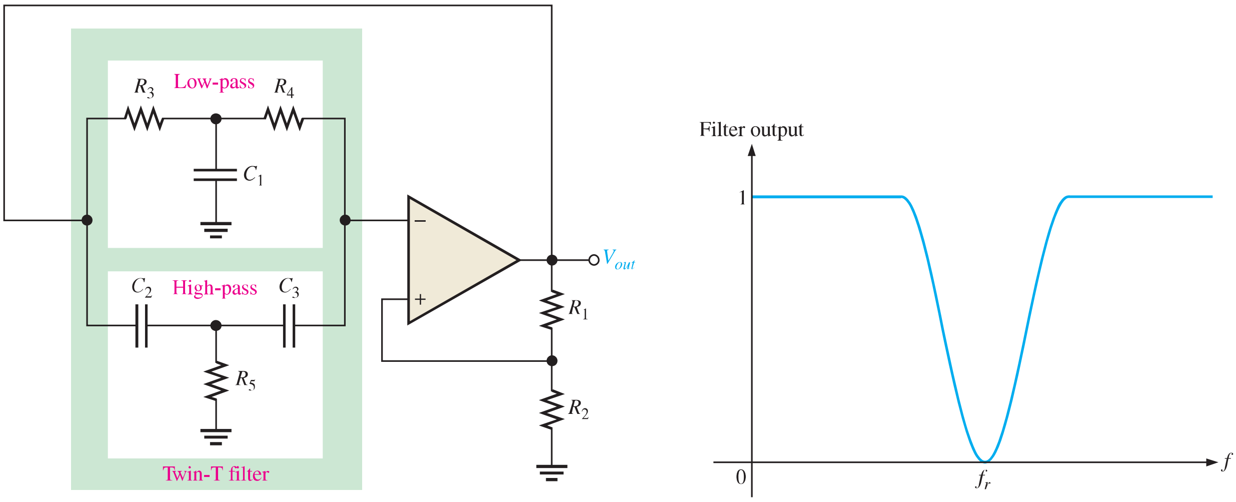
(b) What is the value of f_r?

Open the Multisim file E16-02 in the Examples folder on the companion website. Measure the frequency of oscillation and compare to the calculated value.

Twin-T Oscillator

Another type of *RC* feedback oscillator is called the *twin-T* because of the two T-type *RC* filters used in the feedback loop, as shown in Figure 16–15(a). One of the twin-T filters has a low-pass response, and the other has a high-pass response. The combined parallel filters produce a band-stop or notch response with a center frequency equal to the desired frequency of oscillation, f_r, as shown in Figure 16–15(b).

Oscillation cannot occur at frequencies above or below f_r because of the negative feedback through the filters. At f_r, however, there is negligible negative feedback; thus, the positive feedback through the voltage divider (R_1 and R_2) allows the circuit to oscillate.



(a) Oscillator circuit

(b) Twin-T filter's frequency response curve

▲ **FIGURE 16–15**

Twin-T oscillator and twin-T filter response.

SECTION 16–3 CHECKUP

1. There are two feedback loops in the Wien-bridge oscillator. What is the purpose of each?
2. A certain lead-lag circuit has $R_1 = R_2$ and $C_1 = C_2$. An input voltage of 5 V rms is applied. The input frequency equals the resonant frequency of the circuit. What is the rms output voltage?
3. Why is the phase shift through the *RC* feedback circuit in a phase-shift oscillator 180°?

16–4 OSCILLATORS WITH *LC* FEEDBACK CIRCUITS

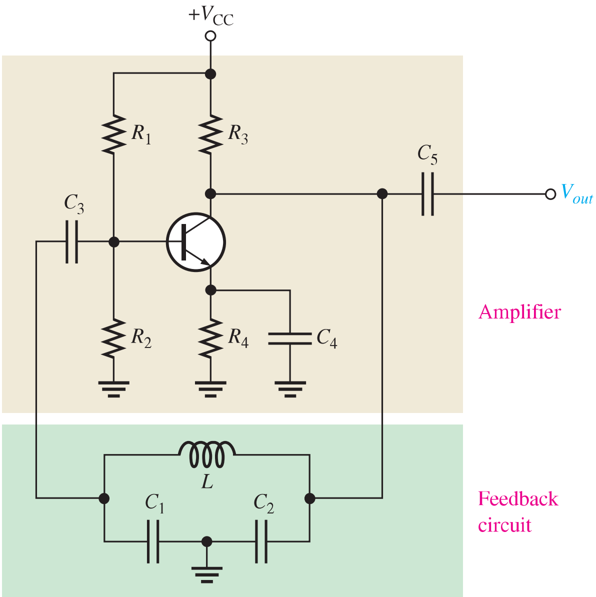
Although the *RC* feedback oscillators, particularly the Wien bridge, are generally suitable for frequencies up to about 1 MHz, *LC* feedback elements are normally used in oscillators that require higher frequencies of oscillation. Also, because of the frequency limitation (lower unity-gain frequency) of most op-amps, discrete transistors (BJT or FET) are often used as the gain element in *LC* oscillators. This section introduces several types of resonant *LC* feedback oscillators: the Colpitts, Clapp, Hartley, Armstrong, and crystal-controlled oscillators.

After completing this section, you should be able to

- **Describe and analyze the operation of *LC* feedback oscillators**
- Identify and analyze a Colpitts oscillator
  ◆ Determine the resonant frequency ◆ Describe the conditions for oscillation and start-up ◆ Discuss and analyze loading of the feedback circuit
- Identify and analyze a Clapp oscillator
  ◆ Determine the resonant frequency
- Identify and analyze a Hartley oscillator
  ◆ Determine the resonant frequency and attenuation of the feedback circuit
- Identify and analyze an Armstrong oscillator
  ◆ Determine the resonant frequency
- Describe the operation of crystal-controlled oscillators
  ◆ Define *piezoelectric effect* ◆ Discuss the quartz crystal ◆ Discuss the modes of operation in the crystal

The Colpitts Oscillator

One basic type of resonant circuit feedback oscillator is the Colpitts, named after its inventor—as are most of the others we cover here. As shown in Figure 16–16, this type of oscillator uses an LC circuit in the feedback loop to provide the necessary phase shift and to act as a resonant filter that passes only the desired frequency of oscillation.



▶ FIGURE 16–16

A basic Colpitts oscillator with a BJT as the gain element.

The approximate frequency of oscillation is the resonant frequency of the LC circuit and is established by the values of C_1, C_2, and L according to this familiar formula:

Equation 16–5

$$\mathbf{f_r \cong \frac{1}{2\pi\sqrt{LC_T}}}$$

where C_T is the total capacitance. Because the capacitors effectively appear in series around the tank circuit, the total capacitance (C_T) is

$$C_T = \frac{C_1C_2}{C_1 + C_2}$$

Conditions for Oscillation and Start-Up The attenuation, B, of the resonant feedback circuit in the Colpitts oscillator is basically determined by the values of C_1 and C_2.

Figure 16–17 shows that the circulating tank current is through both C_1 and C_2 (they are effectively in series). The voltage developed across C_2 is the oscillator's output voltage (V_{out}) and the voltage developed across C_1 is the feedback voltage (V_f), as indicated. The expression for the attenuation (B) is

$$B = \frac{V_f}{V_{out}} \cong \frac{IX_{C1}}{IX_{C2}} = \frac{X_{C1}}{X_{C2}} = \frac{1/(2\pi f_r C_1)}{1/(2\pi f_r C_2)}$$

Cancelling the $2\pi f_r$ terms gives

$$B = \frac{C_2}{C_1}$$

As you know, a condition for oscillation is $A_vB = 1$. Since $B = C_2/C_1$,

Equation 16–6

$$\mathbf{A_v = \frac{C_1}{C_2}}$$

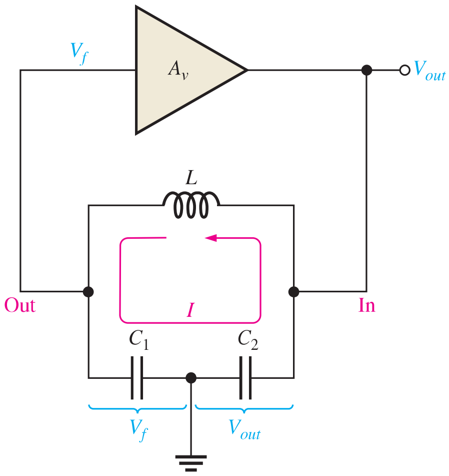


FIGURE 16–17

The attenuation of the tank circuit is the output of the tank (V_f) divided by the input to the tank (V_{out}). $B = V_f/V_{out} = C_2/C_1$. For $A_vB > 1$, A_v must be greater than C_1/C_2.

HISTORY NOTE

Edwin H. Colpitts was involved in the development of oscillators and vacuum tube push-pull amplifiers at Western Electric in the early 1900s. Western Electric research laboratories became part of Bell Laboratories in 1925, and Colpitts became vice-president of Bell Labs before retirement. The Colpitts oscillator is named in his honor.

where A_v is the voltage gain of the amplifier, which is represented by the triangle in Figure 16–17. With this condition met, $A_vB = (C_1/C_2)(C_2/C_1) = 1$. Actually, for the oscillator to be self-starting, A_vB must be greater than 1 (that is, $A_vB > 1$). Therefore, the voltage gain must be made slightly greater than C_1/C_2.

$$A_v > \frac{C_1}{C_2}$$

Loading of the Feedback Circuit Affects the Frequency of Oscillation As indicated in Figure 16–18, the input impedance of the amplifier acts as a load on the resonant feedback circuit and reduces the Q of the circuit. The resonant frequency of a parallel resonant circuit depends on the Q, according to the following formula:

$$f_r = \frac{1}{2\pi\sqrt{LC_T}}\sqrt{\frac{Q^2}{Q^2 + 1}}$$

Equation 16–7

As a rule of thumb, for a Q greater than 10, the frequency is approximately $1/(2\pi\sqrt{LC_T})$, as stated in Equation 16–5. When Q is less than 10, however, f_r is reduced significantly.

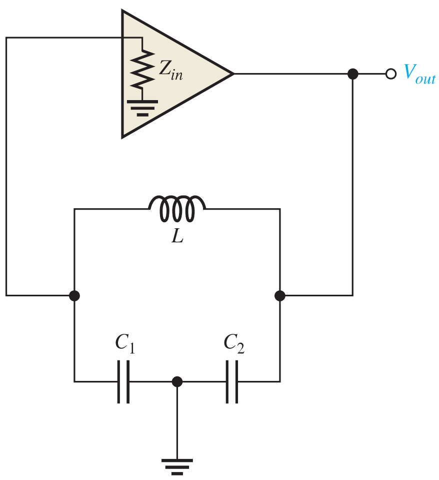
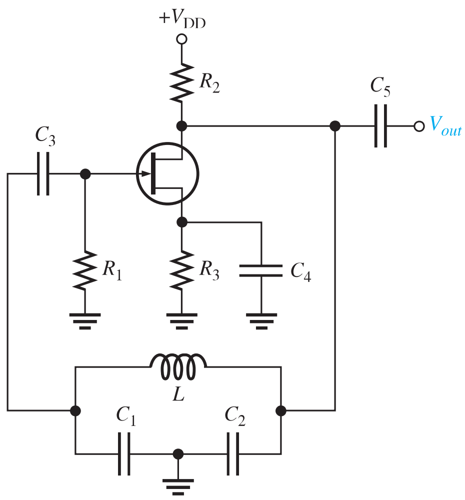


FIGURE 16–18

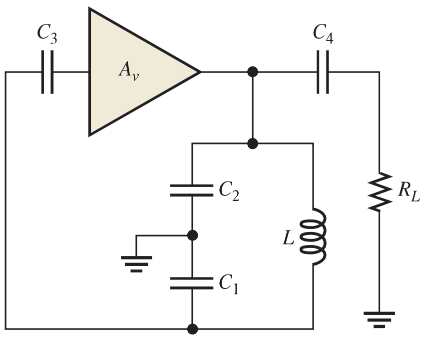
Z_{in} of the amplifier loads the feedback circuit and lowers its Q, thus lowering the resonant frequency.

A FET can be used in place of a BJT, as shown in Figure 16–19, to minimize the loading effect of the transistor's input impedance. Recall that FETs have much higher input impedances than do bipolar junction transistors. Also, when an external load is connected to the oscillator output, as shown in Figure 16–20(a), f_r may decrease, again because of a reduction in Q. This happens if the load resistance is too small. In some cases, one way to eliminate the effects of a load resistance is by transformer coupling, as indicated in Figure 16–20(b).

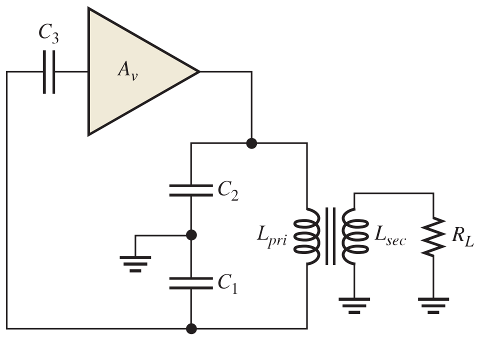


▲ **FIGURE 16–19**

A basic FET Colpitts oscillator.



(a) A load capacitively coupled to oscillator output can reduce circuit Q and f_r.



(b) Transformer coupling of load can reduce loading effect by impedance transformation.

▲ **FIGURE 16–20**

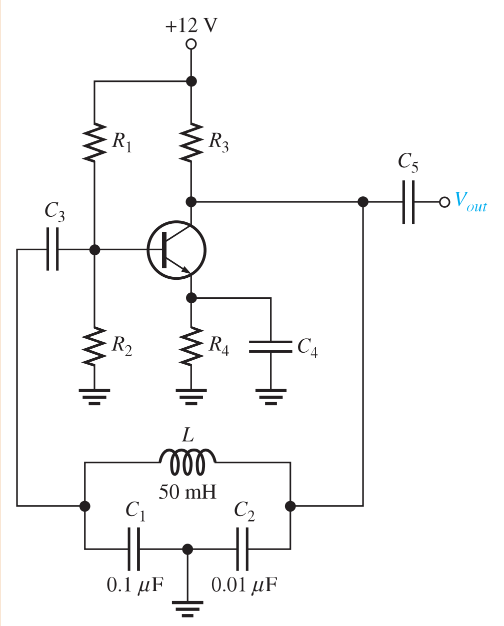
Oscillator loading.

EXAMPLE 16–3

(a) Determine the frequency for the oscillator in Figure 16–21. Assume there is negligible loading on the feedback circuit and that its Q is greater than 10.

(b) Find the frequency if the oscillator is loaded to a point where the Q drops to 8.

▶ FIGURE 16–21



Solution **(a)** $C_T = \dfrac{C_1 C_2}{C_1 + C_2} = \dfrac{(0.1\ \mu\text{F})(0.01\ \mu\text{F})}{0.11\ \mu\text{F}} = 0.0091\ \mu\text{F}$

$$f_r \cong \frac{1}{2\pi\sqrt{LC_T}} = \frac{1}{2\pi\sqrt{(50\text{ mH})(0.0091\ \mu\text{F})}} = \mathbf{7.46\ kHz}$$

(b) $f_r = \dfrac{1}{2\pi\sqrt{LC_T}}\sqrt{\dfrac{Q^2}{Q^2 + 1}} = (7.46\text{ kHz})(0.9923) = \mathbf{7.40\ kHz}$

Related Problem What frequency does the oscillator in Figure 16–21 produce if it is loaded to a point where $Q = 4$?

The Clapp Oscillator

The Clapp oscillator is a variation of the Colpitts. The basic difference is an additional capacitor, C_3, in series with the inductor in the resonant feedback circuit, as shown in Figure 16–22. Since C_3 is in series with C_1 and C_2 around the tank circuit, the total capacitance is

$$C_T = \frac{1}{\dfrac{1}{C_1} + \dfrac{1}{C_2} + \dfrac{1}{C_3}}$$

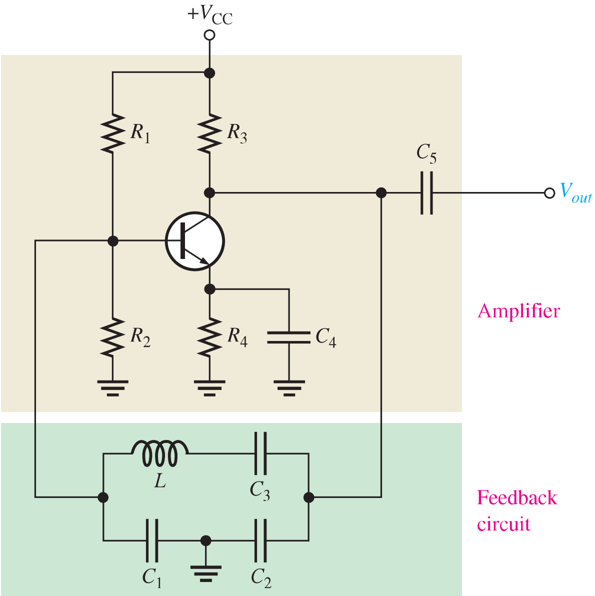
and the approximate frequency of oscillation ($Q > 10$) is

$$f_r \cong \frac{1}{2\pi\sqrt{LC_T}}$$

If C_3 is much smaller than C_1 and C_2, then C_3 almost entirely controls the resonant frequency ($f_r \cong 1/(2\pi\sqrt{LC_3})$). Since C_1 and C_2 are both connected to ground at one end, the junction capacitance of the transistor and other stray capacitances appear in parallel with C_1 and C_2 to ground, altering their effective values. C_3 is not affected, however, and thus provides a more accurate and stable frequency of oscillation.

▶ FIGURE 16–22

A basic Clapp oscillator.

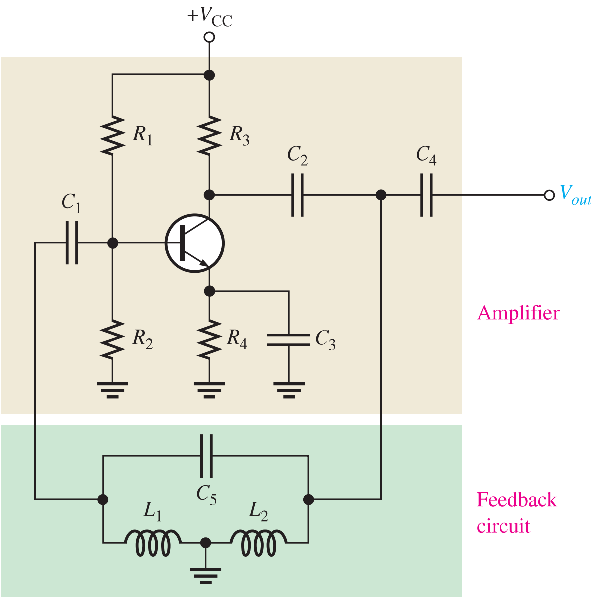


The Hartley Oscillator

The Hartley oscillator is similar to the Colpitts except that the feedback circuit consists of two series inductors and a parallel capacitor as shown in Figure 16–23.

▶ FIGURE 16–23

A basic Hartley oscillator.



HISTORY NOTE

Ralph Vinton Lyon Hartley (1888–1970) invented the Hartley oscillator and the Hartley transform, a mathematical analysis method, which contributed to the foundations of information theory. In 1915 he was in charge of radio receiver development for the Bell System transatlantic radiotelephone tests. During this time he developed the Hartley oscillator. A patent for the oscillator was filed in 1915 and awarded in 1920.

In this circuit, the frequency of oscillation for $Q > 10$ is

$$f_r \cong \frac{1}{2\pi\sqrt{L_T C}}$$

where $L_T = L_1 + L_2$. The inductors act in a role similar to C_1 and C_2 in the Colpitts to determine the attenuation, B, of the feedback circuit.

$$B \cong \frac{L_1}{L_2}$$

To assure start-up of oscillation, A_v must be greater than $1/B$.

$$A_v \cong \frac{L_2}{L_1}$$

Equation 16–8

Loading of the tank circuit has the same effect in the Hartley as in the Colpitts; that is, the Q is decreased and thus f_r decreases.

The Armstrong Oscillator

This type of LC feedback oscillator uses transformer coupling to feed back a portion of the signal voltage, as shown in Figure 16–24. It is sometimes called a "tickler" oscillator in reference to the transformer secondary or "tickler coil" that provides the feedback to keep the oscillation going. The Armstrong is less common than the Colpitts, Clapp, and Hartley, mainly because of the disadvantage of transformer size and cost. The frequency of oscillation is set by the inductance of the primary winding (L_{pri}) in parallel with C_1.

$$f_r = \frac{1}{2\pi\sqrt{L_{pri}C_1}}$$

Equation 16–9

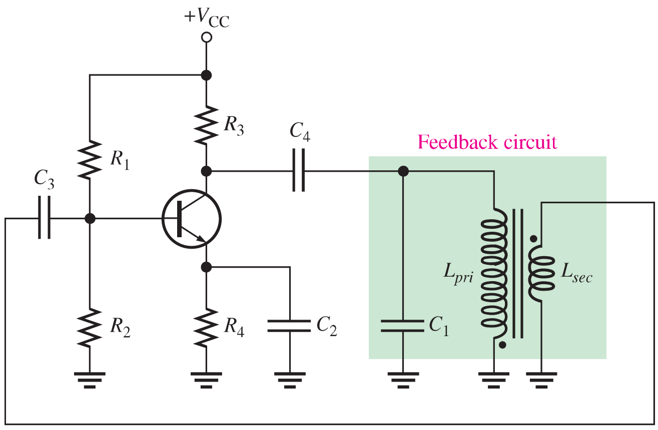


FIGURE 16–24

A basic Armstrong oscillator.

Crystal-Controlled Oscillators

The most stable and accurate type of feedback oscillator uses a piezoelectric **crystal** in the feedback loop to control the frequency.

The Piezoelectric Effect Quartz is one type of crystalline substance found in nature that exhibits a property called the **piezoelectric effect**. When a changing mechanical stress is applied across the crystal to cause it to vibrate, a voltage develops at the frequency of mechanical vibration. Conversely, when an ac voltage is applied across the crystal, it vibrates at the frequency of the applied voltage. The greatest vibration occurs at the crystal's natural resonant frequency, which is determined by the physical dimensions and by the way the crystal is cut.

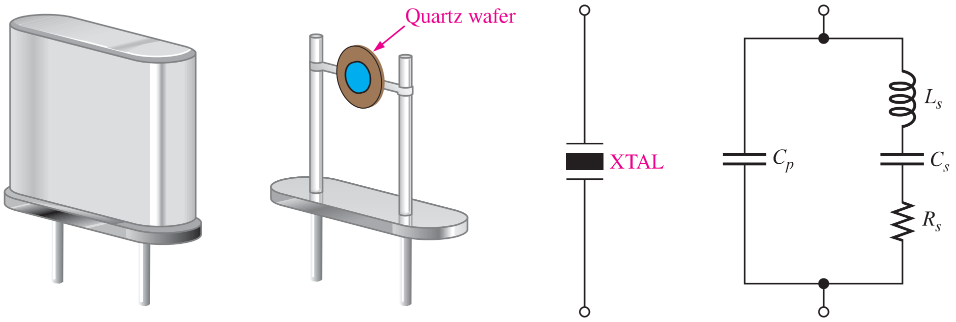
Crystals used in electronic applications typically consist of a quartz wafer mounted between two electrodes and enclosed in a protective "can" as shown in Figure 16–25(a) and (b). A schematic symbol for a crystal is shown in Figure 16–25(c), and an equivalent RLC circuit for the crystal appears in Figure 16–25(d). As you can see, the crystal's equivalent circuit is a series-parallel RLC circuit and can operate in either series resonance or parallel resonance. At the series resonant frequency, the inductive reactance is cancelled by the reactance of C_s. The remaining series resistor, R_s, determines the impedance of the crystal. Parallel resonance occurs when the inductive reactance and the reactance of the parallel capacitance, C_p, are equal. The parallel resonant frequency is usually at least 1 kHz higher

HISTORY NOTE

Edwin Howard Armstrong (1890–1954) was an American electrical engineer and inventor. He was the inventor of the FM radio. Armstrong also invented the regenerative circuit (patented 1914), the superheterodyne receiver (patented 1918) and the superregenerative circuit (patented 1922). Many of Armstrong's inventions were ultimately claimed by others in patent lawsuits. The Armstrong oscillator is named in his honor.

▶ FIGURE 16–25

A quartz crystal.



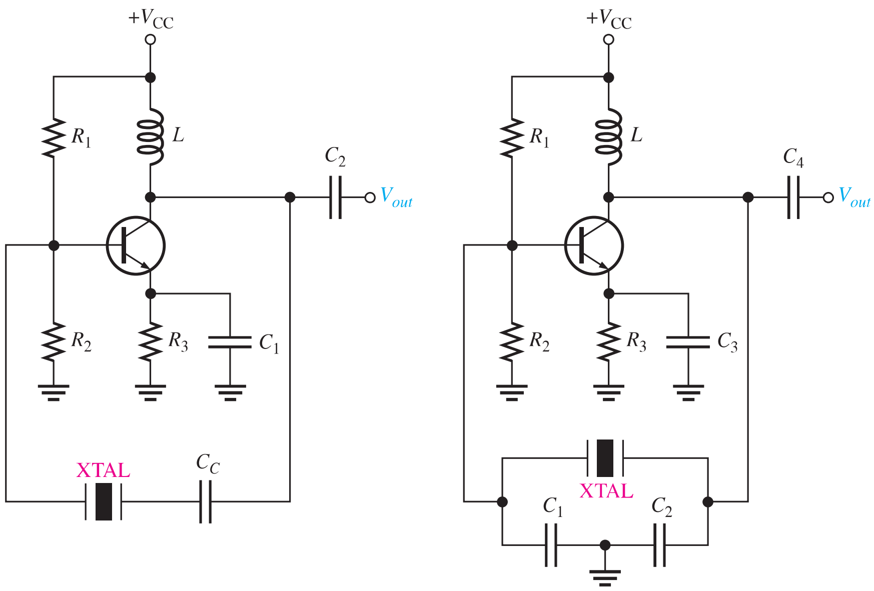
(a) Typical packaged crystal (b) Basic construction (without case) (c) Symbol (d) Electrical equivalent

than the series resonant frequency. A great advantage of the crystal is that it exhibits a very high Q (Qs with values of several thousand are typical).

An oscillator that uses a crystal as a series resonant tank circuit is shown in Figure 16–26(a). The impedance of the crystal is minimum at the series resonant frequency, thus providing maximum feedback. The crystal tuning capacitor, C_C, is used to "fine tune" the oscillator frequency by "pulling" the resonant frequency of the crystal slightly up or down.

▶ FIGURE 16–26

Basic crystal oscillators.



(a) (b)

A modified Colpitts configuration is shown in Figure 16–26(b) with a crystal acting as a parallel resonant tank circuit. The impedance of the crystal is maximum at parallel resonance, thus developing the maximum voltage across the capacitors. The voltage across C_1 is fed back to the input.

Modes of Oscillation in the Crystal Piezoelectric crystals can oscillate in either of two modes—fundamental or overtone. The fundamental frequency of a crystal is the lowest frequency at which it is naturally resonant. The fundamental frequency depends on the crystal's mechanical dimensions, type of cut, and other factors, and is inversely proportional to the thickness of the crystal slab. Because a slab of crystal cannot be cut too thin without fracturing, there is an upper limit on the fundamental frequency. For most crystals, this upper limit is less than 20 MHz. For higher frequencies, the crystal must be operated in the overtone mode. Overtones are approximate integer multiples of the fundamental frequency. The overtone frequencies are usually, but not always, odd multiples (3, 5, 7, . . .) of the fundamental. Many crystal oscillators are available in integrated circuit packages.

SECTION 16–4 CHECKUP

1. What is the basic difference between the Colpitts and the Hartley oscillators?
2. What is the advantage of a FET amplifier in a Colpitts or Hartley oscillator?
3. How can you distinguish a Colpitts oscillator from a Clapp oscillator?

16–5 RELAXATION OSCILLATORS

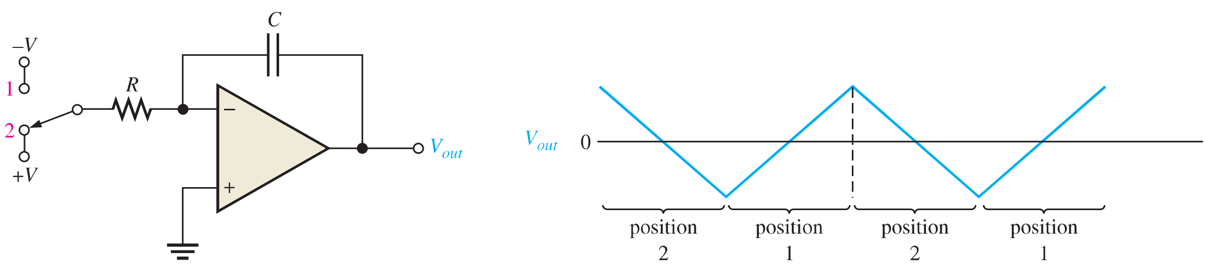
The second major category of oscillators is the relaxation oscillator. Relaxation oscillators use an *RC* timing circuit and a device that changes states to generate a periodic waveform. In this section, you will learn about several circuits that are used to produce nonsinusoidal waveforms.

After completing this section, you should be able to

- **Describe and analyze the operation of relaxation oscillators**
- Describe the operation of a triangular-wave oscillator
  - Discuss a practical triangular-wave oscillator ◆ Define *function generator*
  - Determine the UTP, LTP, and frequency of oscillation
- Describe a sawtooth voltage-controlled oscillator (VCO)
  - Explain the purpose of the PUT in this circuit ◆ Determine the frequency of oscillation
- Describe a square-wave oscillator

A Triangular-Wave Oscillator

The op-amp integrator covered in Chapter 13 can be used as the basis for a triangular-wave oscillator. The basic idea is illustrated in Figure 16–27(a) where a dual-polarity, switched input is used. We use the switch only to introduce the concept; it is not a practical way to implement this circuit. When the switch is in position 1, the negative voltage is applied, and the output is a positive-going ramp. When the switch is thrown into position 2, a negative-going ramp is produced. If the switch is thrown back and forth at fixed intervals, the output is a triangular wave consisting of alternating positive-going and negative-going ramps, as shown in Figure 16–27(b).



(a)

(b) Output voltage as the switch is thrown back and forth at regular intervals

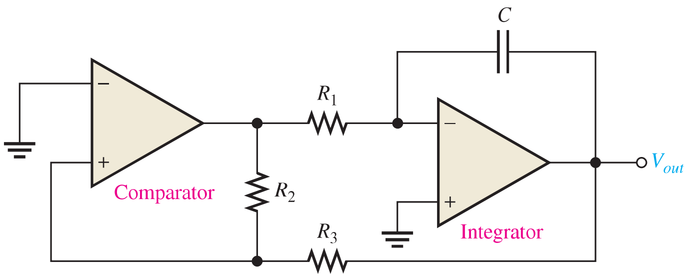
▲ FIGURE 16–27

Basic triangular-wave oscillator.

A Practical Triangular-Wave Oscillator One practical implementation of a triangular-wave oscillator utilizes an op-amp comparator with hysteresis to perform the switching function, as shown in Figure 16–28. The operation is as follows. To begin, assume that the output voltage of the comparator is at its maximum negative level. This output is connected to the inverting input of the integrator through R_1, producing a positive-going ramp on the output of the integrator. When the ramp voltage reaches the upper trigger point (UTP), the comparator switches to its maximum positive level. This positive level causes the integrator ramp to change to a negative-going direction. The ramp continues in this direction until the lower trigger point (LTP) of the comparator is reached. At this point, the comparator output switches back to the maximum negative level and the cycle repeats. This action is illustrated in Figure 16–29.

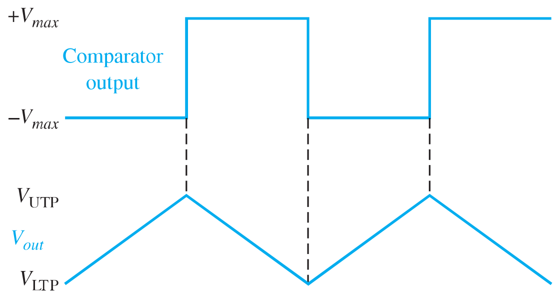
▶ FIGURE 16–28

A triangular-wave oscillator using two op-amps.



▶ FIGURE 16–29

Waveforms for the circuit in Figure 16–28.



Since the comparator produces a square-wave output, the circuit in Figure 16–28 can be used as both a triangular-wave oscillator and a square-wave oscillator. Devices of this type are commonly known as **function generators** because they produce more than one output function. The output amplitude of the square wave is set by the output swing of the comparator, and the resistors R_2 and R_3 set the amplitude of the triangular output by establishing the UTP and LTP voltages according to the following formulas:

$$V_{\text{UTP}} = +V_{max}\left(\frac{R_3}{R_2}\right)$$

$$V_{\text{LTP}} = -V_{max}\left(\frac{R_3}{R_2}\right)$$

where the comparator output levels, $+V_{max}$ and $-V_{max}$, are equal. The frequency of both waveforms depends on the R_1C time constant as well as the amplitude-setting resistors, R_2 and R_3. By varying R_1, the frequency of oscillation can be adjusted without changing the output amplitude.

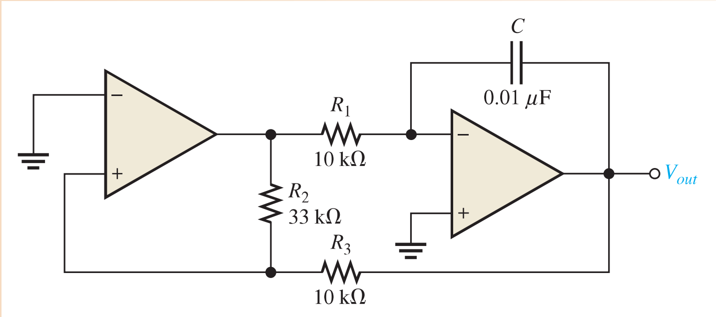
Equation 16–10

$$f_r = \frac{1}{4R_1C}\left(\frac{R_2}{R_3}\right)$$

EXAMPLE 16–4

Determine the frequency of oscillation of the circuit in Figure 16–30. To what value must R_1 be changed to make the frequency 20 kHz?

▶ FIGURE 16–30



Solution

$$f_r = \frac{1}{4R_1C}\left(\frac{R_2}{R_3}\right) = \left(\frac{1}{4(10\text{ k}\Omega)(0.01\ \mu\text{F})}\right)\left(\frac{33\text{ k}\Omega}{10\text{ k}\Omega}\right) = \mathbf{8.25\ kHz}$$

To make $f = 20$ kHz,

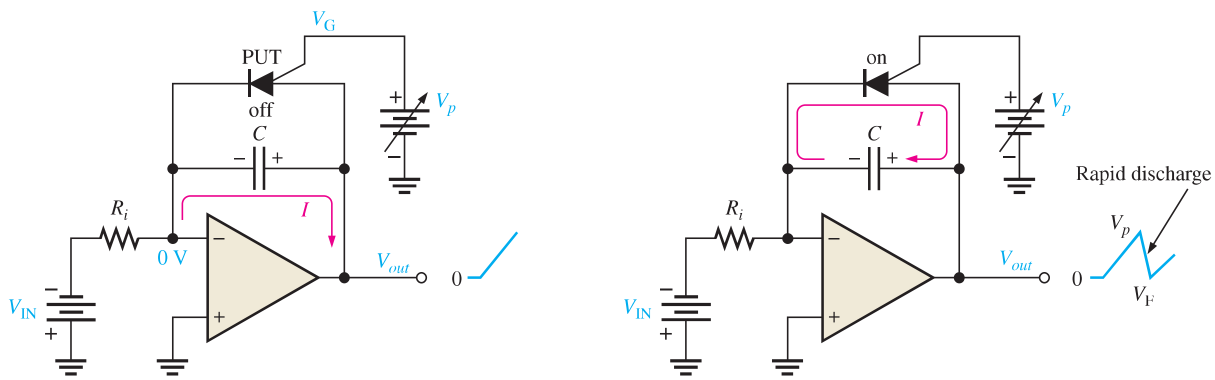
$$R_1 = \frac{1}{4fC}\left(\frac{R_2}{R_3}\right) = \left(\frac{1}{4(20\text{ kHz})(0.01\ \mu\text{F})}\right)\left(\frac{33\text{ k}\Omega}{10\text{ k}\Omega}\right) = \mathbf{4.13\ k\Omega}$$

Related Problem What is the amplitude of the triangular wave in Figure 16–30 if the comparator output is ±10 V?

A Sawtooth Voltage-Controlled Oscillator (VCO)

The **voltage-controlled oscillator (VCO)** is a relaxation oscillator whose frequency can be changed by a variable dc control voltage. VCOs can be either sinusoidal or nonsinusoidal. One way to build a sawtooth VCO is with an op-amp integrator that uses a switching device (PUT) in parallel with the feedback capacitor to terminate each ramp at a prescribed level and effectively “reset” the circuit. Figure 16–31(a) shows the implementation.

As you learned in Chapter 11, the PUT is a programmable unijunction transistor with an anode, a cathode, and a gate terminal. The gate is always biased positively with respect to



(a) Initially, the capacitor charges, the output ramp begins, and the PUT is off.

(b) The capacitor rapidly discharges when the PUT momentarily turns on.

▲ FIGURE 16–31

Sawtooth VCO operation.

the cathode. When the anode voltage exceeds the gate voltage by approximately 0.7 V, the PUT turns on and acts as a forward-biased diode. When the anode voltage falls below this level, the PUT turns off. Also, the current must be above the holding value to maintain conduction.

The operation of the sawtooth VCO begins when the negative dc input voltage, $-V_{IN}$, produces a positive-going ramp on the output. During the time that the ramp is increasing, the circuit acts as a regular integrator. The PUT triggers on when the output ramp (at the anode) exceeds the gate voltage by 0.7 V. The gate is set to the approximate desired sawtooth peak voltage. When the PUT turns on, the capacitor rapidly discharges, as shown in Figure 16–31(b). The capacitor does not discharge completely to zero because of the PUT's forward voltage, V_F. Discharge continues until the PUT current falls below the holding value. At this point, the PUT turns off and the capacitor begins to charge again, thus generating a new output ramp. The cycle continually repeats, and the resulting output is a repetitive sawtooth waveform, as shown. The sawtooth amplitude and period can be adjusted by varying the PUT gate voltage.

The frequency of oscillation is determined by the R_iC time constant of the integrator and the peak voltage set by the PUT. Recall that the charging rate of a capacitor is V_{IN}/R_iC. The time it takes a capacitor to charge from V_F to V_p is the period, T, of the sawtooth waveform (neglecting the rapid discharge time).

$$T = \frac{V_p - V_F}{|V_{IN}|/R_iC}$$

From $f = 1/T$,

Equation 16–11

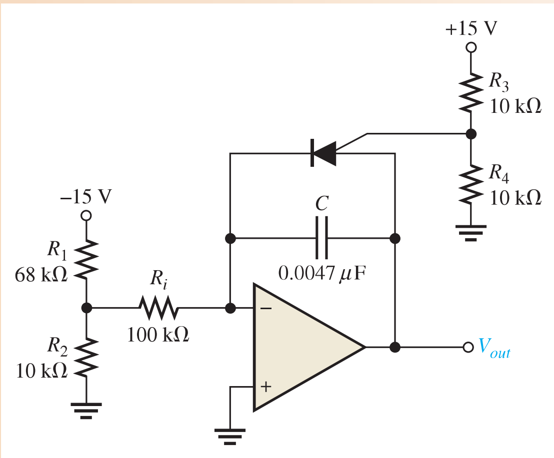
$$\boldsymbol{f = \frac{|V_{IN}|}{R_iC}\left(\frac{1}{V_p - V_F}\right)}$$

EXAMPLE 16–5

(a) Find the amplitude and frequency of the sawtooth output in Figure 16–32. Assume that the forward PUT voltage, V_F, is approximately 1 V.

(b) Sketch the output waveform.

▶ FIGURE 16–32



Solution **(a)** First, find the gate voltage in order to establish the approximate voltage at which the PUT turns on.

$$V_G = \frac{R_4}{R_3 + R_4}(+V) = \frac{10\ k\Omega}{20\ k\Omega}(15\ V) = 7.5\ V$$

This voltage sets the approximate maximum peak value of the sawtooth output (neglecting the 0.7 V).

$$V_p \cong 7.5\text{ V}$$

The minimum peak value (low point) is

$$V_F \cong 1\text{ V}$$

So the peak-to-peak amplitude is

$$V_{pp} = V_p - V_F = 7.5\text{ V} - 1\text{ V} = \mathbf{6.5\ V}$$

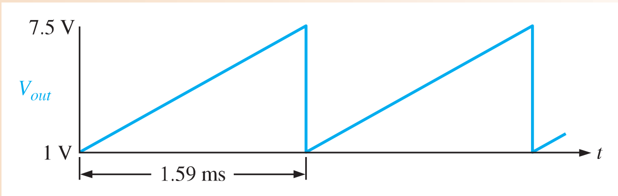
Determine the frequency as follows:

$$V_{IN} = \frac{R_2}{R_1 + R_2}(-V) = \frac{10\text{ k}\Omega}{78\text{ k}\Omega}(-15\text{ V}) = -1.92\text{ V}$$

$$f = \frac{|V_{IN}|}{R_iC}\left(\frac{1}{V_p - V_F}\right) = \left(\frac{1.92\text{ V}}{(100\text{ k}\Omega)(0.0047\mu\text{F})}\right)\left(\frac{1}{7.5\text{ V} - 1\text{ V}}\right) = \mathbf{628\ Hz}$$

(b) The output waveform is shown in Figure 16–33, where the period is determined as follows:

$$T = \frac{1}{f} = \frac{1}{628\text{ Hz}} = 1.59\text{ ms}$$



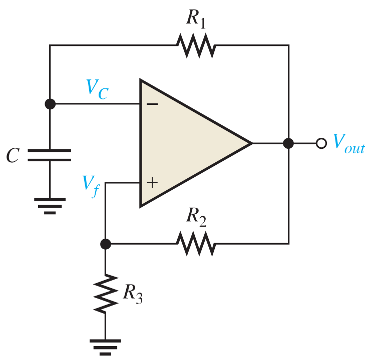
▲ **FIGURE 16–33**

Output of the circuit in Figure 16–32.

Related Problem If R_i is changed to 56 kΩ in Figure 16–32, what is the frequency?

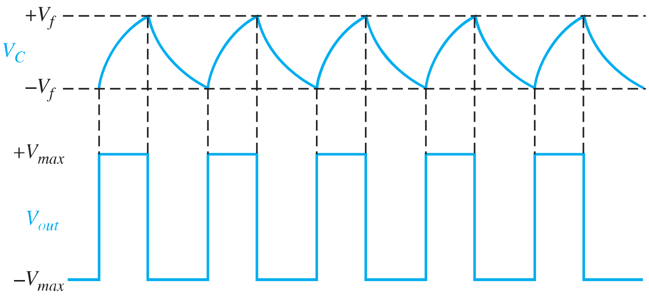
A Square-Wave Oscillator

The basic square-wave oscillator shown in Figure 16–34 is a type of relaxation oscillator because its operation is based on the charging and discharging of a capacitor. Notice that the op-amp's inverting input is the capacitor voltage and the noninverting input is a portion of the output fed back through resistors R_2 and R_3 to provide hysteresis. When the circuit is first turned on, the capacitor is uncharged, and thus the inverting input is at 0 V. This makes the output a positive maximum, and the capacitor begins to charge toward V_{out} through R_1. When the capacitor voltage (V_C) reaches a value equal to the feedback voltage (V_f) on the noninverting input, the op-amp switches to the maximum negative state. At this point, the capacitor begins to discharge from $+V_f$ toward $-V_f$. When the capacitor voltage reaches $-V_f$, the op-amp switches back to the maximum positive state. This action continues to repeat, as shown in Figure 16–35, and a square-wave output voltage is obtained.



▲ **FIGURE 16–34**

A square-wave relaxation oscillator.



▶ FIGURE 16–35

Waveforms for the square-wave relaxation oscillator.

SECTION 16–5 CHECKUP

1. What is a VCO, and basically, what does it do?
2. Upon what principle does a relaxation oscillator operate?

16–6 THE 555 TIMER AS AN OSCILLATOR

The 555 timer is a versatile integrated circuit with many applications. In this section, you will see how the 555 is configured as an astable or free-running multivibrator, which is essentially a square-wave oscillator. The use of the 555 timer as a voltage-controlled oscillator (VCO) is also discussed.

After completing this section, you should be able to

- **Discuss and analyze the 555 timer and use it in oscillator applications**
- Describe the astable operation of a 555 timer
  - Determine the frequency of oscillation
  - Determine the duty cycle
- Discuss the 555 timer as a voltage-controlled oscillator
  - Describe the connections

The 555 timer consists basically of two comparators, a flip-flop, a discharge transistor, and a resistive voltage divider, as shown in Figure 16–36. The flip-flop (bistable multivibrator) is a digital device that may be unfamiliar to you at this point unless you already have taken a digital fundamentals course. Briefly, it is a two-state device whose output can be at either a high voltage level (set, *S*) or a low voltage level (reset, *R*). The state of the output can be changed with proper input signals.

The resistive voltage divider is used to set the voltage comparator levels. All three resistors are of equal value; therefore, the upper comparator has a reference of $\frac{2}{3}V_{CC}$, and the lower comparator has a reference of $\frac{1}{3}V_{CC}$. The comparators' outputs control the state of the flip-flop. When the trigger voltage goes below $\frac{1}{3}V_{CC}$, the flip-flop sets and the output jumps to its high level. The threshold input is normally connected to an external *RC* timing circuit. When the external capacitor voltage exceeds $\frac{2}{3}V_{CC}$, the upper comparator resets the flip-flop, which in turn switches the output back to its low level. When the device output is low, the discharge transistor (Q_d) is turned on and provides a path for rapid discharge of the external timing capacitor. This basic operation allows the timer to be configured with external components as an oscillator, a one-shot, or a time-delay element.

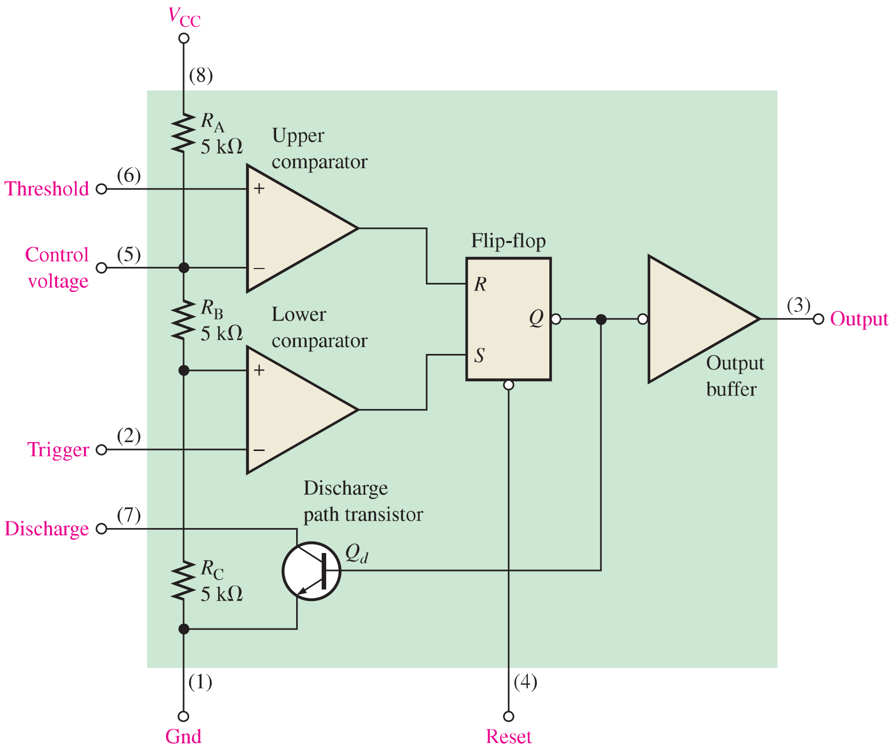


FIGURE 16–36

Internal diagram of a 555 integrated circuit timer. (IC pin numbers are in parentheses.)

Astable Operation

A 555 timer connected to operate in the **astable** mode as a free-running relaxation oscillator (astable multivibrator) is shown in Figure 16–37. Notice that the threshold input (THRESH) is now connected to the trigger input (TRIG). The external components R_1, R_2, and C_{ext} form the timing circuit that sets the frequency of oscillation. The 0.01 μF capacitor connected to the control (CONT) input is strictly for decoupling and has no effect on the operation.

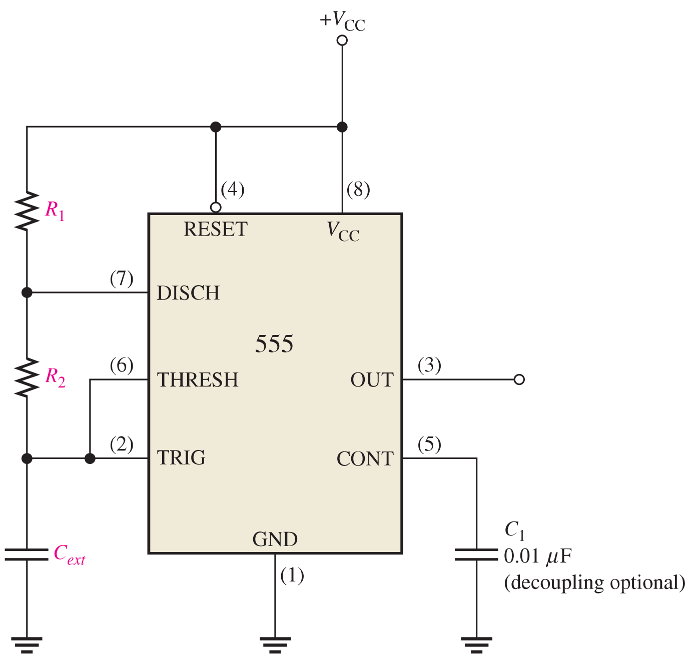
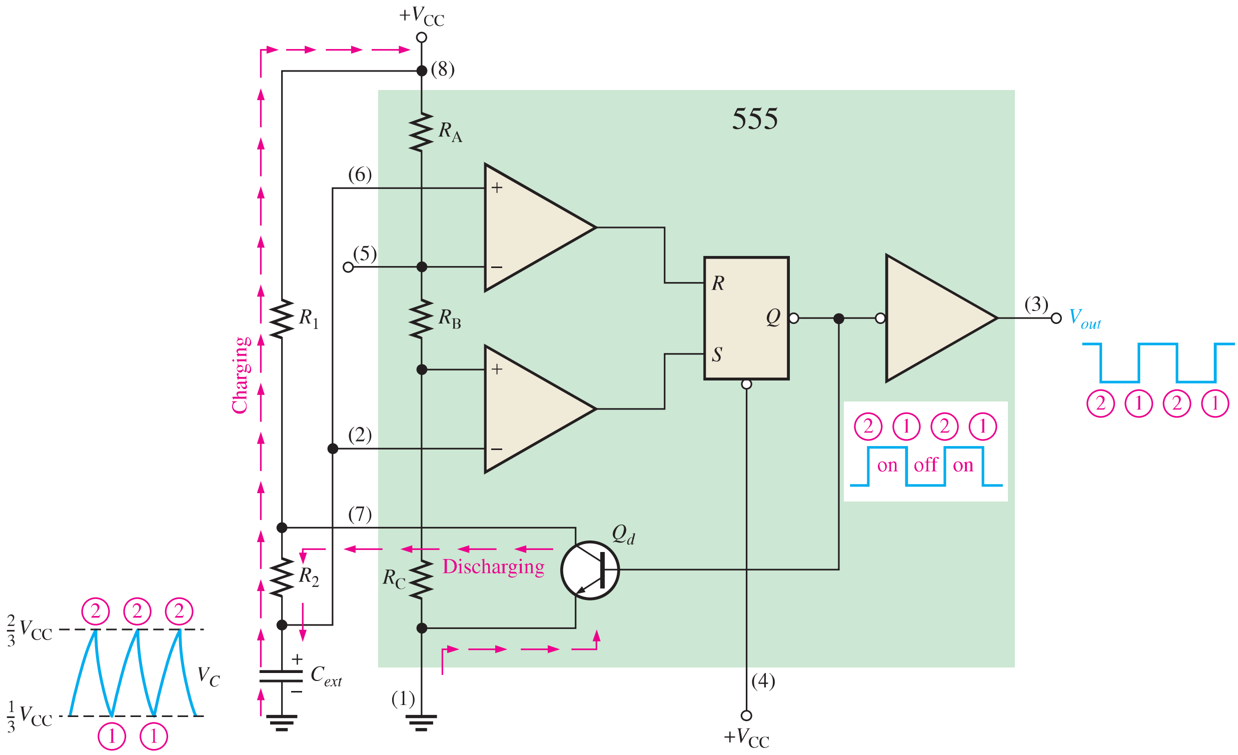


FIGURE 16–37

The 555 timer connected as an astable multivibrator.

Initially, when the power is turned on, the capacitor C_{ext} is uncharged and thus the trigger voltage (pin 2) is at 0 V. This causes the output of the lower comparator to be high and the output of the upper comparator to be low, forcing the output of the flip-flop, and thus the base of Q_d, low and keeping the transistor off. Now, C_{ext} begins charging through R_1 and R_2 as indicated in Figure 16–38. When the capacitor voltage reaches $\frac{1}{3}V_{CC}$, the lower comparator switches to its low output state, and when the capacitor voltage reaches $\frac{2}{3}V_{CC}$, the upper comparator switches to its high output state. This resets the flip-flop, causes the base of Q_d to go high, and turns on the transistor. This sequence creates a discharge path for the capacitor through R_2 and the transistor, as indicated. The capacitor now begins to discharge, causing the upper comparator to go low. At the point where the capacitor discharges down to $\frac{1}{3}V_{CC}$, the lower comparator switches high, setting the flip-flop, which makes the base of Q_d low and turns off the transistor. Another charging cycle begins, and the entire process repeats. The result is a rectangular wave output whose duty cycle depends on the values of R_1 and R_2.



▲ **FIGURE 16–38**

Operation of the 555 timer in the astable mode.

The frequency of oscillation is given by Equation 16–12, or it can be found using the graph in Figure 16–39.

Equation 16–12

$$f_r = \frac{\mathbf{1.44}}{(R_1 + 2R_2)C_{ext}}$$

By selecting R_1 and R_2, the duty cycle of the output can be adjusted. Since C_{ext} charges through $R_1 + R_2$ and discharges only through R_2, duty cycles approaching a minimum of 50 percent can be achieved if $R_2 >> R_1$ so that the charging and discharging times are approximately equal.

A formula to calculate the duty cycle is developed as follows. The time that the output is high (t_H) is how long it takes C_{ext} to charge from $\frac{1}{3}V_{CC}$ to $\frac{2}{3}V_{CC}$. It is expressed as

$$t_H = 0.694(R_1 + R_2)C_{ext}$$

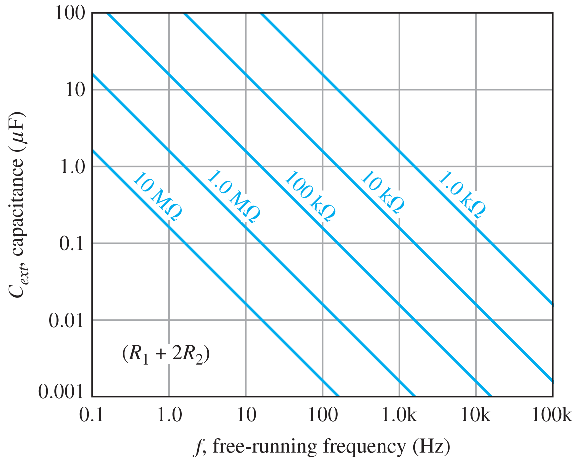


FIGURE 16–39

Frequency of oscillation (free-running frequency) of a 555 timer in the astable mode as a function of C_{ext} and $R_1 + 2R_2$. The sloped lines are values of $R_1 + 2R_2$.

The time that the output is low (t_L) is how long it takes C_{ext} to discharge from ⅔V_{CC} to ⅓V_{CC}. It is expressed as

$$t_L = 0.694R_2C_{ext}$$

The period, T, of the output waveform is the sum of t_H and t_L. The following formula for T is the reciprocal of f in Equation 16–12.

$$T = t_H + t_L = 0.694(R_1 + 2R_2)C_{ext}$$

Finally, the percent duty cycle is

$$\text{Duty cycle} = \left(\frac{t_H}{T}\right)100\% = \left(\frac{t_H}{t_H + t_L}\right)100\%$$

$$\textbf{Duty cycle} = \left(\frac{\boldsymbol{R_1 + R_2}}{\boldsymbol{R_1 + 2R_2}}\right)\mathbf{100\%}$$

Equation 16–13

To achieve duty cycles of less than 50 percent, the circuit in Figure 16–37 can be modified so that C_{ext} charges through only R_1 and discharges through R_2. This is achieved with a diode, D_1, placed as shown in Figure 16–40. The duty cycle can be made less than 50

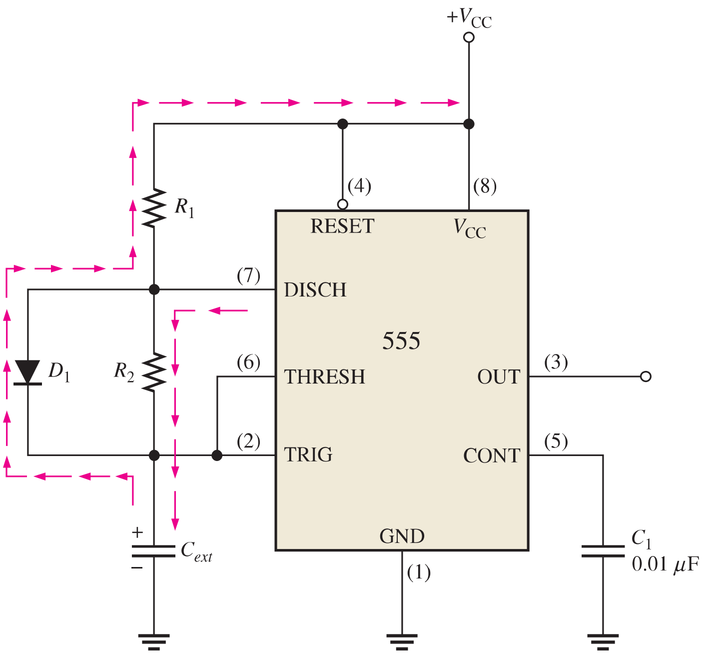


FIGURE 16–40

The addition of diode D_1 allows the duty cycle of the output to be adjusted to less than 50 percent by making $R_1 < R_2$.

percent by making R_1 less than R_2. Under this condition, the formulas for the frequency and percent duty cycle are (assuming an ideal diode)

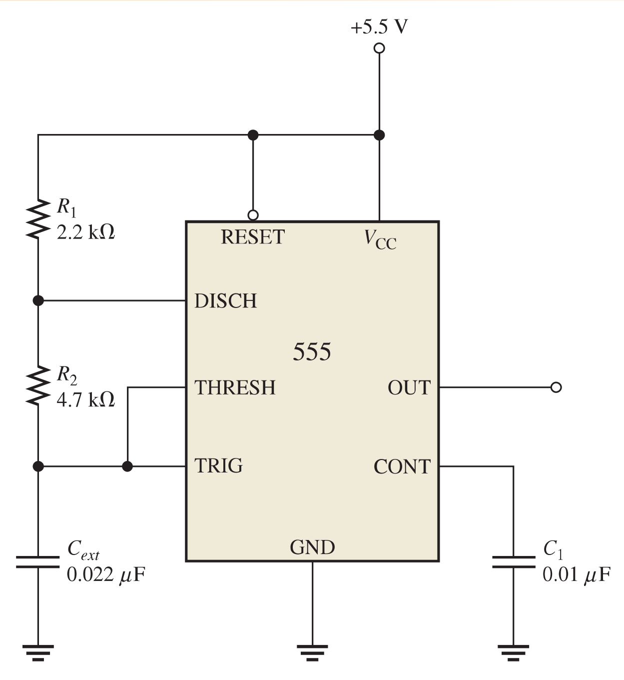
$$f_r \cong \frac{1.44}{(R_1 + R_2)\, C_{ext}}$$

$$\text{Duty cycle} \cong \left(\frac{R_1}{R_1 + R_2}\right)100\%$$

EXAMPLE 16–6

A 555 timer configured to run in the astable mode (oscillator) is shown in Figure 16–41. Determine the frequency of the output and the duty cycle.

▶ FIGURE 16–41



Solution

$$f_r = \frac{1.44}{(R_1 + 2R_2)C_{ext}} = \frac{1.44}{(2.2\text{ k}\Omega + 9.4\text{ k}\Omega)0.022\ \mu\text{F}} = \mathbf{5.64\ kHz}$$

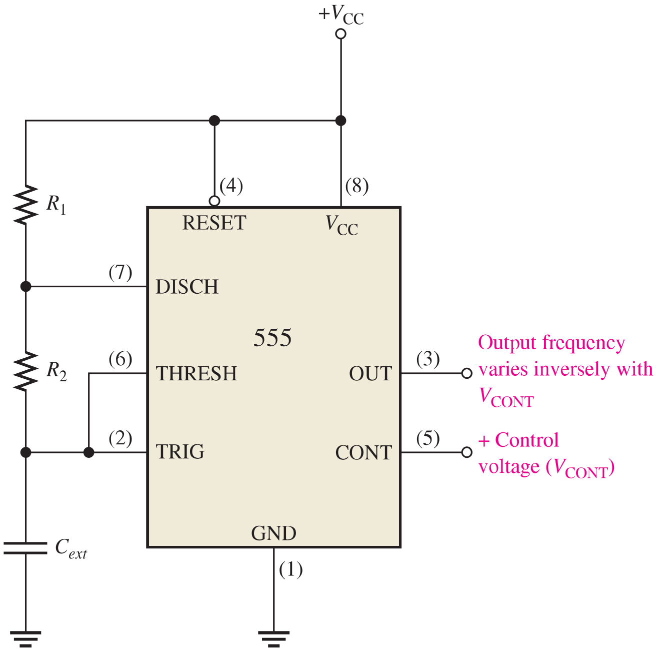
$$\text{Duty cycle} = \left(\frac{R_1 + R_2}{R_1 + 2R_2}\right)100\% = \left(\frac{2.2\text{ k}\Omega + 4.7\text{ k}\Omega}{2.2\text{ k}\Omega + 9.4\text{ k}\Omega}\right)100\% = \mathbf{59.5\%}$$

Related Problem Determine the duty cycle in Figure 16–41 if a diode is connected across R_2 as indicated in Figure 16–40.

Operation as a Voltage-Controlled Oscillator (VCO)

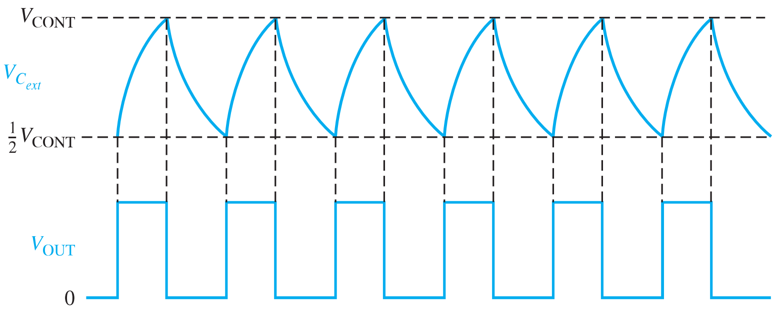
A 555 timer can be set up to operate as a VCO by using the same external connections as for astable operation, with the exception that a variable control voltage is applied to the CONT input (pin 5), as indicated in Figure 16–42.

As shown in Figure 16–43, the control voltage (V_{CONT}) changes the threshold values of $\frac{1}{3}V_{CC}$ and $\frac{2}{3}V_{CC}$ for the internal comparators. With the control voltage, the upper value is V_{CONT} and the lower value is $\frac{1}{2}V_{CONT}$, as you can see by examining the internal diagram of the 555 timer. When the control voltage is varied, the output frequency also varies. An



▲ **FIGURE 16–42**

The 555 timer connected as a voltage-controlled oscillator (VCO). Note the variable control voltage input on pin 5.



▲ **FIGURE 16–43**

The VCO output frequency varies inversely with V_{CONT} because the charging and discharging time of C_{ext} is directly dependent on the control voltage.

increase in V_{CONT} increases the charging and discharging time of the external capacitor and causes the frequency to decrease. A decrease in V_{CONT} decreases the charging and discharging time of the capacitor and causes the frequency to increase.

An interesting application of the VCO is in phase-locked loops, which are used in various types of communication receivers to track variations in the frequency of incoming signals.

SECTION 16–6 CHECKUP

1. Name the five basic elements in a 555 timer IC.
2. When the 555 timer is configured as an astable multivibrator, how is the duty cycle determined?