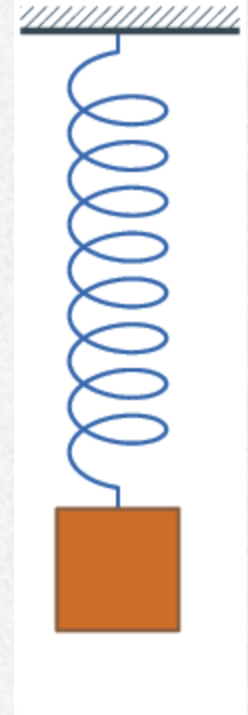


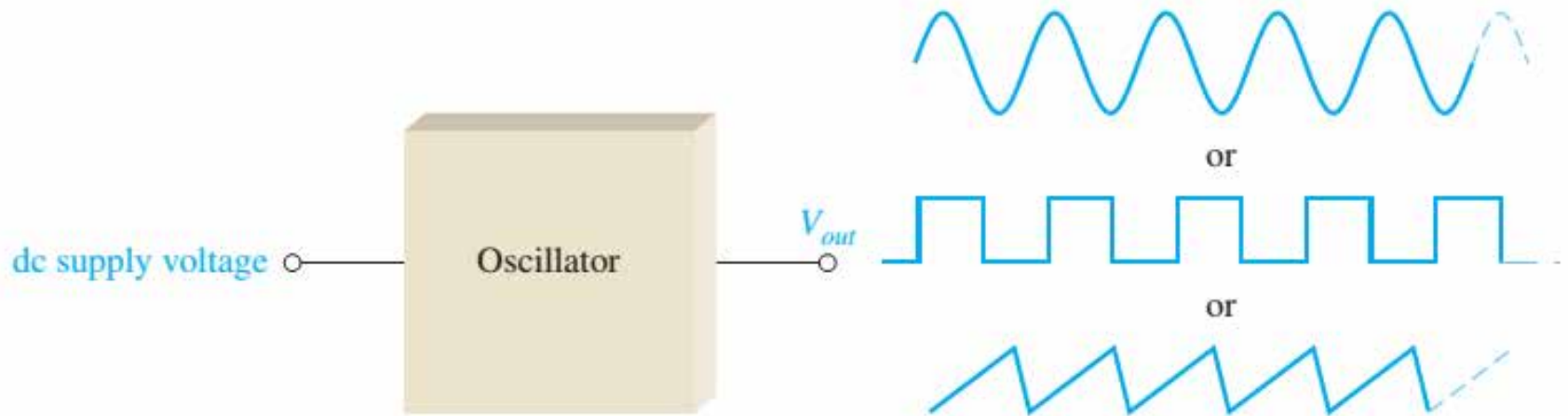
# OSCILLATORS



# Oscillators

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

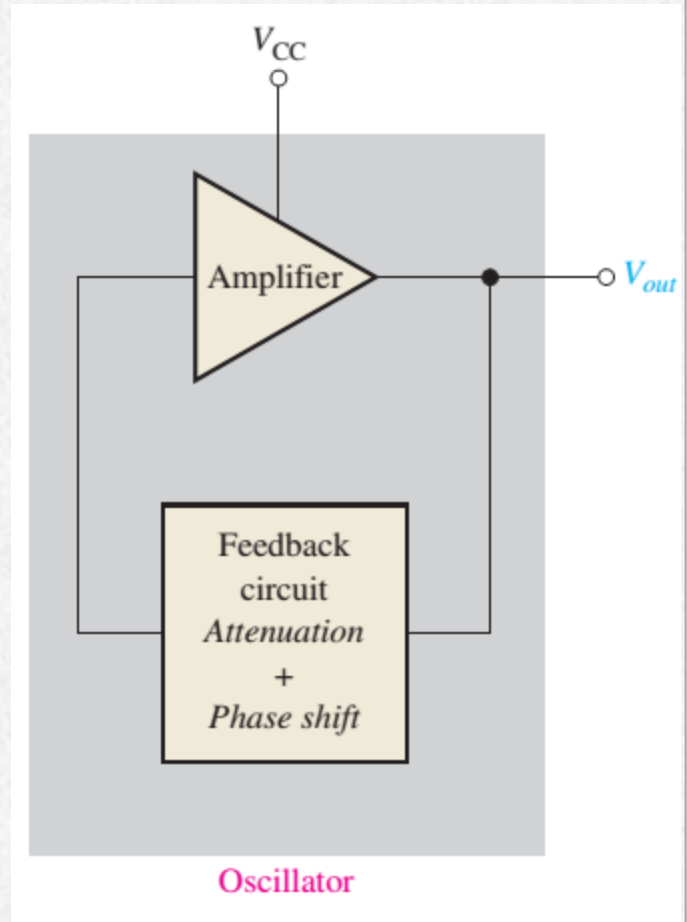
# Oscillators



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

# Oscillators

- Q There are two major classifications for oscillators: **feedback oscillators** and **relaxation oscillators**.
- Q **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.
- Q A feedback oscillator consists of an amplifier for gain and a positive feedback circuit that produces phase shift and provides attenuation.





# Oscillators

## Relaxation Oscillators

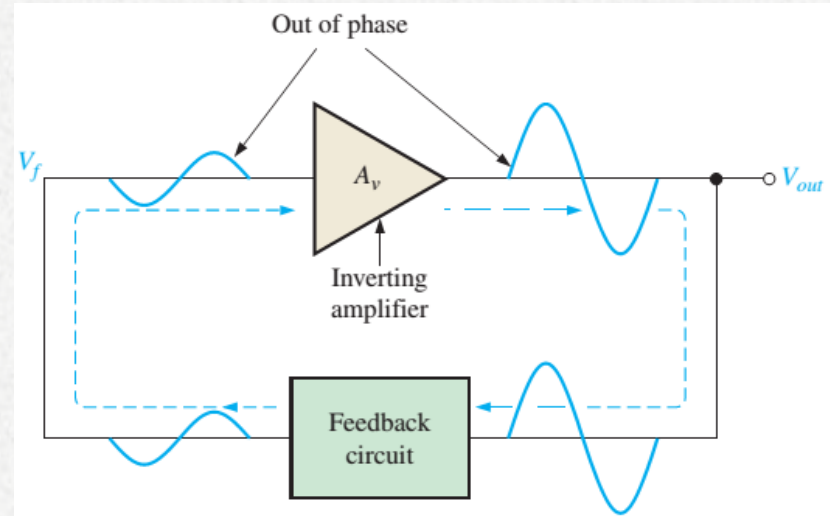
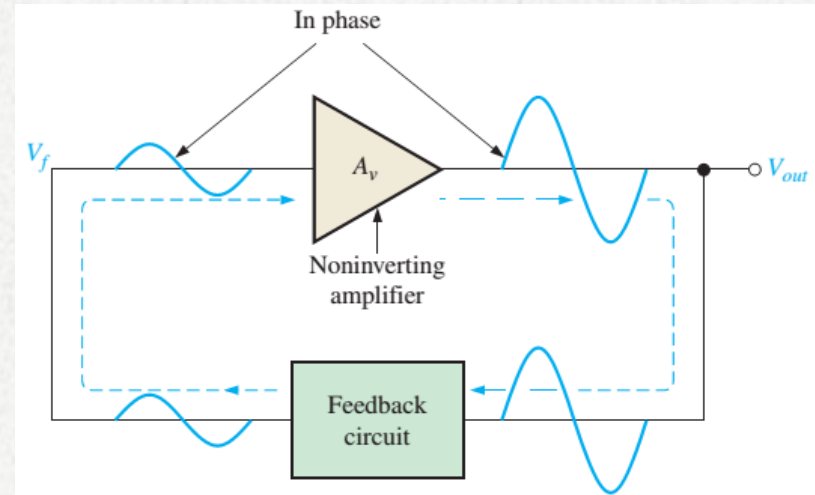
- Q A second type of oscillator is the relaxation oscillator.
- Q Instead of feedback, a relaxation oscillator uses an RC timing circuit to generate a waveform that is generally a square wave or other nonsinusoidal waveform.
- Q Typically, a relaxation oscillator uses a Schmitt trigger or other device that changes states to alternately charge and discharge a capacitor through a resistor.

# Feedback Oscillators

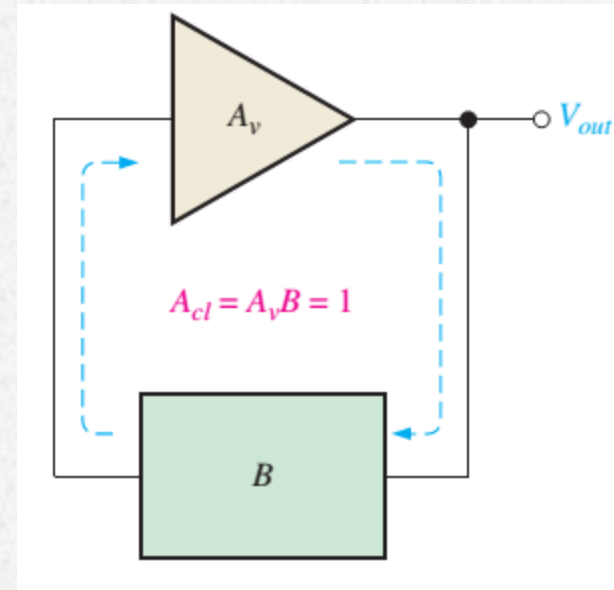
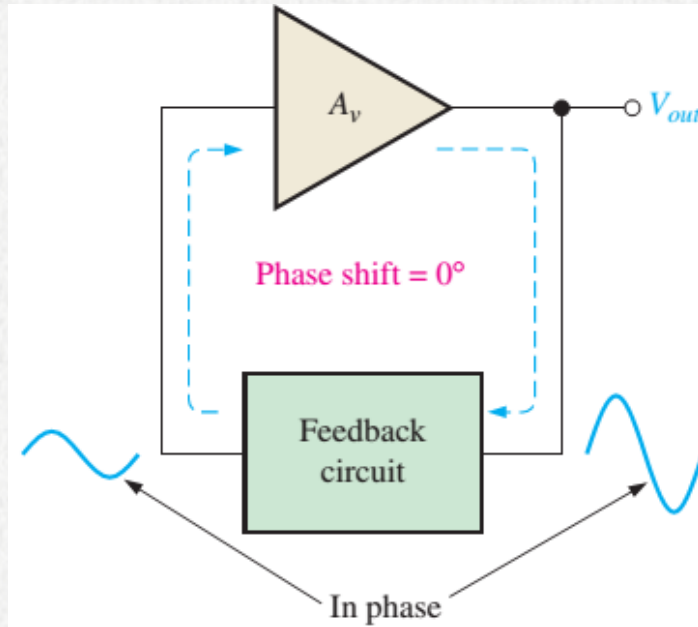
- Q Feedback oscillator operation is based on the principle of positive feedback.
- Q We will look at the general conditions required for oscillation to occur.
- Q Feedback oscillators are widely used to generate sinusoidal waveforms.
- Q In **positive feedback**, a portion of the output voltage of an amplifier is fed back to the input with no net phase shift, resulting in a strengthening of the output signal
- Q This basic idea is illustrated in figure

# Feedback Oscillators

- q The in-phase feedback voltage is amplified to produce the output voltage, which in turn produces the feedback voltage.
- q A loop is created in which the signal maintains itself and a continuous sinusoidal output is produced.
- q This phenomenon is called oscillation



# Feedback Oscillators

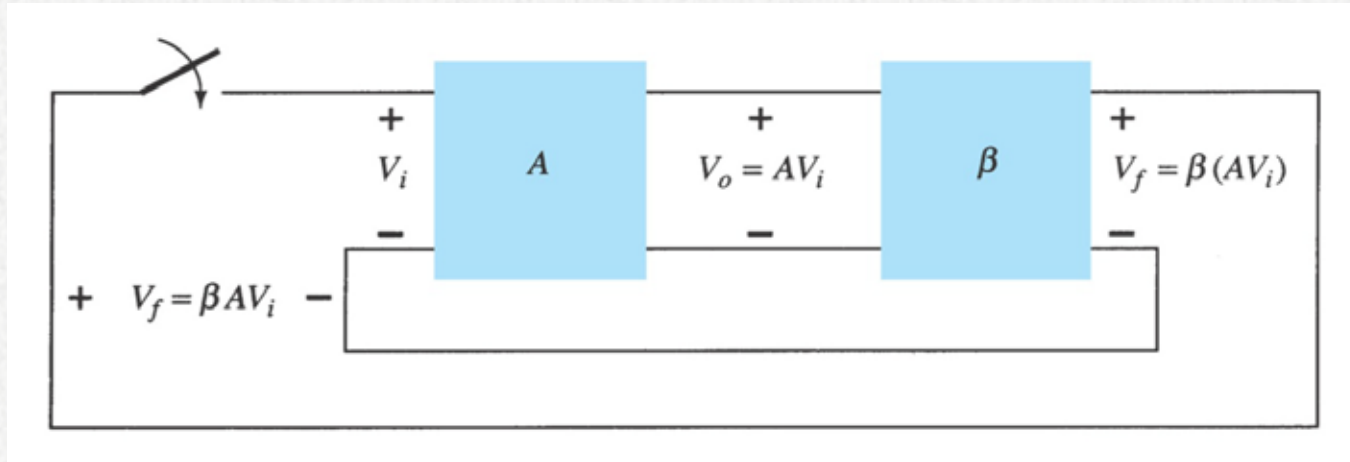


Q Two conditions are required for a sustained state of oscillation:

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



# Feedback Oscillators



- Q When switch at the amplifier input is open, no oscillation occurs.
- Q For input  $V_i$ , the feedback voltage  $V_f = (BA)V_i$ .
- Q In order to maintain  $V_f = V_i$ ,  $BA$  must be in the correct magnitude and phase.
- Q When the switch is closed and  $V_i$  is removed, the circuit will continue operating since the feedback voltage is sufficient to drive the amplifier and feedback circuit, resulting in proper input voltage to sustain the loop operation.

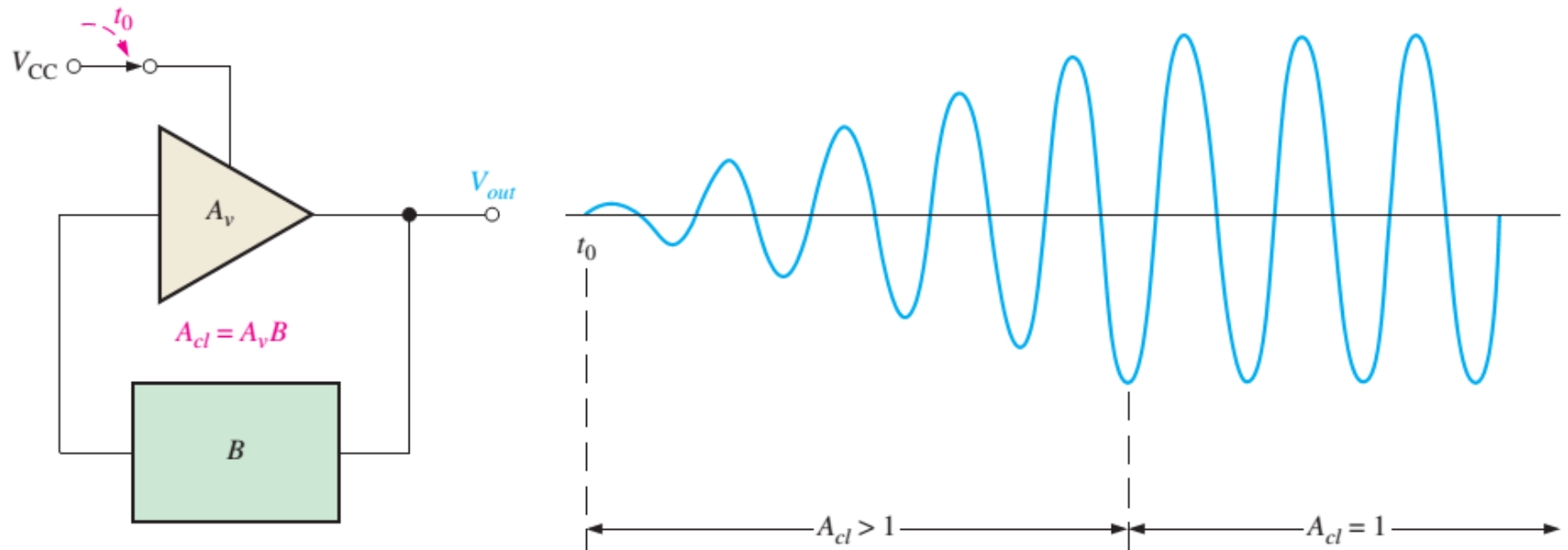
# Feedback Oscillators

- Q 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  $A_{cl} = A_v B$
- Q 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
- Q To avoid this, some form of gain control must be used to keep the loop gain at exactly 1 once oscillations have started.

# Start-up Conditions

- Q We have seen what it takes for an oscillator to produce a continuous sinusoidal output.
- Q What are the requirements for the oscillation to start when the dc supply voltage is first turned on?
- Q The unity-gain condition must be met for oscillation to be maintained.
- Q 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.
- Q The gain must then decrease to 1 so that the output stays at the desired level and oscillation is sustained.

# Start-up Conditions



▲ 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.

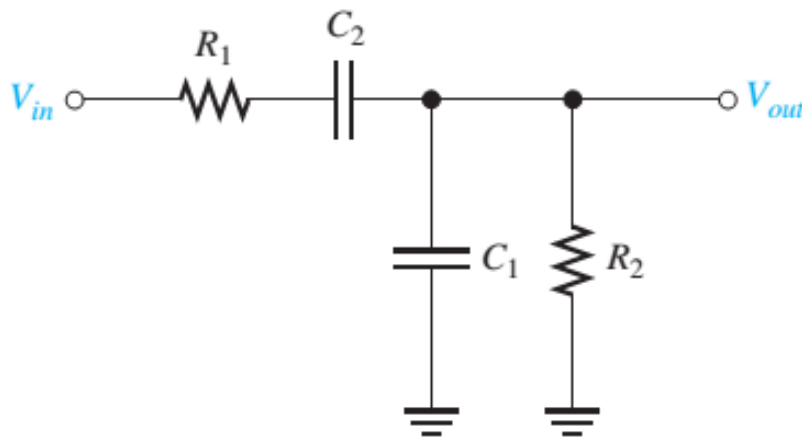


# RC Feedback Circuits

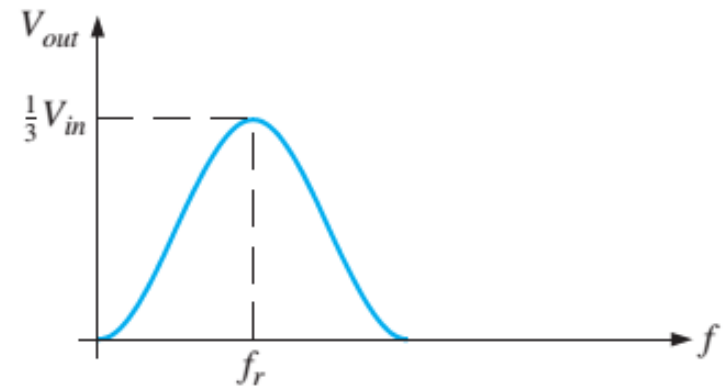
- Q Three types of feedback oscillators that use RC circuits to produce sinusoidal outputs are the
  1. Wien-bridge oscillator
  2. Phase-shift oscillator
  3. Twin-T oscillator
- Q Generally, RC feedback oscillators are used for frequencies up to about 1 MHz.
- Q The Wien-bridge is by far the most widely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

# Wien-Bridge Oscillator

- Q The feedback circuit in a Wien-bridge uses a lead-lag circuit
- Q  $R_1$  and  $C_1$  together form the lag portion of the circuit;  $R_2$  and  $C_2$  form the lead portion.



(a) Circuit



(b) Response curve

# Wien-Bridge Oscillator

- Q At lower frequencies, the lead circuit takes over due to the high reactance of  $C_2$ .
- Q As the frequency increases,  $X_{C2}$  decreases, thus allowing the output voltage to increase.
- Q 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.
- Q The output voltage peaks at a frequency called the resonant frequency,  $f_r$  given by  $f_r = \frac{1}{2\pi RC}$  ; (when  $R_1=R_2$  and  $C_1=C_2$ )
- Q At resonant frequency, the phase shift through the circuit is  $0^\circ$  and the attenuation is  $\frac{V_{out}}{V_{in}} = \frac{1}{3}$

# Wien-Bridge Oscillator

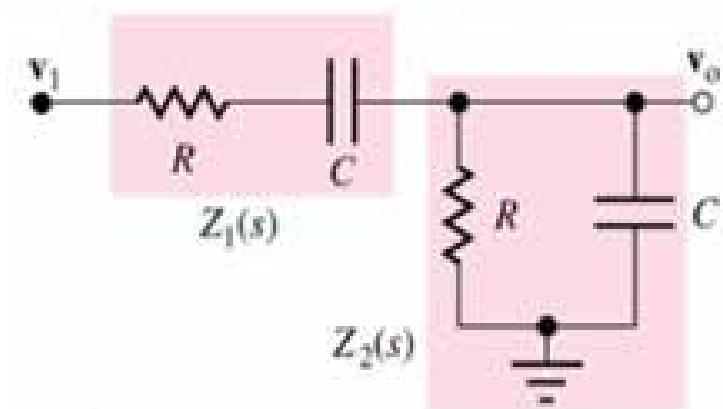
$$V_o(s) = V_1(s) \frac{Z_2(s)}{Z_1(s) + Z_2(s)}$$

$$T(s) = \frac{V_o(s)}{V_1(s)} = \frac{sRC}{s^2 R^2 C^2 + 3sRC + 1}$$

$$T(j\omega) = \frac{j\omega RC}{1 - \omega^2 R^2 C^2 + 3j\omega RC}$$

Phase shift will be zero for  $(1 - \omega_o^2 R^2 C^2) = 0$

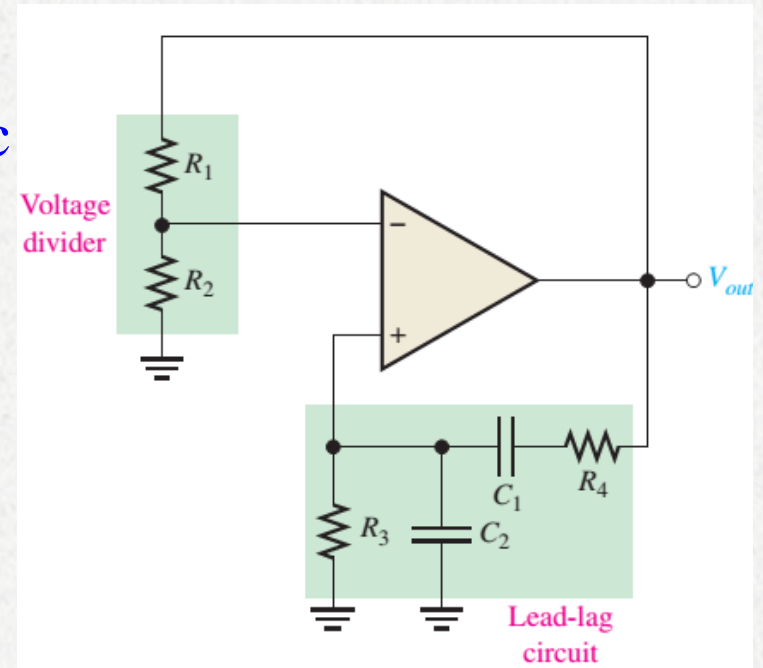
$$\therefore \omega_o = \frac{1}{RC} \quad T(j\omega_o) = \frac{1}{3}$$





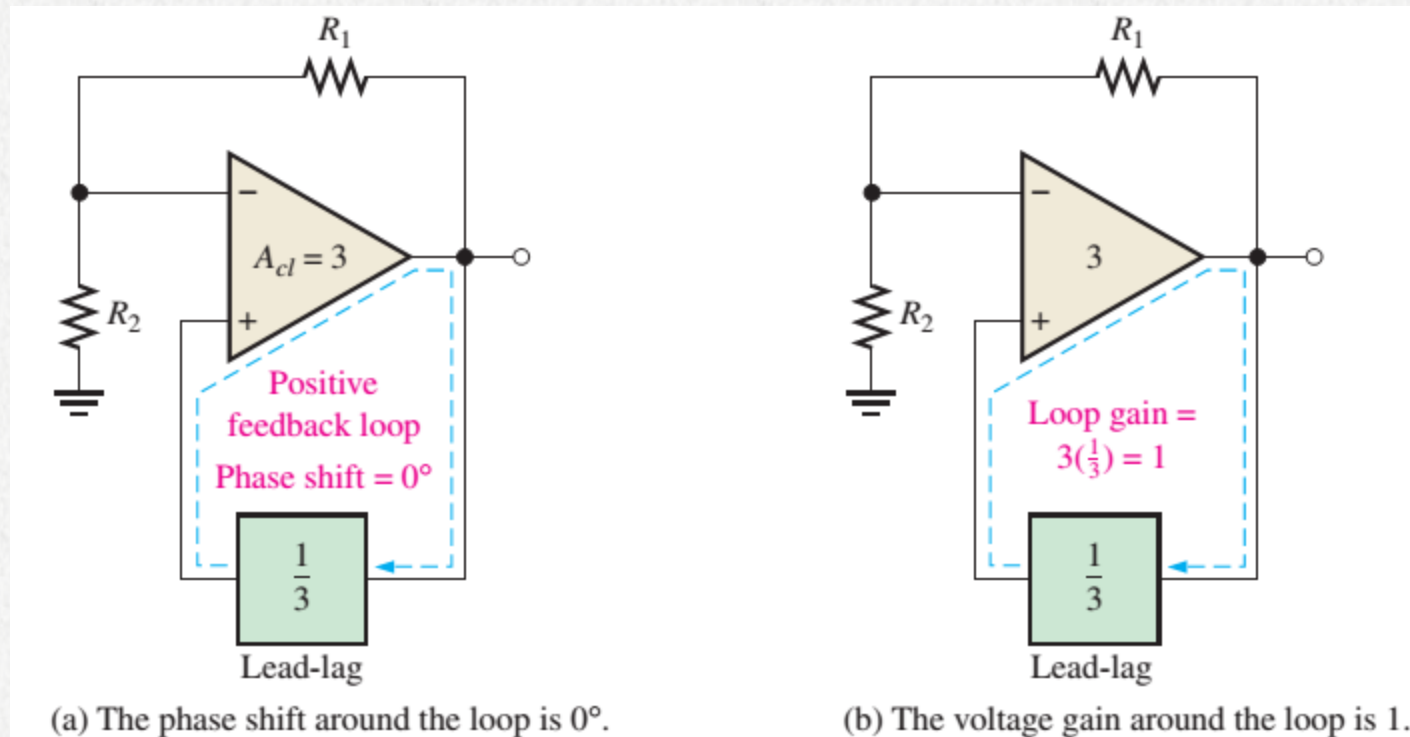
# Wien-Bridge Oscillator

- q The basic Wien-bridge uses the lead-lag network in the positive feedback loop to select a specific frequency that is amplified
- q The voltage divider in the negative feedback loop sets the gain to make up for the attenuation of the feedback network.
- q 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



# Wien-Bridge Oscillator

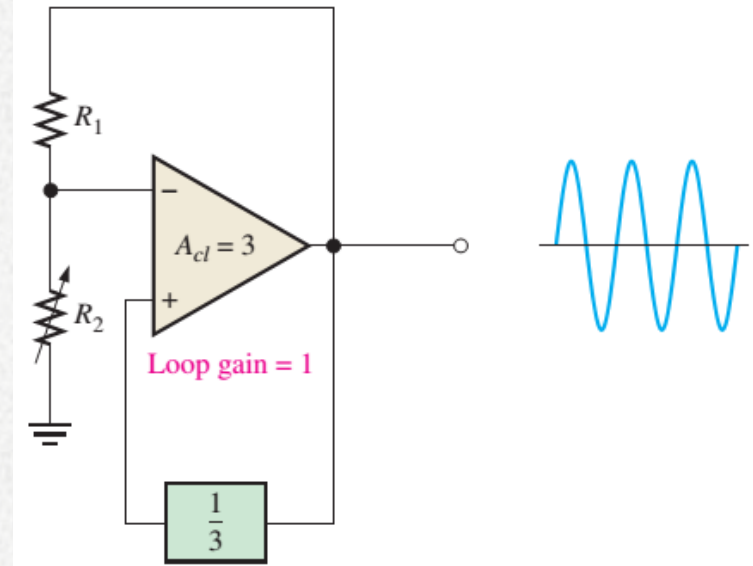
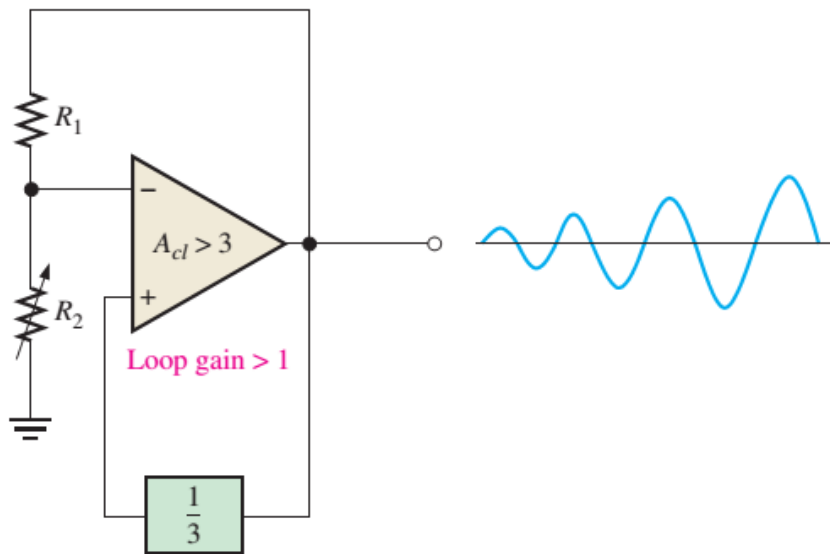
The closed-loop gain of the noninverting amplifier is  $(1+R_1/R_2)$ . Since there is a loss of  $1/3$  of the signal in the positive feedback loop, the noninverting amplifier must have a gain of exactly 3.0 as set by  $R_1$  and  $R_2$  to make up for the attenuation. The unity-gain condition is met when  $R_1 = 2R_2$ .



# Wien-Bridge Oscillator

To start the oscillations an initial closed-loop gain of the amplifier more than 3 must be achieved until the output signal builds up to a desired level.

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.



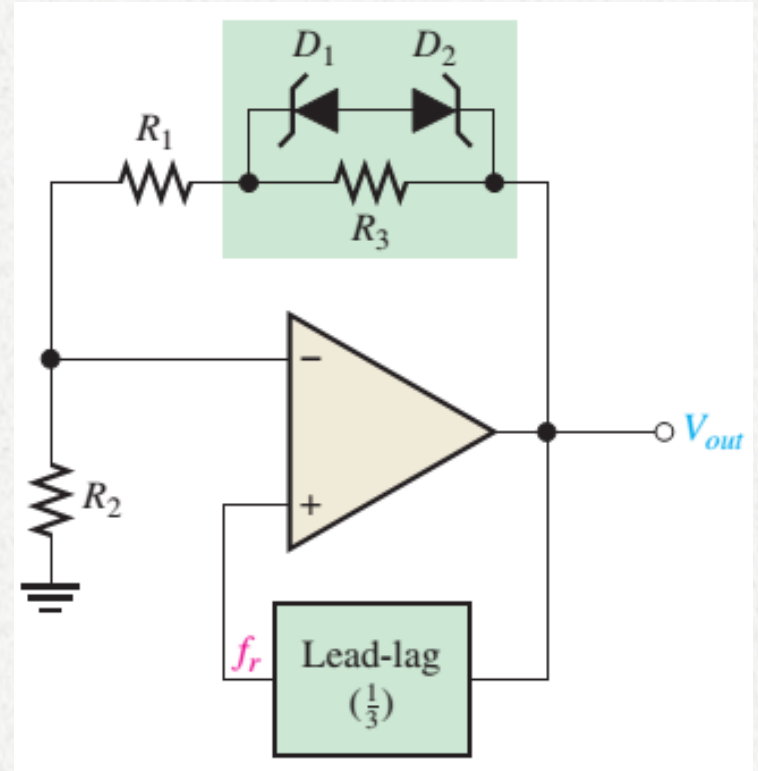
# Wien-Bridge Oscillator

The back-to-back zener diode arrangement is one way of achieving sustained oscillations.

When dc is first applied the zeners appear as opens. This places  $R_3$  in series with  $R_1$ , thus increasing the closed-loop gain of the amplifier.

A small positive feedback signal develops from noise 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 the amplifier's gain is reduced to 3.

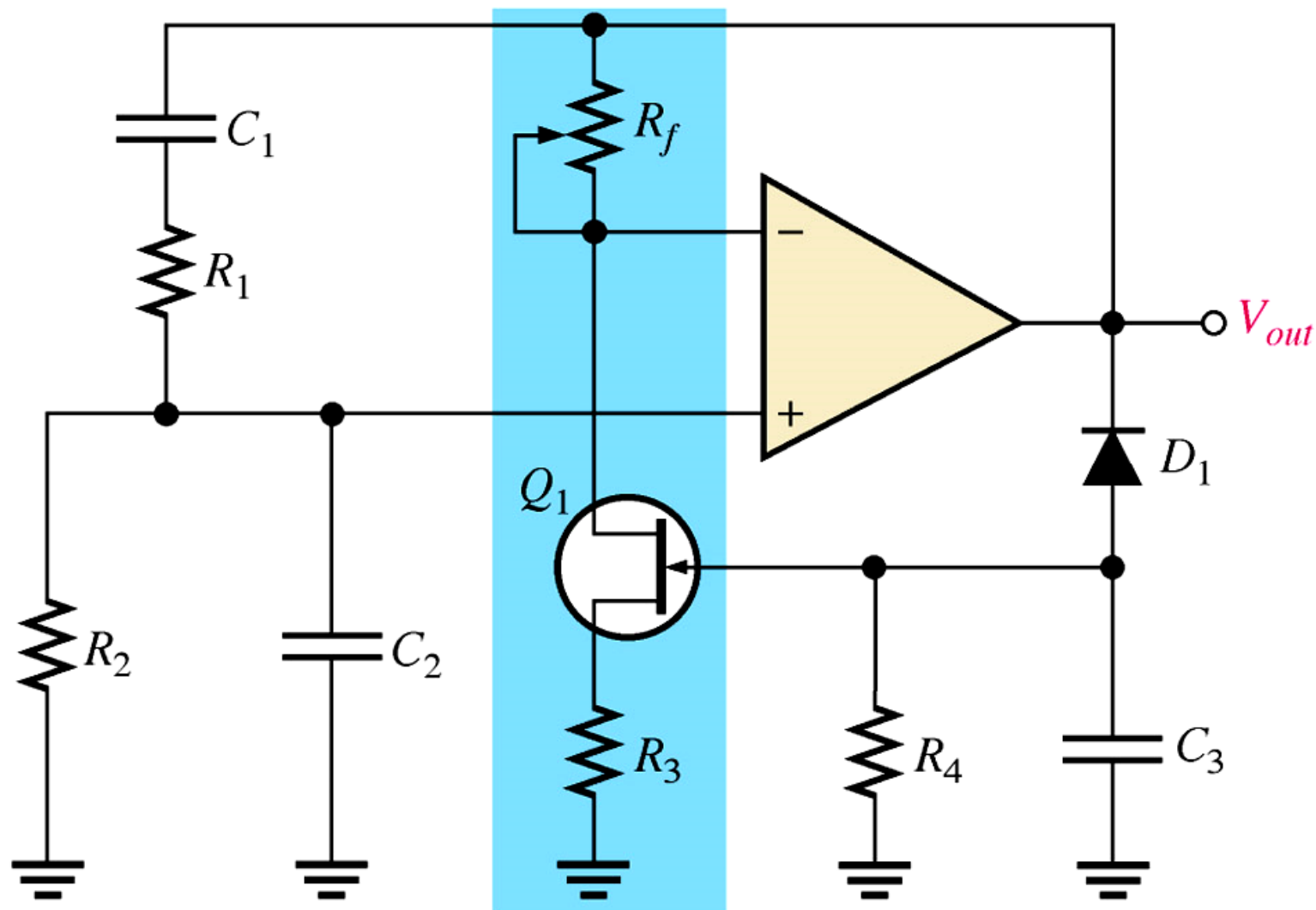




# Wien-Bridge Oscillator

- Q Automatic gain control is necessary to maintain a gain of exact unity.
- Q The zener arrangement for gain control is simple but produces distortion because of the nonlinearity of zener diodes.
- Q A better method to control the gain uses a JFET as a voltage controlled resistor in a negative feedback path.
- Q This method can produce an excellent sinusoidal waveform that is stable.
- Q A JFET operating with a small or zero  $V_{DS}$  is operating in the ohmic region.
- Q As the gate voltage increases, the drain-source resistance increases.
- Q If the JFET is placed in the negative feedback path, automatic gain control can be achieved because of this voltage-controlled resistance.

# Wien-Bridge Oscillator



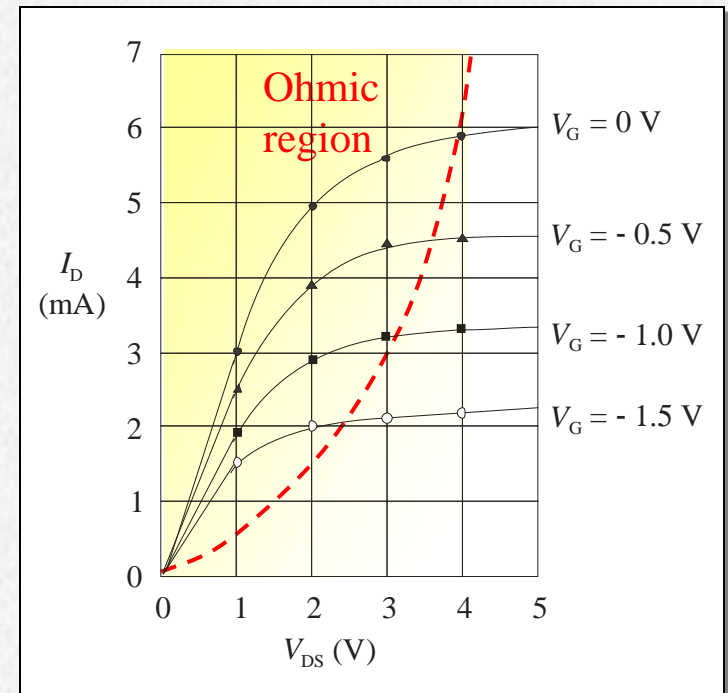
# Wien-Bridge Oscillator

- Q The gain of the op-amp is controlled by the components shown in the green box, which include the JFET
- Q The JFET's drain-source resistance depends on the gate voltage.
- Q With no output signal, the gate is at zero volts, causing the drain-source resistance to be at the minimum and the loop gain is greater than 1.
- Q Oscillations begin and rapidly build to a large output signal.
- Q Negative output signal forward-bias  $D_1$  causing capacitor  $C_3$  to charge to a negative voltage.
- Q This voltage increases the drain-source resistance of the JFET and reduces the gain (and hence the output).
- Q With the proper selection of components, the gain can be stabilized at the required level.

# Wien-Bridge Oscillator

The JFET is operated in the ohmic region and can change its resistance rapidly if conditions change.

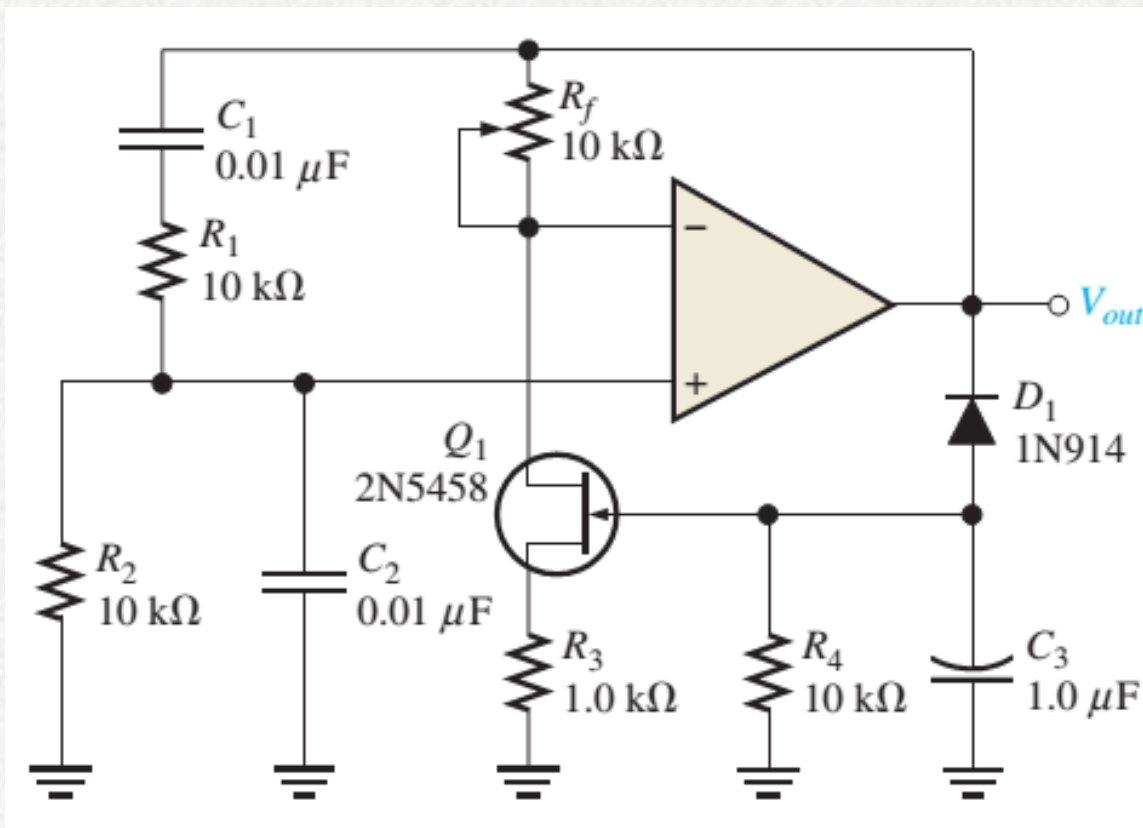
Recall from Chapter 8 that a JFET acts as a variable resistor in the ohmic region. If the output increases, the bias tends to be larger, and the drain-source resistance increases (and vice-versa). In the Wien-bridge, the JFET drain-source resistance controls the gain of the op-amp and will compensate for any change to the output.





# Wien-Bridge Oscillator

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  $500\ \Omega$  when oscillations are stable.



# Wien-Bridge Oscillator

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

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

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,

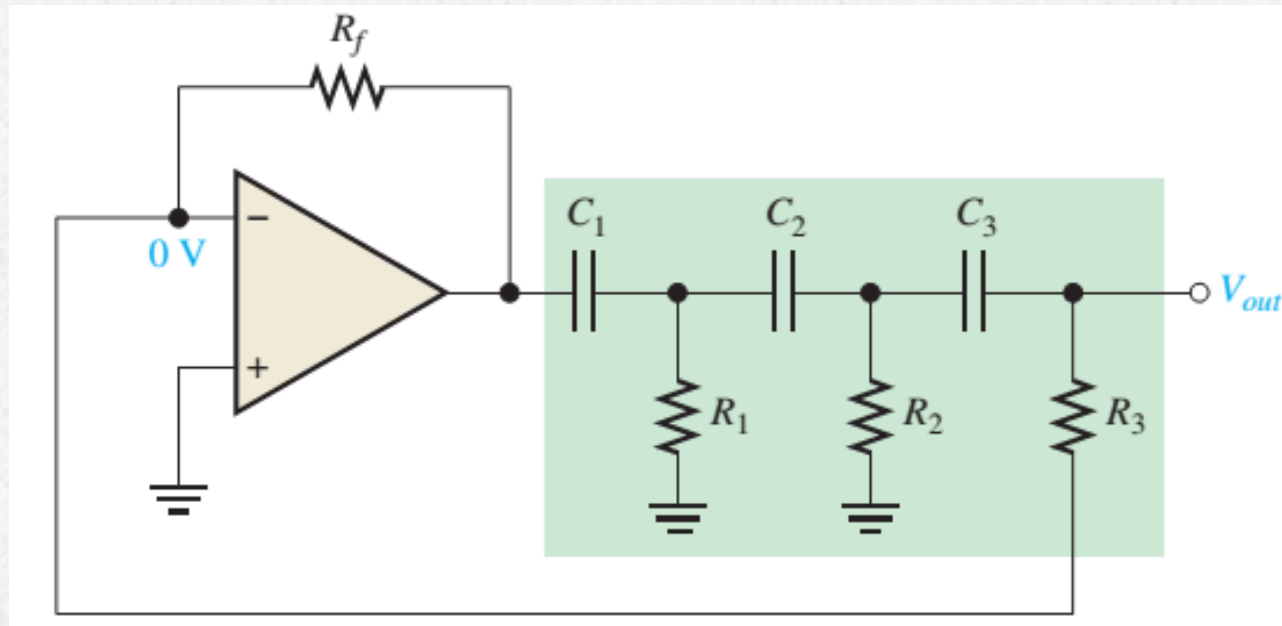
$$A_v = \frac{R_f}{R_3 + r'_{ds}} + 1$$

Rearranging and solving for  $R_f$ ,

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

# The Phase-Shift Oscillator

The phase-shift oscillator uses three RC circuits in the feedback path that have a total phase shift of  $180^\circ$  at one frequency – for this reason an inverting amplifier is required for this circuit



# The Phase-Shift Oscillator

- Q Each of the three RC circuits in the feedback loop can provide a maximum phase shift approaching  $90^\circ$ .
- Q Oscillation occurs at the frequency where the total phase shift through the three RC circuits is  $180^\circ$ .
- Q The inversion of the op-amp itself provides the additional  $180^\circ$  to meet the requirement for oscillation of a  $360^\circ$  (or  $0^\circ$ ) phase shift around the feedback loop.
- Q The attenuation of the three-section RC feedback circuit is  $1/29$
- Q To meet the unity loop gain requirement, the closed-loop voltage gain of the inverting op-amp must be 29

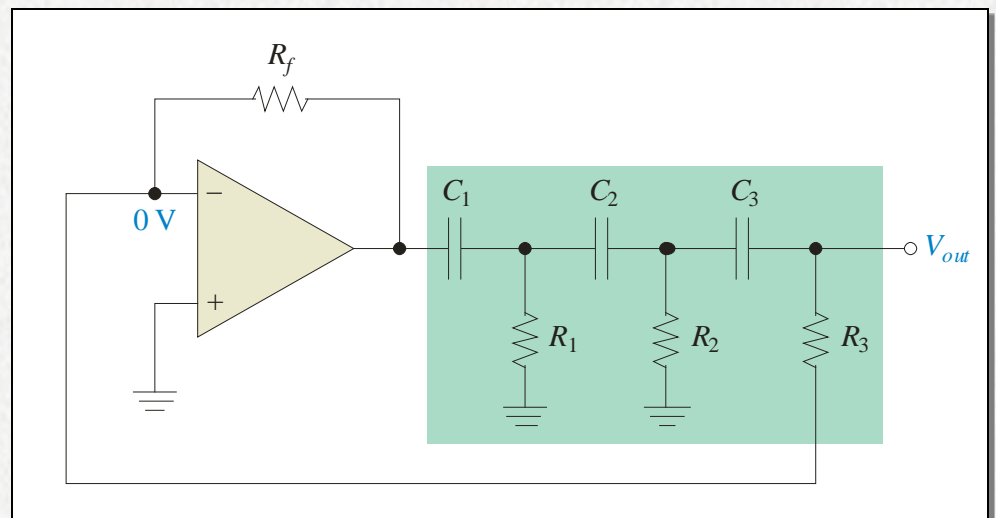


## The Phase-Shift Oscillator

Conditions for oscillation with the phase-shift oscillator is that if all  $R$ 's and  $C$ 's are equal, the amplifier must have a gain of at least 29 to make up for the attenuation of the feedback circuit. This means that  $R_f/R_3 \geq 29$ .

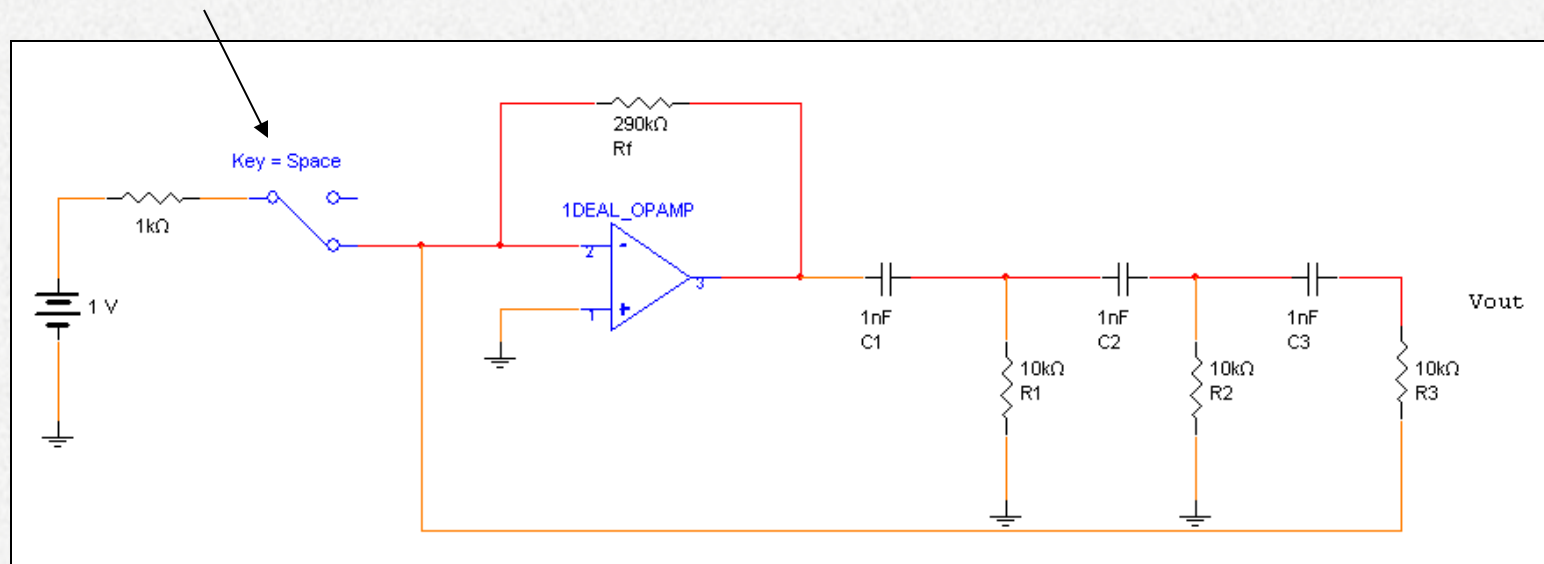
Under these conditions, the frequency of oscillation is given by

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



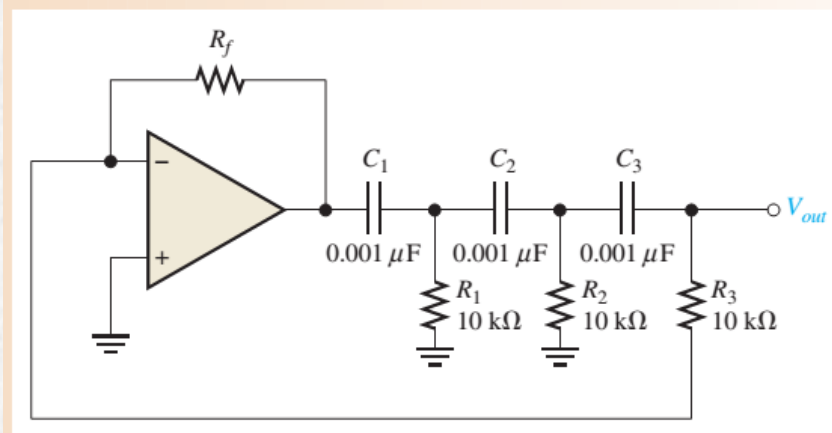
## The Phase-Shift Oscillator

Multisim can simulate the phase-shift oscillator, but has difficulty starting. In the Multisim file for Example 16-3, a switch is provided to provide a voltage spike to start oscillations. This is not needed in the actual circuit.



# The Phase-Shift Oscillator

- (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.



**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,

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

# The Phase-Shift Oscillator

**Example:** Design a phase-shift oscillator for a frequency of 800 Hz.  
The capacitors are to be 10 nF.

**Solution:**

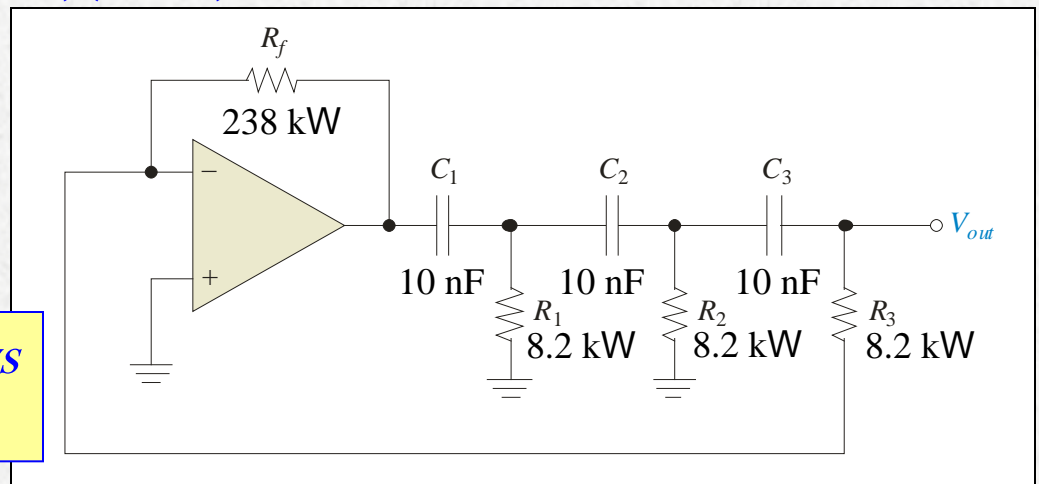
Start by solving for the resistors needed in the feedback circuit:

$$R = \frac{1}{2\pi\sqrt{6}f_r C} = \frac{1}{2\pi\sqrt{6}(800 \text{ Hz})(10 \text{ nF})} = 8.12 \text{ kW} \quad (\text{Use } 8.2 \text{ kW.})$$

Calculate the feedback resistor needed:

$$R_f = 29R = 238 \text{ kW.}$$

*The following slide shows the Multisim check.*

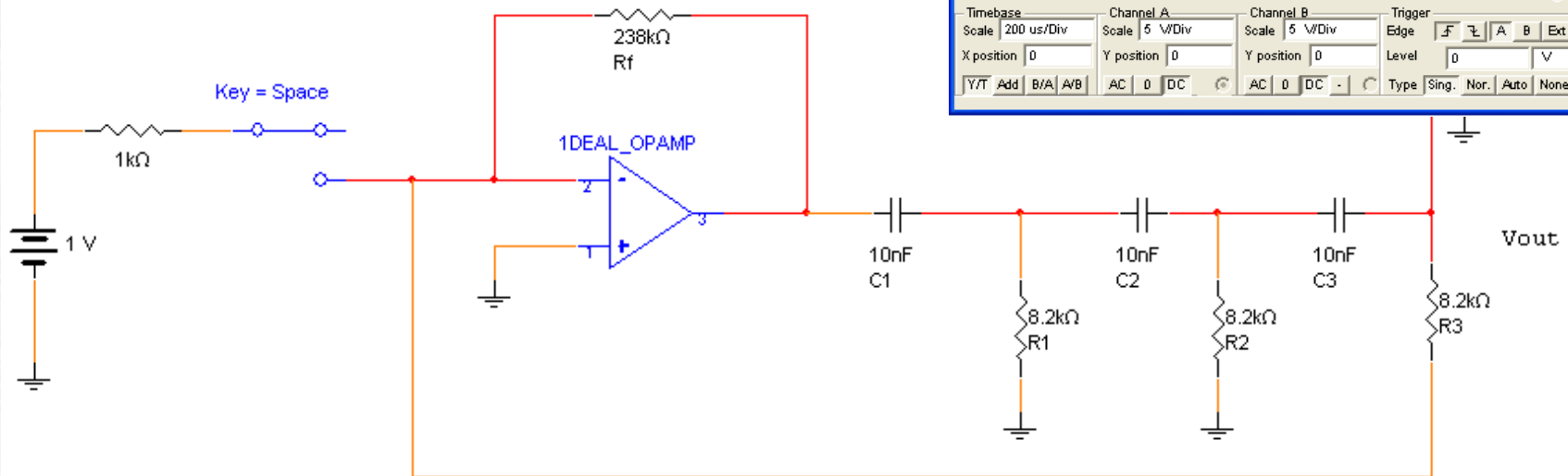
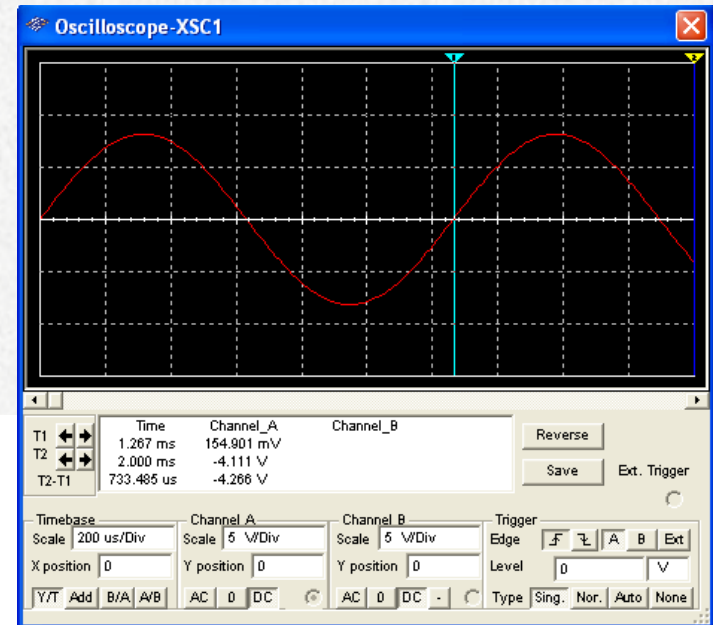




# Summary

## The Phase-Shift Oscillator

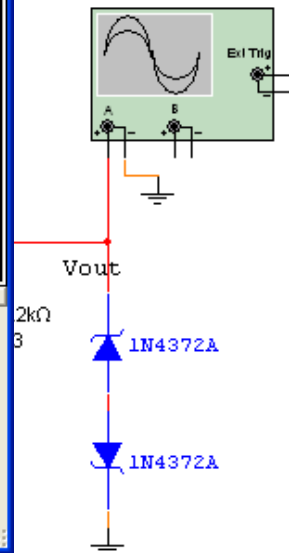
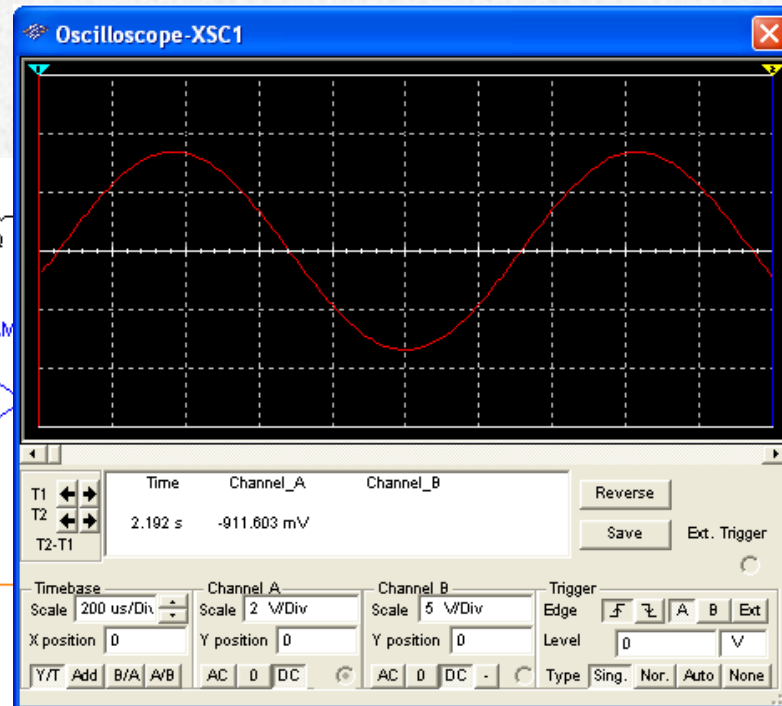
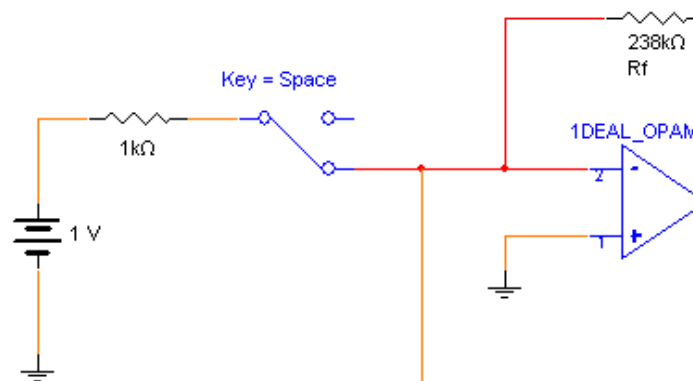
Because the  $R_f$  is not precise, you will see the output “grow” in Multisim. In actual circuits, you can use a potentiometer to adjust a precise gain, but the circuit will be sensitive to temperature change.



# Summary

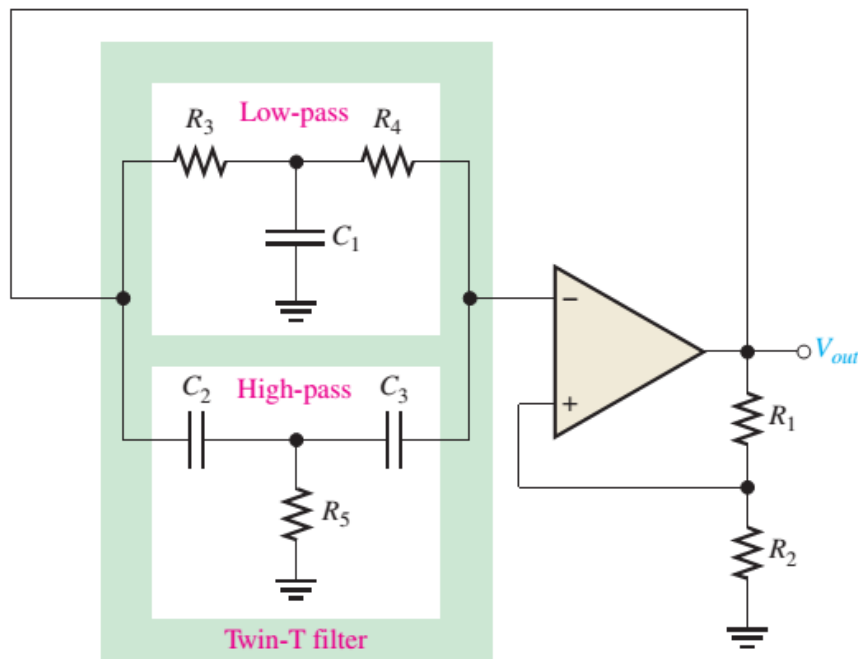
## The Phase-Shift Oscillator

You can also use back-to back zener diodes to limit the output. The output is limited to about  $7 V_{pp}$  with 1N4372A (3.0 V) zeners.

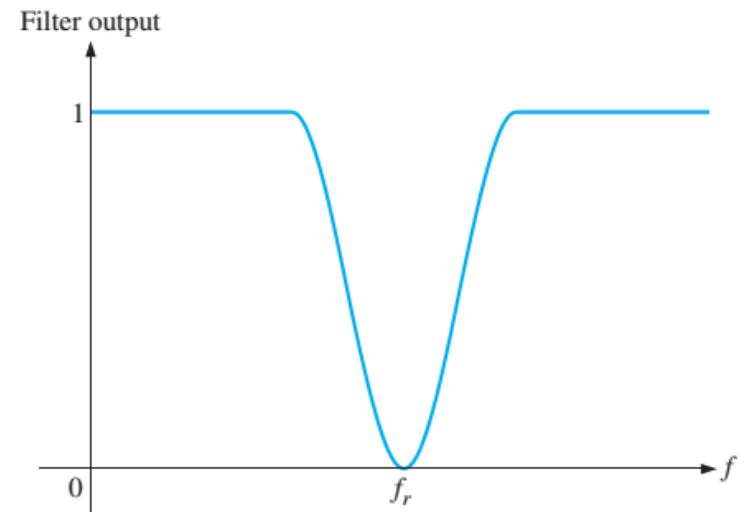


# The Twin-T Oscillator

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



(a) Oscillator circuit



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

# The Twin-T Oscillator

- Q One of the twin-T filters has a low-pass response, and the other has a high-pass response.
- Q The combined parallel filters produce a band-stop or notch response with a center frequency equal to the desired frequency of oscillation  $f_r$ .
- Q Oscillation cannot occur at frequencies above or below  $f_r$  because of the negative feedback through the filters.
- Q 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.



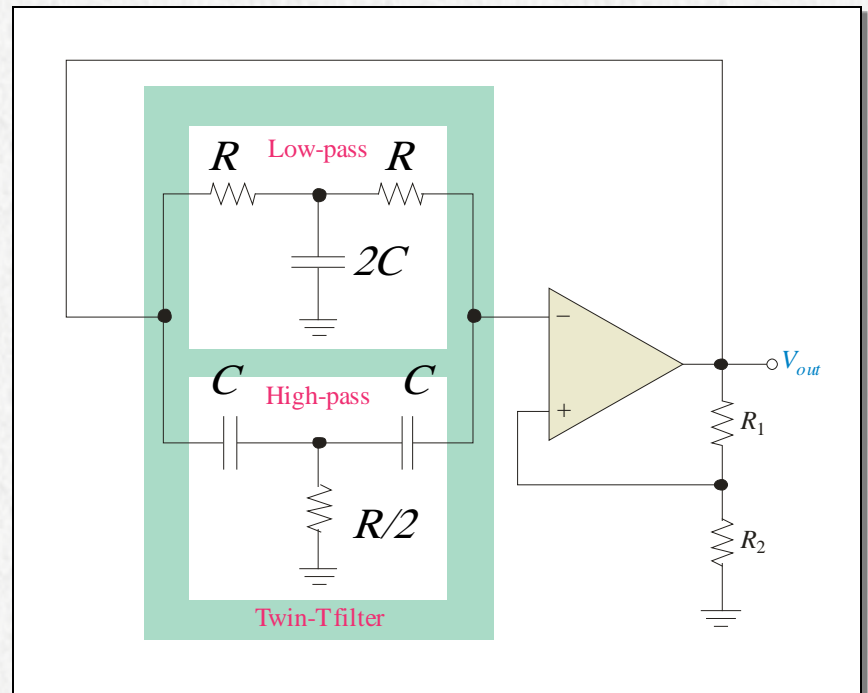
# The Twin-T Oscillator

The basic twin-T oscillator combines a low-pass and high-pass filter to form a notch filter at the oscillation frequency.

An excellent notch filter can be formed by using  $R$ 's and  $C$ 's related by a factor of 2 as shown here.

With this relationship, the oscillation frequency is approximately

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

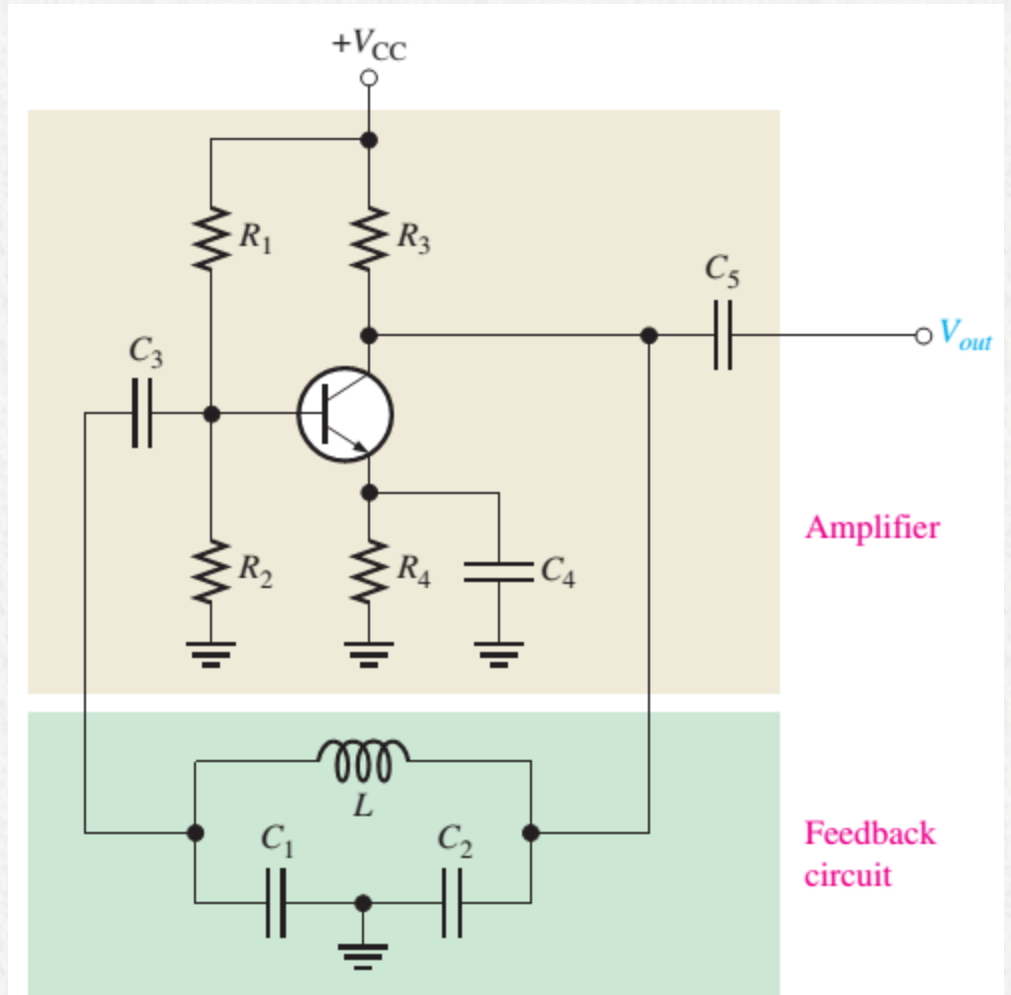


# LC Oscillators

- Q 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.
- Q 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.
- Q This section introduces several types of resonant LC feedback oscillators like the Colpitts, Clapp, Hartley, Armstrong, and crystal-controlled oscillators.

# The Colpitts Oscillator

One basic type of resonant circuit feedback oscillator is the Colpitts shown in the figure. 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.



# The Colpitts Oscillator

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 the series capacitors around the tank circuit, given by:

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

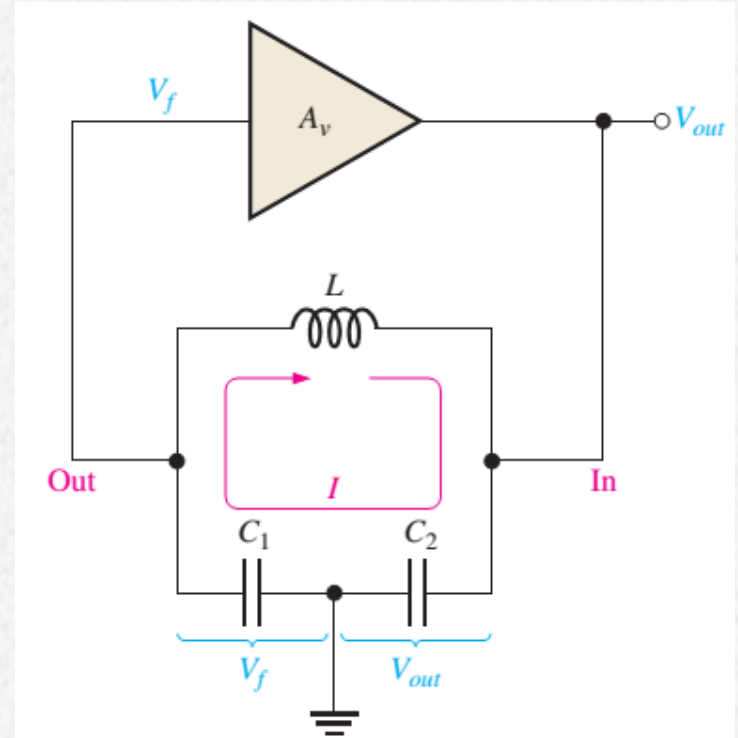
The output voltage is developed across  $C_1$  and the feedback voltage is developed across  $C_2$ .



# The Colpitts Oscillator

The attenuation,  $B$ , of the resonant feedback circuit in the Colpitts oscillator is basically determined by the values of  $C_1$ , and  $C_2$ .

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  $V_f$ .



The expression for the attenuation is  $B = C_2/C_1$

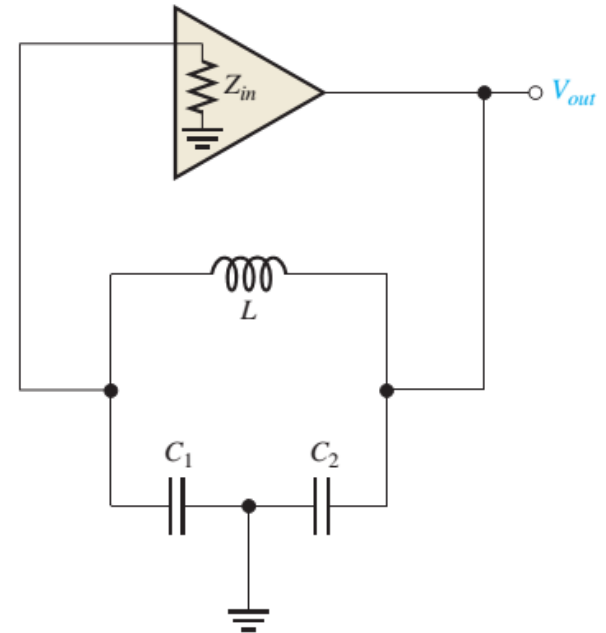
The condition for oscillation is  $A_v B = 1$  or  $A_v = C_1/C_2$

# The Colpitts Oscillator

- Q The input impedance of the amplifier acts as a load on the resonant feedback circuit and reduces the  $Q$  of the circuit.
- Q The resonant frequency of a parallel resonant circuit depends on the  $Q$  as:

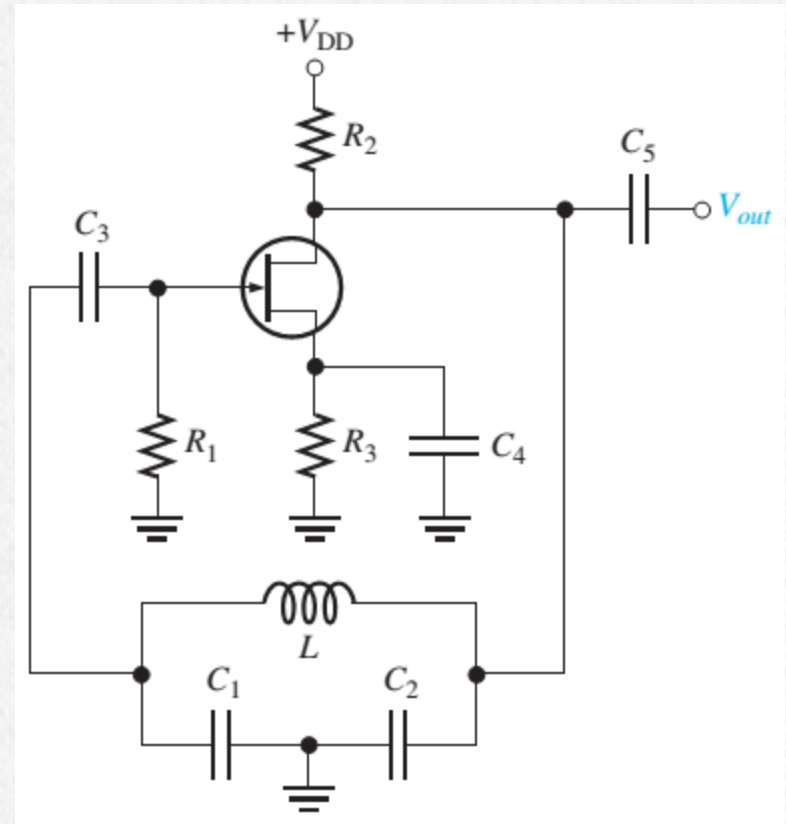
$$f_r = \frac{1}{2\pi\sqrt{LC_T}} \sqrt{\frac{Q^2}{Q^2 + 1}}$$

- Q For a  $Q$  greater than 10,  $f_r$  is approximately  $1/(2\pi\sqrt{LC_T})$
- Q When  $Q$  is less than 10,  $f_r$  is reduced significantly

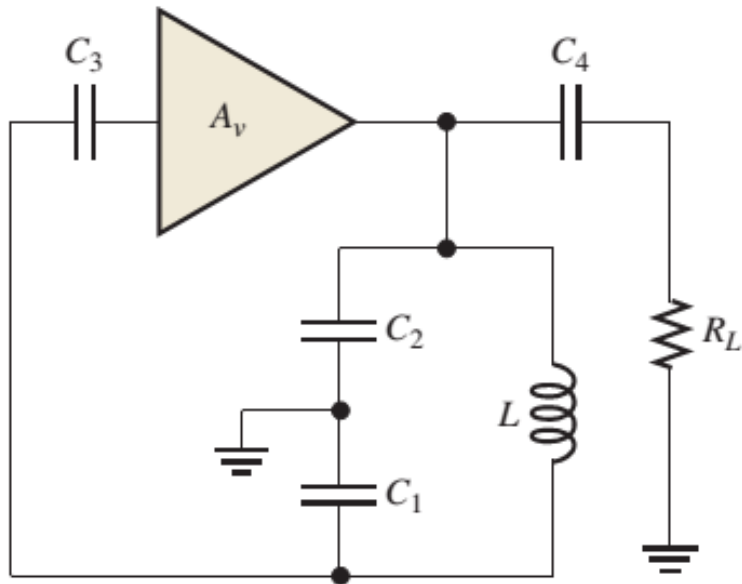


# The Colpitts Oscillator

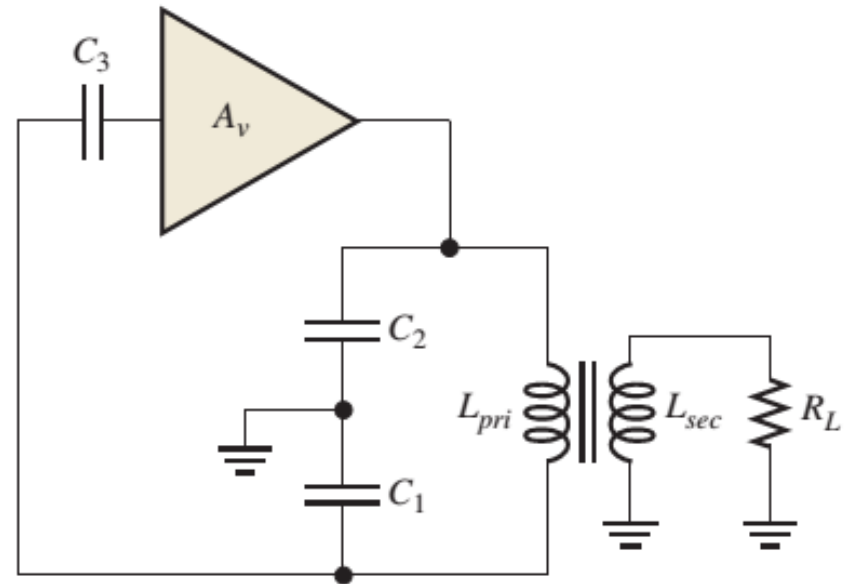
- Q A FET can be used in place of a BJT to minimize the loading effect of the transistor's input impedance because of the higher input impedance of FET.
- Q Also, when an external load is connected to the oscillator output,  $f_r$  may decrease because of a reduction in  $Q$  if the load resistance is too small .
- Q One way to eliminate the effects of a load resistance is by transformer coupling.



# The 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.



### EXAMPLE 16-3

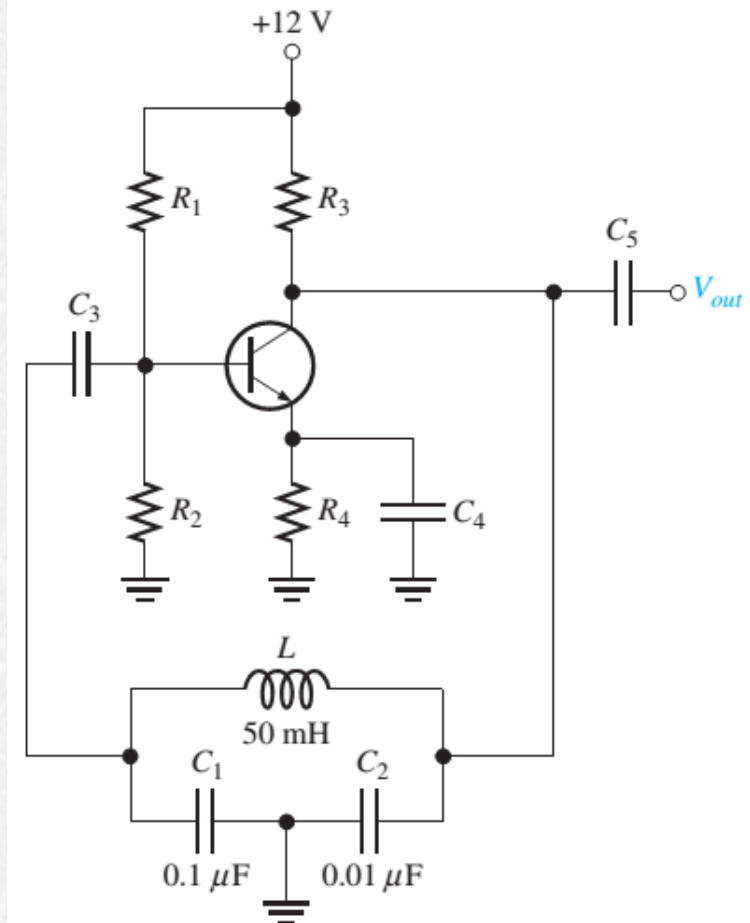
- (a) Determine the frequency for the oscillator in Figure 16-21. Assume there is negligible loading on the feedback circuit and that its  $Q$  is greater than 10.
- (b) Find the frequency if the oscillator is loaded to a point where the  $Q$  drops to 8.

#### Solution

$$\begin{aligned}\text{(a)} \quad C_T &= \frac{C_1 C_2}{C_1 + C_2} = \frac{(0.1 \mu\text{F})(0.01 \mu\text{F})}{0.11 \mu\text{F}} \\ &= 0.0091 \mu\text{F}\end{aligned}$$

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

$$\begin{aligned}\text{(b)} \quad f_r &= \frac{1}{2\pi\sqrt{LC_T}} \sqrt{\frac{Q^2}{Q^2 + 1}} = (7.46 \text{ kHz})(0.9923) \\ &= 7.40 \text{ kHz}\end{aligned}$$



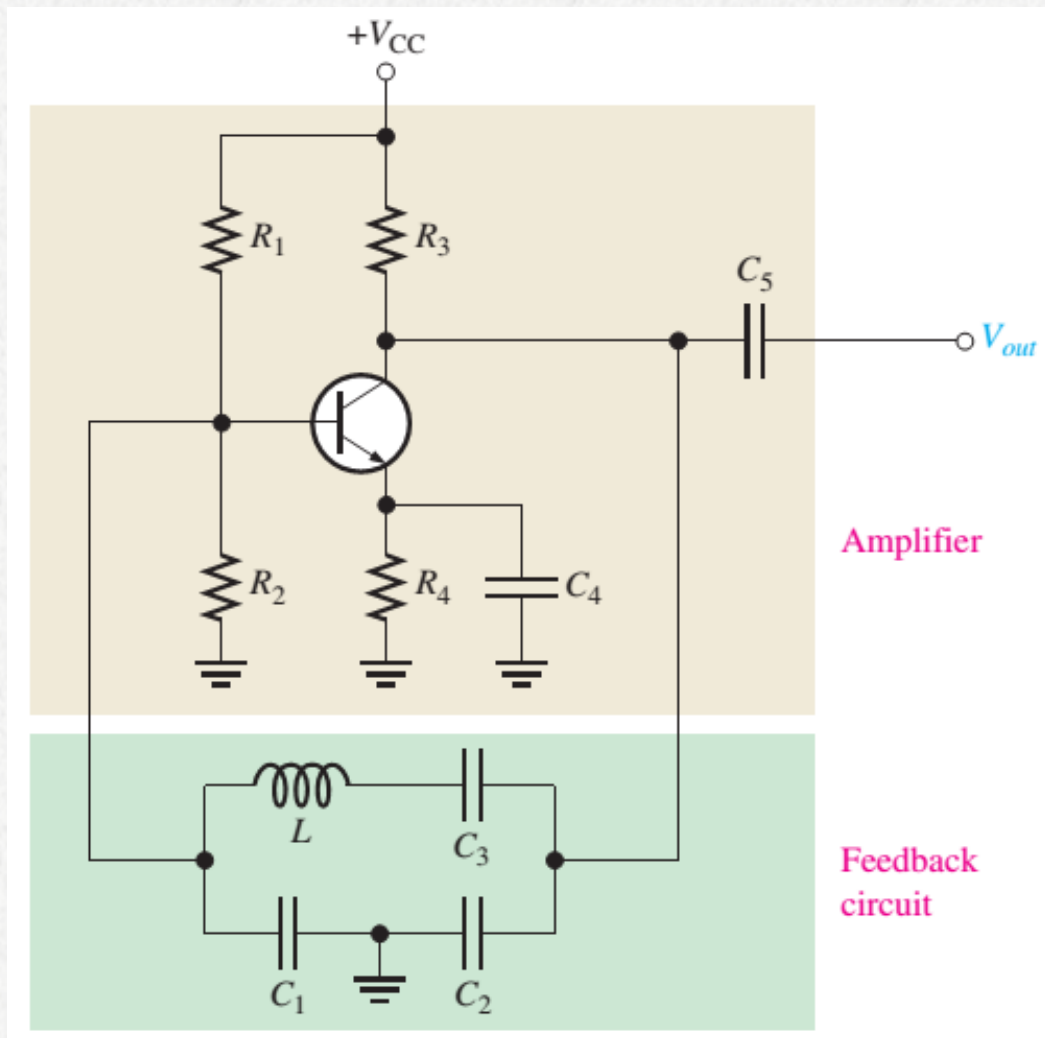
# The Clapp Oscillator

- Q The Clapp oscillator is a variation of the Colpitts.
- Q The basic difference is an additional capacitor,  $C_3$  in series with the inductor in the resonant feedback circuit.
- Q Since  $C_3$  is in series with  $C_1$  and  $C_2$  around the tank circuit, the total capacitance is

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

- Q In Clapp oscillator,  $C_3$  is much smaller than  $C_1$  and  $C_2$ . As a result  $C_T$  is approximately equal to  $C_3$  and the resonant frequency is controlled by  $C_3$ .
- Q Clapp provides a more accurate and stable frequency of oscillation since  $C_1$  and  $C_2$  are shunted by transistor and the stray capacitances alter their values.

# The Clapp Oscillator



# The Hartley Oscillator

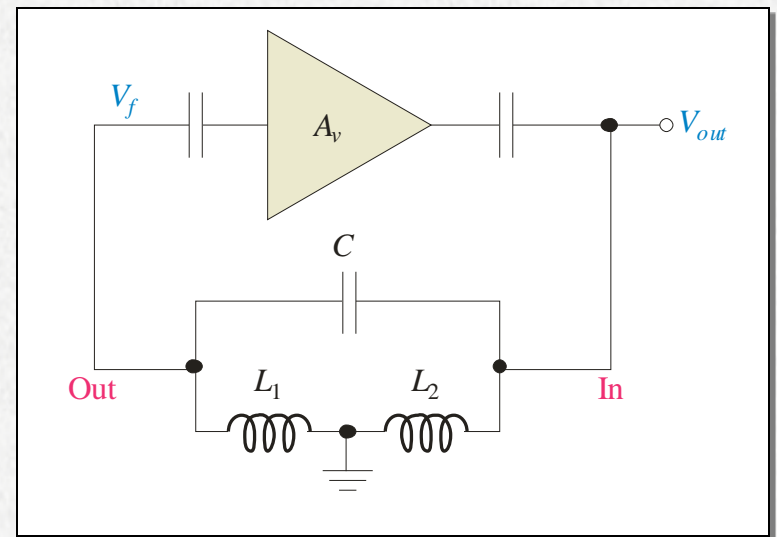
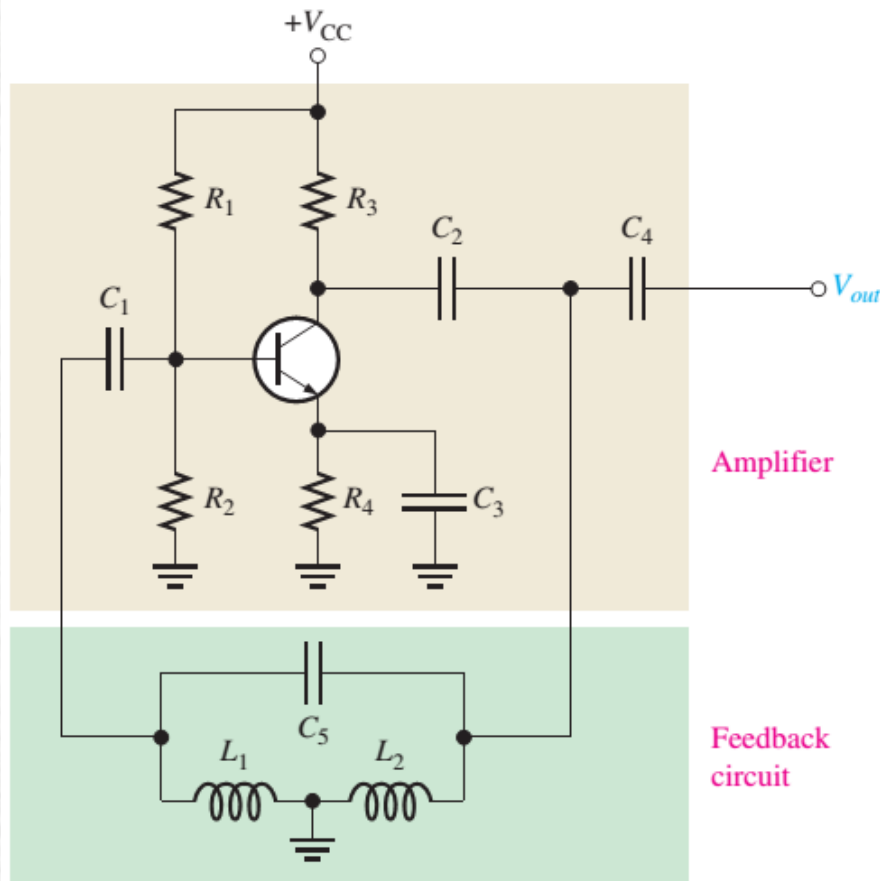
- Q The Hartley oscillator is similar to the Colpitts oscillator, except the resonant circuit consists of two series inductors (or a single tapped inductor) and a parallel capacitor. The frequency for  $Q > 10$  is

$$f_r = \frac{1}{2\pi\sqrt{L_T C}} = \frac{1}{2\pi\sqrt{(L_1 + L_2) C}}$$

- Q 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  $B = (L_1 / L_2)$ .
- Q To assure start-up of oscillation,  $A_v$  must be greater than  $1/B$ .
- Q 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 Hartley Oscillator

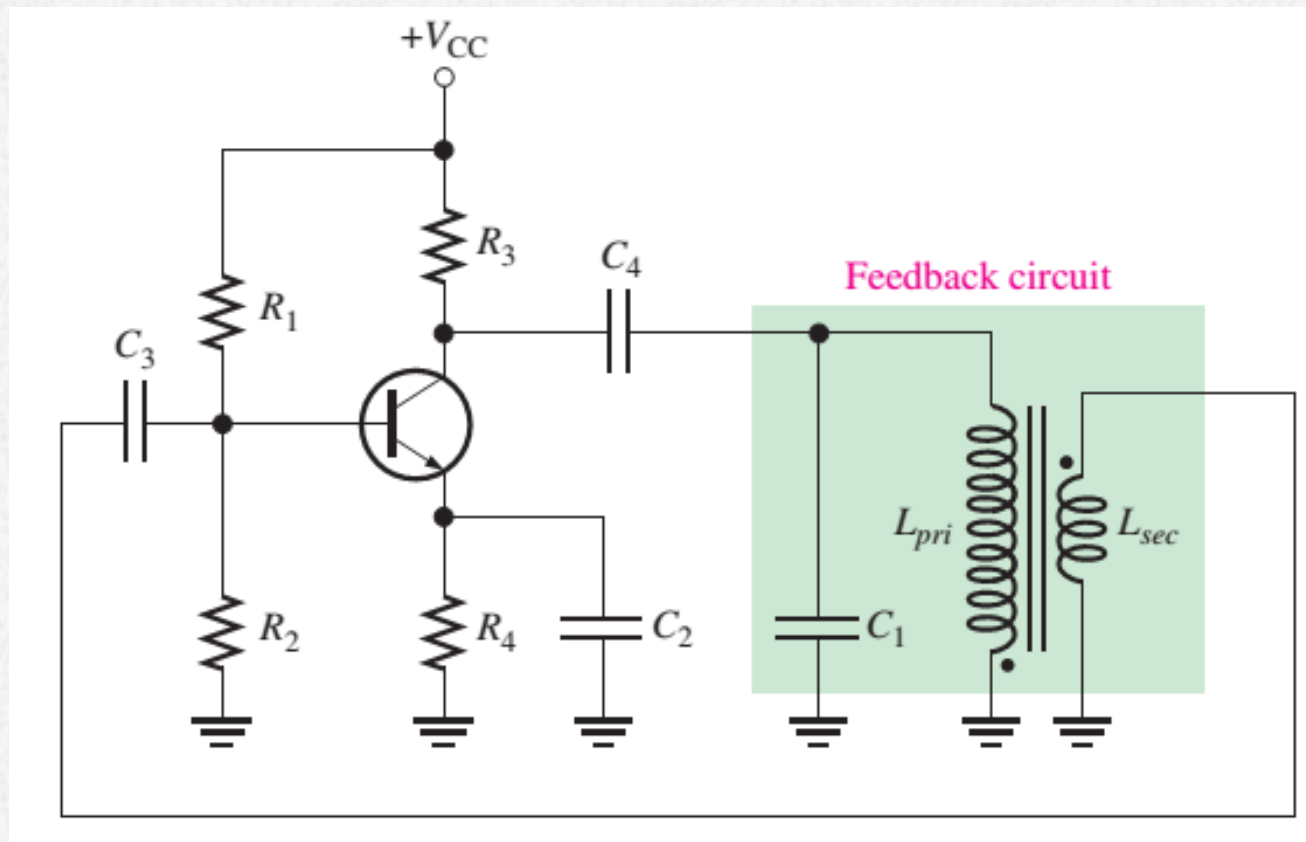


# The Armstrong Oscillator

- Q This type of LC feedback oscillator uses transformer coupling to feed back a portion of the signal voltage.
- Q The transformer secondary coil provides the feedback to keep the oscillation going.
- Q The Armstrong is less common than the Colpitts, Clapp, and Hartley, mainly because of the disadvantage of transformer size and cost.
- Q The frequency of oscillation is set by the inductance of the primary winding ( $L_{pri}$ ) in parallel with  $C_1$

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

# The Armstrong Oscillator



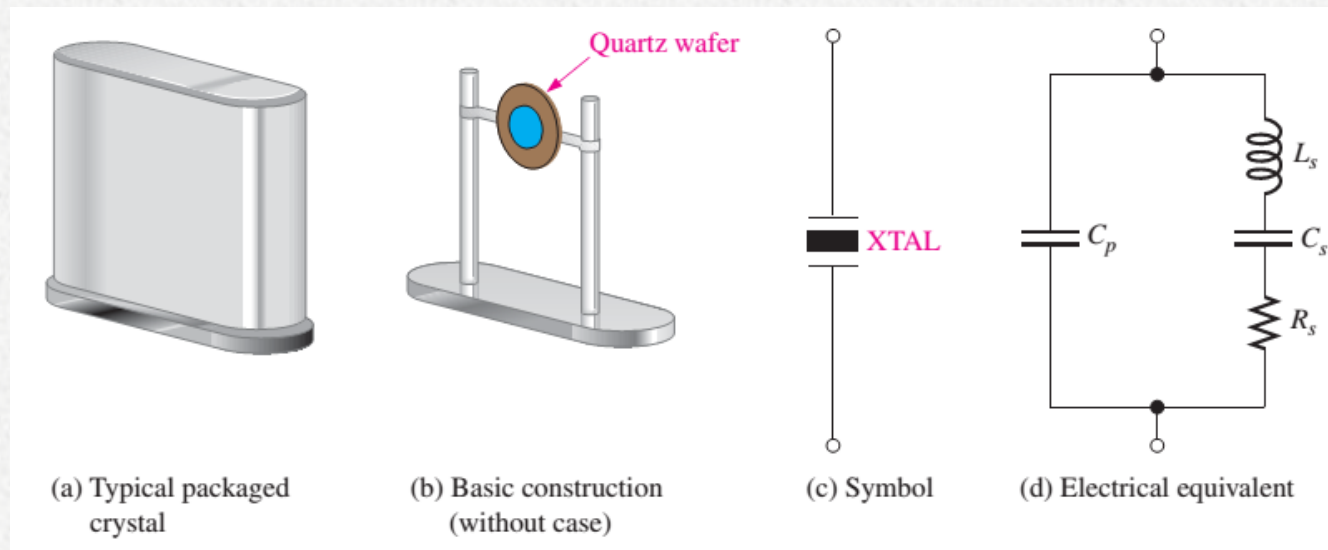
# The Crystal Oscillator

- Q The most stable and accurate type of feedback oscillator uses a piezoelectric crystal in the feedback loop to control the frequency.
- Q Quartz is one type of crystalline substance found in nature that exhibits a property called the **piezoelectric effect**.
- Q When a changing mechanical stress is applied across the crystal to cause it to vibrate, a voltage develops at the frequency of mechanical vibration.
- Q Conversely, when an AC voltage is applied across the crystal, it vibrates at the frequency of the applied voltage.
- Q 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.



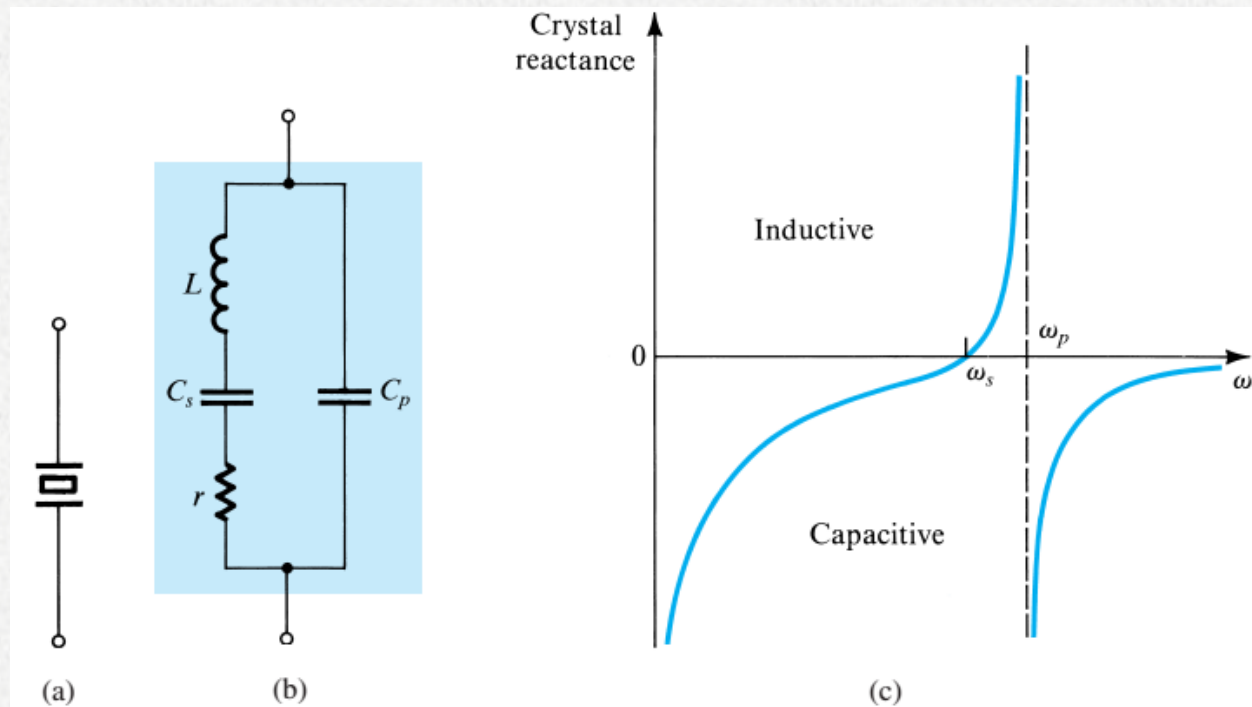
# The Crystal Oscillator

- Q The crystal's equivalent circuit is a series-parallel  $RLC$  circuit and can operate in either series resonance or parallel resonance.
- Q At the series resonant frequency, the inductive reactance is cancelled by the reactance of  $C_s$ .
- Q At this frequency, crystal offers a very low impedance to the external circuit where  $Z = R_s$ .



# The Crystal Oscillator

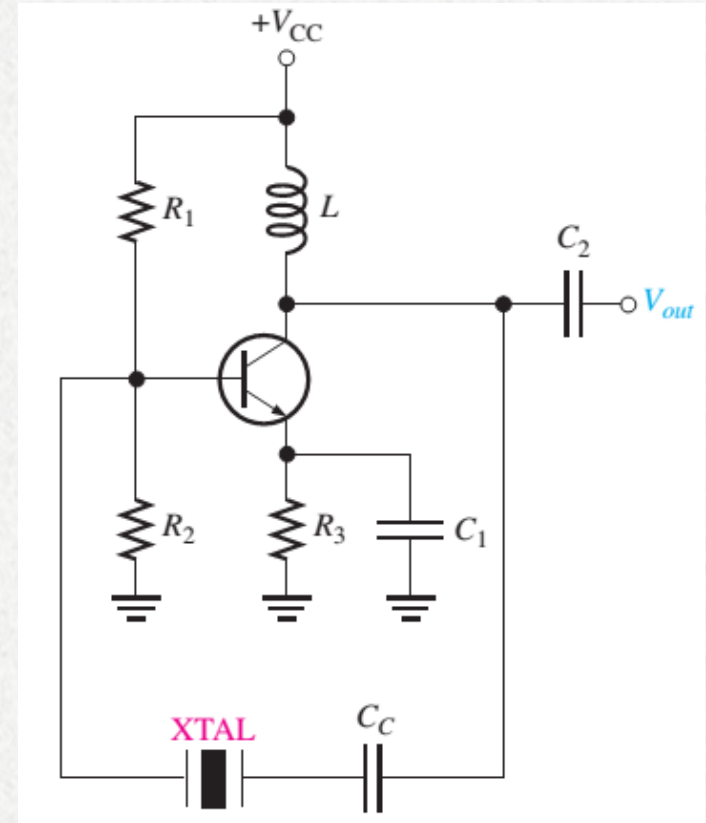
Parallel resonance (antiresonance) occurs when reactance of the series leg equals the reactance of  $C_p$ . At this frequency, crystal offers a very high impedance to the external circuit. The parallel resonant frequency is usually at least 1 kHz higher than the series resonant frequency.



**Figure 17.15** A piezoelectric crystal. (a) Circuit symbol. (b) Equivalent circuit. (c) Crystal reactance versus frequency [note that, neglecting the small resistance  $r$ ,  $Z_{\text{crystal}} = jX(\omega)$ ].

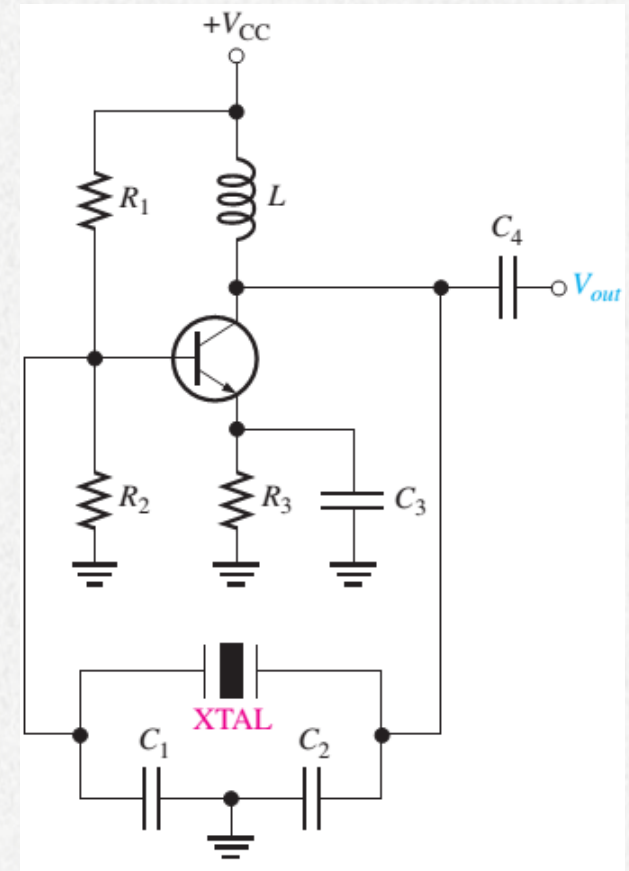
# The Crystal Oscillator

- Q A great advantage of the crystal is that it exhibits a very high  $Q$ .
- Q An oscillator that uses a crystal as a series resonant tank circuit is shown
- Q The impedance of the crystal is minimum at the series resonant frequency, thus providing maximum feedback.
- Q The crystal tuning capacitor,  $C_C$  is used to “fine tune” the oscillator frequency



# The Crystal Oscillator

- Q A modified Colpitts configuration is shown with a crystal acting as a parallel resonant tank circuit.
- Q At the parallel-resonant operating frequency, a crystal appears as an inductive reactance of largest value.
- Q Under this condition, Maximum voltage is developed across the capacitor. The voltage across  $C_1$  is fed back to the input.





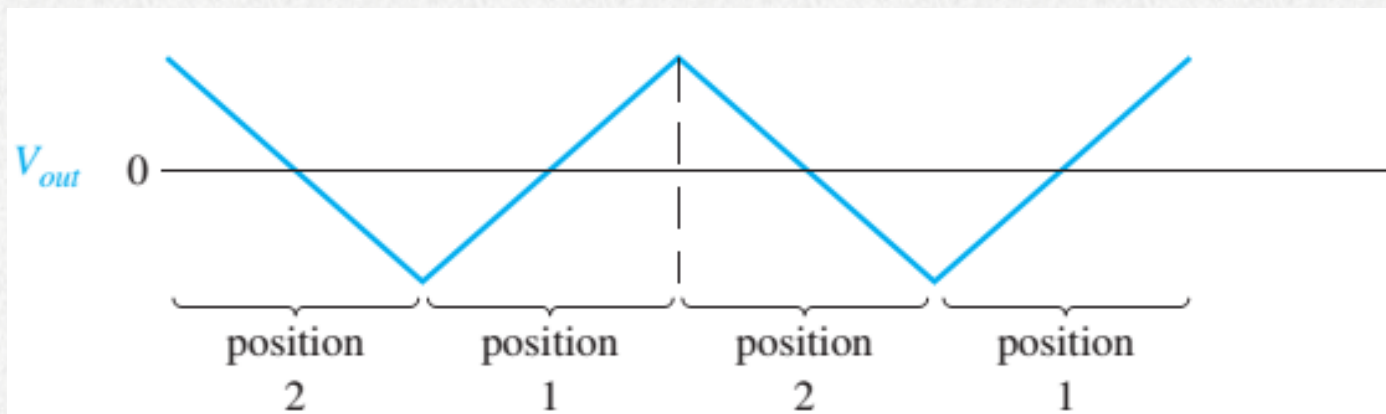
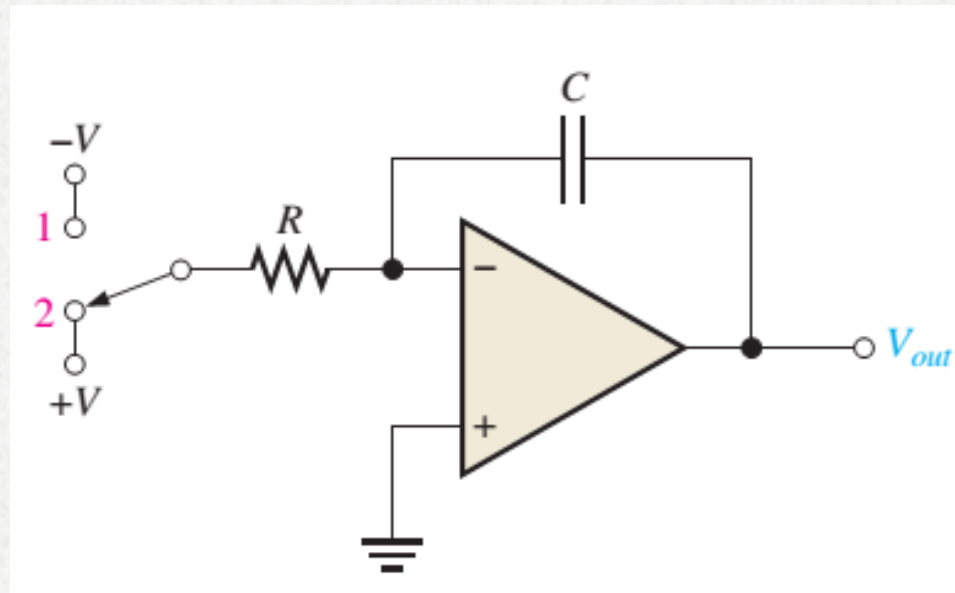
# Relaxation Oscillators

- Q The second major category of oscillators is the relaxation oscillator.
- Q Relaxation oscillators make use of an RC timing and a device that changes states to generate a periodic waveform (non-sinusoidal).
- Q In this section, you will learn about several circuits that are used to produce the following nonsinusoidal waveforms
  1. Triangular-wave
  2. Square-wave
  3. Sawtooth

# A Triangular-Wave Oscillator

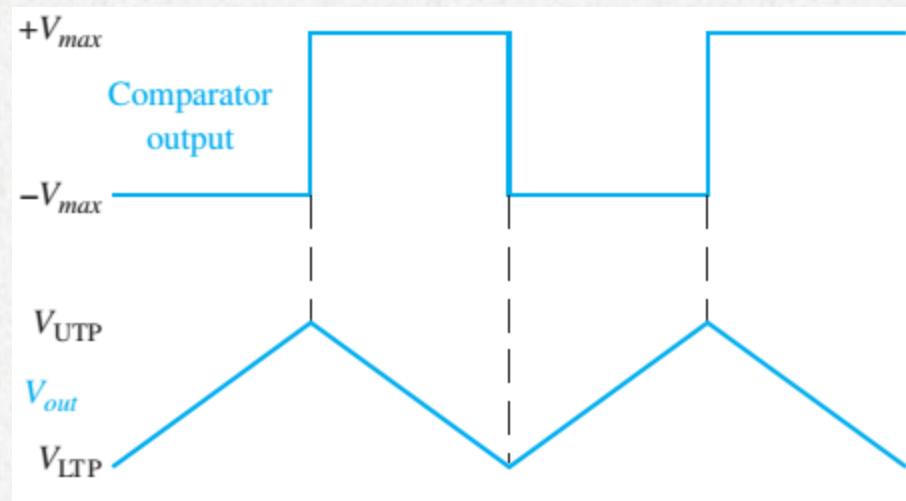
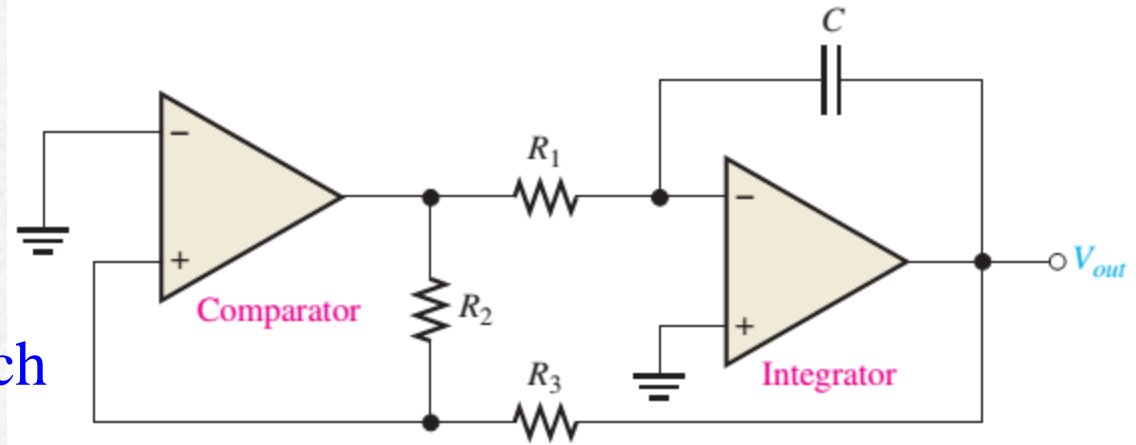
- Q The op-amp integrator can be used as the basis for a triangular-wave oscillator.
- Q The basic idea is illustrated in Figure where a dual-polarity, switched input is used to introduce the concept.
- Q When the switch is in position 1, the negative voltage is applied, and the output is a positive-going ramp.
- Q When the switch is thrown into position 2, a negative-going ramp is produced.
- Q 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.

# A Triangular-Wave Oscillator



# A Triangular-Wave Oscillator

A practical implementation of a triangular-wave oscillator circuit which is a combination of a comparator and integrator is shown.





# A Triangular-Wave Oscillator

- Q Assume that the output voltage of the comparator is at its maximum negative level.
- Q This output is connected to the inverting input of the integrator through  $R_I$ , producing a positive-going ramp on the output of the integrator.
- Q When the ramp voltage reaches the upper trigger point (UTP), the comparator switches to its maximum positive level.
- Q This positive level causes the integrator ramp to change to a negative-going direction.
- Q The ramp continues in this direction until the lower trigger point (LTP) of the comparator is reached and the cycle repeats.

# A Triangular-Wave Oscillator

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

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

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.

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

# A Triangular-Wave Oscillator

## Example:

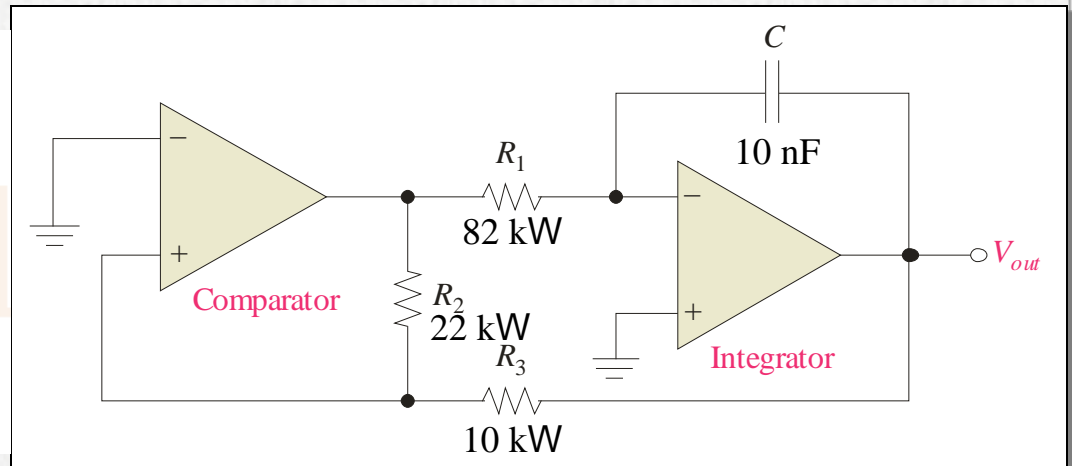
What is the frequency of the circuit shown here? To what value  $R_1$  must be changed to make the frequency 20 kHz?

## Solution:

$$f_r = \frac{1}{4R_1C} \left( \frac{R_2}{R_3} \right) = \frac{1}{4(82 \text{ k}\Omega)(10 \text{ nF})} \left( \frac{22 \text{ k}\Omega}{10 \text{ k}\Omega} \right) = 671 \text{ Hz}$$

To make the frequency 20 kHz:

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

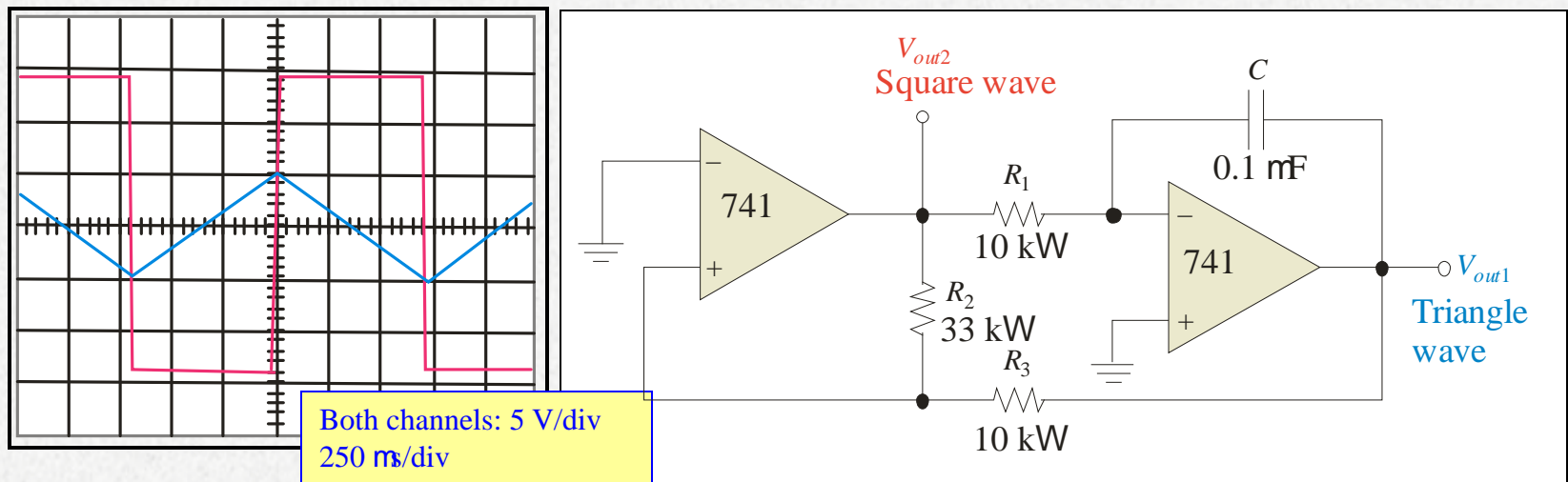


# Summary

## Relaxation Oscillators

Normally, the triangle wave generator uses fast comparators to avoid slew rate problems. For non-critical applications, a 741 will work nicely for low frequencies (<2 kHz). The circuit here is one you can construct easily in lab. (The circuit is the same as Example 16-4 but with a larger  $C$ .)

The waveforms are:





## A Sawtooth VCO

- Q It is a relaxation oscillator whose frequency can be changed by a variable dc control voltage.
- Q The PUT is a programmable unijunction transistor with an anode, a cathode, and a gate terminal.
- Q The gate is always biased positively with respect to the cathode.
- Q When the anode voltage exceeds the gate voltage by approximately 0.7 V, the PUT turns on and acts as a forward-biased diode.
- Q The current must be above the holding value to maintain conduction.

# A Sawtooth VCO

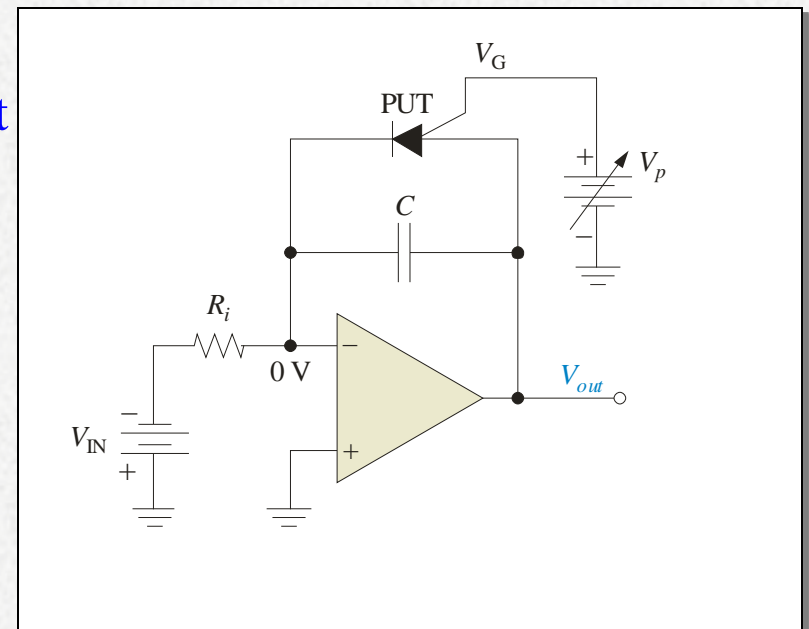
A sawtooth VCO uses an integrator to create the ramp portion of the waveform. In this case, when  $V_C > V_G + 0.7 \text{ V}$ , the PUT fires and the capacitor discharges rapidly until the PUT current falls below the holding value. The sawtooth amplitude and period can be adjusted by varying the PUT gate voltage

In this circuit, the device that changes state is a PUT and the  $RC$  timing circuit is an integrator.

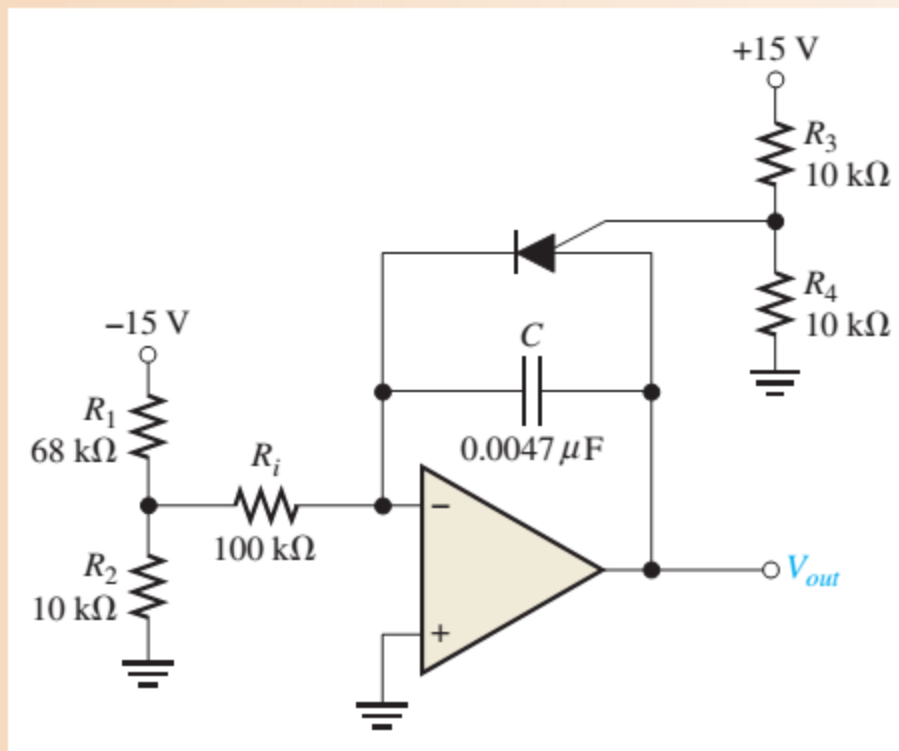
The frequency is found by:

$$f = \frac{V_{IN}}{R_i C} \left( \frac{1}{V_P - V_F} \right)$$

$V_F$  is the PUT forward voltage



- (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.



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

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

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

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

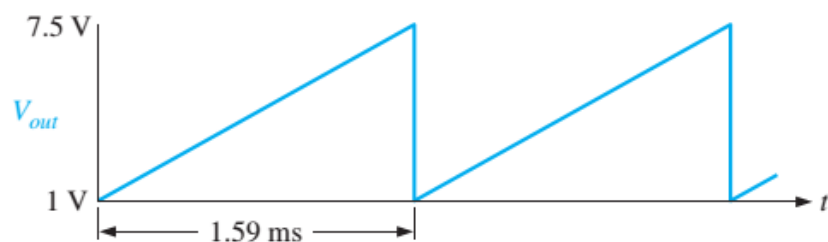
Determine the frequency as follows:

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

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

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

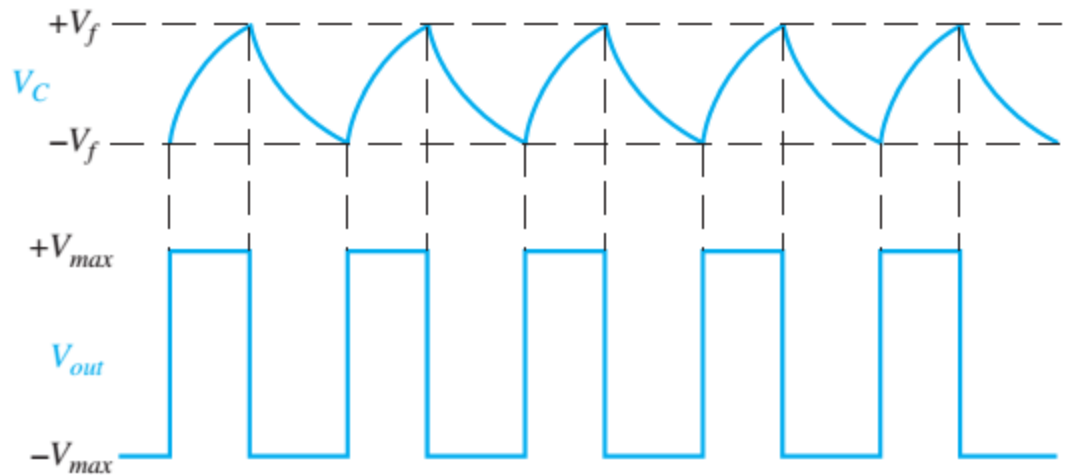
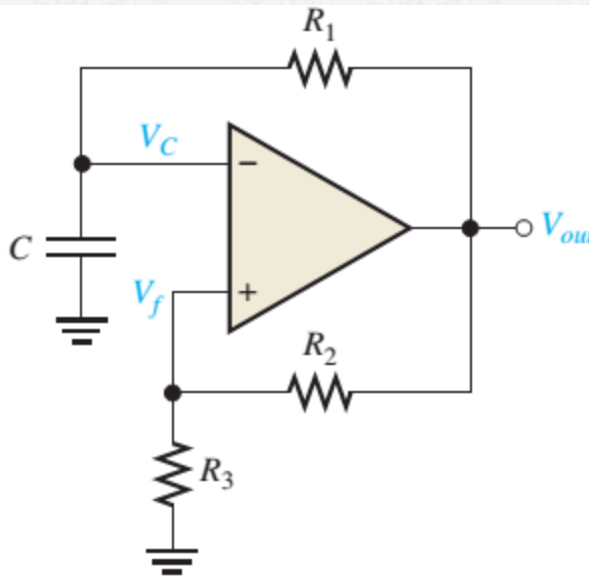
$$T = \frac{1}{f} = \frac{1}{628 \text{ Hz}} = 1.59 \text{ ms}$$





# A Square-Wave Oscillator

The basic square-wave oscillator shown is a type of relaxation oscillator because its operation is based on the charging and discharging of a capacitor.

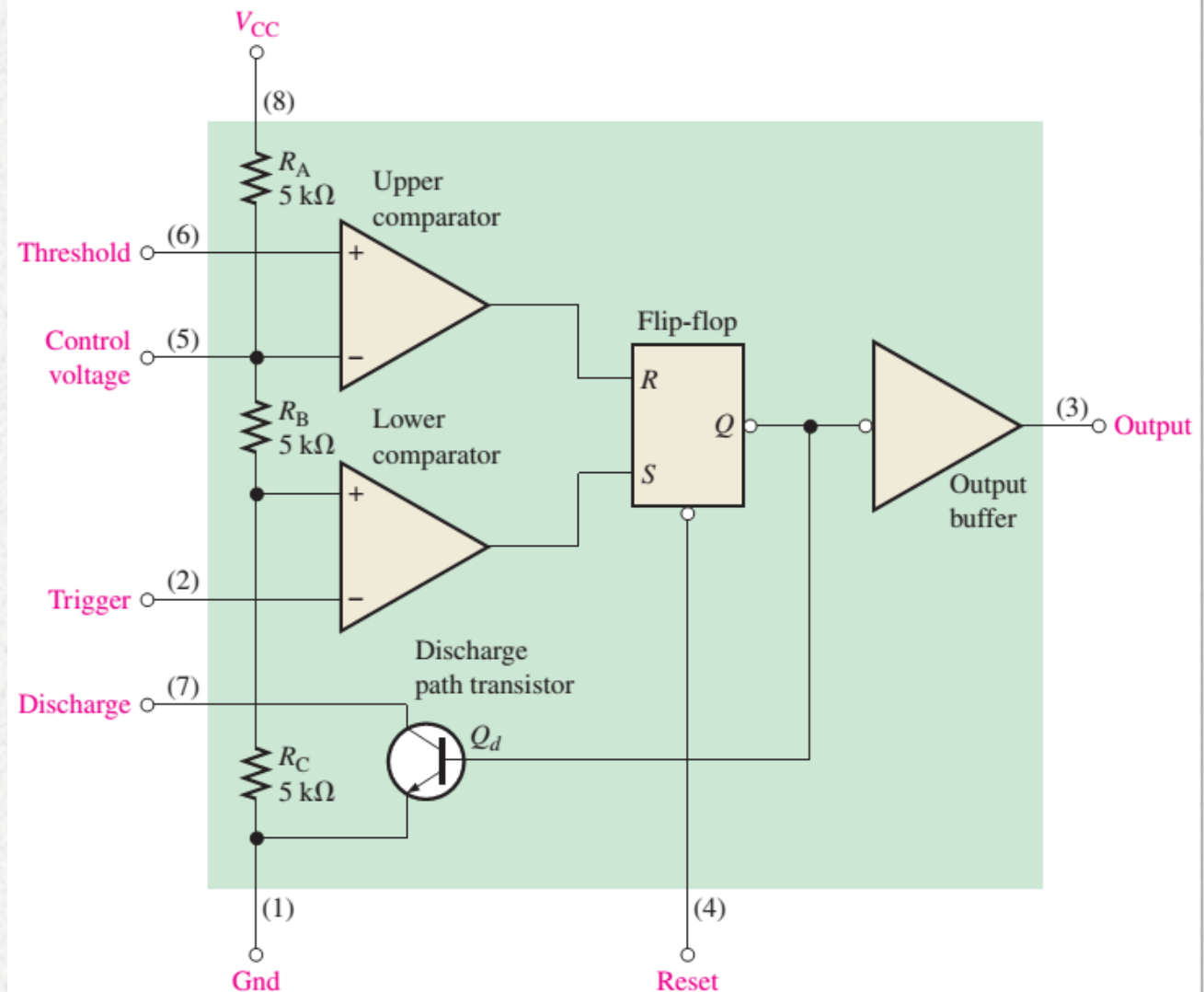


# A Square-Wave Oscillator

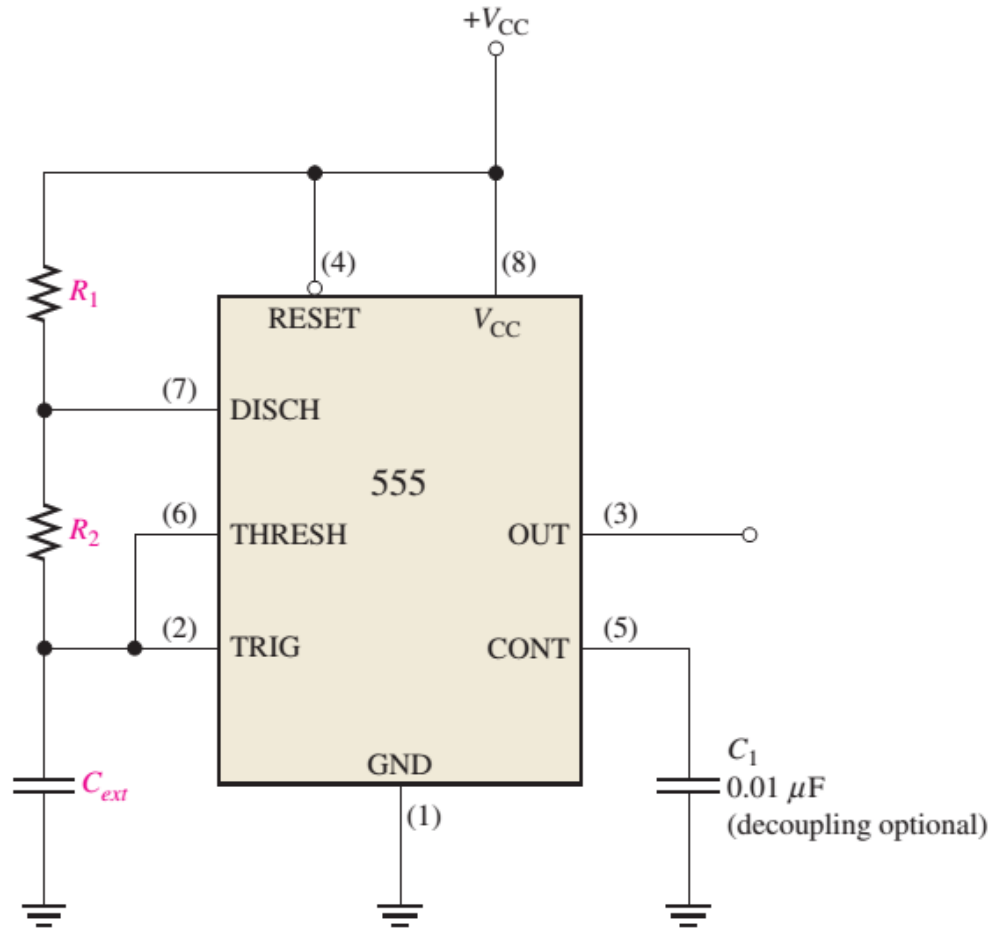
- Q When the circuit is first turned on, the capacitor is uncharged, and thus the inverting input is at 0 V.
- Q This makes the output a positive maximum, and the capacitor begins to charge toward  $V_{out}$  through  $R_1$ .
- Q When the capacitor voltage  $V_C$  reaches a value equal to the feedback voltage  $V_f$  on the noninverting input, the op-amp switches to the maximum negative state.
- Q The capacitor begins to discharge from  $V_f$  toward  $-V_f$ .
- Q When the capacitor voltage reaches  $-V_f$  the op-amp switches back to the maximum positive state and the action continues to repeat.

# THE 555 TIMER AS AN OSCILLATOR

The 555 timer consists basically of two comparators, a flip-flop, a discharge transistor, and a resistive voltage divider.



# THE 555 TIMER AS AN OSCILLATOR



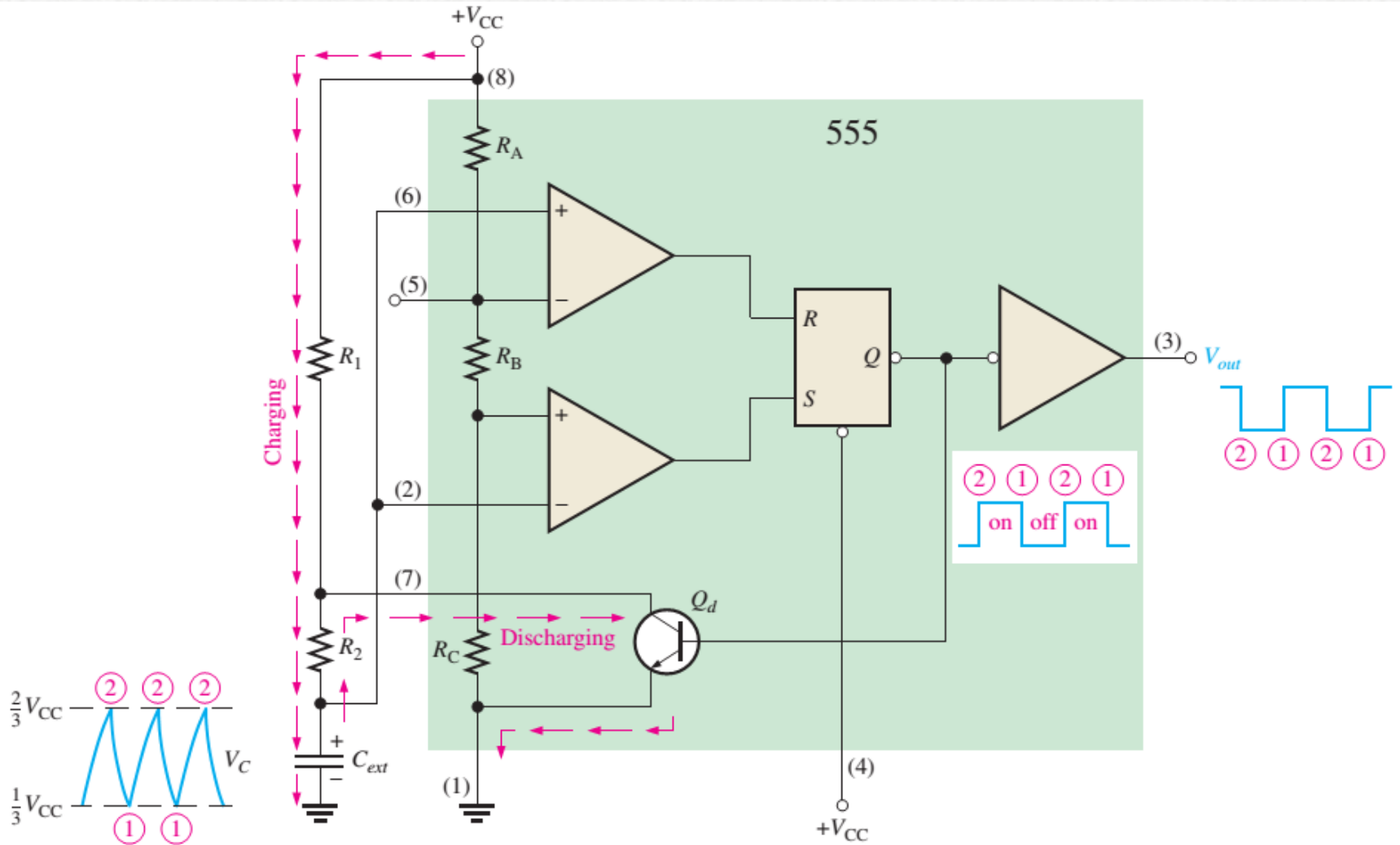
A 555 timer connected to operate in the astable mode as a free-running relaxation oscillator (astable multivibrator) is shown.



# THE 555 TIMER AS AN OSCILLATOR

- Q Initially, when the power is turned on, the capacitor  $C_{ext}$  is uncharged and thus the trigger voltage (pin 2) is at 0 V.
- Q 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 the base of  $Q_d$  low and keeping the transistor off.
- Q Now,  $C_{ext}$  begins charging through  $R_1$  and  $R_2$ . When the capacitor voltage reaches  $(1/3) V_{CC}$ , the lower comparator switches to its low output state, and when the capacitor voltage reaches  $(2/3) V_{CC}$ , the upper comparator switches to its high output state.
- Q This resets the flip-flop, causes the base of  $Q_d$  to go high, and turns on the transistor. This creates a discharge path for the capacitor through  $R_2$  and the transistor.

# THE 555 TIMER AS AN OSCILLATOR



# THE 555 TIMER AS AN OSCILLATOR

- Q The capacitor begins to discharge, causing the upper comparator to go low. When the capacitor discharges down to  $(1/3) V_{CC}$ , the lower comparator switches high, setting the flip-flop, which makes the base of  $Q_d$  low and turns off the transistor.
- Q Another charging cycle begins, and the entire process repeats.
- Q The frequency of oscillation is given as

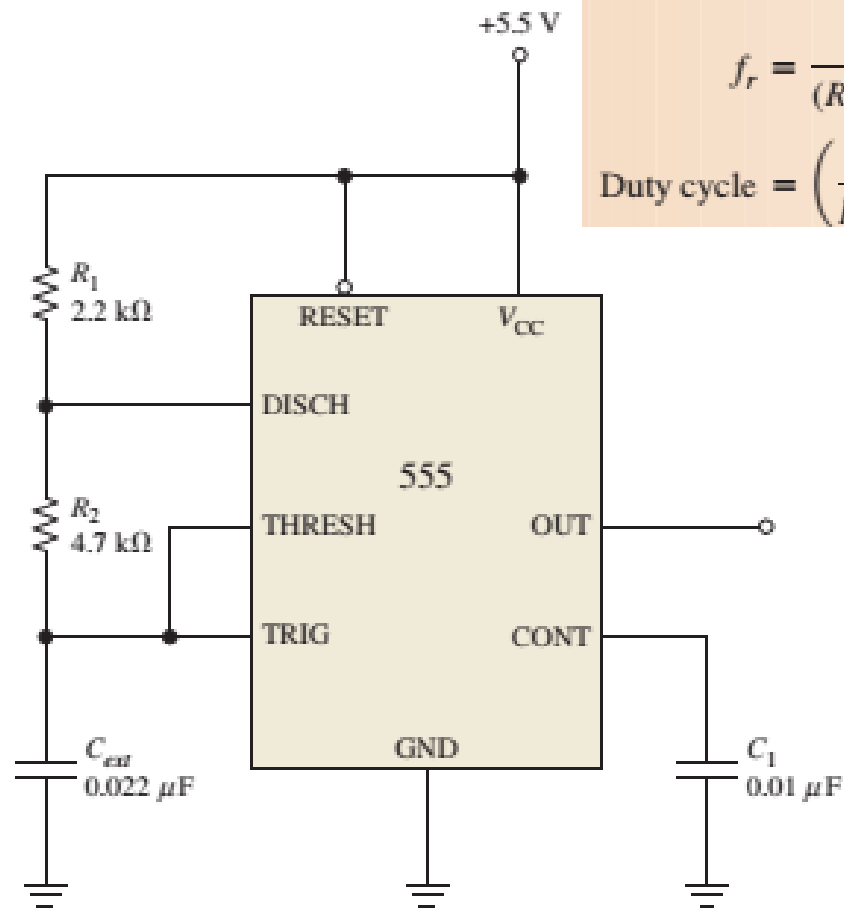
$$f_r = \frac{1.44}{(R_1 + 2R_2)C_{ext}}$$

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

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

# THE 555 TIMER AS AN OSCILLATOR

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.



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

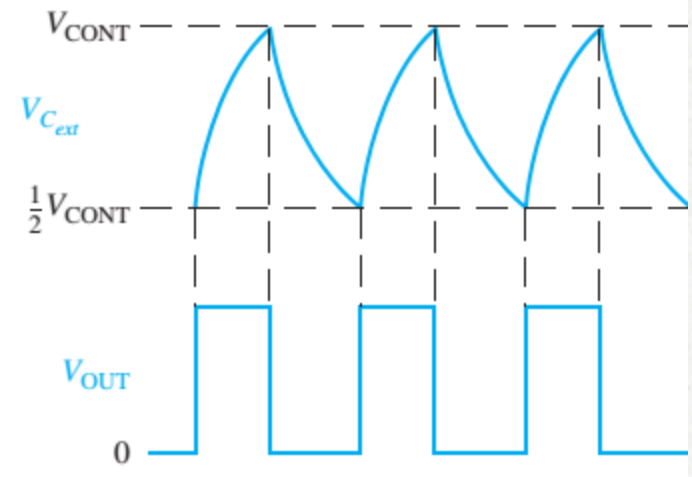
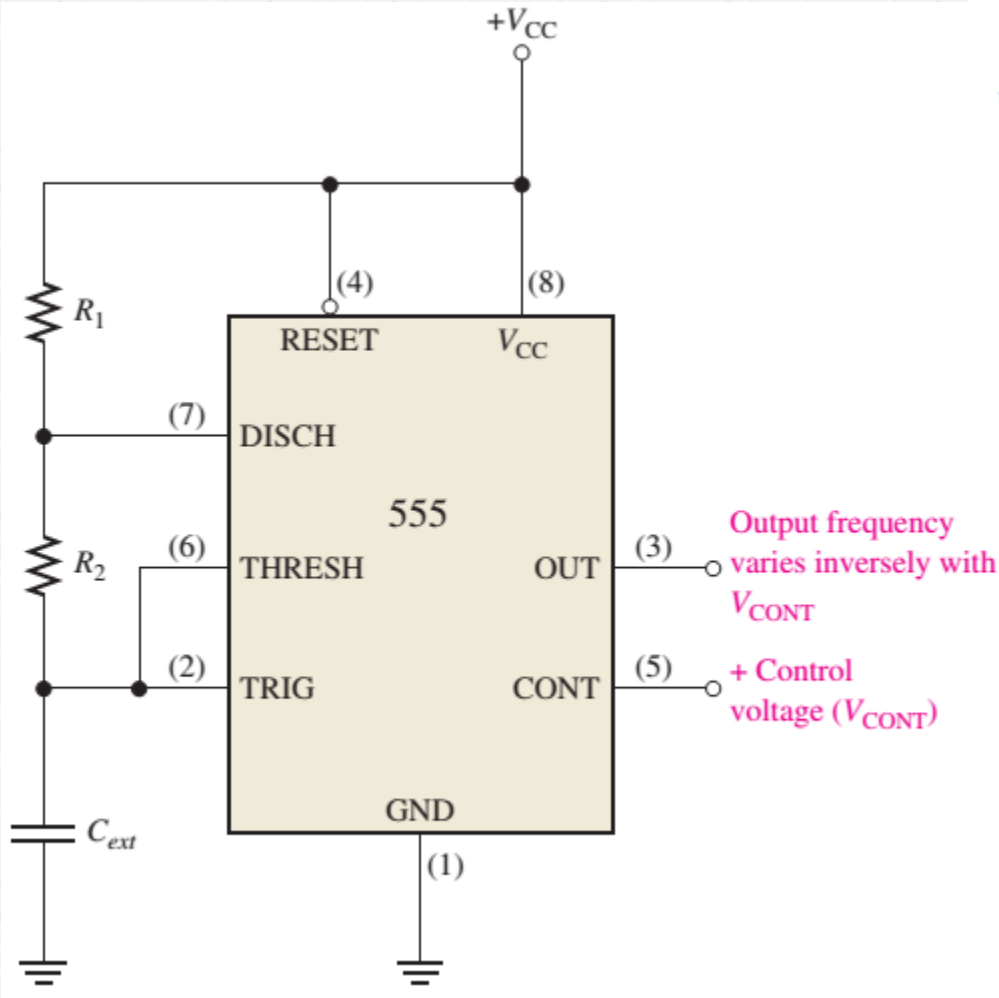
$$\text{Duty cycle} = \left( \frac{R_1 + R_2}{R_1 + 2R_2} \right) 100\% = \left( \frac{2.2 \text{ k}\Omega + 4.7 \text{ k}\Omega}{2.2 \text{ k}\Omega + 9.4 \text{ k}\Omega} \right) 100\% = 59.5\%$$



## Operation as a VCO

- Q 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.
- Q The control voltage changes the threshold values of  $(1/3) V_{CC}$  and  $(2/3) V_{CC}$  for the internal comparators.
- Q With the control voltage, the upper value is  $V_{CONT}$  and the lower value is  $(1/2) V_{CONT}$ .
- Q An increase in  $V_{CONT}$  increases the charging and discharging time of the external capacitor and causes the frequency to decrease.
- Q A decrease in  $V_{CONT}$  decreases the charging and discharging time of the capacitor and causes the frequency to increase.

# Operation as a VCO



# Selected Key Terms

***Feedback oscillator*** An electronic circuit that operates with positive feedback and produces a time-varying output signal without an external input signal.

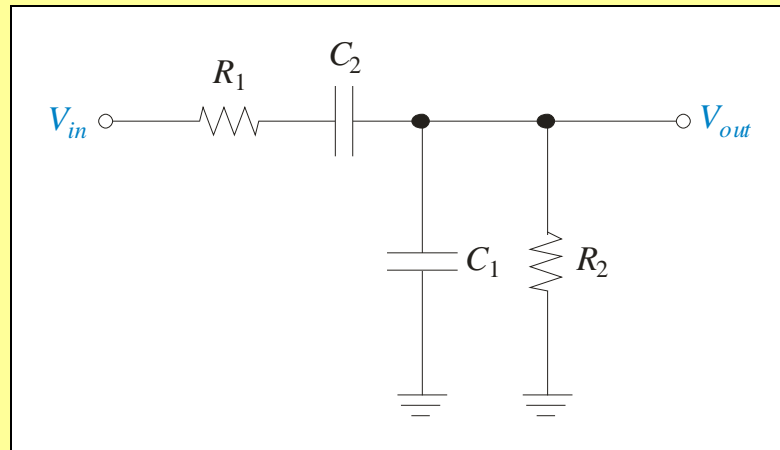
***Relaxation oscillator*** An electronic circuit that uses an  $RC$  timing circuit to generate a nonsinusoidal waveform without an external input signal.

***Positive feedback*** The return of a portion of the output signal such that it reinforces and sustains the input signal.

# Quiz

1. The Wien-bridge oscillator uses the network shown. If  $R$ 's and  $C$ 's are equal, the maximum  $V_{out}$  will be phase-shifted by

- a.  $0^\circ$
- b.  $90^\circ$
- c.  $180^\circ$
- d.  $270^\circ$

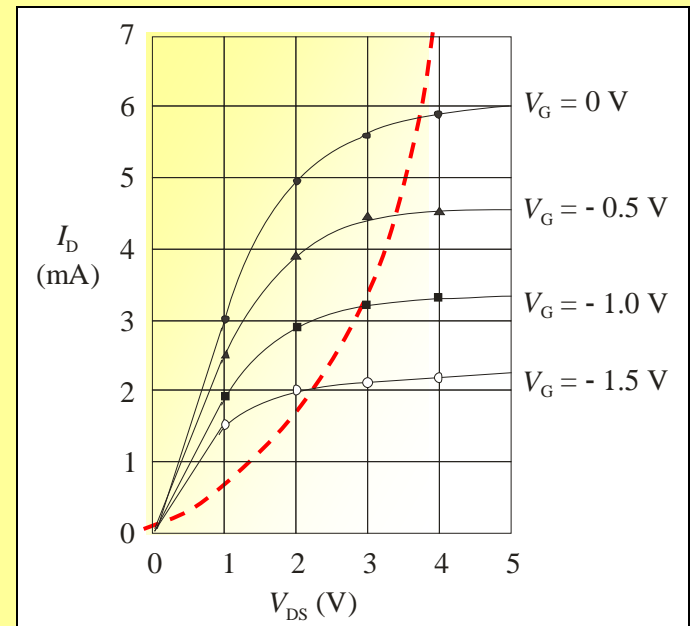




# Quiz

2. The ohmic region of a JFET is the operating region for a JFET used in a Wien-bridge AGC circuit because the

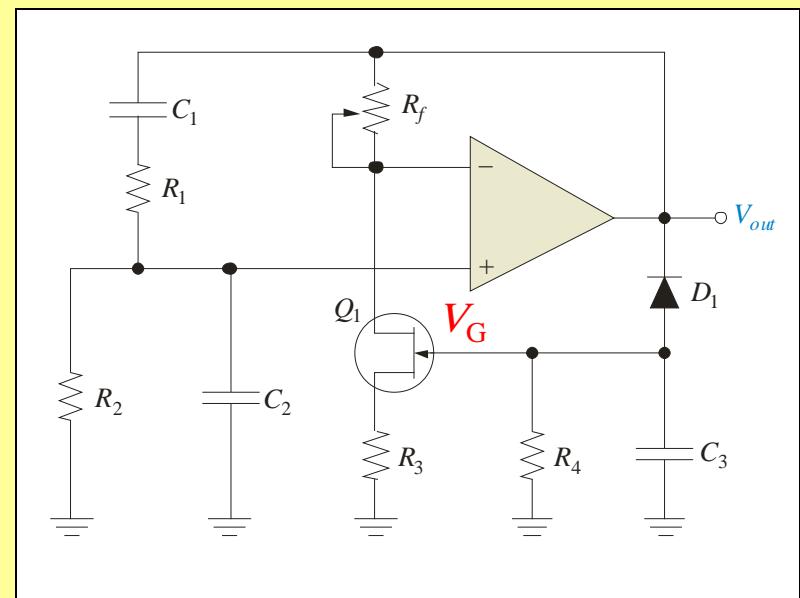
- a. resistance is constant
- b. resistance depends on  $V_{DS}$
- c. resistance depends on  $V_G$
- d. resistance depends on  $I_D$



# Quiz

3. Assume the Wien-bridge oscillator shown is operating normally and the output voltage is a  $6\text{ V}_{pp}$  sine wave.  $V_G$  should be

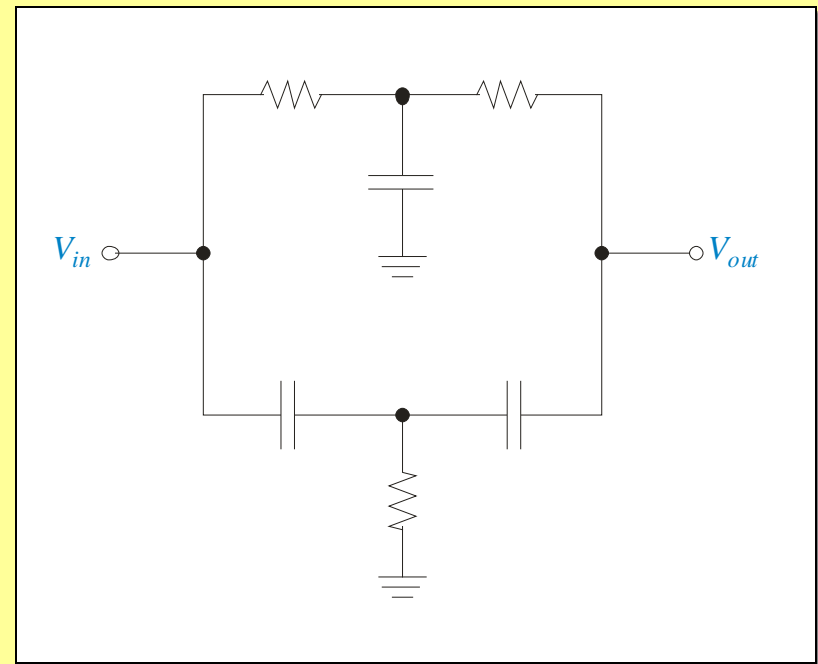
- a.  $1\text{ V}_{pp}$  sine wave
- b.  $2\text{ V}_{pp}$  sine wave
- c.  $+3\text{ V}_{DC}$
- d.  $-2.3\text{ V}_{DC}$



# Quiz

4. The twin-t oscillator uses the network shown. At the oscillator frequency, the output of this network is phase-shifted by

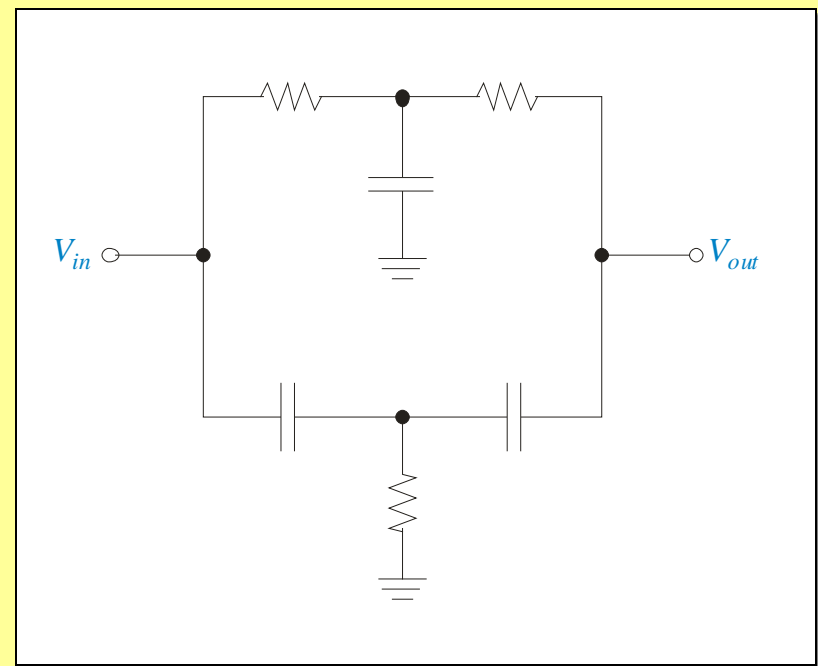
- a.  $0^\circ$
- b.  $90^\circ$
- c.  $180^\circ$
- d.  $270^\circ$



# Quiz

5. The overall frequency response characteristic of the twin-t oscillator network shown is that of a

- a. low-pass filter
- b. high-pass filter
- c. band-pass filter
- d. notch filter





A square graphic with a colorful, abstract background of green, blue, and red patterns. The word "Quiz" is written in a white, serif font in the center.

# Quiz

6. An example of an  $LC$  feedback oscillator is a
- a. phase-shift oscillator
  - b. relaxation oscillator
  - c. Colpitts oscillator
  - d. Wien-bridge oscillator

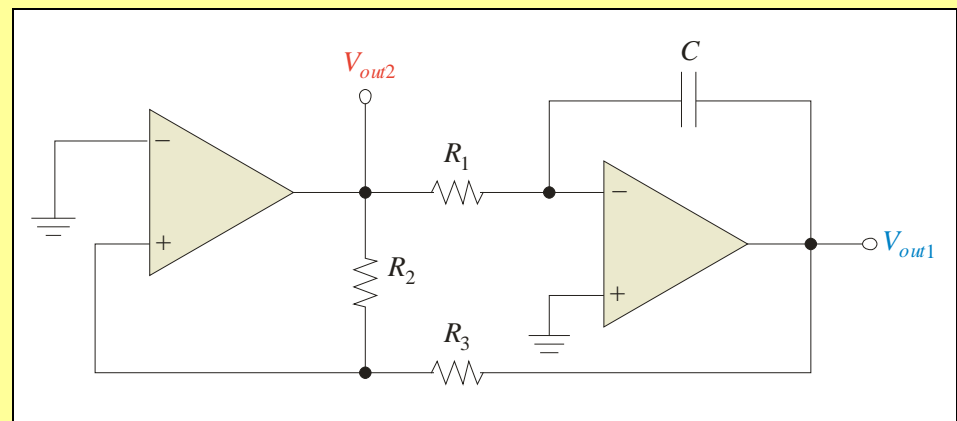
A square graphic with a colorful, abstract background of green, blue, and red patterns. The word "Quiz" is written in a white, serif font in the center.

# Quiz

7. In a crystal oscillator, the crystal acts like a
- a. band-pass filter
  - b. resonant circuit
  - c. notch filter
  - d. power source

# Quiz

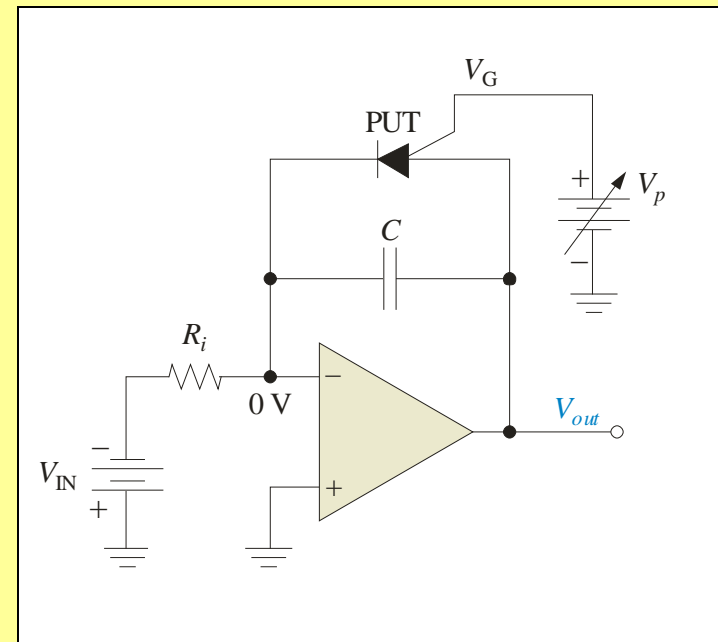
8. The waveforms at  $V_{out1}$  and  $V_{out2}$  should be a
- a. sawtooth wave and a sine wave
  - b. triangle wave and a square wave
  - c. sawtooth wave and a square wave
  - d. triangle wave and a sine wave



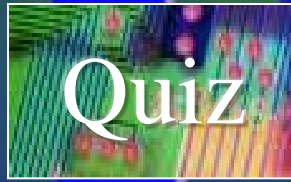
# Quiz

9. The output waveform from this circuit should be a

- a. sawtooth wave
- b. triangle wave
- c. square wave
- d. sine wave







10. To make a basic astable multivibrator using a 555 timer, as a minimum you need

- a. one resistor and one capacitor
- b. one resistor and two capacitors
- c. two resistors and one capacitor
- d. two resistors and two capacitors

# Quiz

## Answers:

- |      |       |
|------|-------|
| 1. a | 6. c  |
| 2. c | 7. b  |
| 3. d | 8. b  |
| 4. c | 9. a  |
| 5. d | 10. c |