CHAPTER 16
OSCILLATORS

16-1 THE OSCILLATOR

- **Oscillators** are electronic circuits that generate an output signal without the necessity of an input signal.
- It produces a periodic waveform on its output **with only the DC supply voltage as an input**.
- The output voltage can be either sinusoidal or nonsinusoidal, depending on the type of oscillator.
- Different types of oscillators produce various types of outputs including sine waves, square waves, triangular waves, and sawtooth waves.
- A basic oscillator is shown in Figure 1.

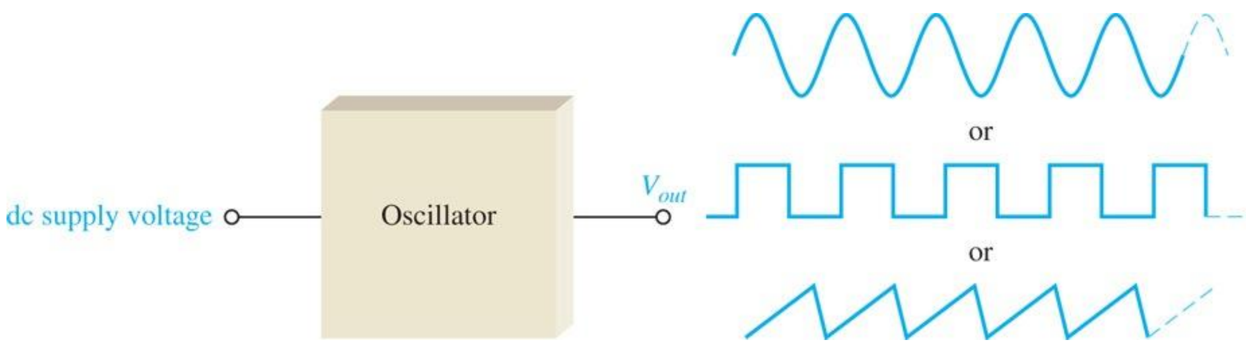


Figure 1 The basic oscillator concept showing three common types of output wave-forms: sine wave, square wave, and sawtooth.

- Oscillators can be of 2 types.

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 2.

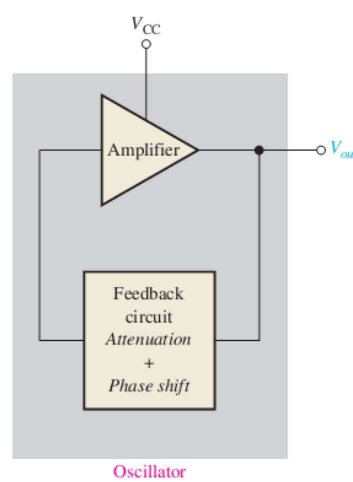


Figure 2 Basic elements of a feedback oscillator.

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.

16-2 FEEDBACK OSCILLATORS

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

16.2.1 Positive Feedback

- In **positive feedback,** a portion of the output voltage of an amplifier is fed back to the input with no net phase shift, resulting in a strengthening of the output signal.
- This basic idea is illustrated in Figure 3(a).

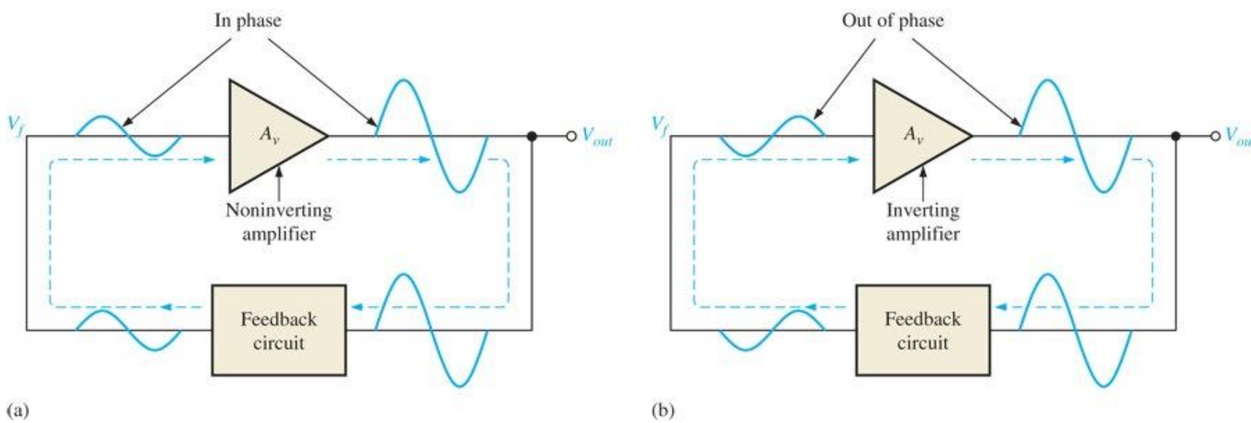


Figure 3 Positive feedback produces oscillation.

- As you can see, the in-phase feedback voltage is amplified to produce the output voltage, which in turn produces the feedback voltage.
- That is, a loop is created in which the signal maintains itself and a continuous sinusoidal output is produced.
- This phenomenon is called **oscillation**.
- In some types of amplifiers, the feedback circuit shifts the phase and an inverting amplifier is required to provide another phase shift so that there is no net phase shift.
- This is illustrated in Figure 3(b).

16.2.2 Conditions for Oscillation

- Two conditions, illustrated in Figure 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).

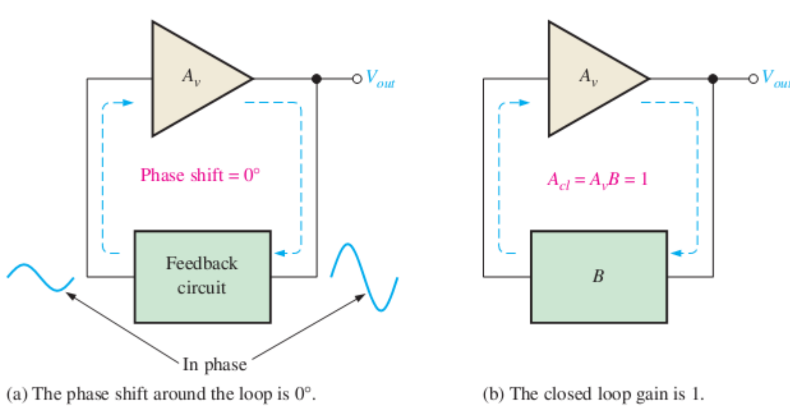


Figure 4 General conditions to sustain oscillation.

- 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 $(100 \times 0.01 = 1)$.
- An amplifier gain of greater than 100 will cause the oscillator to limit both peaks of the waveform.

16.2.3 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 maintained.
- 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.
- The voltage gain conditions for both starting and sustaining oscillation are illustrated in Figure 5.

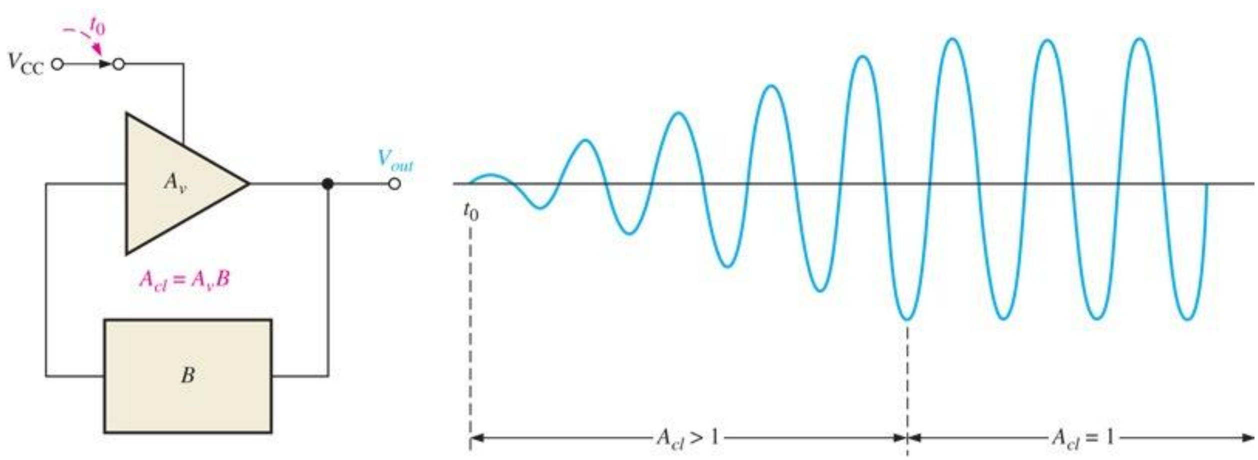


Figure 5 When oscillation starts at t_0, the condition $A_{cl} > 1$ causes the sinusoidal output voltage amplitude to build up to a desired level. Then A_{cl} decreases to 1 and maintains the desired amplitude.

16-3 OSCILLATION WITH *RC* FEEDBACK CIRCUITS

- Three types of feedback oscillators that use RC circuits to produce sinusoidal outputs are the
  - **Wien-bridge oscillator**
  - **Phase-shift oscillator**
  - **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.

16.3.1 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 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 takes over 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.

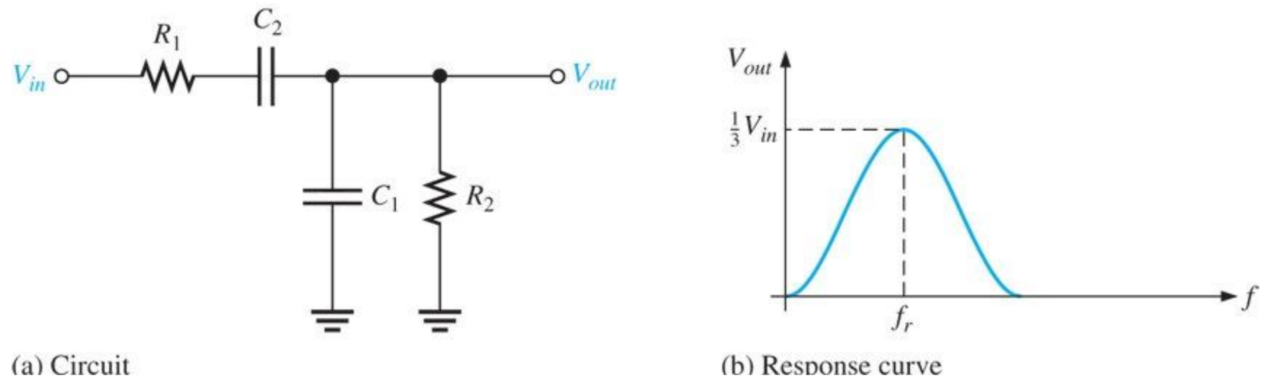


Figure 6 A lead-lag circuit and its response curve.

- The response curve for the lead-lag circuit shown in Figure 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

$$\frac{V_{out}}{V_{in}} = \frac{1}{3}$$

- The formula for the resonant frequency is

$$f_r = \frac{1}{2\pi RC}$$

- 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 7(a).
- A voltage divider is used in the negative feedback loop.
- 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 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.

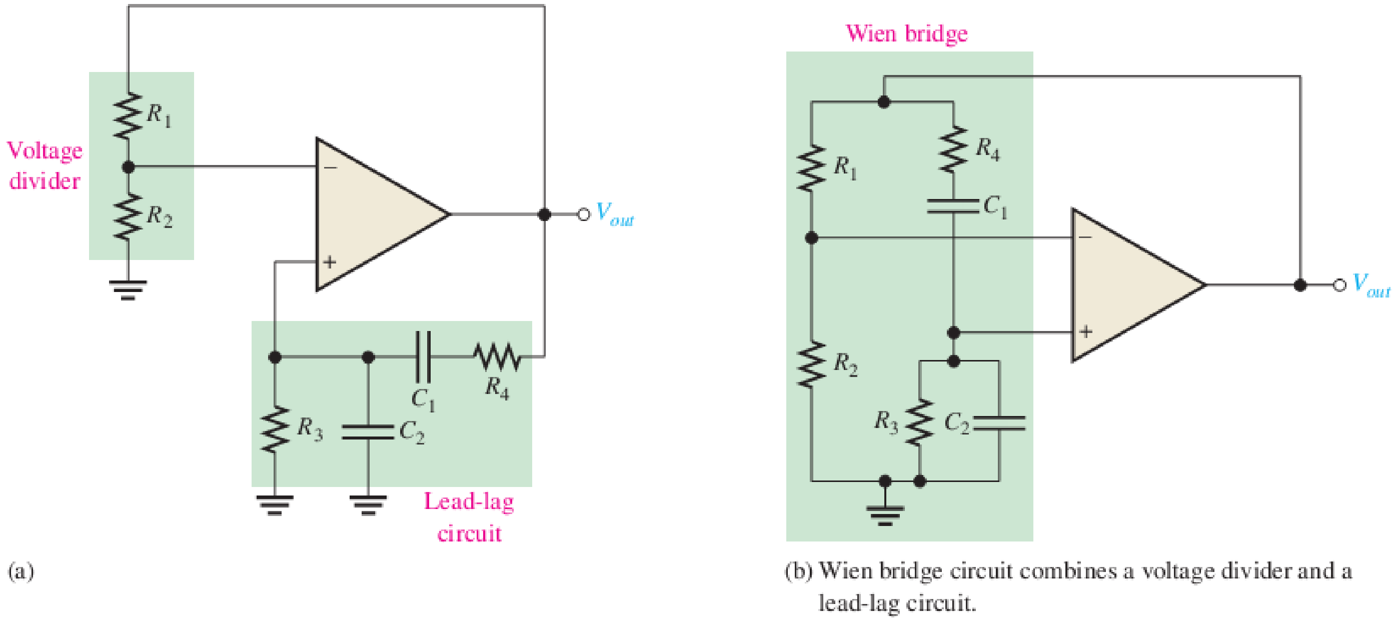


Figure 7 The Wien-bridge oscillator schematic drawn in two different but equivalent ways.

Positive Feedback Conditions for Oscillation

- As you know, for the circuit output to 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 8(a).

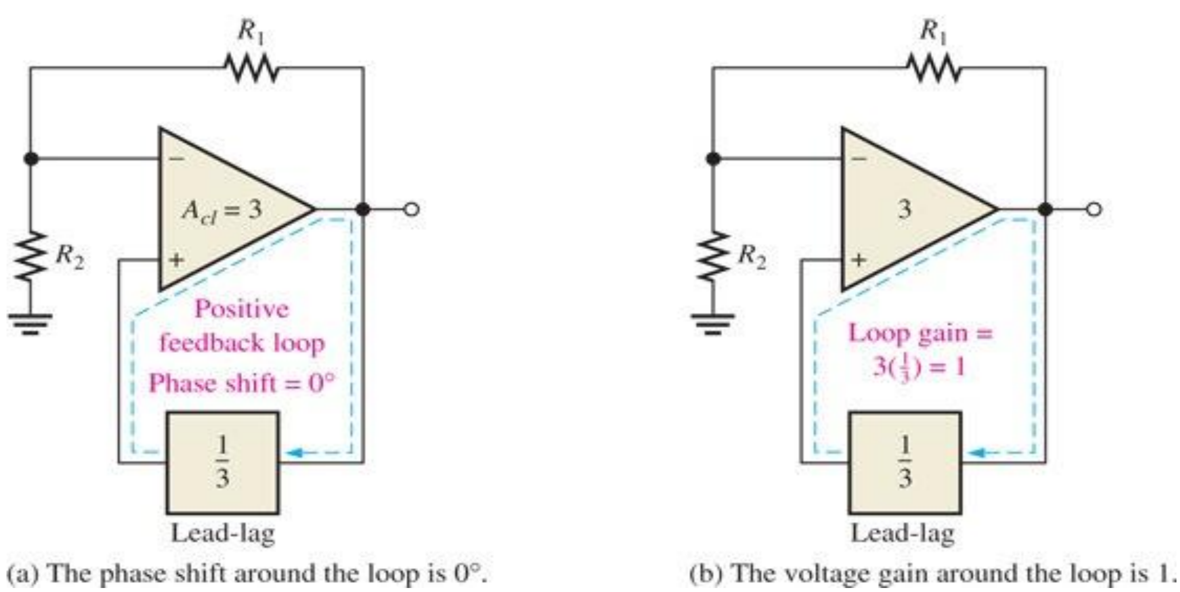


Figure 8 Conditions for sustained oscillation.

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

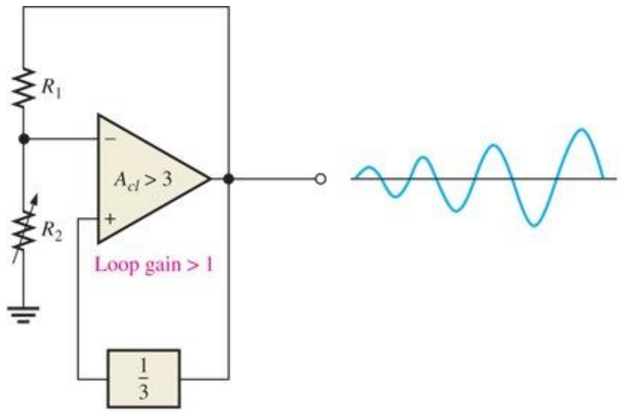
$$A_{cl} = 3$$

- 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 shown in Figure 8(b).
- To achieve a closed-loop gain of 3,

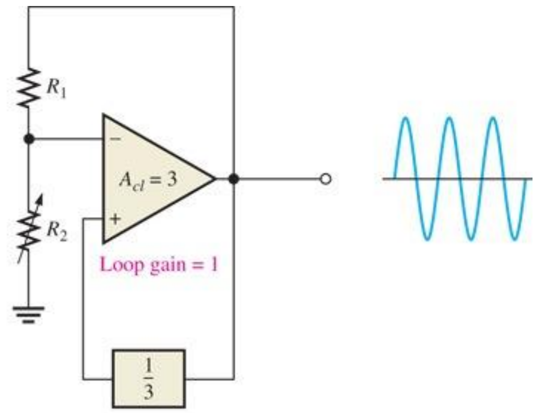
$$R_1 = 2R_2$$

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 9.



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



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

Figure 9 Conditions for start-up and sustained oscillations.

- The circuit in Figure 10 illustrates a method for achieving sustained oscillations.
- Notice that the voltage-divider circuit has been modified to include an additional resistor in parallel with a back-to-back zener diode arrangement.
- When DC power is first applied, 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.
- 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 strengthened, 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.
- A better method to control the gain uses a JFET as a voltage-controlled resistor in a negative feedback path.

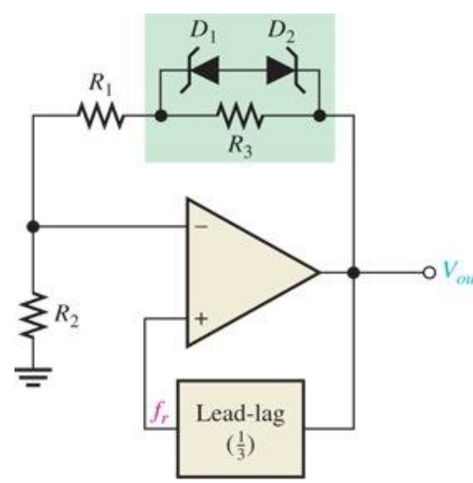


Figure 10 Self-starting Wien-bridge oscillator using back-to-back zener diodes.

- 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 11.
- The gain of the op-amp is controlled by the components shown in the green box, which include the JFET.

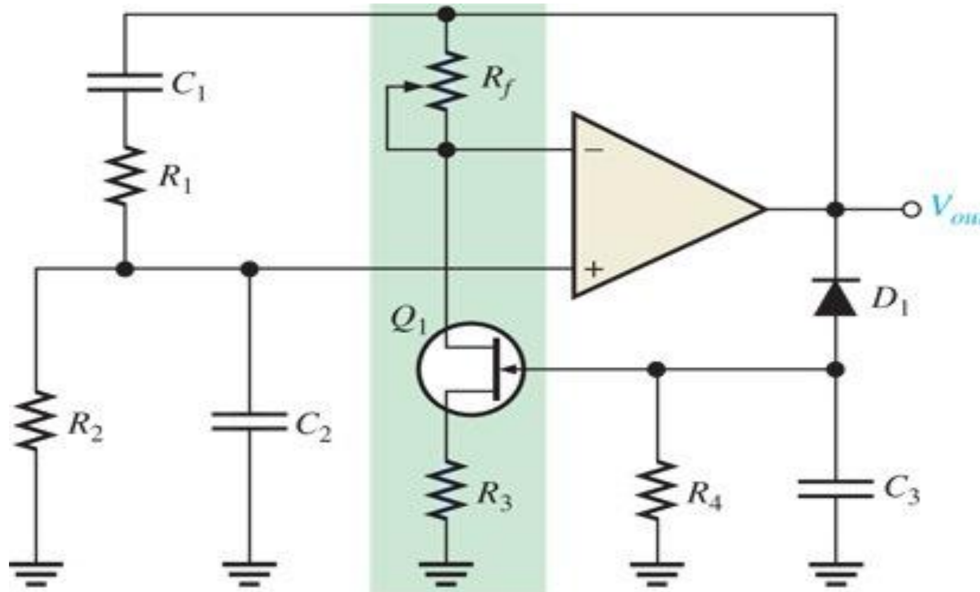


Figure 11 Self-starting Wien-bridge oscillator using a JFET in the negative feedback loop.

- 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 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).
- 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.

NOTE: REFER EXAMPLE 16-1 PAGE 814

16.3.2 The Phase-Shift Oscillator

- Figure 12 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°.

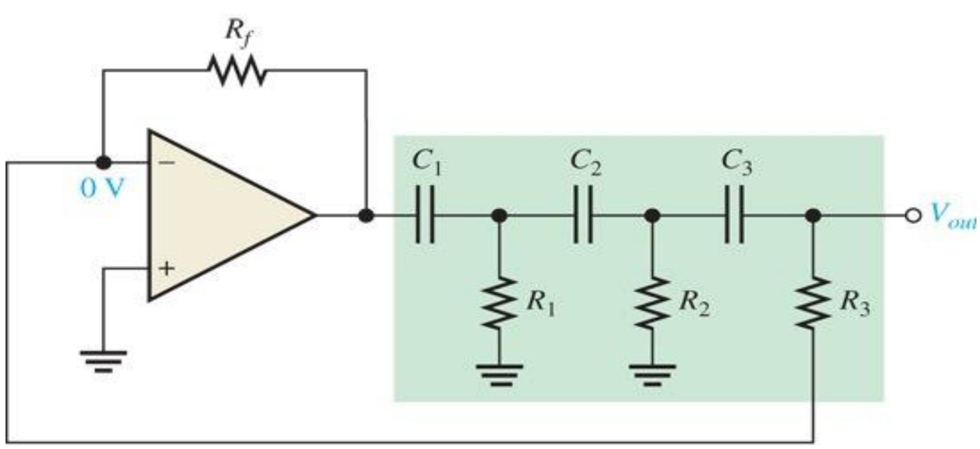


Figure 12 Phase-shift oscillator.

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

$$B = \frac{1}{29}$$

where $B = R_3/R_f$.
- 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_3 and R_f).
- The frequency of oscillation f_r is given as

$$f_r = \frac{1}{2\pi\sqrt{6}RC}$$

Where $R_1 = R_2 = R_3 = R$ and $C_1 = C_2 = C_3 = C$.

NOTE: REFER EXAMPLE 16-2 PAGE 816

16.3.3 The 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 13(a).

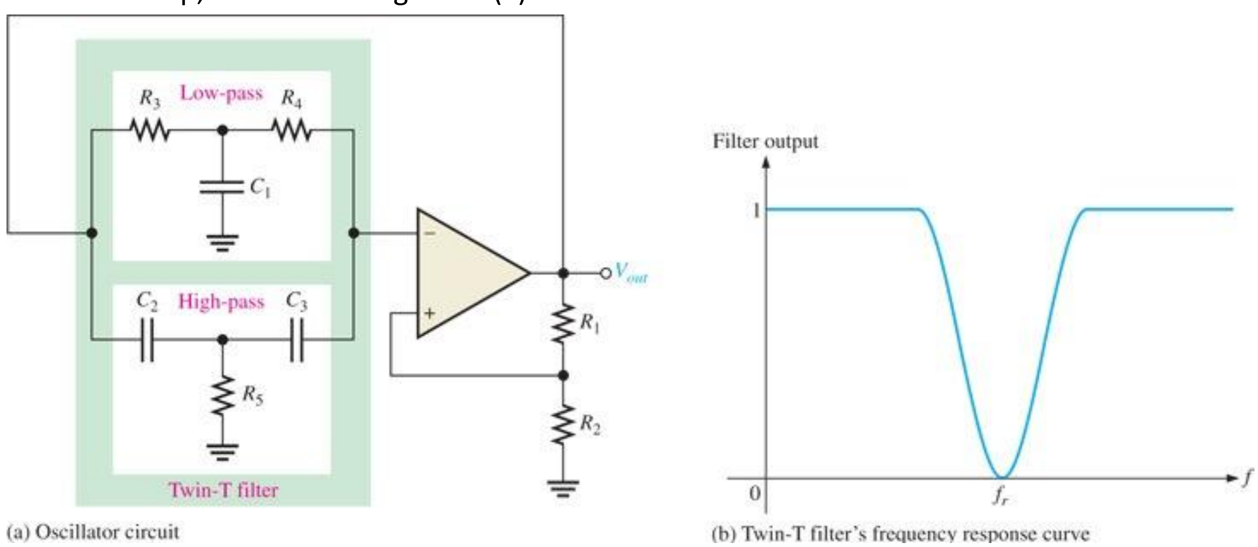


Figure 13 Twin-T oscillator and twin-T filter response.

- 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 response with a center frequency equal to the desired frequency of oscillation, f_r as shown in Figure 13(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.

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, transistors (BJT or FET) are often used as the gain element in LC oscillators.
- This section introduces several types of resonant LC feedback oscillators like the Colpitts, Clapp, Hartley, Armstrong, and crystal-controlled oscillators.

16.4.1 The Colpitts Oscillator

- One basic type of resonant circuit feedback oscillator is the Colpitts shown in Figure 14.
- 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.

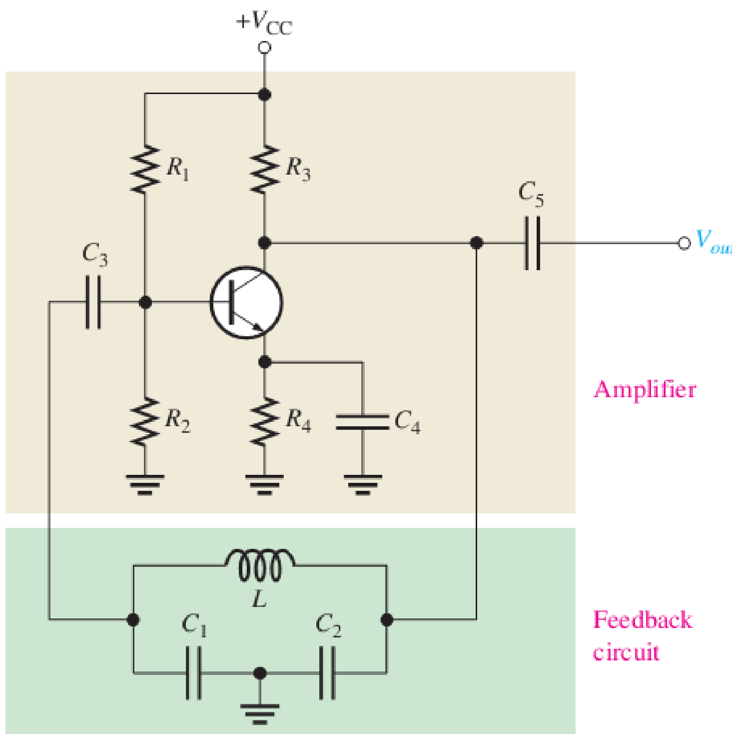


Figure 14 A basic Colpitts oscillator with a BJT as the gain element.

- 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 the formula:

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

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

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

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 15 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

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

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

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

- where A_v is the voltage gain of the amplifier, which is represented by the triangle in Figure 15.

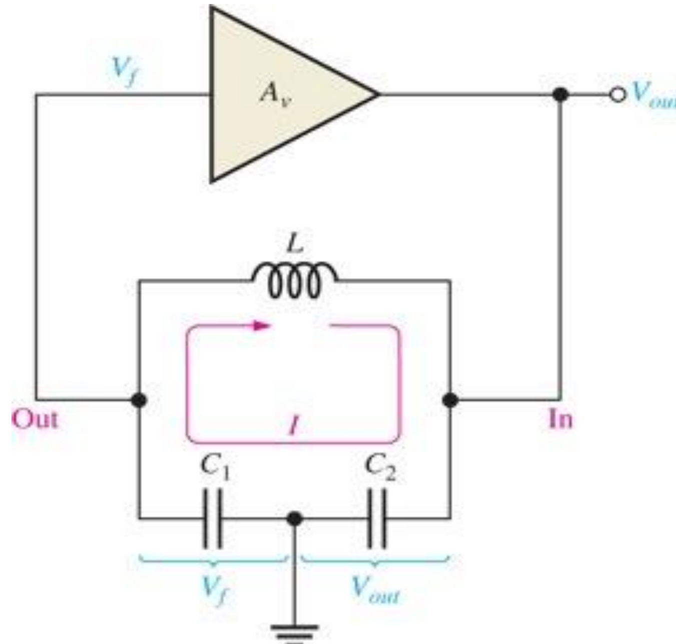


Figure 15 The attenuation of the tank circuit is the output of the tank (V_f) divided by the input to the tank (V_{out}). $B = V_f/V_{out} = C_2/C_1$

- For the oscillator to be self-starting, $A_v B$ must be greater than 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, the input impedance of the amplifier acts as a load on the resonant feed-back circuit and reduces the Q of the circuit.

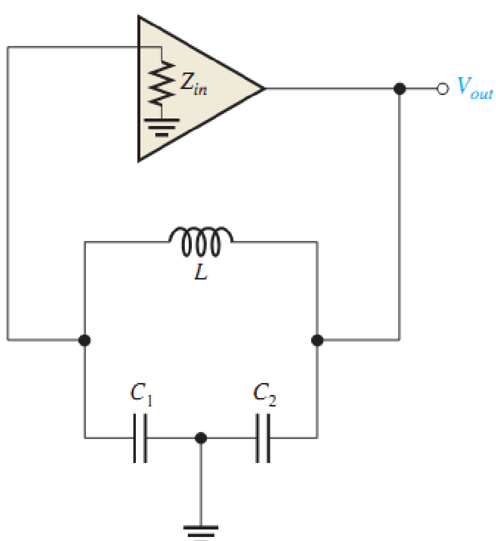


Figure 17 Z_{in} of the amplifier loads the feed-back circuit and lowers its Q, thus lowering the resonant frequency.

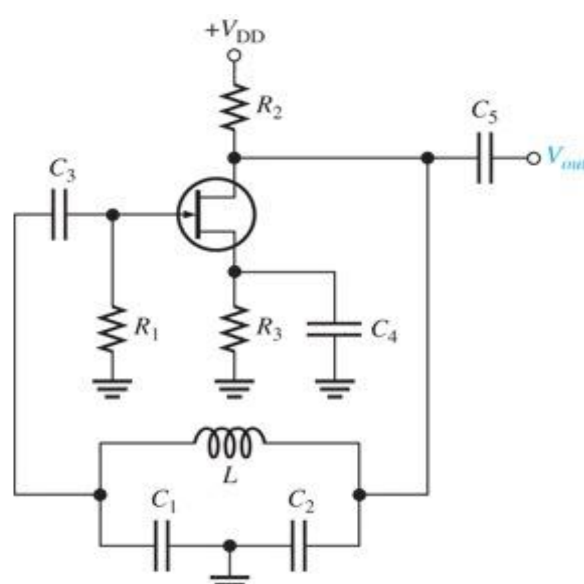
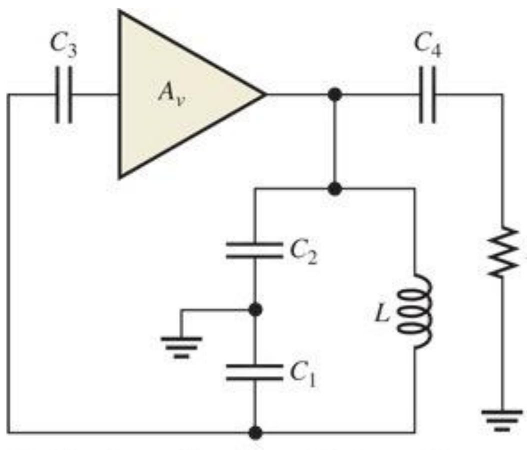


Figure 16 A basic FET Colpitts oscillator.

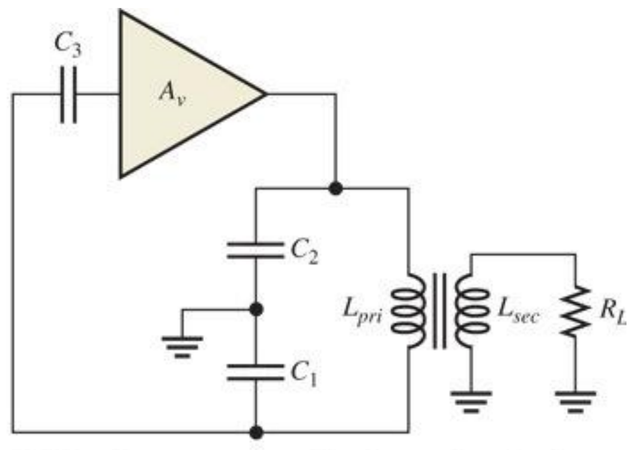
- The resonant frequency of a parallel resonant circuit depends on the Q, according to the following formula

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

- As a rule of thumb, for a $Q > 10$, the frequency is approximately $f_r = \frac{1}{2\pi\sqrt{LC_T}}\sqrt{\frac{Q^2}{Q^2+1}}$.
- When $Q < 10$, however, f_r is reduced significantly.
- A FET can be used in place of a BJT, as shown in Figure 17 to minimize the loading effect of the transistor's input impedance.
- Recall that FETs have much higher input impedances than bipolar junction transistors.
- Also, when an external load is connected to the oscillator output, as shown in Figure 18(a), f_r may decrease 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 18(b).



(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 18 Oscillator loading.

NOTE: REFER EXAMPLE 16-3 PAGE 820

16.4.2 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 19.
- Since C_3 is in series with C_1 and C_2 around the tank circuit, the total capacitance is

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

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

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

- If C_3 is much smaller than C_1 and C_2 then C_3 almost entirely controls the resonant frequency ($f_r = 1/2\pi\sqrt{LC_3}$).

- Clapp provides a more accurate and stable frequency of oscillation.

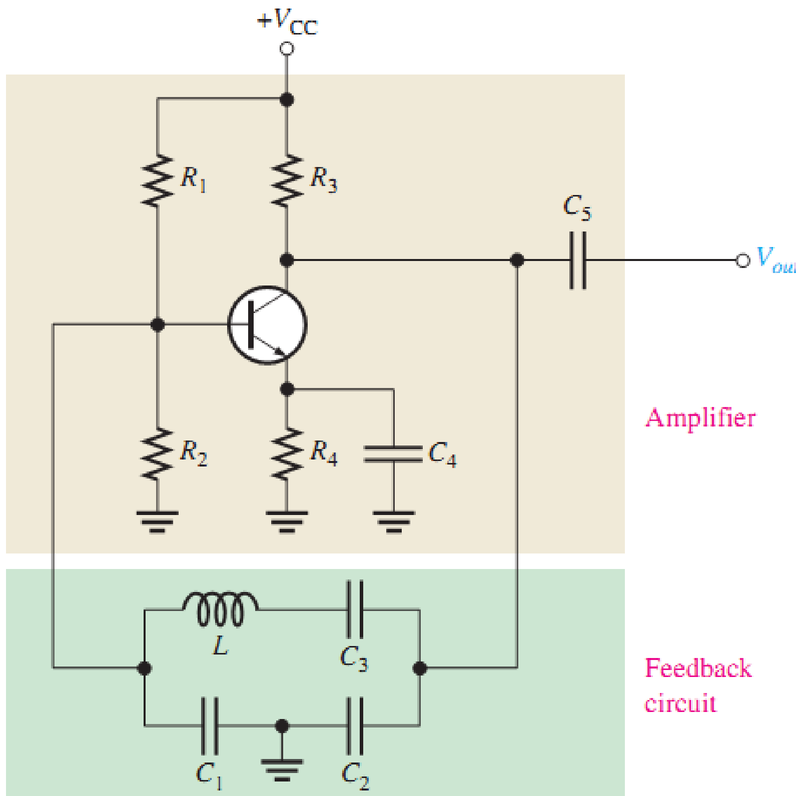


Figure 19 A basic Clapp oscillator.

16.4.3 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 20.

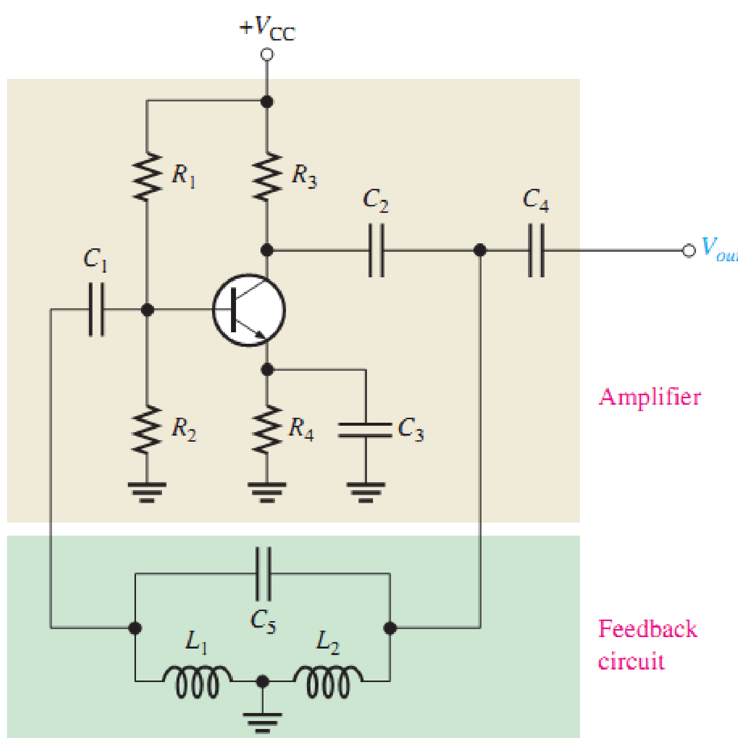


Figure 20 A basic Hartley oscillator.

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

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

- 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.

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

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

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

- 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.

16.4.4 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 21.
- The transformer secondary coil 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.

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

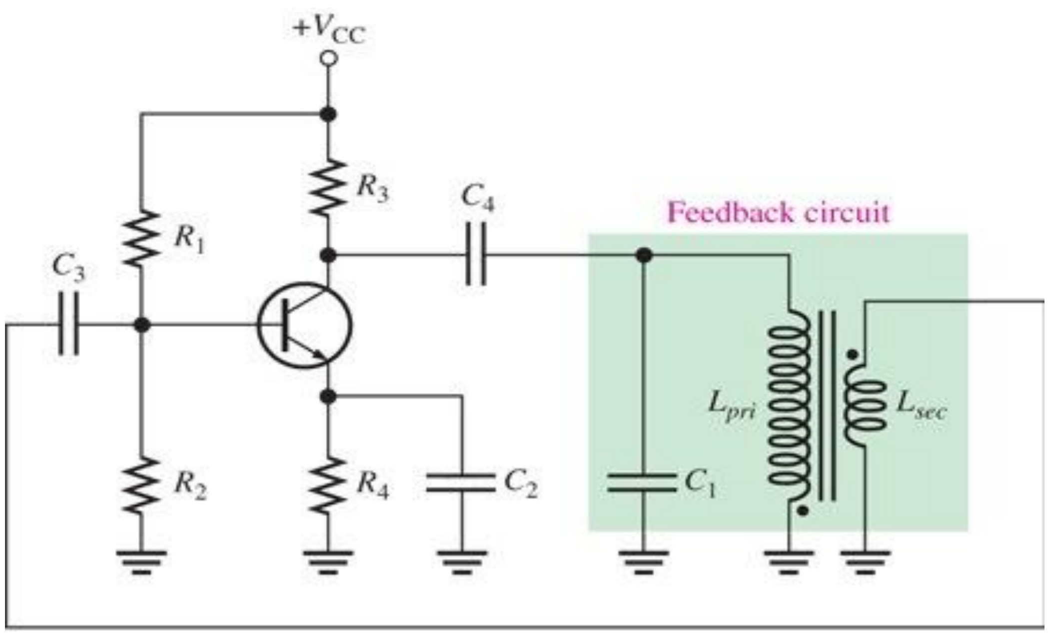


Figure 21 A basic Armstrong oscillator.

16.4.5 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 as shown in Figure 22(a) and (b).
- A schematic symbol for a crystal is shown in Figure 22(c), and an equivalent RLC circuit for the crystal appears in Figure 22(d).

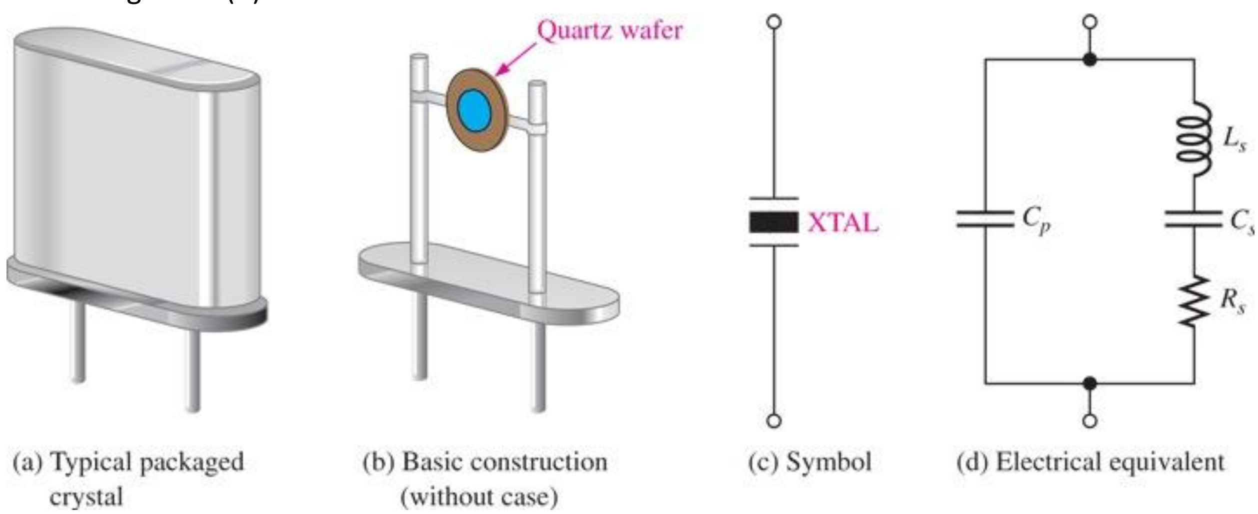


Figure 22 A quartz crystal.

- 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 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 23(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.

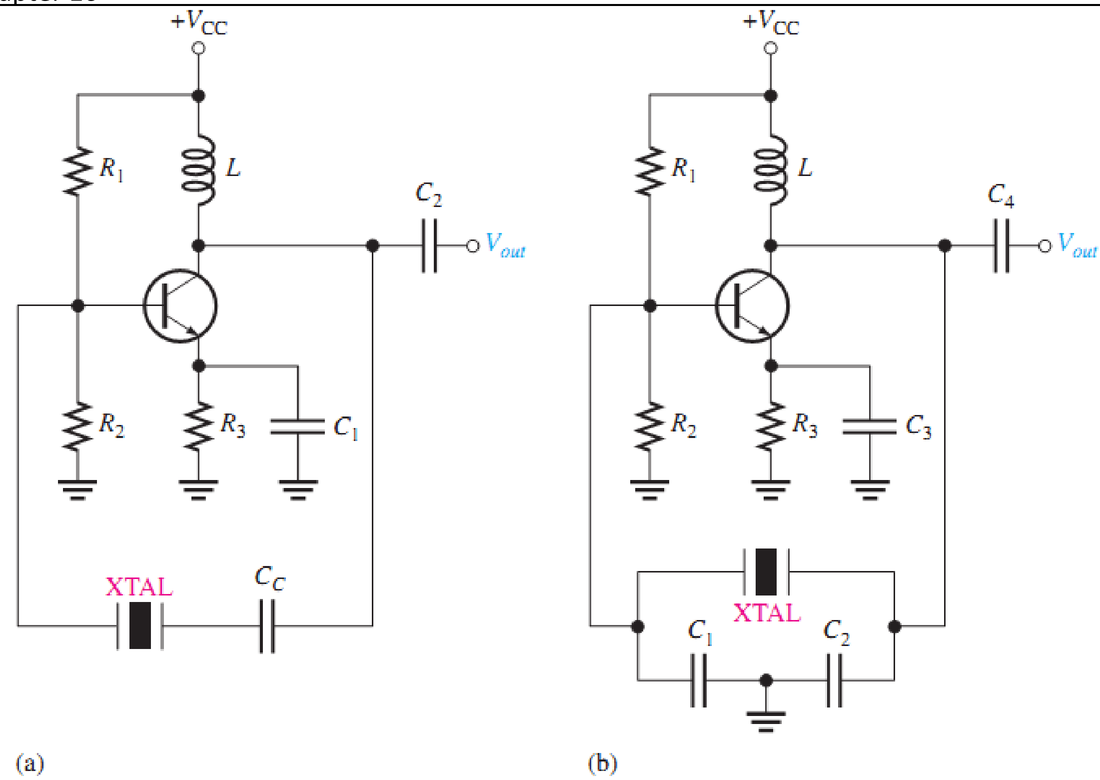


Figure 23 Basic crystal oscillators.

- A modified Colpitts configuration is shown in Figure 23(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.

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.

16.5.1 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 24(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 24(b).

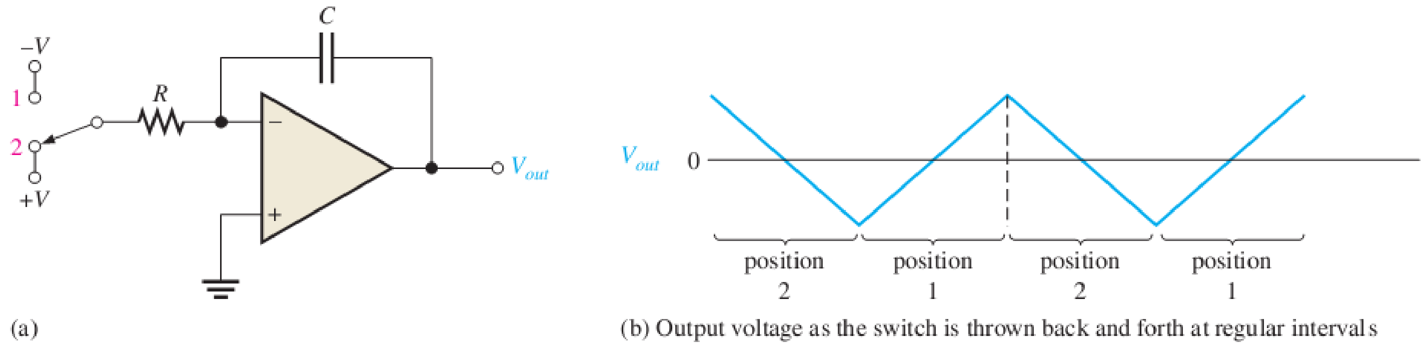


Figure 24 Basic triangular-wave oscillator.

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 25.
- 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 26.

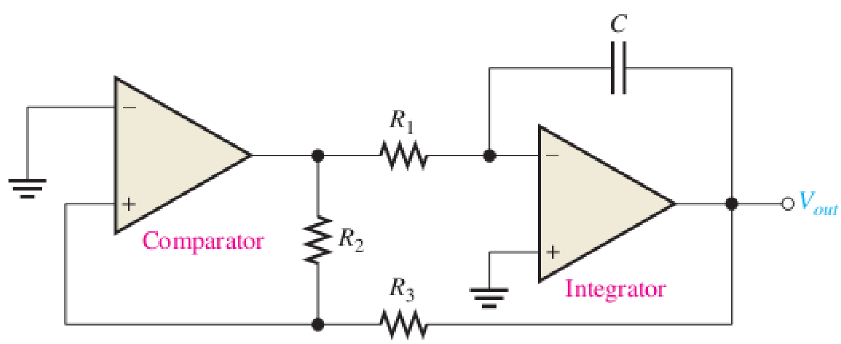


Figure 25 A triangular-wave oscillator using two op-amps.

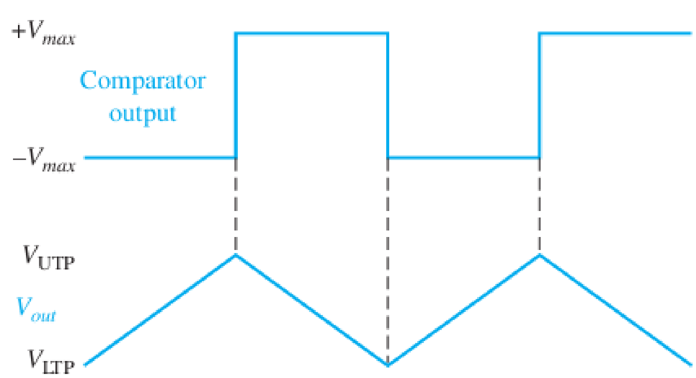


Figure 26 Waveforms for the circuit in Figure 25.

- The output amplitude 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

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

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

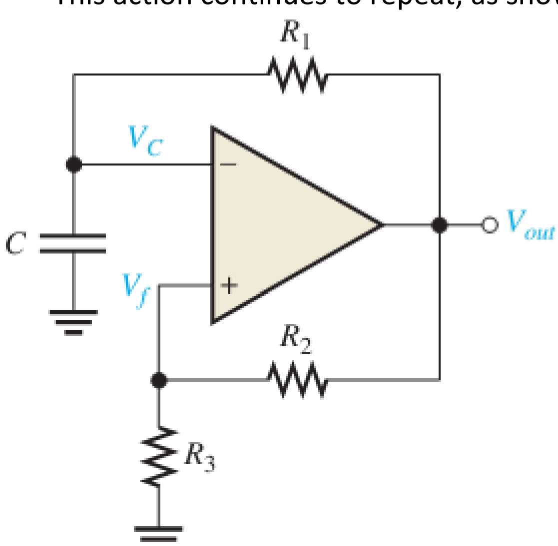
- The frequency of both waveforms depends on the R_1C time constant as well as the amplitude-setting resistors, R_2 and R_3.
- By varying R_1, the frequency of oscillation can be adjusted without changing the output amplitude.

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

NOTE: REFER EXAMPLE 16-4 PAGE 827

16.5.2 A Square-Wave Oscillator

- The basic square-wave oscillator shown in Figure 27 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 28, and a square-wave output voltage is obtained.



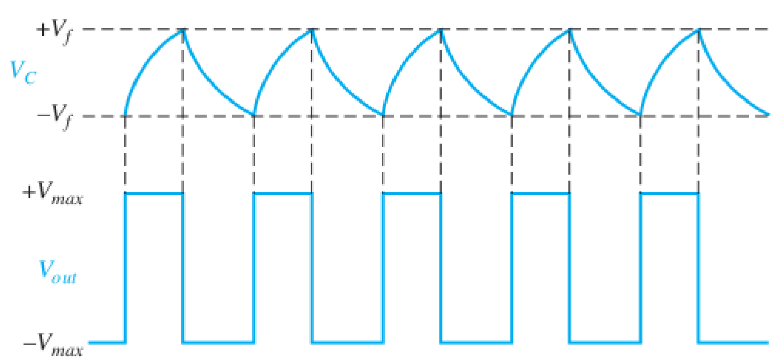


Figure 27 Waveforms for the square-wave relaxation oscillator.

Figure 28 A square-wave relaxation oscillator.

16-6 THE 555 TIMER AS AN OSCILLATOR

- The 555 timer is an 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.
- The 555 timer consists basically of two comparators, a flip-flop, a discharge transistor, and a resistive voltage divider, as shown in Figure 29.

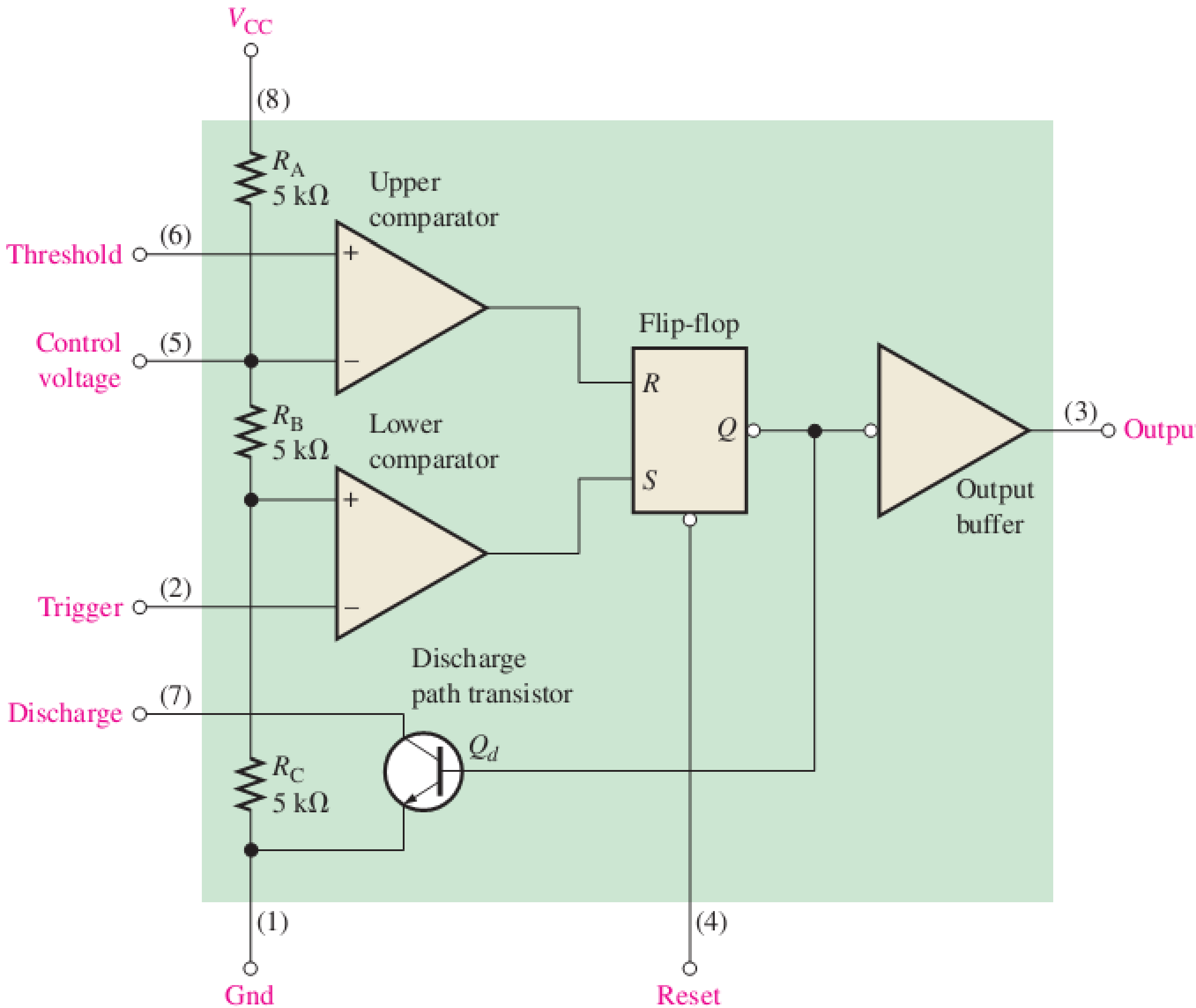


Figure 29 Internal diagram of a 555 integrated circuit timer. (IC pin numbers are in parentheses.)

16.6.1 Astable Operation

- A 555 timer connected to operate in the astable mode as a free-running relaxation oscillator (astable multivibrator) is shown in Figure 30.
- 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 $0.01\mu F$ capacitor connected to the control (CONT) input is strictly for decoupling and has no effect on the operation.

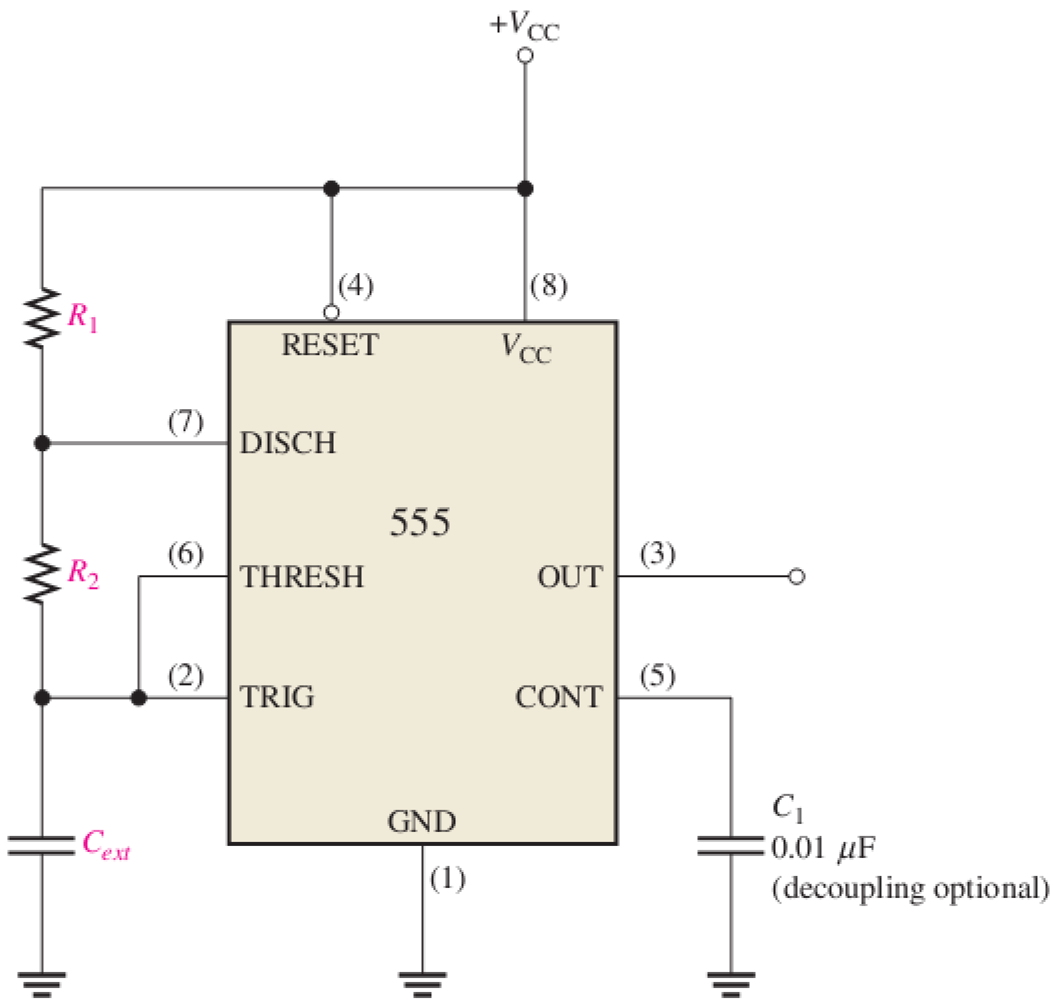


Figure 30 The 555 timer connected as an astable multivibrator.

- 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 31.
- When the capacitor voltage reaches $1/3V_{CC}$, the lower comparator switches to its low output state, and when the capacitor voltage reaches $2/3V_{CC}$, 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 $1/3V_{CC}$, 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.

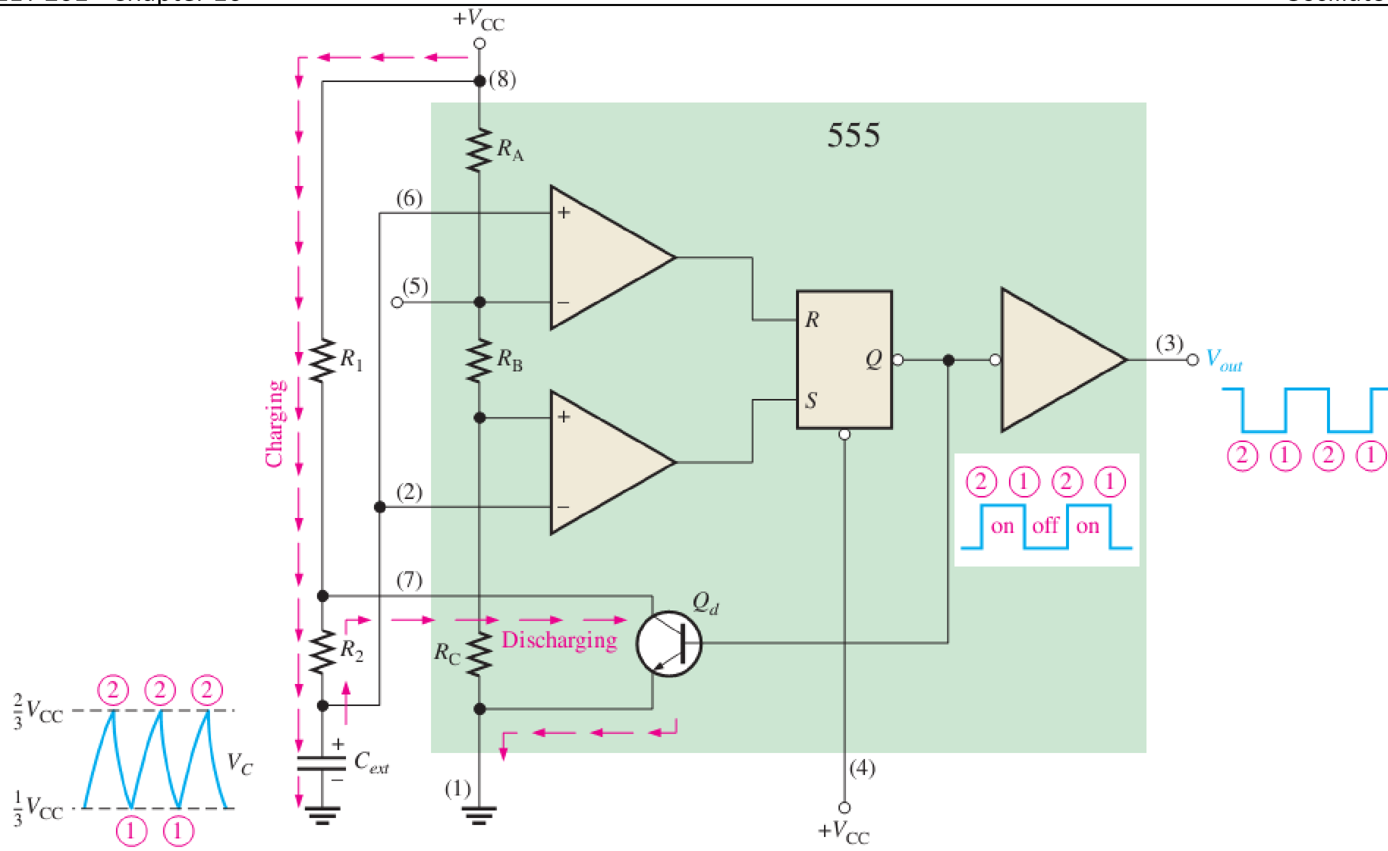


Figure 31 Operation of the 555 timer in the astable mode.

- The frequency of oscillation is given as

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

- By selecting R_1 and R_2 the duty cycle of the output can be adjusted as

$$Duty\ Cycle = \left(\frac{t_H}{t_H + t_L}\right)100\% = \left(\frac{R_1 + R_2}{R_1 + 2R_2}\right)100\%$$

NOTE: REFER EXAMPLE 16-6 PAGE 834

16.6.2 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 32.
- As shown in Figure 33, the control voltage changes the threshold values of $1/3V_{CC}$ and $2/3V_{CC}$ for the internal comparators.
- With the control voltage, the upper value is V_{CONT} and the lower value is $1/2V_{CONT}$.
- When the control voltage is varied, the output frequency also varies.
- An 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.

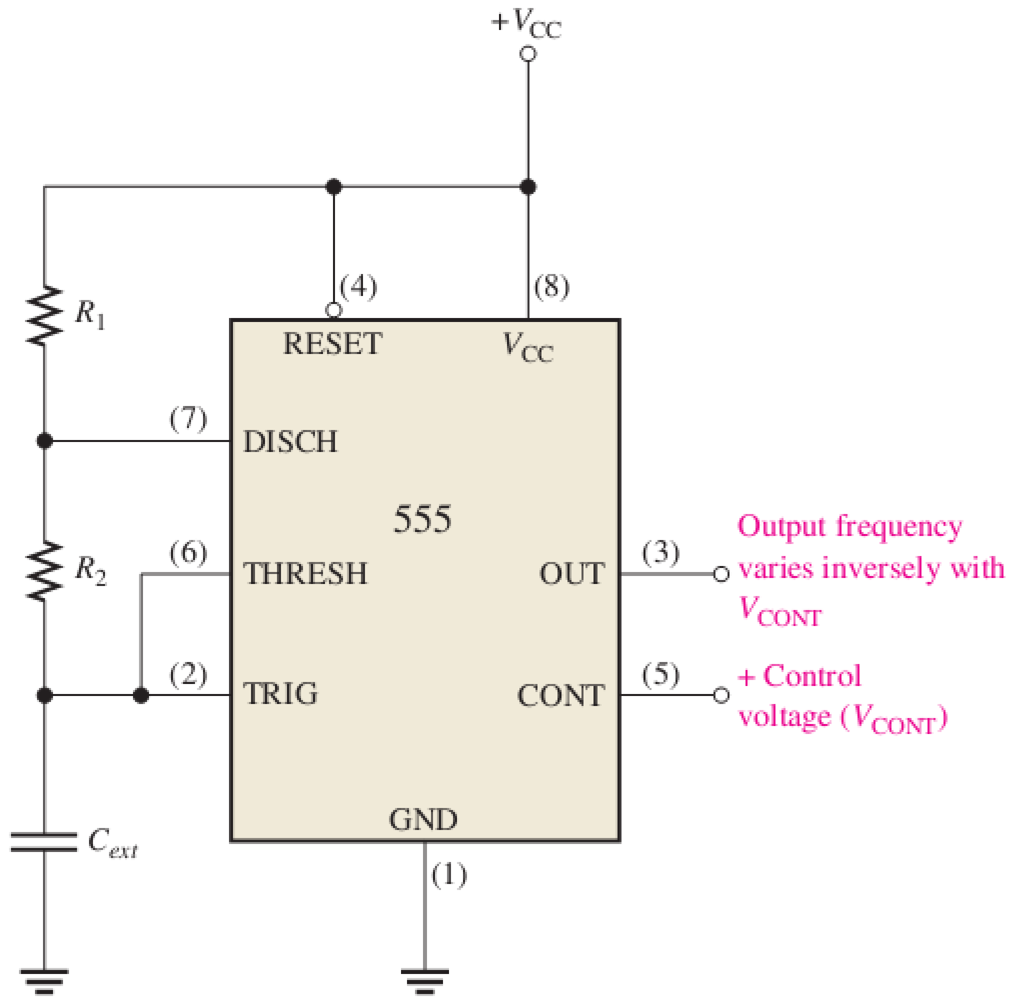


Figure 32 The 555 timer connected as a voltage-controlled oscillator (VCO). Note the variable control voltage input on pin 5.

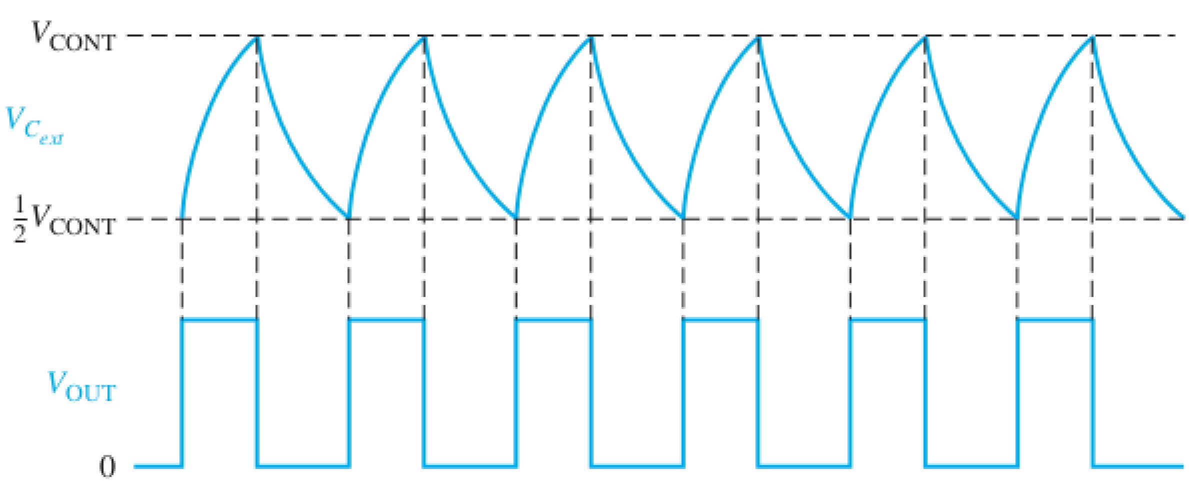


Figure 33 The VCO output frequency varies inversely with V_{CONT} because the charging and discharging time of C_{ext} is directly dependent on the control voltage.