

POWER AMPLIFIERS

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Power amplifiers Analysis and design of class A, class B, class AB, class C, class D amplifiers. Design of heat sink, IC power amplifiers.(5L + 2T)

Classification Of Amplifiers

1. According to frequency capabilities.

Amplifiers are classified as audio amplifiers , radio frequency amplifiers

- **AF Amplifier** are used to amplify the signals lying in the audio range (i.e. 20 Hz to 20 kHz)
- **RF amplifiers** are used to amplify signals having very high frequency.

2. According to coupling methods.

- R-C coupled amplifiers,
- Transformer coupled amplifiers
- Direct Coupled

Classification Of Amplifiers

3. According to use.

a. Voltage amplifiers

- Amplify the input voltage, if possible with minimal current at the output.
- The power gain of the voltage amplifier is low.
- The main application is to strengthen the signal to make it less affected by noise and attenuation.
- Ideal voltage amp. have infinite input impedance & zero output impedance.

b. Power amplifiers

- Amplify the input power, if possible with minimal change in the output voltage
- Power amp. are used in devices which require a large power across the loads.
- In multi stage amplifiers, power amplification is made in the final stages
 - ✓ Audio amplifiers and RF amplifiers use it to deliver sufficient power the load.
 - ✓ Servo motor controllers use power amplifiers to drive the motors.

Classification Of Amplifiers

Parameters	Voltage amplifiers	Power amplifiers
current gain	low	high
Voltage gain	high	low
Heat dissipation	low	high
cooling mechanism	not required	required
Transistor Size	Small	Large to dissipate heat
Base Width	small	Wide to handle higher current
Coupling	usually R – C coupling	transformer coupling
Input voltage	low (a few mV)	High (2 – 4 V)
Collector current	low ($\cong 1$ mA)	High (> 100 mA)
Output impedance	High ($\cong 12$ k Ω)	low ($\cong 16$ Ω)

Power Amplifier Characteristics

- Deliver a large current to a small load resistance e.g. audio speaker; or to deliver a large voltage to a large load resistance e.g. switching power supply;
- Requires large voltage swings.
- Draws a large amount of power from supply.
- Deliver power to the load efficiently
- Dissipates a large amount of power, therefore gets “hot”.
 - Requires heat sink

- When designing a power amplifier we normally require a low output resistance so that the circuit can deliver a high output current
- we often use an **emitter-follower/ Source Follower**
 - ✓ this does not produce voltage gain but has a **low output resistance**
- in many cases the load applied to a power amplifier is not simply resistive but also has an **inductive** or **capacitive** element

POWER TRANSISTORS - BJT

Transistor Ratings

- 1 maximum rated current,
- 2 maximum rated voltage,
- 3 maximum rated power, and
- 4 maximum allowed temperature.

Figure of Merits

➤ **Amplifier efficiency**

an important consideration in the design of power amplifiers is efficiency

$$\checkmark. \quad \text{Efficiency} = \frac{\text{power dissipated in the load}}{\text{power absorbed from the supply}}$$

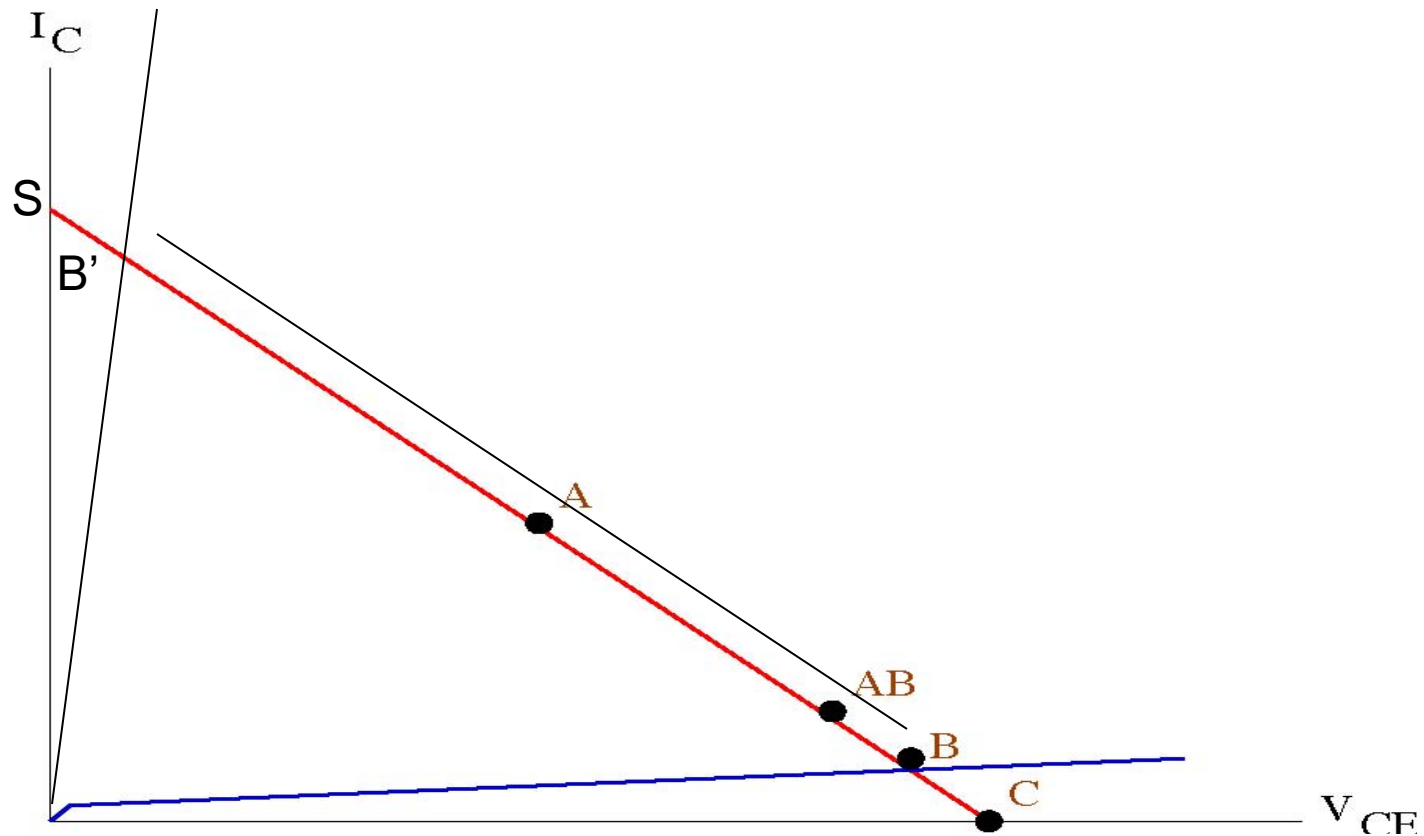
efficiency determines the power dissipated in the amplifier itself

➤ **power dissipation** is important because it determines the amount of waste heat produced

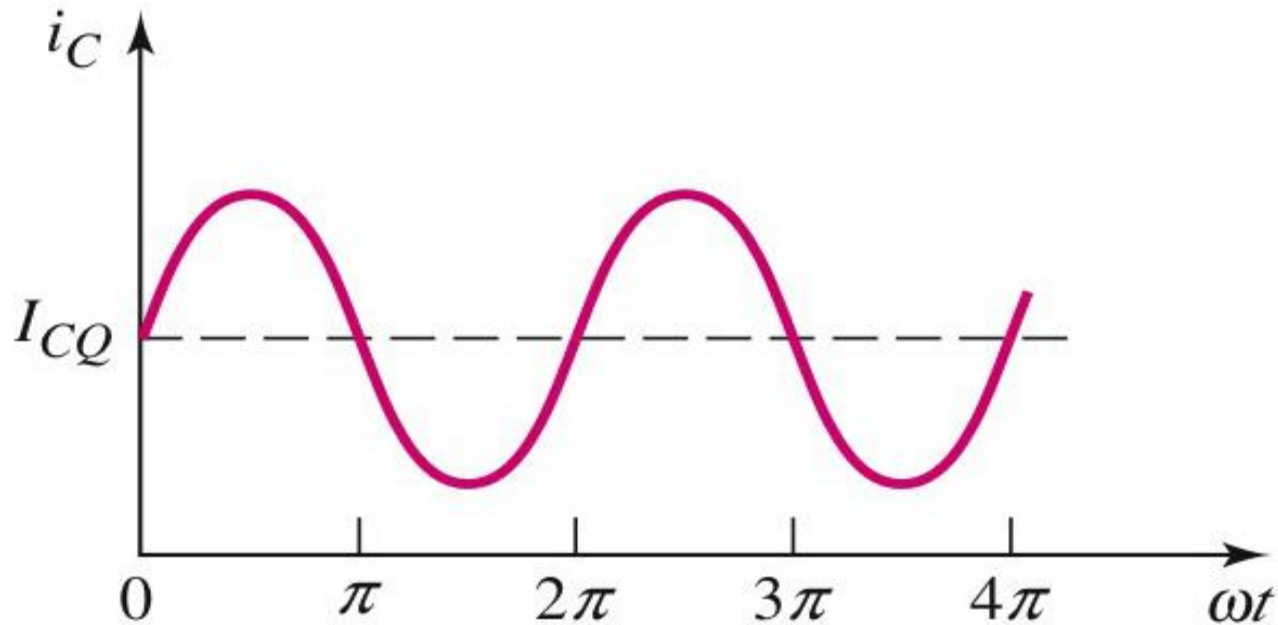
✓ excess heat may require heat sinks, cooling fans, etc.

Classes of Amplifiers

They are grouped together based on their Q-points on the DC load line.

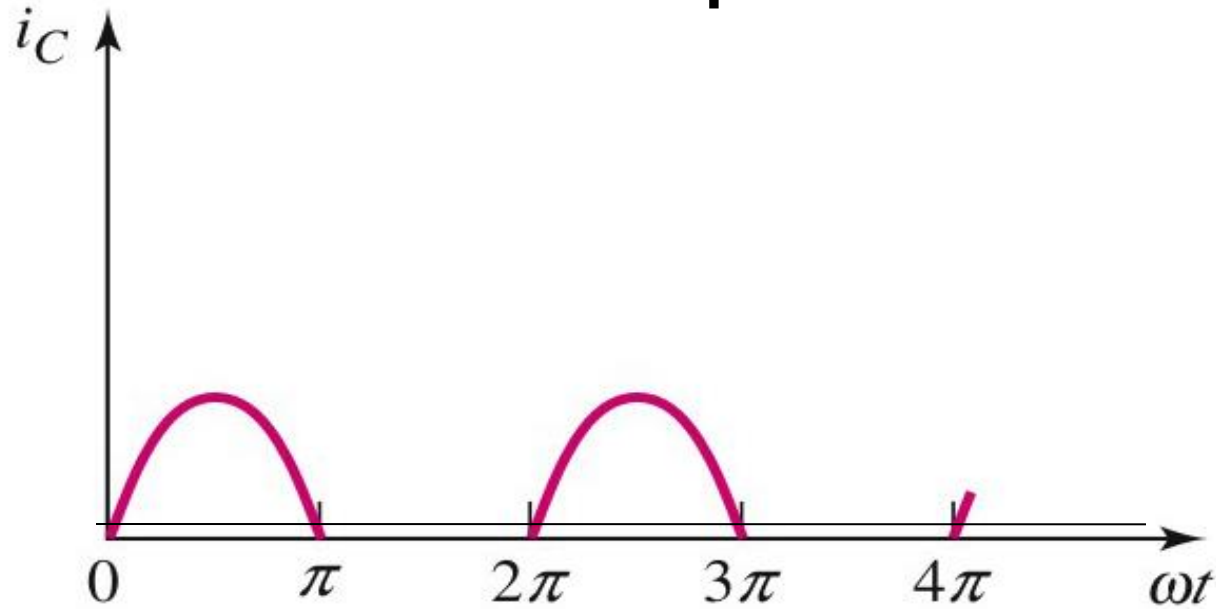


Class A Amplifier



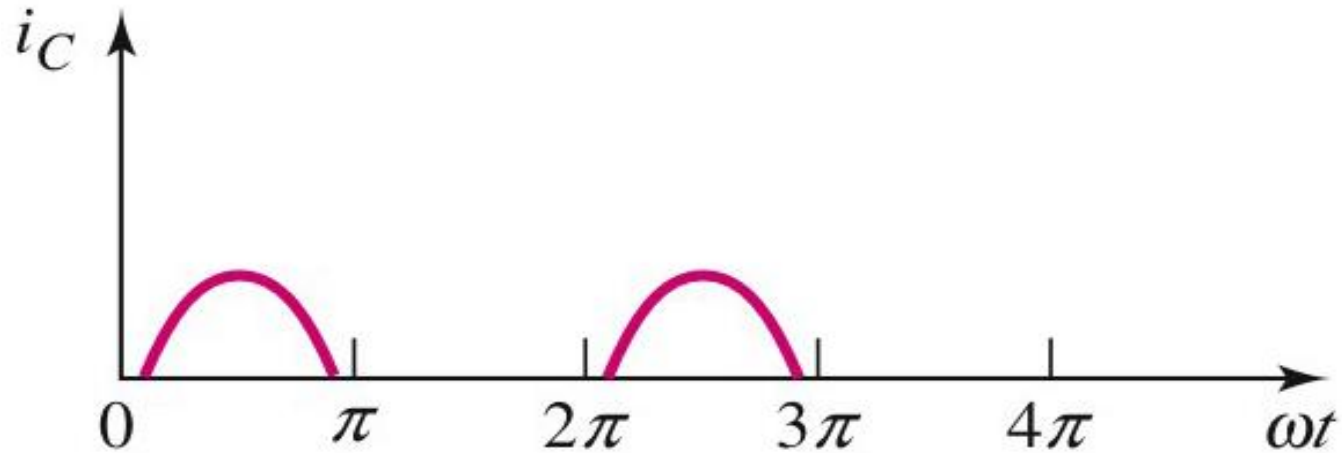
In class-A; the transistor conducts during the whole cycle of sinusoidal input signal

Class B Amplifier



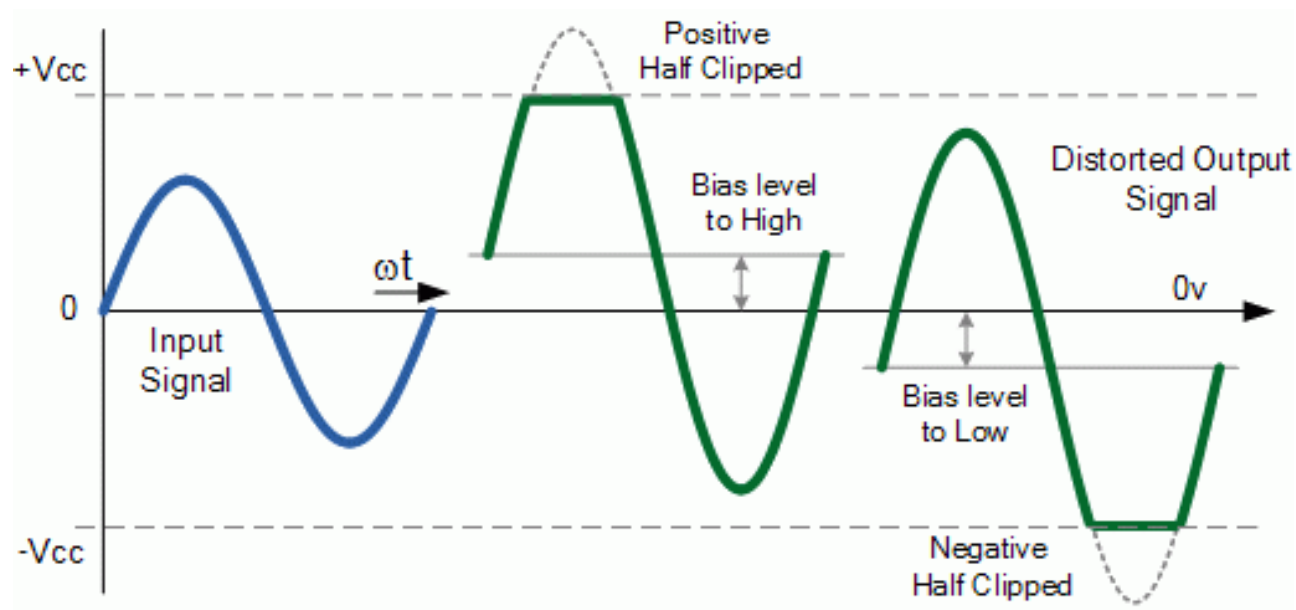
In class-B; the transistor conducts during one-half cycle of input signal

Class C Amplifier

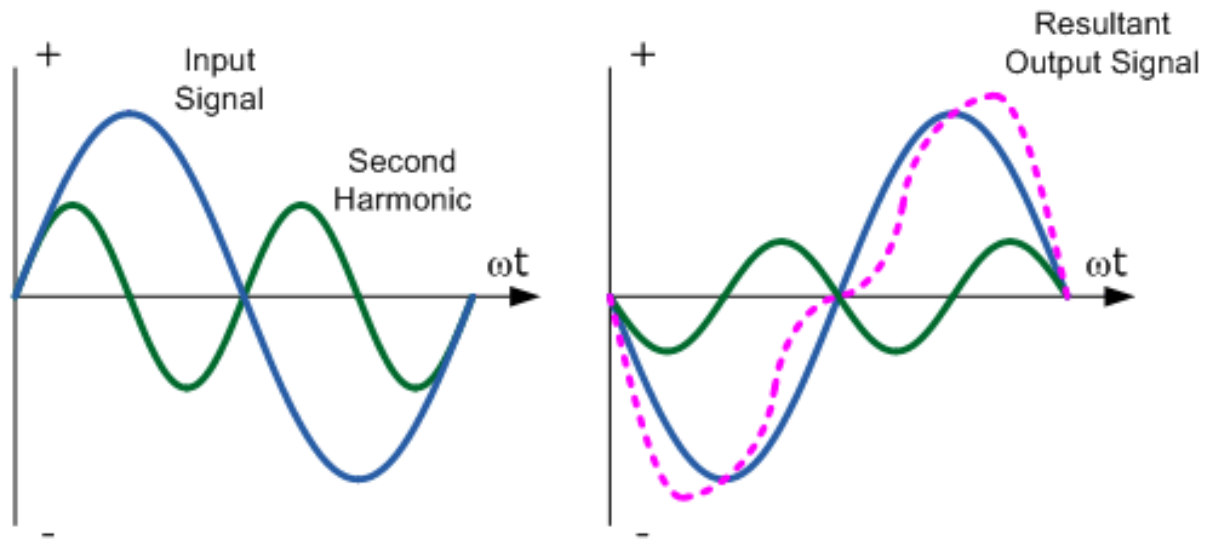


In class-C; the transistor conducts for less than half a cycle of input signal

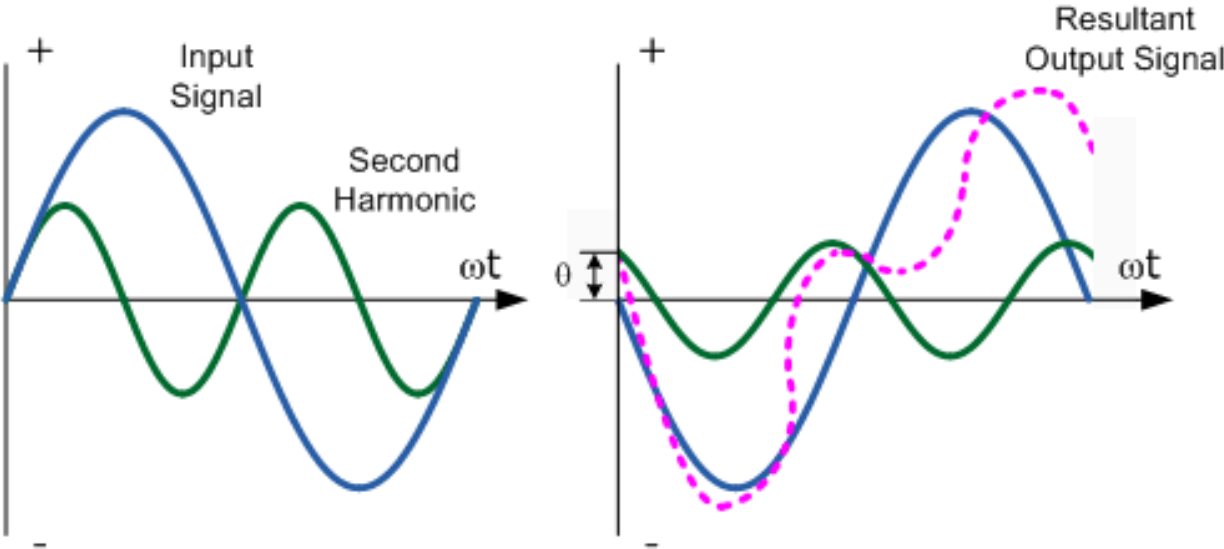
Amplitude Distortion



Frequency Distortion



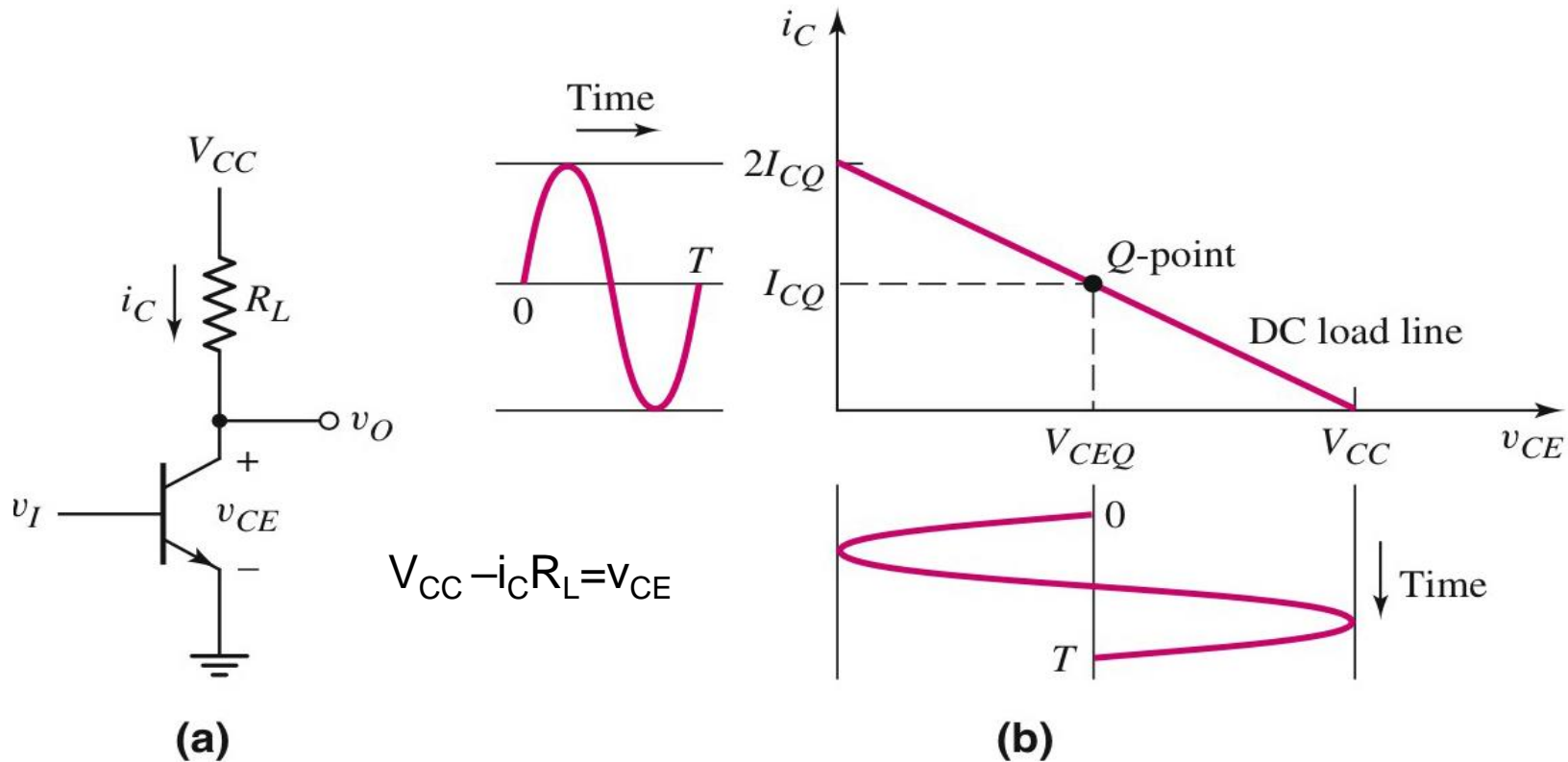
Phase Distortion



Cass-A operation

For maximum swing (+ve and -ve), transistor is biased such that the Q point is at centre of the load line.

The transistor conducts for a full cycle of the input signal



Instantaneous power dissipation in transistor is;

$$p_Q(t) = v_{CE}(t)i_C(t)$$

For sinusoidal input signal;

$$i_C = I_{CQ} + I_p \sin \omega t$$

And;

$$v_{CE} = V_{CEQ} - V_p \sin \omega t$$

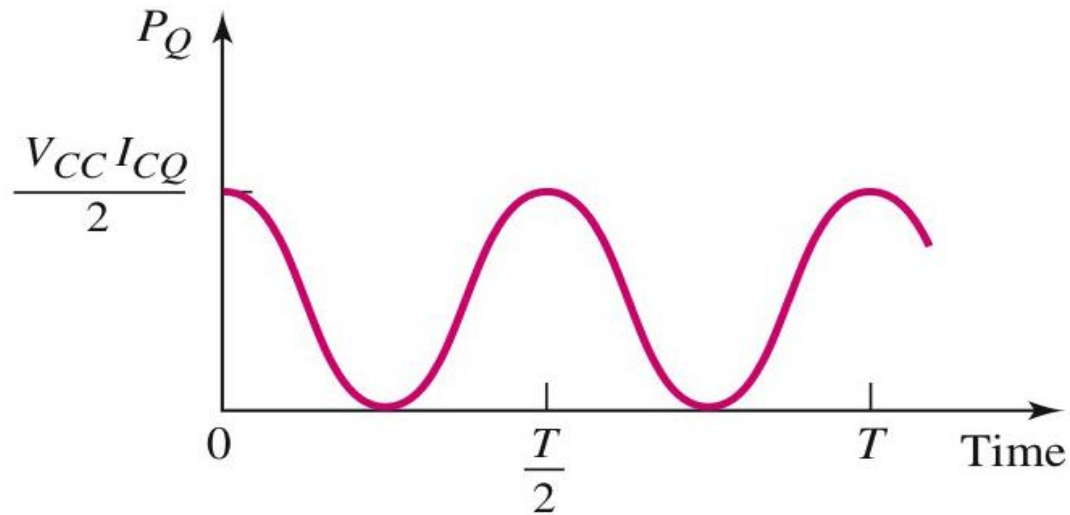
For maximum possible swing;

$$I_p = I_{CQ} \quad V_{CEQ} = \frac{V_{CC}}{2} \quad \text{and} \quad V_p = \frac{V_{CC}}{2}$$

Therefore;

$$P_Q = \frac{V_{CC}I_{CQ}}{2} (1 - \sin^2 \omega t)$$

(See graphical representation)



(c)

When the input signal = 0, the transistor must be capable of handling a continuous power of;

$$\frac{V_{CC}I_{CQ}}{2}$$

Efficiency;

$$\eta = \frac{P_L}{P_S}$$

P_L = average ac power to the load

P_S = average power supplied by the source (V_{CC})

For maximum possible swing;

$$P_L = \frac{1}{2} V_p I_p = \frac{1}{2} \left(\frac{V_{CC}}{2} \right) I_{CQ} = \frac{V_{CC} I_{CQ}}{4}$$

Power supplied by the source;

$$P_S = V_{CC} I_{CQ}$$

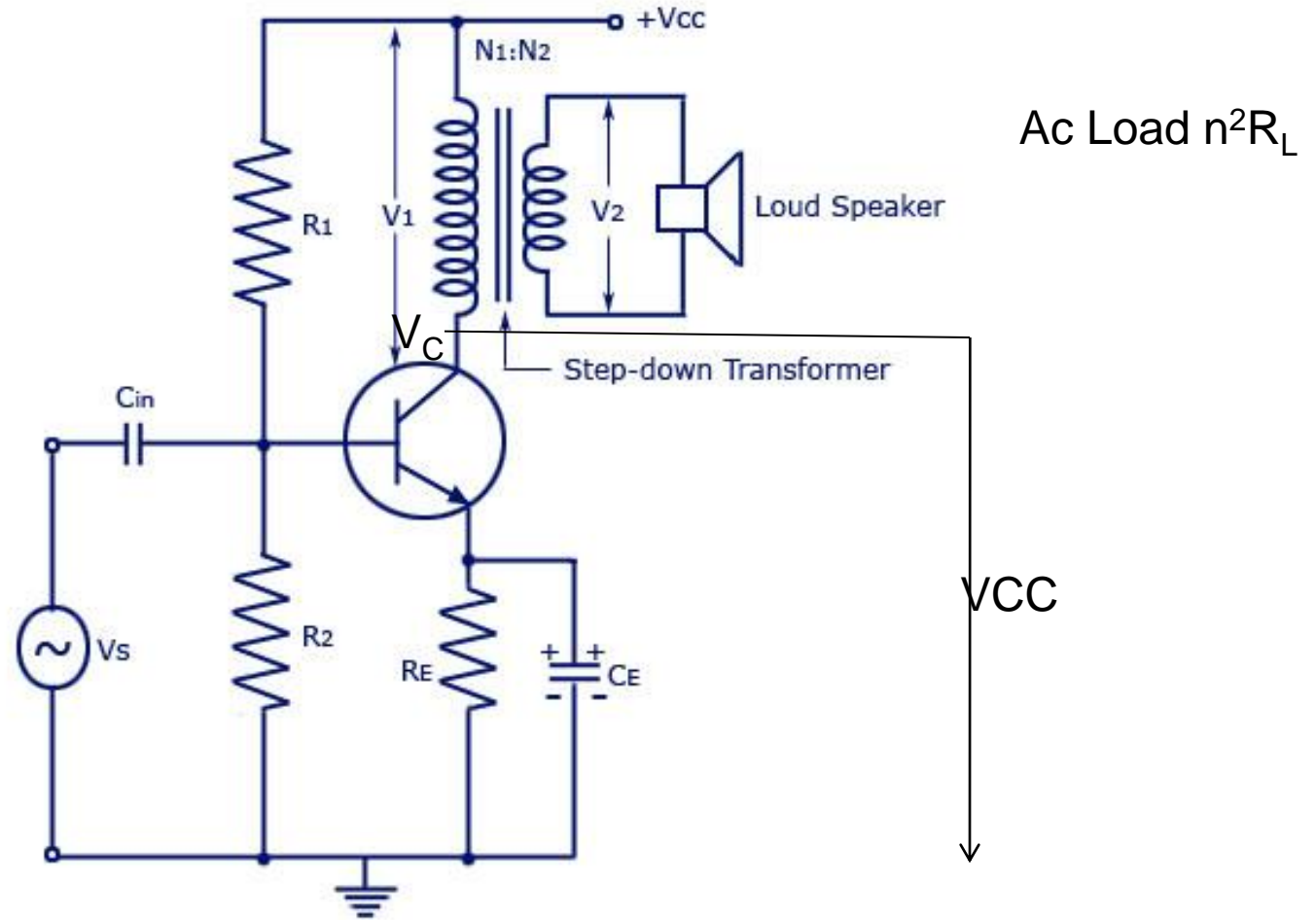
The efficiency;

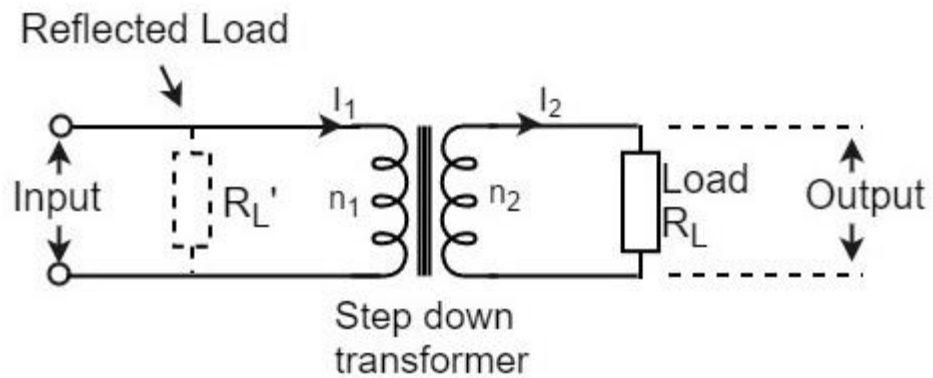
$$\eta = \frac{V_{CC} I_{CQ}}{4} \frac{1}{V_{CC} I_{CQ}} = 0.25$$

Maximum theoretical efficiency of class A amplifier is therefore 25%

Transformer Coupled Class A Power Amplifier

Transformer-Coupled-Class-A-Power Amplifier





We know that

$$\frac{V_1}{V_2} = \frac{n_1}{n_2} \text{ and } \frac{I_1}{I_2} = \frac{n_1}{n_2}$$

n_2/n_1

Or

$$V_1 = \frac{n_1}{n_2} V_2 \text{ and } I_1 = \frac{n_1}{n_2} I_2$$

Hence

$$\frac{V_1}{I_1} = \left(\frac{n_1}{n_2} \right)^2 \frac{V_2}{I_2}$$

But $V_1/I_1 = R_L' =$ effective input resistance

And $V_2/I_2 = R_L =$ effective output resistance

Therefore,

$$R_L' = \left(\frac{n_1}{n_2} \right)^2 R_L = n^2 R_L$$

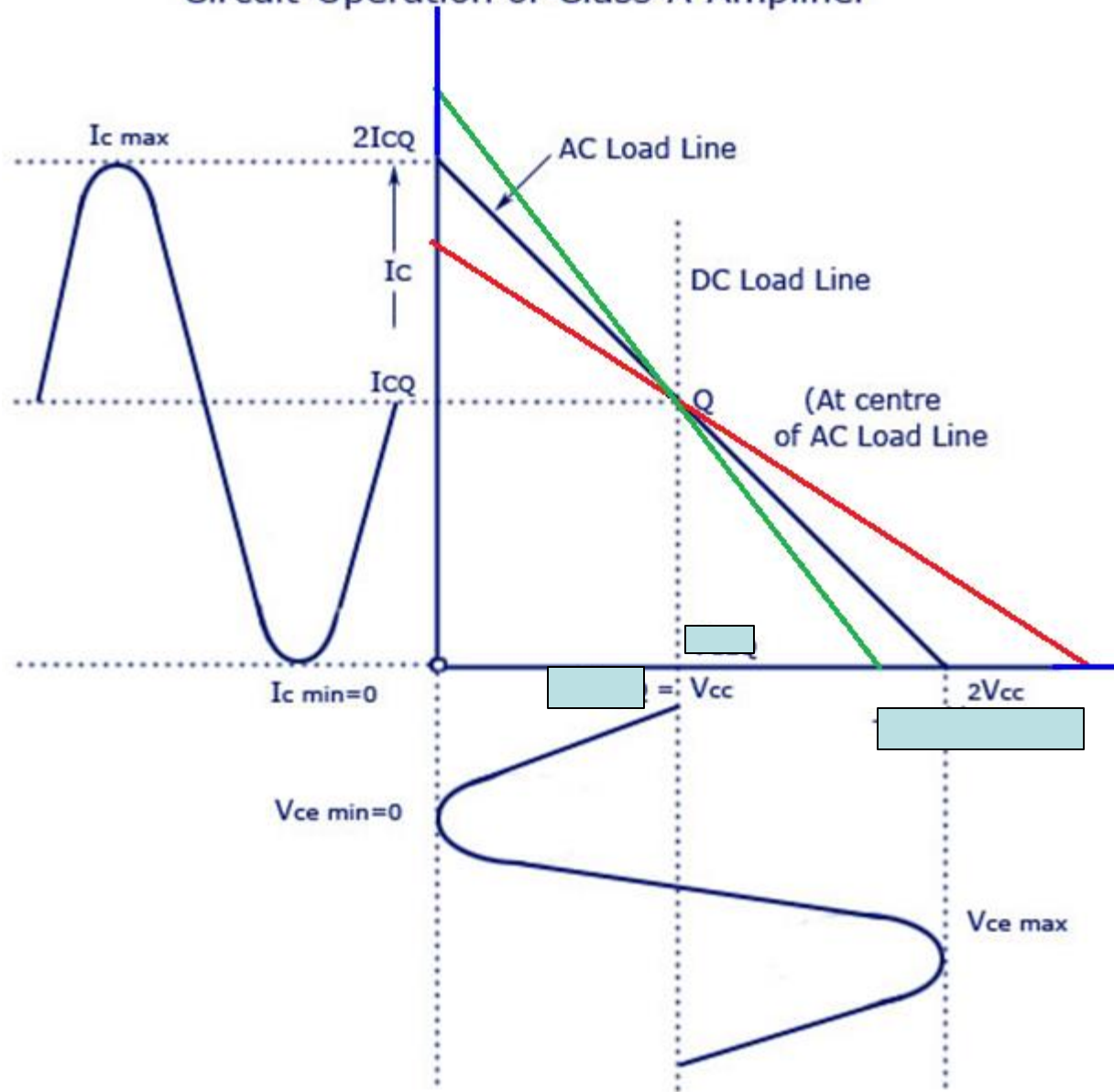
Advantages

- No loss of signal power in the base or collector resistors.
- Excellent impedance matching is achieved.
- Gain is high.
- DC isolation is provided.

Disadvantages

- Low frequency signals are less amplified comparatively.
- Hum noise is introduced by transformers.
- Transformers are bulky and costly.
- Poor frequency response.

Circuit-Operation of-Class-A-Amplifier



$$V_{CE} = V_C + V_{ce}$$

$$(P_{in})_{dc} = (P_{tr})_{dc} = V_{CC} \times (I_C)Q$$

$$V_{rms} = \frac{1}{\sqrt{2}} \left[\frac{(V_{ce})_{max} - (V_{ce})_{min}}{2} \right] = \frac{1}{\sqrt{2}} \left[\frac{(V_{ce})_{max}}{2} \right] = \frac{2V_{CC}}{2\sqrt{2}} = \frac{V_{CC}}{\sqrt{2}}$$

$$I_{rms} = \frac{1}{\sqrt{2}} \left[\frac{(I_C)_{max} - (I_C)_{min}}{2} \right] = \frac{1}{\sqrt{2}} \left[\frac{(I_C)_{max}}{2} \right] = \frac{2(I_C)Q}{2\sqrt{2}} = \frac{(I_C)Q}{\sqrt{2}}$$

Therefore,

$$(P_O)_{ac} = V_{rms} \times I_{rms} = \frac{V_{CC}}{\sqrt{2}} \times \frac{(I_C)Q}{\sqrt{2}} = \frac{V_{CC} \times (I_C)Q}{2}$$

Therefore,

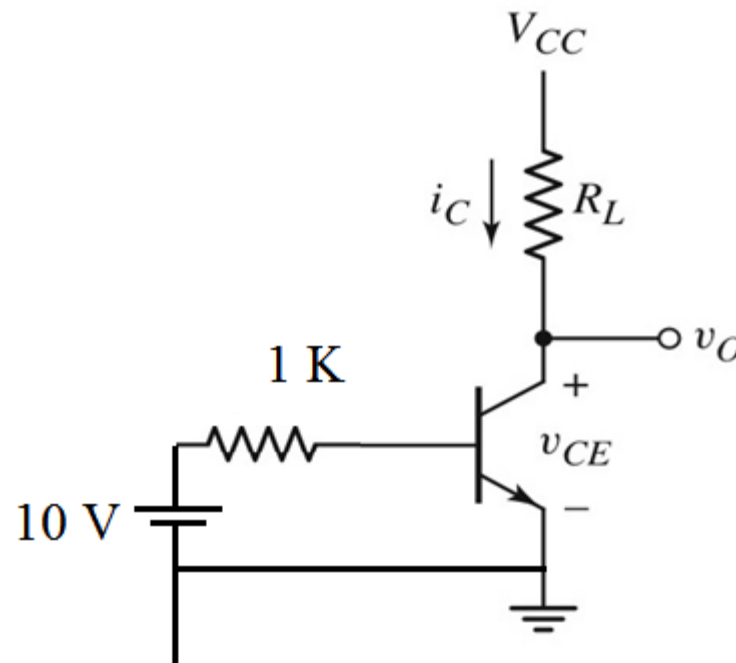
$$\boxed{\text{Efficiency}} = \frac{(P_O)_{ac}}{(P_{tr})_{dc}} \quad P_L/P_S$$

Or,

$$\begin{aligned} (\eta)_{collector} &= \frac{V_{CC} \times (I_C)Q}{2 \times V_{CC} \times (I_C)Q} = \frac{1}{2} \\ &= \frac{1}{2} \times 100 = 50\% \end{aligned}$$

$I_{bp}=7\text{mA}$
 $h_{fe}=50$
 $R_L=10\ \Omega$
 $V_{CC}=12\ \text{V}$

$10-0.7=I_b(\text{mA})$
 $I_{CQ}=50 \cdot 9.3\ \text{mA}=465\ \text{mA}$
 $P_{dc}=V_{CC} \cdot I_{CQ}=5.58\ \text{W}$
 $P_{ac}=0.6125\ \text{W}$
 $\text{Efficiency}=10.98\%$



DRAWBACKS of Class A amplifier

15/03/2021

- (1) Total harmonic distortion is very high.
- (2) The output transformer is subject to saturation problem due to the dc current in the primary.

I_d vs $v_g \rightarrow$ transfer characteristics
 $I_c = \beta I_b$

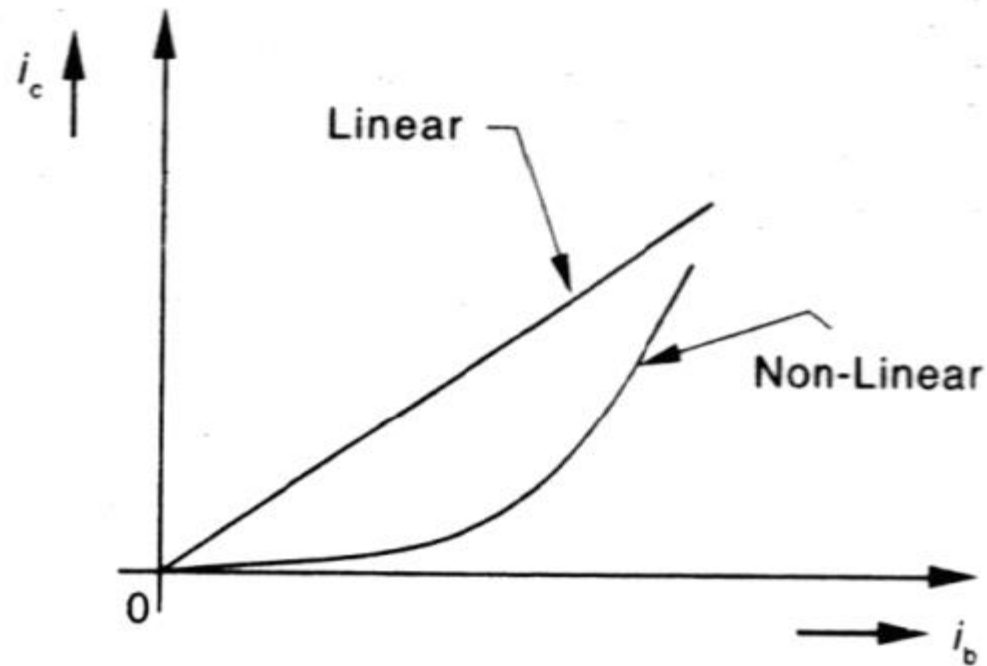


Fig. 4 Nonlinear dynamic characteristics

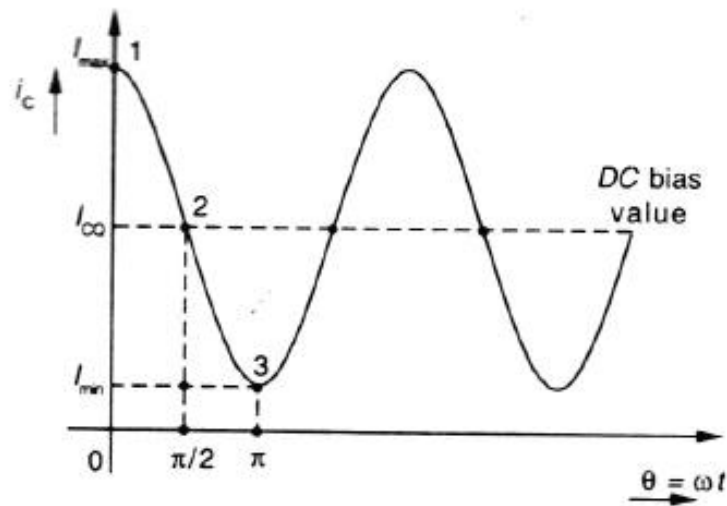
$$i_c = G_1 i_b + G_2 i_b^2 \quad \text{-----} (1)$$

$$i_b = I_{bm} \text{Cos } \omega t \quad \text{-----} (2)$$

$$i_c = G_1 I_{bm} \cos \omega t + G_2 I_{bm}^2 \cos^2 \omega t$$

$$\cos^2 \omega t = \frac{1}{2} + \frac{1}{2} \cos 2\omega t$$

$$i_c = I_C + i_c = I_C + B_0 + B_1 \cos \omega t + B_2 \cos 2\omega t \quad \text{----- (3)}$$



When $\omega t = 0$, $i_c = I_{\max}$

$\omega t = \pi/2$, $i_c = I_C$

$\omega t = \pi$, $i_c = I_{\min}$

$$I_{\max} = I_C + B_0 + B_1 + B_2$$

$$I_C = I_C + B_0 - B_2$$

$$I_{\min} = I_C + B_0 - B_1 + B_2$$

$$B_1 = \frac{I_{\max} - I_{\min}}{2}$$

$$B_2 = B_0 = \frac{I_{\max} + I_{\min} - 2I_C}{4}$$

Second order harmonic Distortion

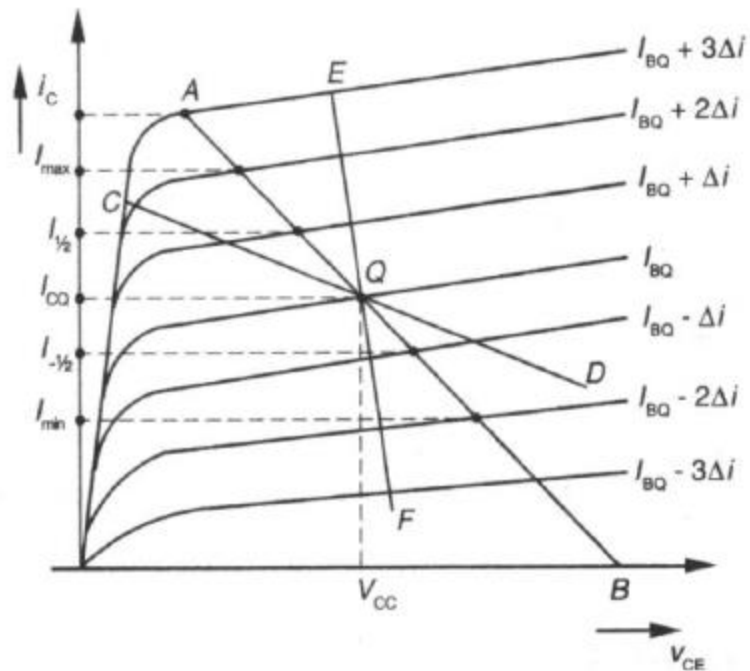
$$D_2 = \frac{|B_2|}{|B_1|}$$

w1 and w2

$\omega_1, \omega_2, 2\omega_1, 2\omega_2, \omega_1 + \omega_2$ and $\omega_1 - \omega_2$.

$$i_c = G_1 i_b + G_2 i_b^2 + G_3 i_b^3$$

$$i_c = B_0 + B_1 \cos \omega t + B_2 \cos 2\omega t + B_3 \cos 3\omega t$$



$$D_2 = \frac{|B_2|}{|B_1|}, \quad D_3 = \frac{|B_3|}{|B_1|}, \quad D_4 = \frac{|B_4|}{|B_1|}$$

the power delivered to the load at the fundamental frequency

$$P_1 = \frac{B_1^2 R_L}{2}$$

The ac power output

$$P_{ac} = \left(B_1^2 + B_2^2 + B_3^2 + \dots \right) \frac{R_L}{2}$$

$$= \left(1 + D_2^2 + D_3^2 + \dots \right) P_1$$

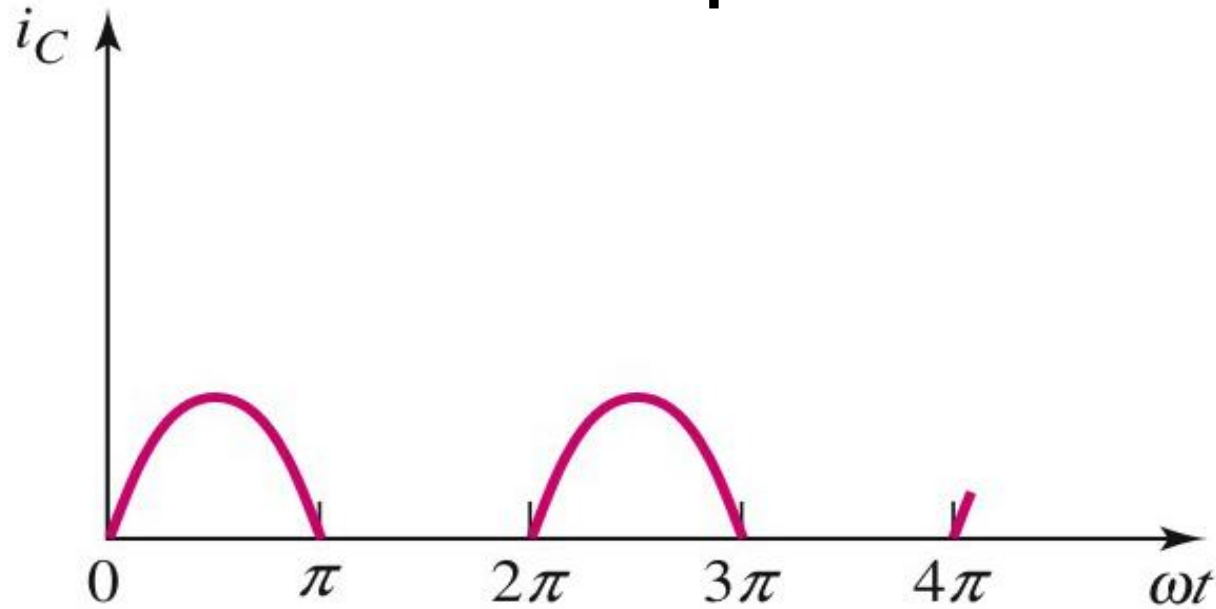
$$P_{ac} = (1 + D^2) P_1$$

THD

$$D = \sqrt{D_2^2 + D_3^2 + D_4^2 + \dots}$$

$P_1 = 5 \text{ Watt}$
 $D = 10\% \text{ of } P_1$
 $P_{ac} = 5.05 \text{ Watt}$

Class B Amplifier



In class-B; the transistor conducts during one-half cycle of input signal

$$i_1 = I_C + B_0 + B_1 \cos \omega t + B_2 \cos 2\omega t + B_3 \cos 3\omega t -$$

$$i_{b2} = -i_{b1} = I_{bm} \cos(\omega t + \pi)$$

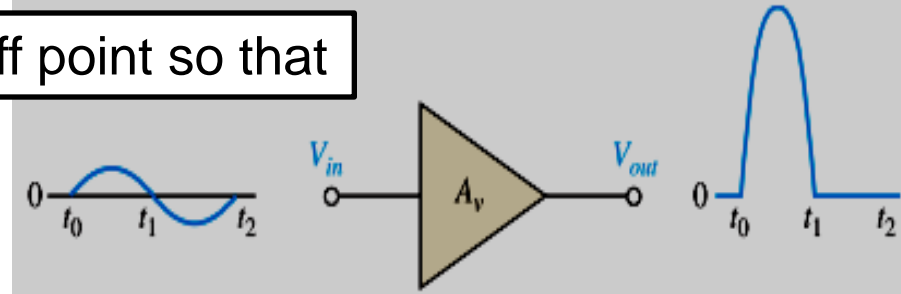
$$i_2 = I_C + B_0 + B_1 \cos(\omega t + \pi)$$

$$= I_C + B_0 - B_1 \cos \omega t + B_2 \cos 2\omega t - B_3 \cos 3\omega t$$

Class B Amplifier

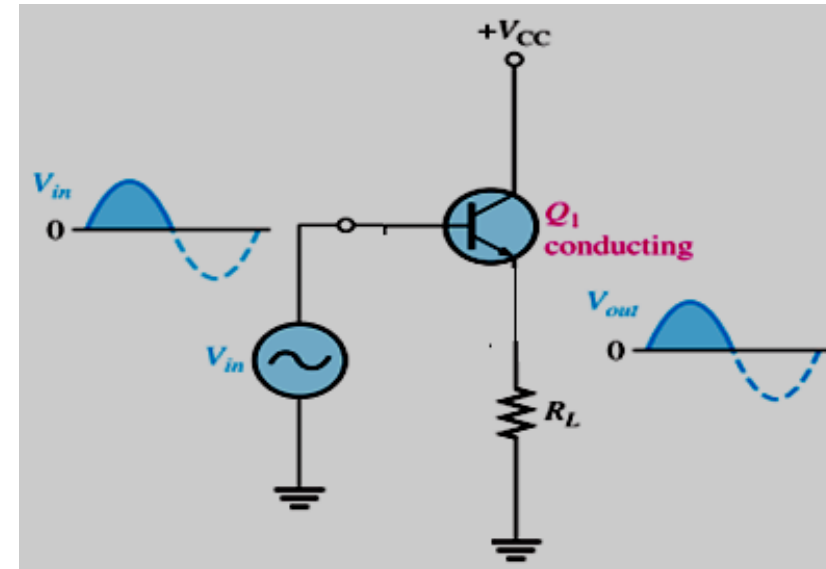
- The class B amplifier is biased at the cutoff point so that

$$V_{CEQ} = V_{CE(cut-off)} = V_{CC} \quad \text{and} \quad I_{CQ} = 0$$



- It is brought out of cutoff and operates in its linear region when the input signal drives the transistor into conduction.

- The Circuit only conducts for the positive half of the cycle.
- Can not amplify the entire cycle



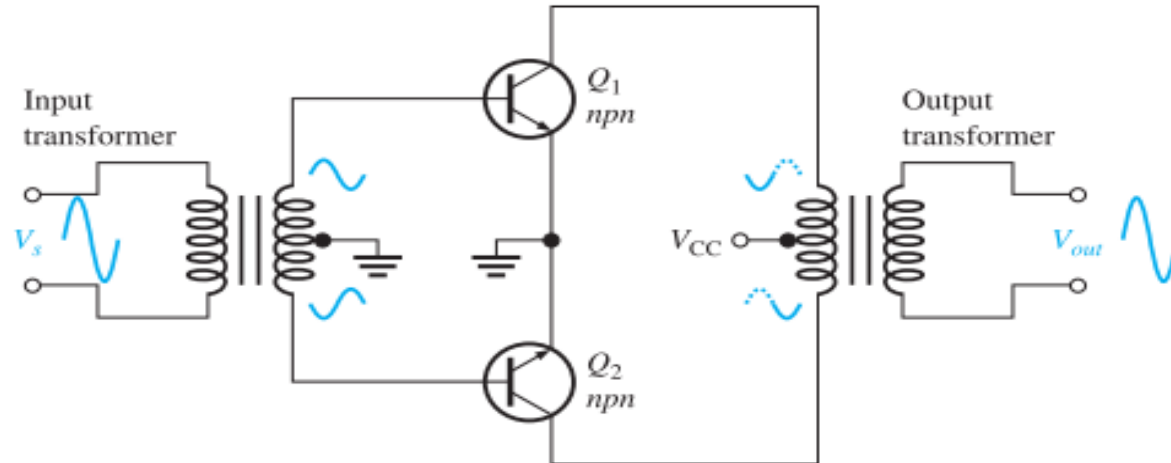
emitter-follower circuit

Class B Push-Pull Operation

- To amplify the entire cycle, it is necessary to add a second class B amplifier that operates on the negative half of the cycle.
- The combination of two class B amplifiers working together is called push-pull operation
 - There are **two common approaches** for using push-pull amplifiers to reproduce the entire waveform.

1. Transformer Coupling

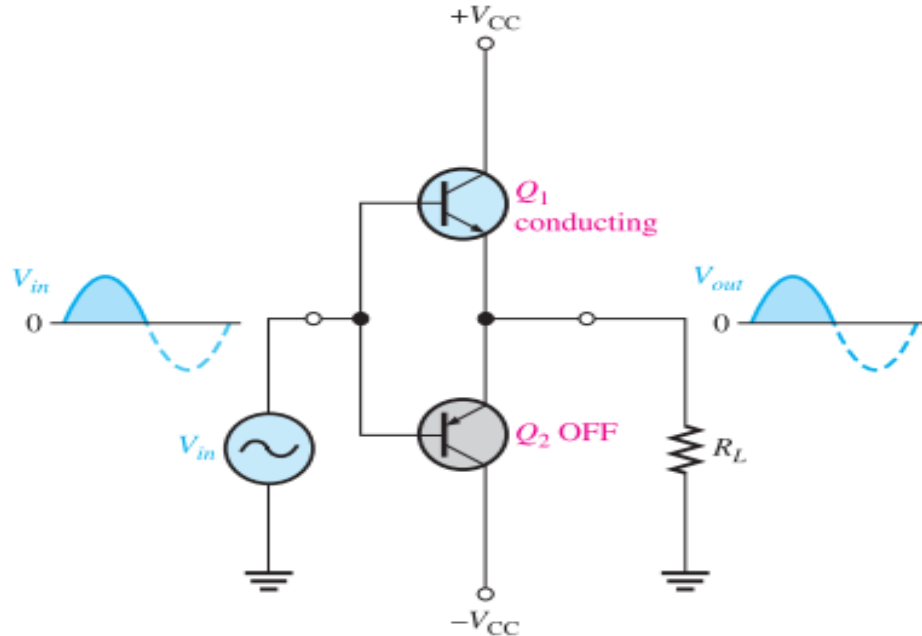
- ✓ The input transformer thus converts the input signal to two out-of-phase signals for the two npn transistors.



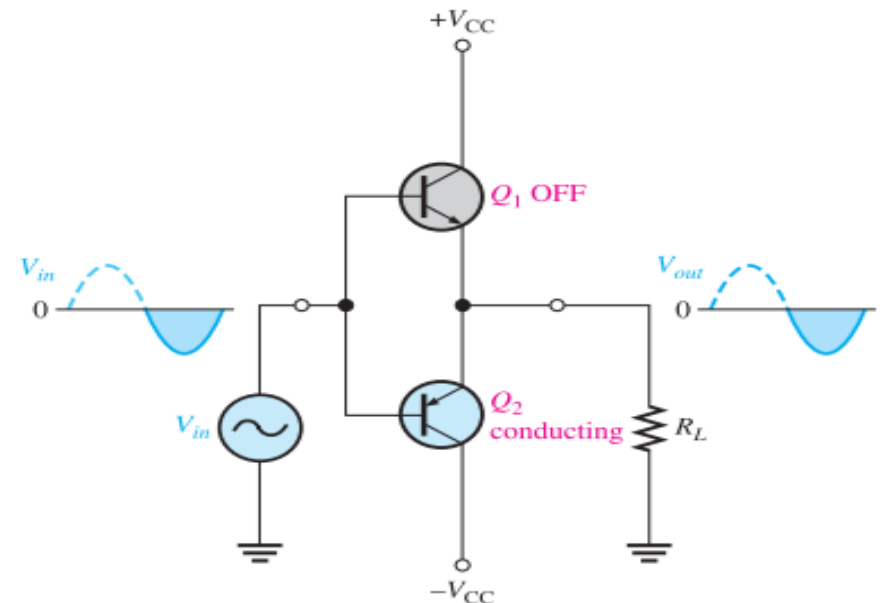
- ✓ The output transformer combines the signals by permitting current in both directions, even though one transistor is always cut off.

2. Complementary Symmetry Transistors

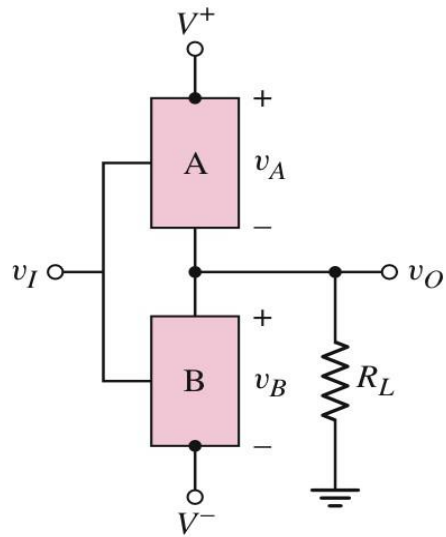
- ✓ The figure shows one of the most popular types of push-pull class B amplifiers using two emitter-followers and both positive and negative power supplies.
- ✓ This is a complementary amplifier because one emitter-follower uses an npn transistor and the other a pnp, which conduct on opposite alternations of the input cycle.



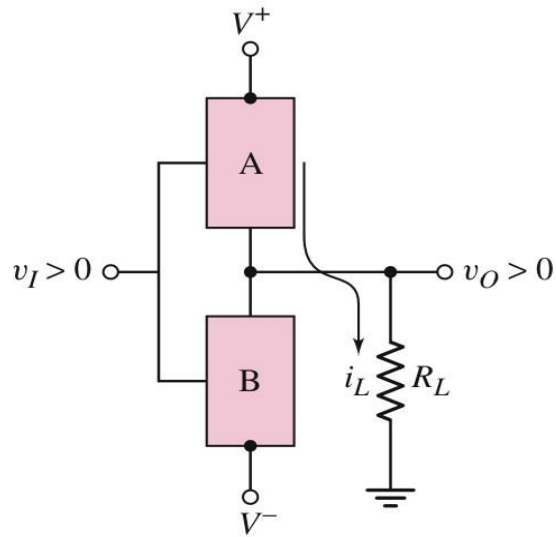
(a) During a positive half-cycle



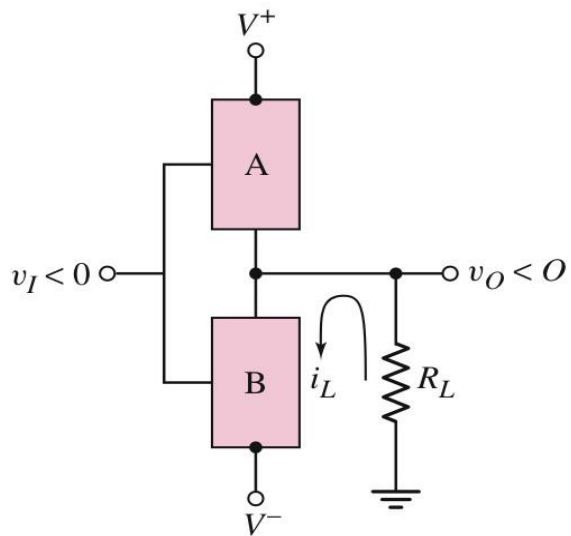
(b) During a negative half-cycle



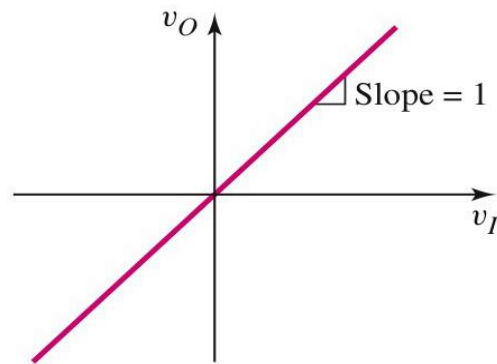
(a)



(b)



(c)



(d)

Complementary push-pull circuit

Assuming ideal transistor;

when $v_I = 0$;

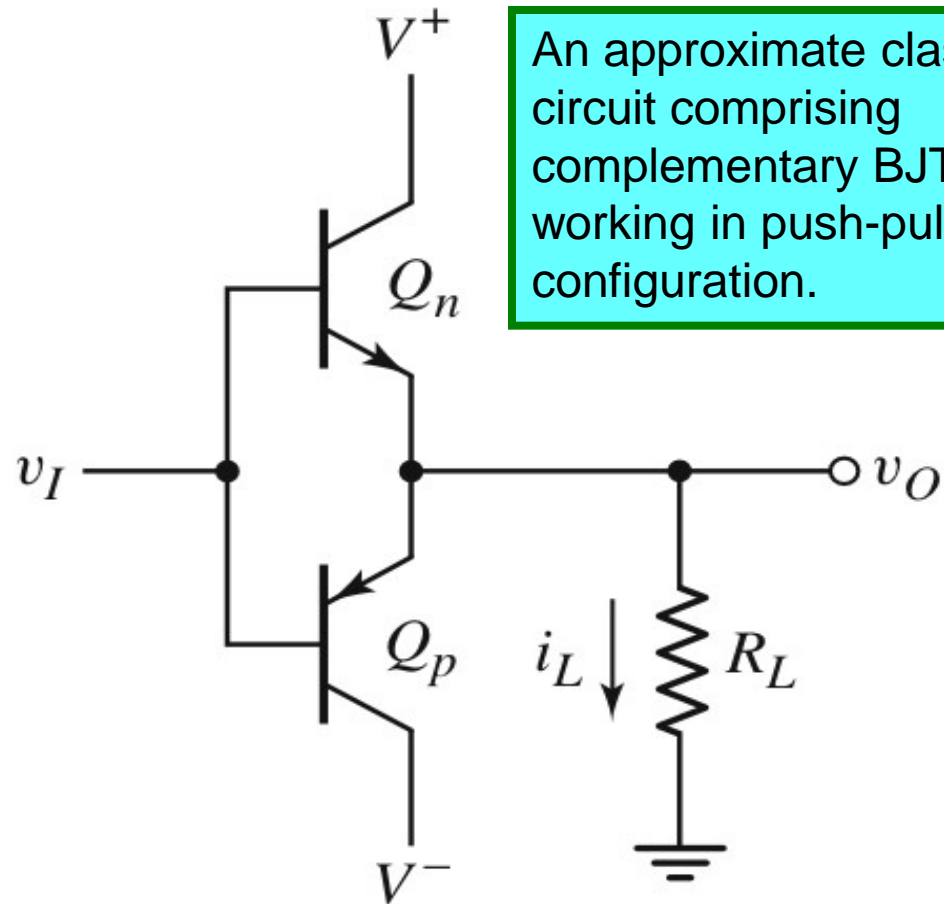
both Q_n & Q_p are off;

when $v_I > 0$;

Q_n conducts & Q_p is off;

when $v_I < 0$;

Q_p conducts & Q_n is off



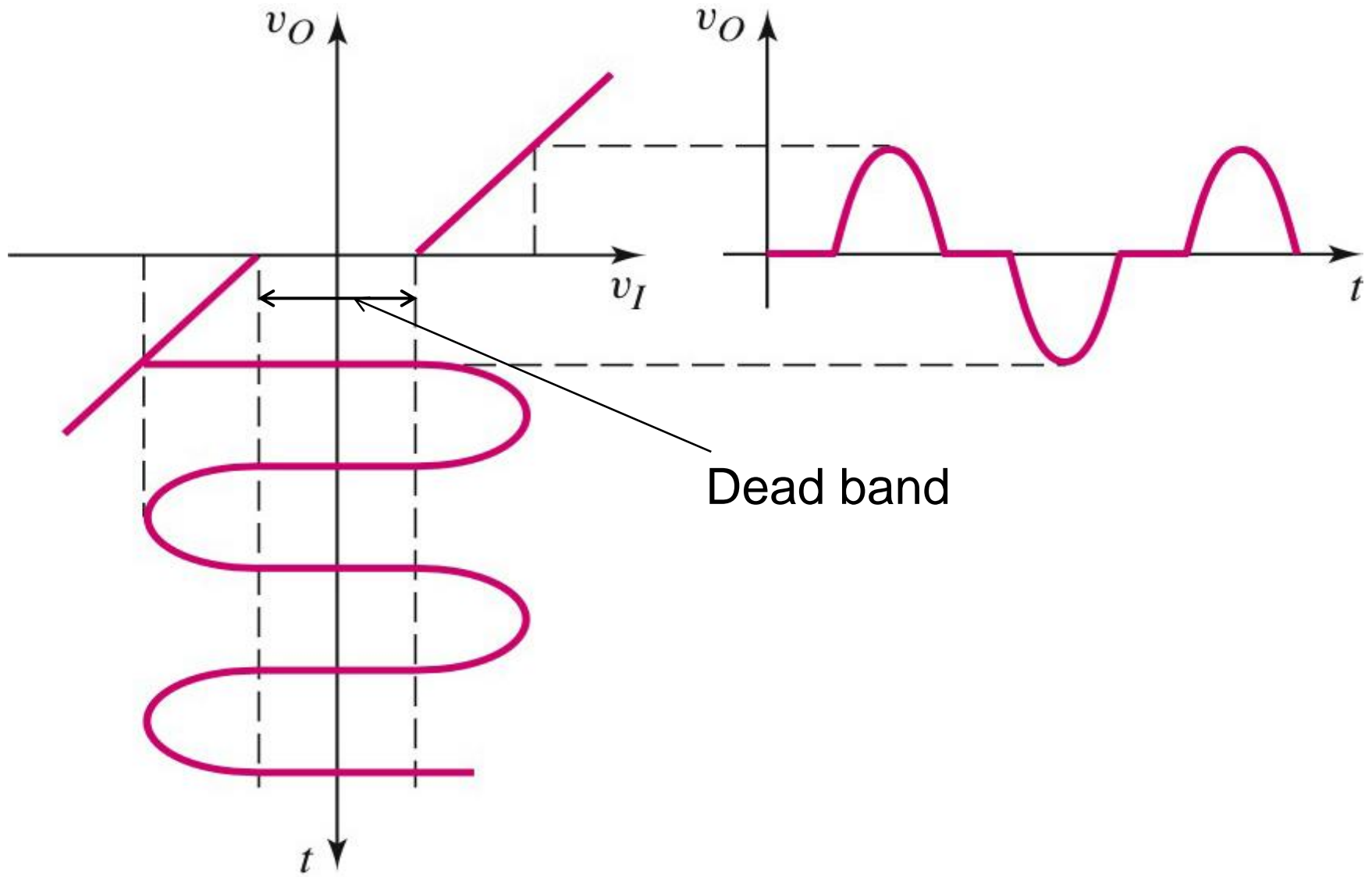
Assuming cut-in voltage of transistor is 0.6 V, $v_O = 0$ for a range $0.6 \text{ V} < v_I < -0.6 \text{ V}$.

The transfer characteristic becomes non-linear (See Figure)

The range where both transistors are simultaneously off known as the *dead band*

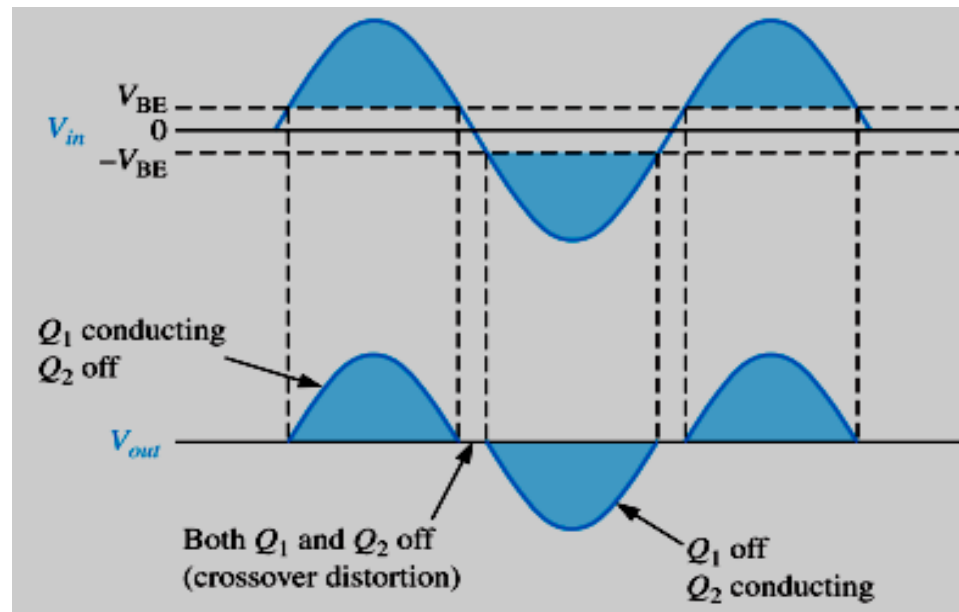
The output will be distorted – **crossover distortion** (See Figure)

Crossover distortion can be eliminated by biasing the transistor with small quiescent current – class-AB

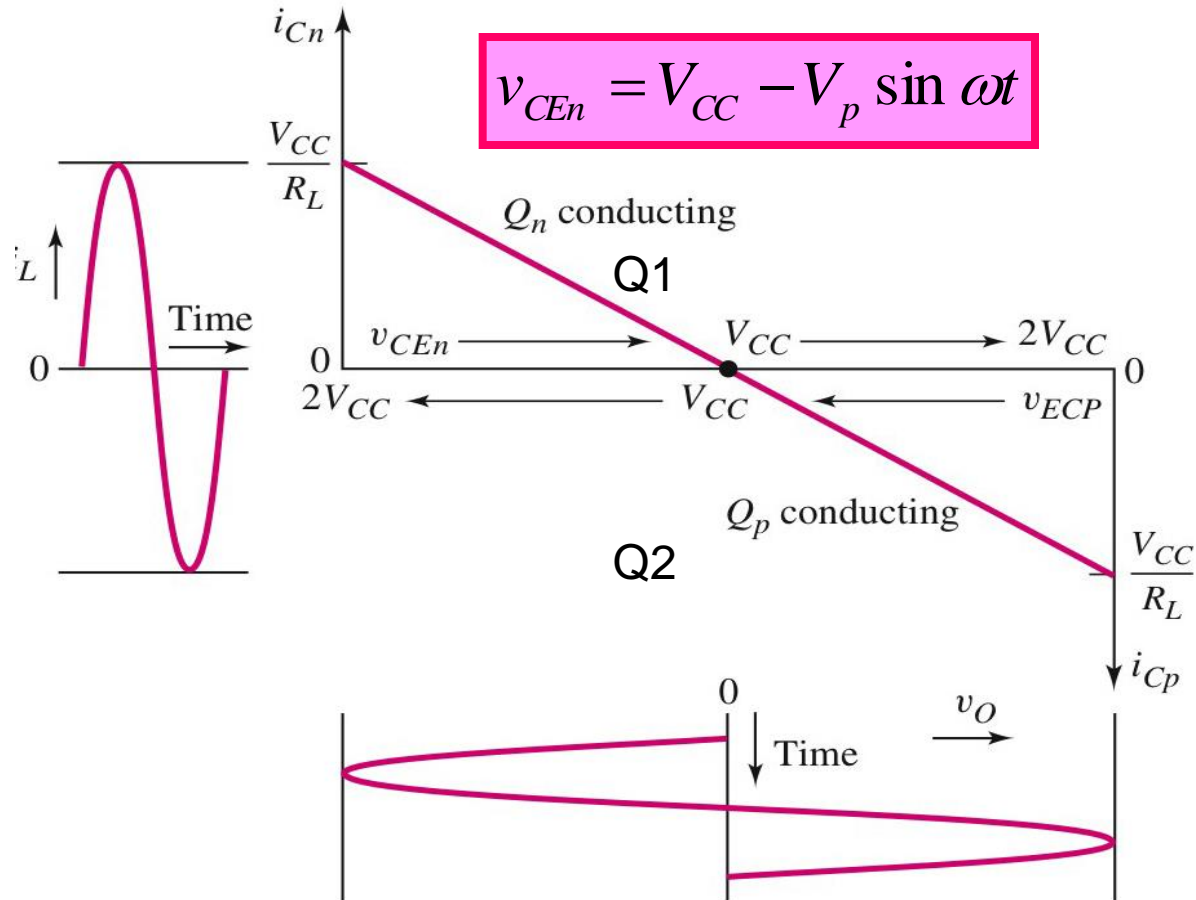


Crossover Distortion

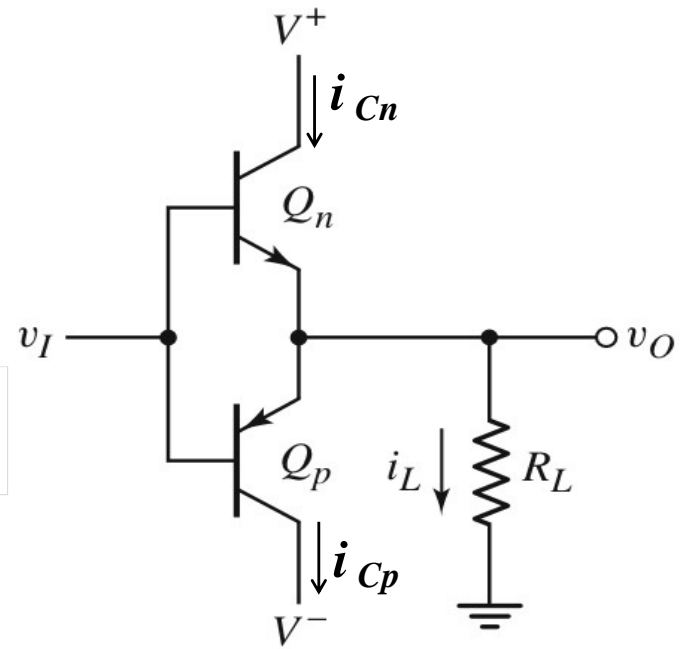
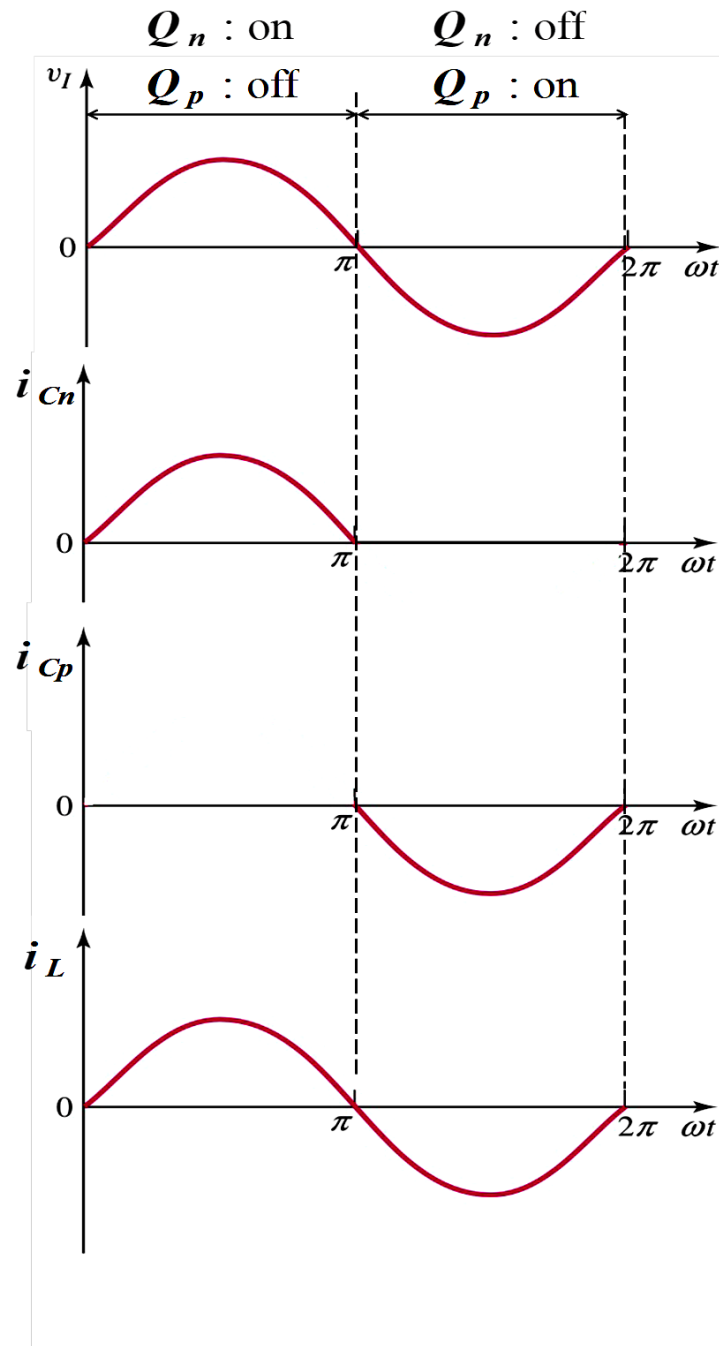
- ✓ When the dc base voltage is zero, both transistors are off and the input signal voltage must exceed V_{BE} before a transistor conducts.
- ✓ Because of this, there is a time interval between the positive and negative alternations of the input when neither transistor is conducting, as shown in Figure.
- ✓ The resulting distortion in the output waveform is called **crossover distortion**.



Theoretical maximum efficiency of class-B amplifiers



$$v_O = V_p \sin \omega t$$



$$v_O = V_p \sin \omega t$$

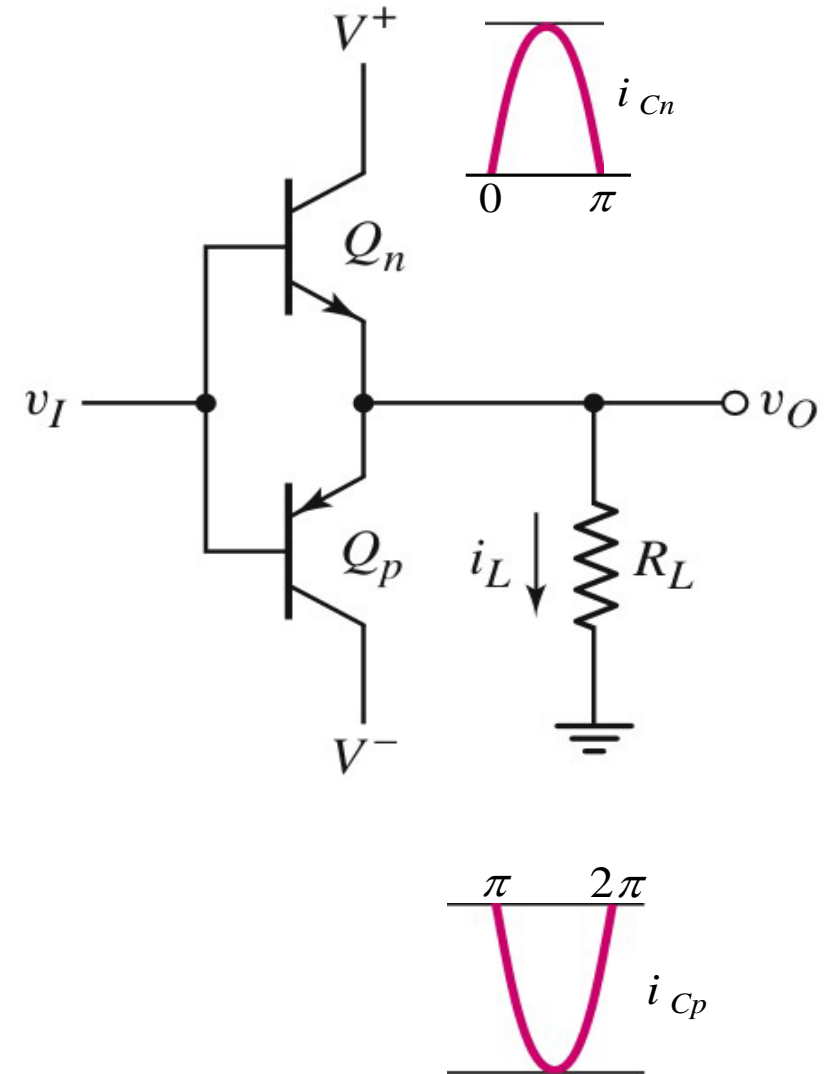
Maximum possible value of V_p is V_{CC} .

$$v_{CEn} = V_{CC} - V_p \sin \omega t$$

$$i_{Cn} = \frac{V_p}{R_L} \sin \omega t \quad \text{for } 0 < \omega t < \pi$$

and

$$i_{Cn} = 0 \quad \text{for } \pi < \omega t < 2\pi$$



The instantaneous power in Q_n is;

$$\begin{aligned} P_{Q_n}(t) &= v_{CE_n}(t) i_{C_n}(t) \\ &= (V_{CC} - V_p \sin \omega t) \left(\frac{V_p}{R_L} \sin \omega t \right) \quad \text{for } 0 < \omega t < \pi \end{aligned}$$

and

$$P_{Q_n} = 0 \quad \text{for } \pi < \omega t < 2\pi$$

$$P_{Q_n} = P_{Q_p} \quad (\text{symmetry})$$

The total power supplied by the two sources is;

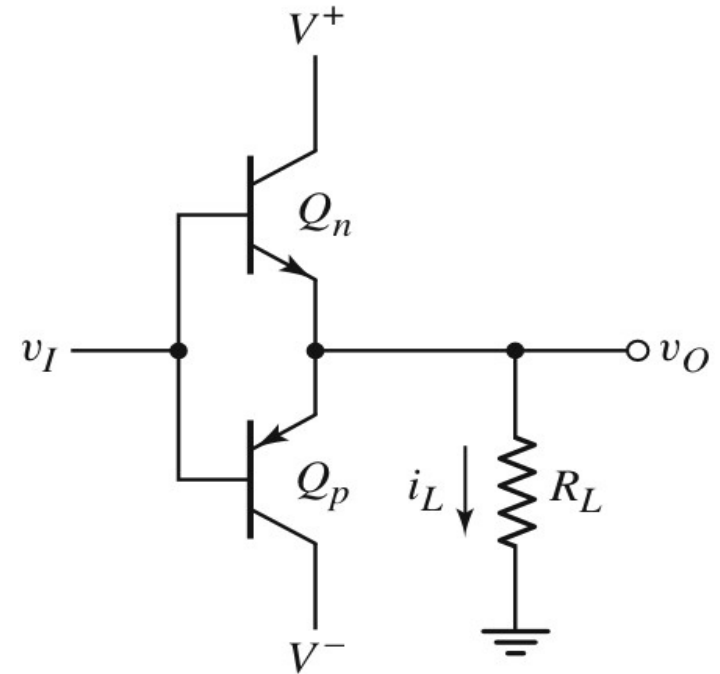
$$P_S = 2V_{CC} I_S = 2V_{CC} \left(\frac{V_p}{\pi R_L} \right)$$

The ac power delivered to the load is;

$$P_L = \frac{V_{O(\text{rms})}^2}{R_L} = \frac{(V_p / \sqrt{2})^2}{R_L} = \frac{V_p^2}{2R_L}$$

The efficiency is;

$$\eta = \frac{P_L}{P_S} = \frac{\pi V_p}{4V_{CC}}$$



Maximum efficiency occurs when $V_p = V_{CC}$

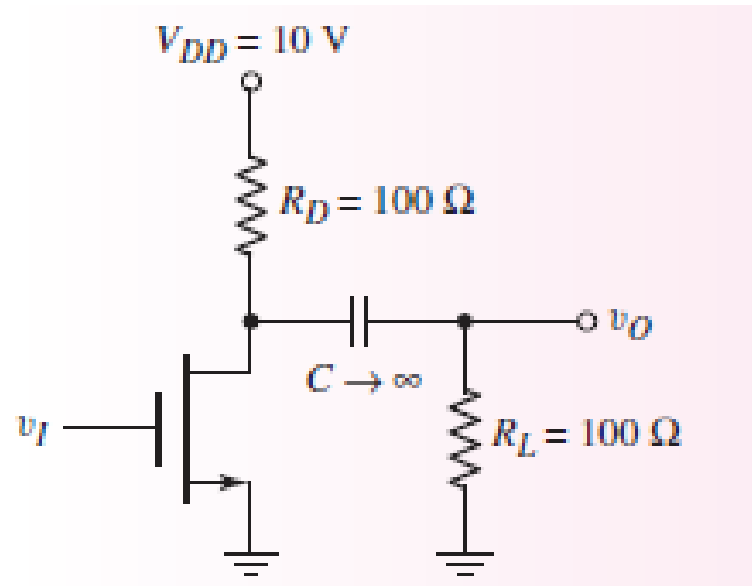
Under this condition;

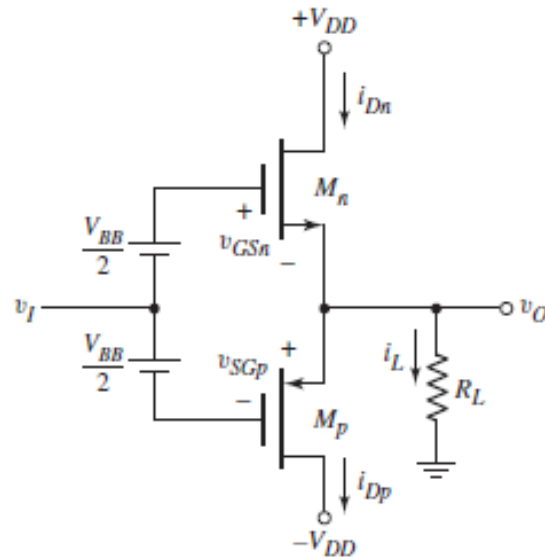
$$\eta = \frac{\pi}{4} = 0.785$$

Maximum theoretical efficiency
of class B amplifier is therefore
78.5%

For the common-source circuit, the Q -point is $V_{DSQ} = 4$ V. (a) Find I_{DQ} . (b) The minimum value of the instantaneous drain current must be no less than 1/10 th of I_{DQ} , and the minimum value of the instantaneous drain–source voltage must be no less than $v_{DS} = 1.5$ V. Determine the maximum peak-to-peak amplitude of a symmetrical sinusoidal output voltage.

(c) For the conditions of part (b), calculate the power conversion efficiency, where the signal power is the power delivered to R_L . (Ans. (a) $I_{DQ} = 60$ mA (b) $V_{p-p} = 5.0$ V (c) $PL = 1.25$ mW, $\eta = 5.2\%$)





Determine the required biasing in a MOSFET class-AB output stage. The parameters are $V_{DD} = 10 \text{ V}$ and $R_L = 20 \text{ } \Omega$. The transistors are matched, and the parameters are $K = 0.20 \text{ A/V}^2$ and $|V_T| = 1\text{V}$. The quiescent drain current is to be 20 percent of the load current when $v_O = 5 \text{ V}$.

Class AB

- Class AB is probably the most common amplifier class currently used in home stereo and similar amplifiers.
- Class AB amps combine the good points of class A and B amps.
- They have the improved efficiency and less harmonic distortion of class B amplifiers and no cross-over distortion a lot closer to that of a class A amplifier.

Biasing the Push-Pull Amplifier for **Class AB Operation**

- ✓ To overcome crossover distortion, the biasing is adjusted to just overcome the V_{BE} of the transistors
- ✓ In class AB operation, the push-pull stages are biased into slight conduction, even when no input signal is present.
- ✓ This can be done with a voltage-divider and diode arrangement, as shown

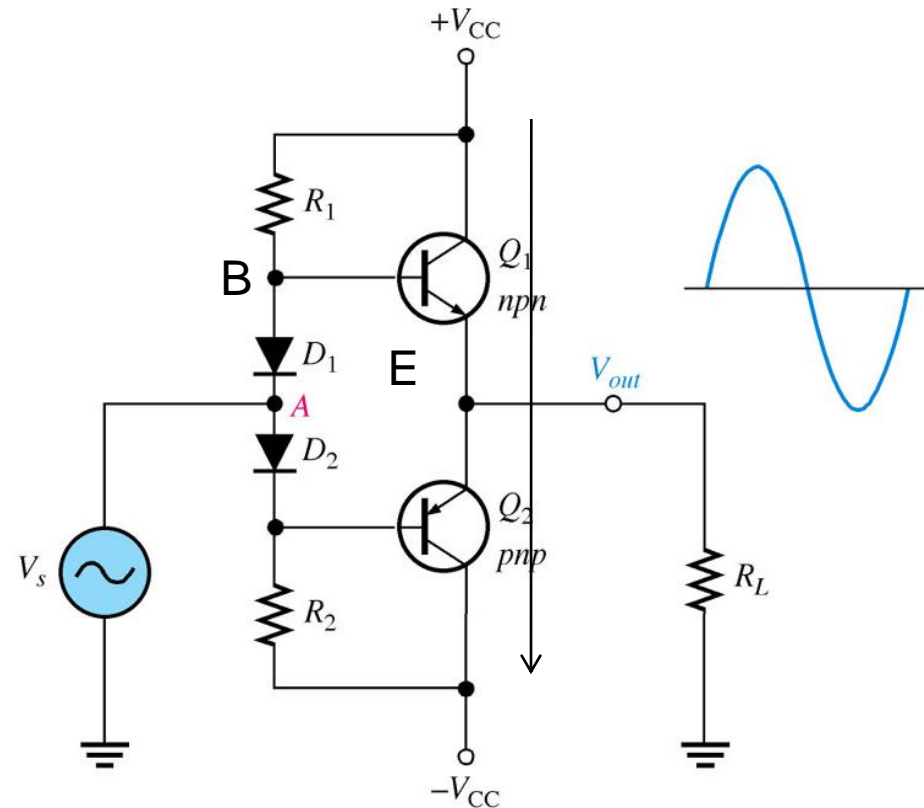
➤ Using equal values of R_1 and R_2 the positive and negative supply voltages forces the voltage at point **A** to equal 0 V and eliminates the need for an input coupling capacitor.

➤ When the diode characteristics of D_1 and D_2 are closely matched to the characteristics of the transistor BE junctions, the current in the diodes and the current in the transistors are the same;

((current mirror.))

The diode current will be the same as I_{EQ}

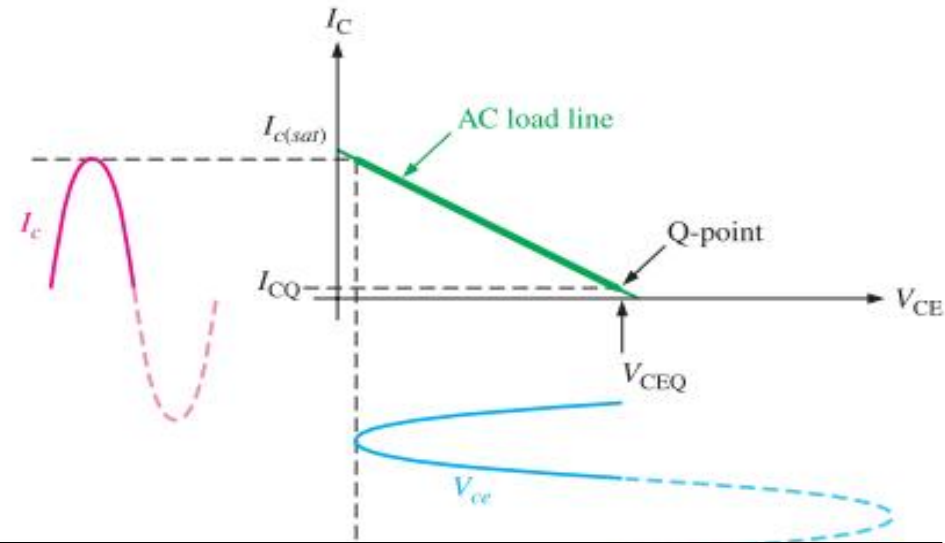
$$I_{CQ} = \frac{V_{CC} - 0.7 \text{ V}}{R_1}$$



✓ AC Operation

- The Q-point is slightly above cutoff.
- The ac cutoff voltage is at V_{CC}
- The **ac** saturation current is:

$$I_{csat} = \frac{V_{CEQ}}{R_{Lac}}$$



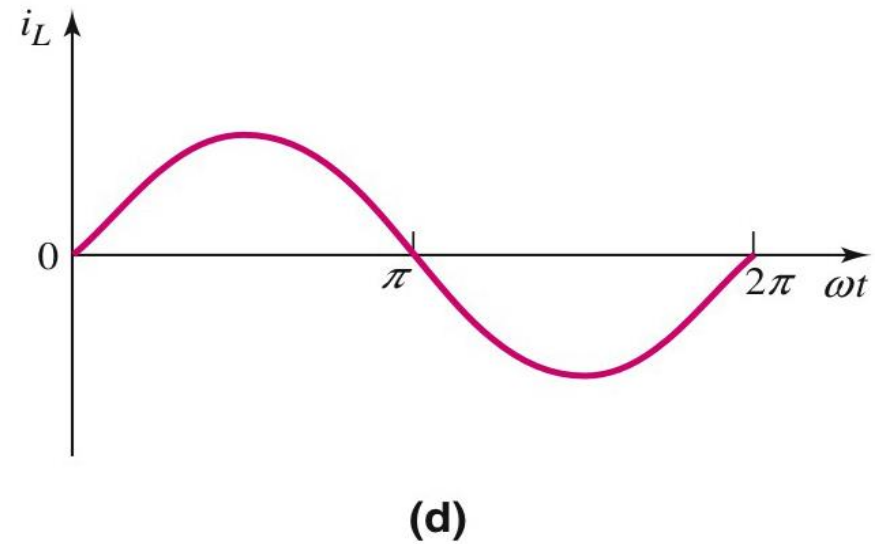
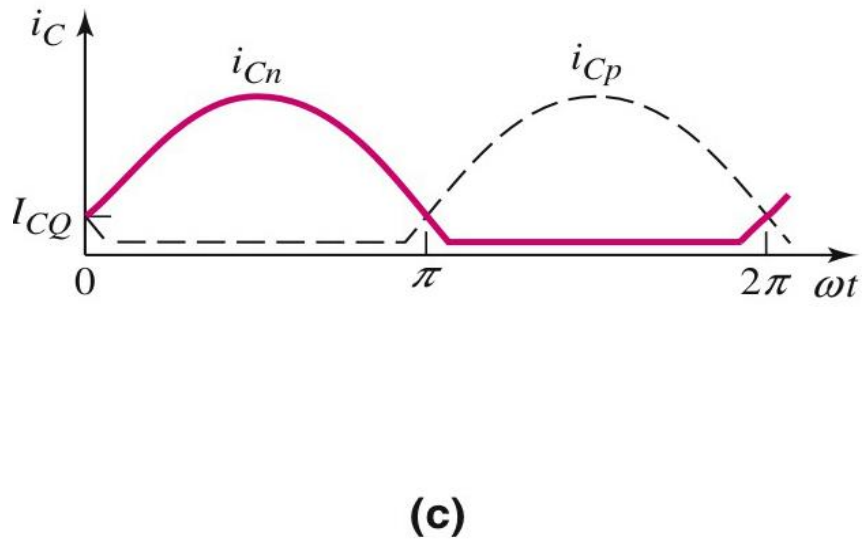
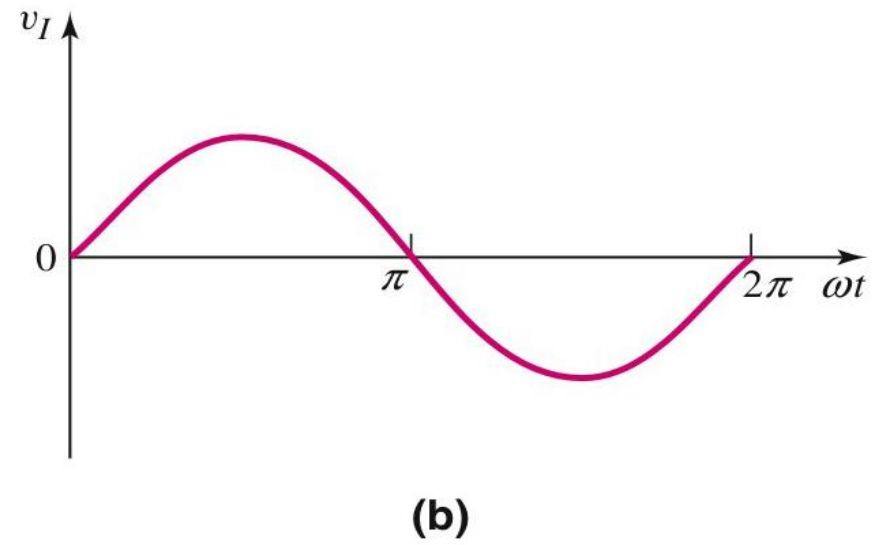
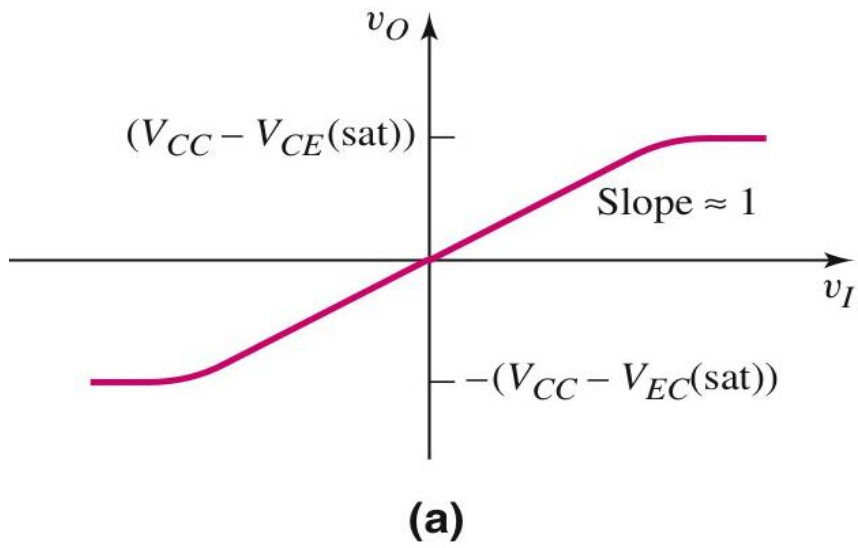
- ✓ In class A , the Q-point is near the middle and there is significant current in the transistors even with no signal.
- ✓ In class A B , when there is no signal, the transistors have only a very small current and therefore dissipate very little power.
- ✓ Thus, the efficiency of a class AB amplifier can be much higher than a class A amplifier.

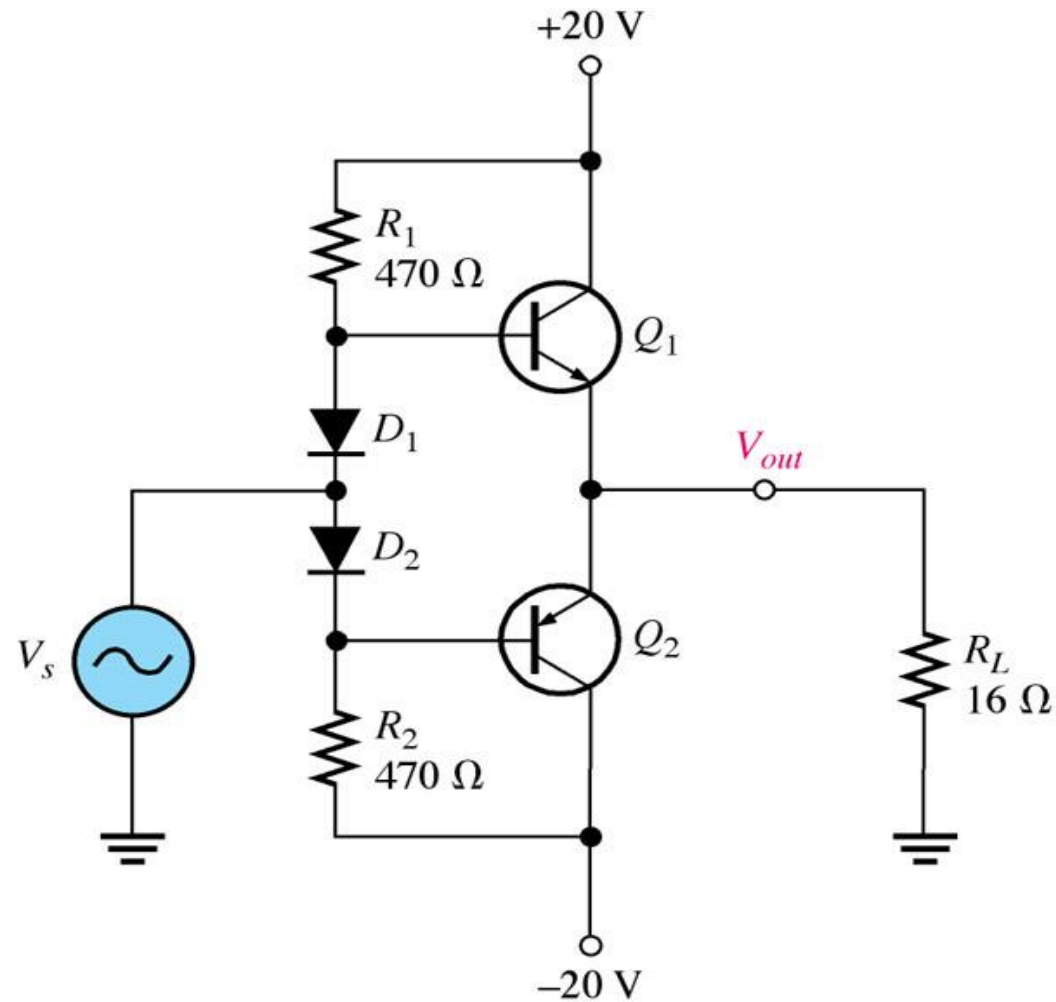
The ideal maximum peak output voltage is

$$V_{out(peak)} \cong V_{CEQ} \cong V_{CC}$$

The ideal maximum peak current is

$$I_{out(peak)} \cong I_{c(sat)} \cong \frac{V_{CC}}{R_L}$$





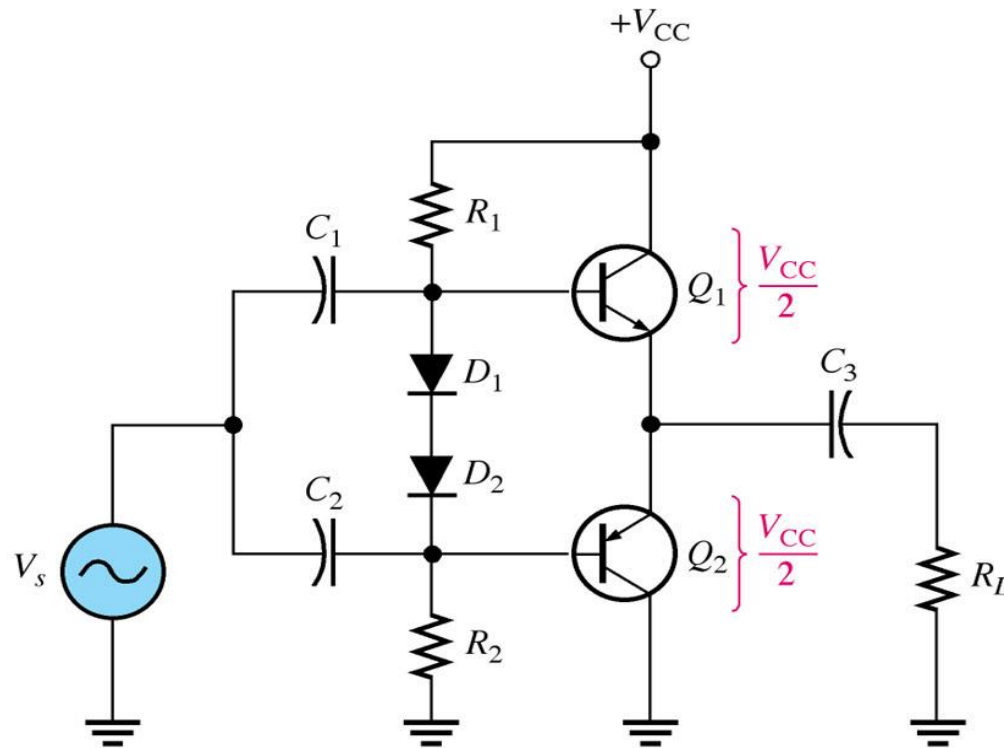
$$V_{CEQ} = 20V$$

$$I_{CQ} = (20 - 0.7) / 470 = 41 \text{ mA}$$

$$V_p(\text{out}) = V_{CEQ} = 20V$$

$$I_p(\text{out}) = 20 / 16 \text{ A} = 1.260 \text{ A}$$

Single-ended push-pull amplifier.

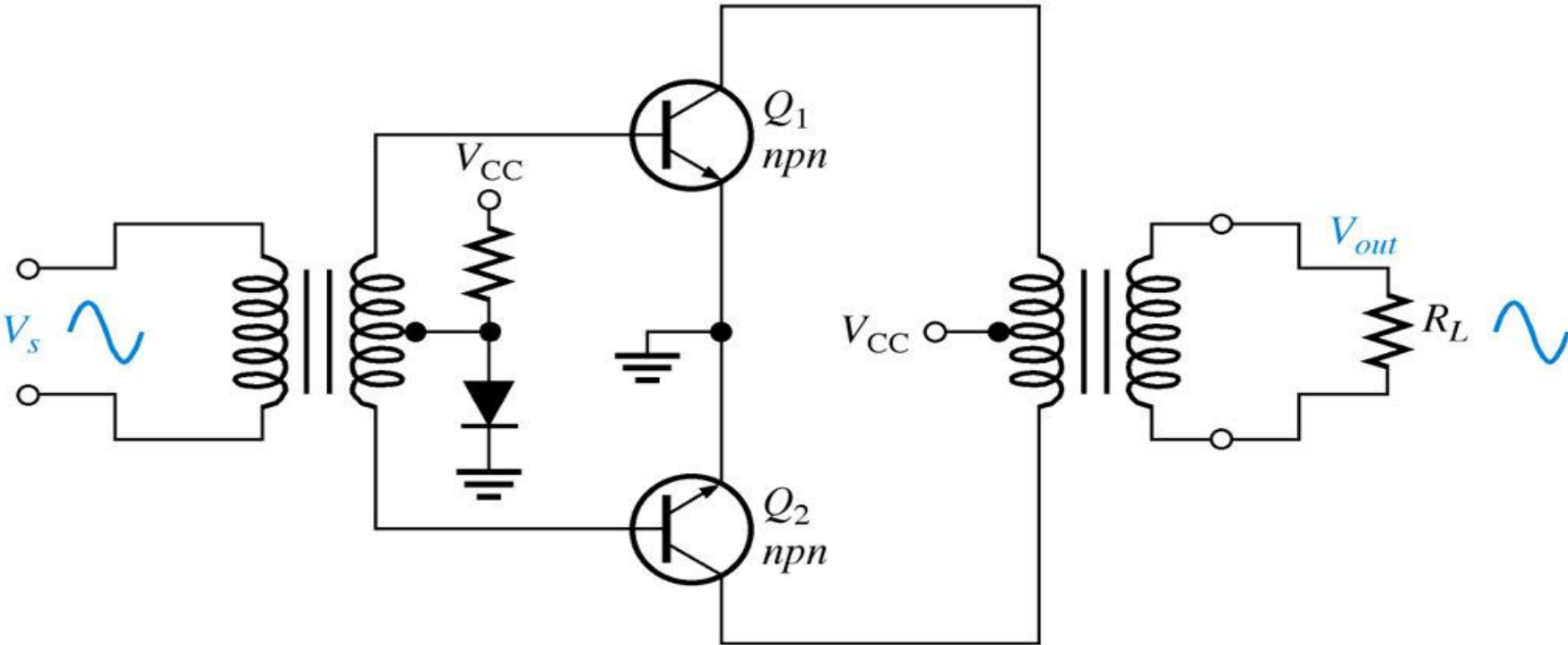


- The circuit operation is the same as that described previously, except the bias is set to force the output emitter voltage to be

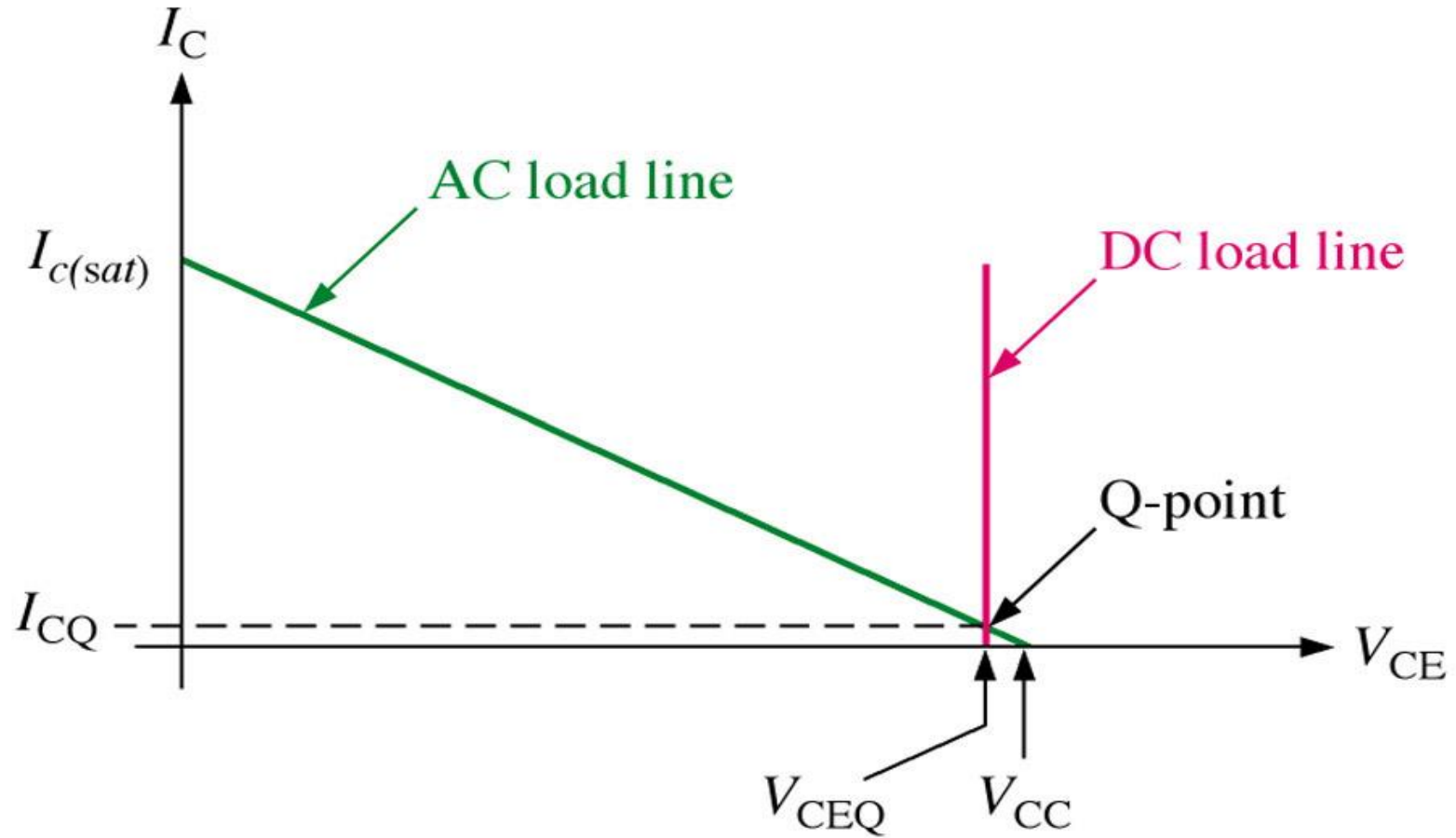
$$V_{out(peak)} \cong V_{CEQ} = \frac{V_{CC}}{2}$$

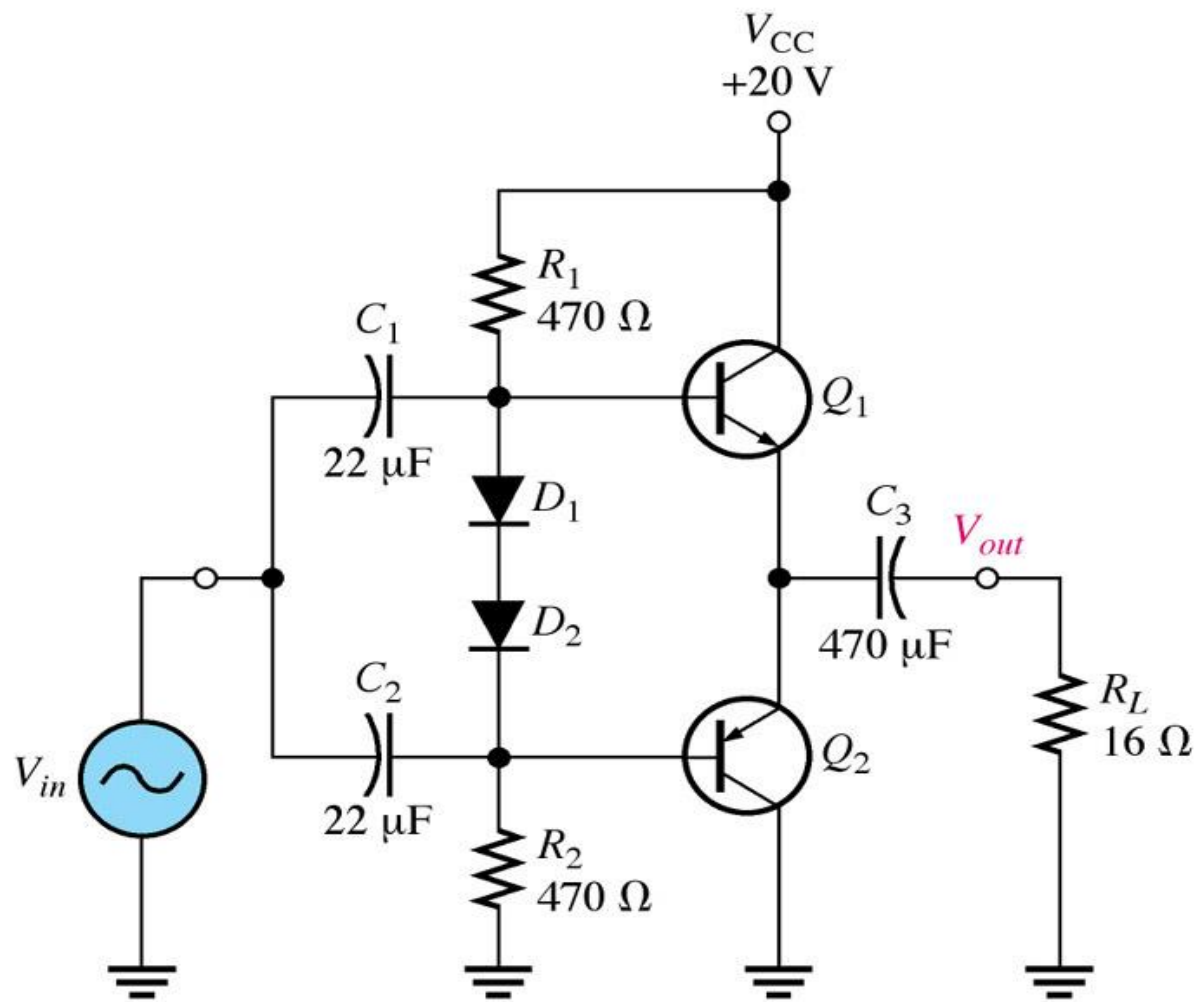
$$I_{out(peak)} \cong I_{c(sat)} = \frac{V_{CEQ}}{R_L}$$

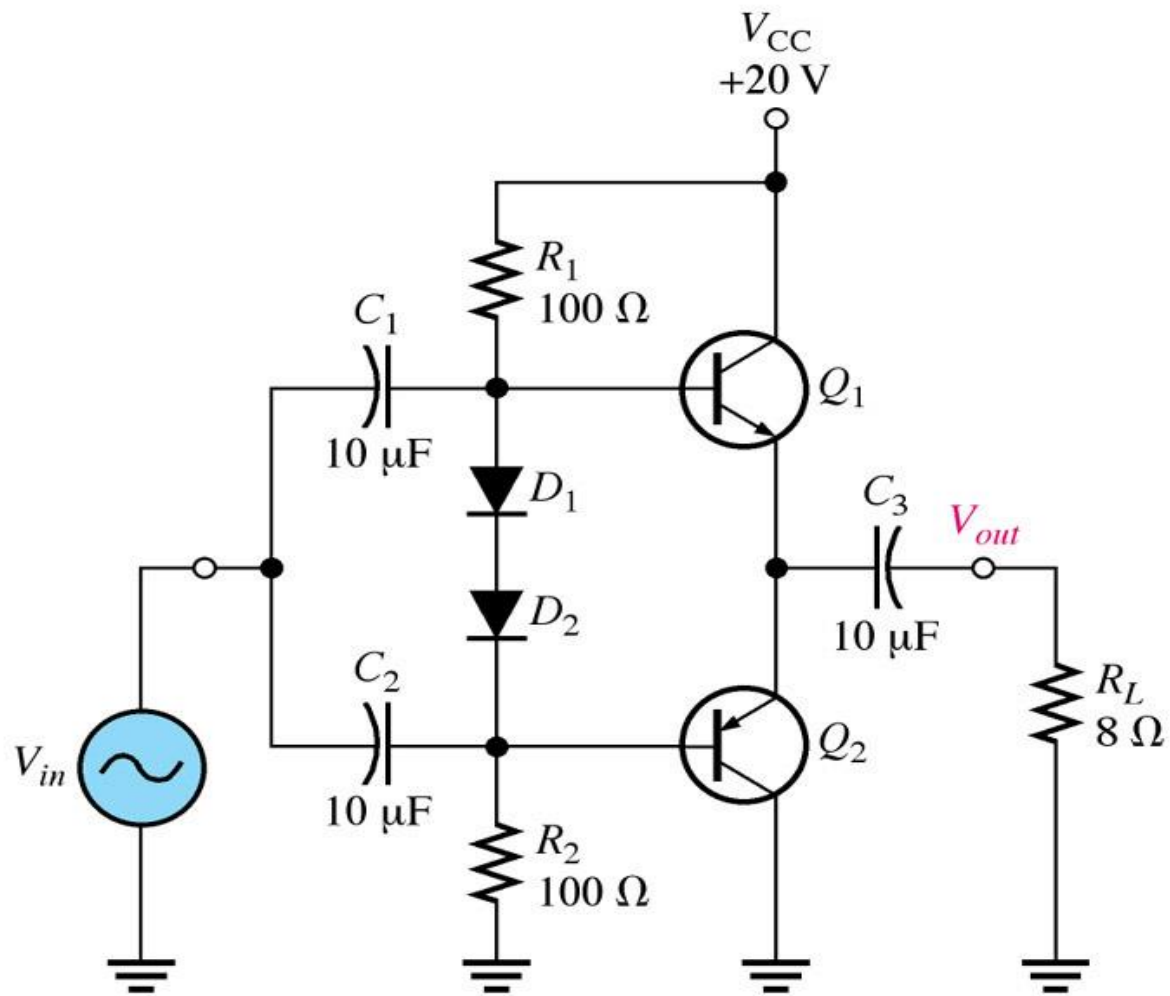
Eliminating crossover distortion in a transformer-coupled push-pull amplifier. The diode compensates for the base-emitter drop of the transistors and produces class AB operation.



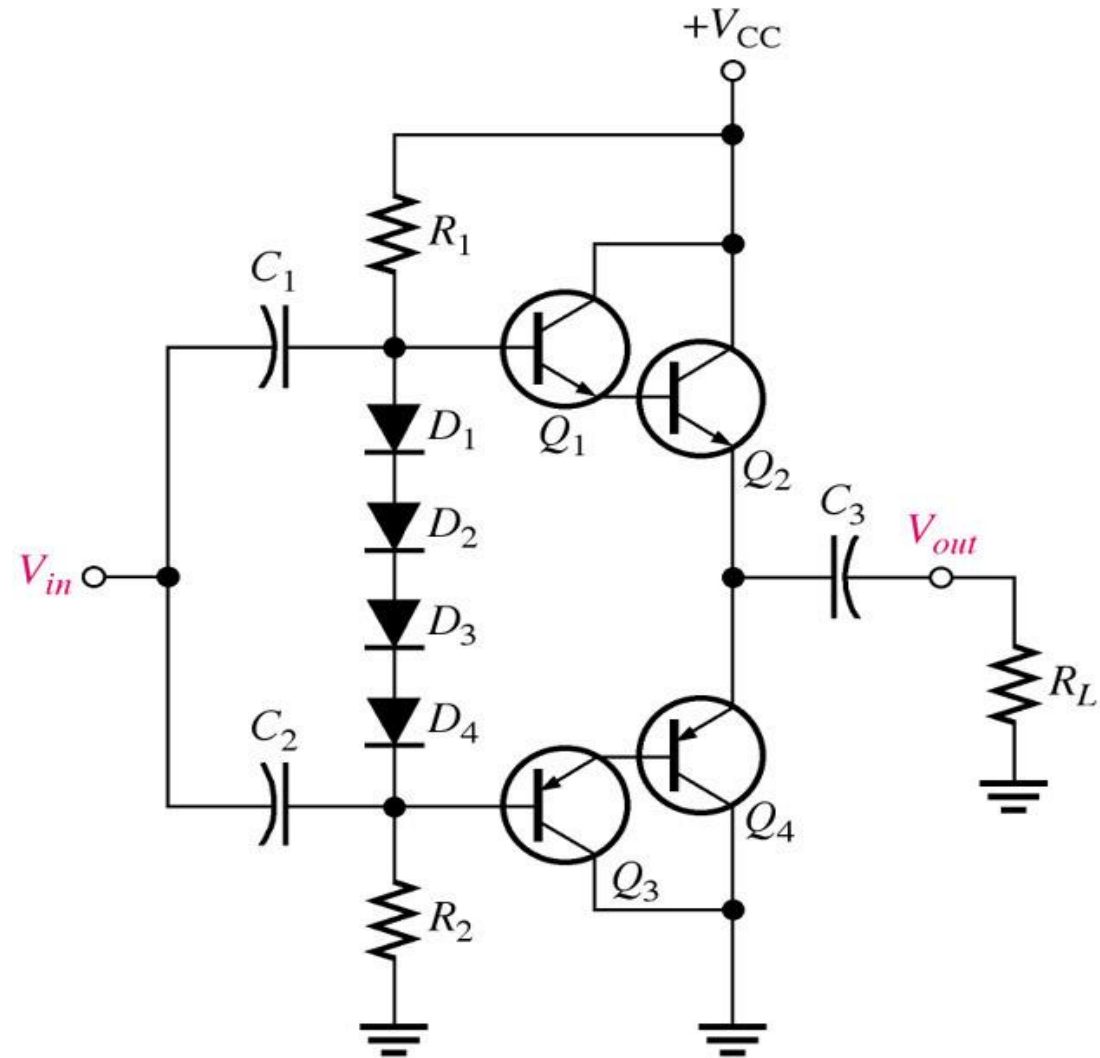
Load lines for a complementary symmetry push-pull amplifier. Only the load lines for the *npn* transistor are shown.







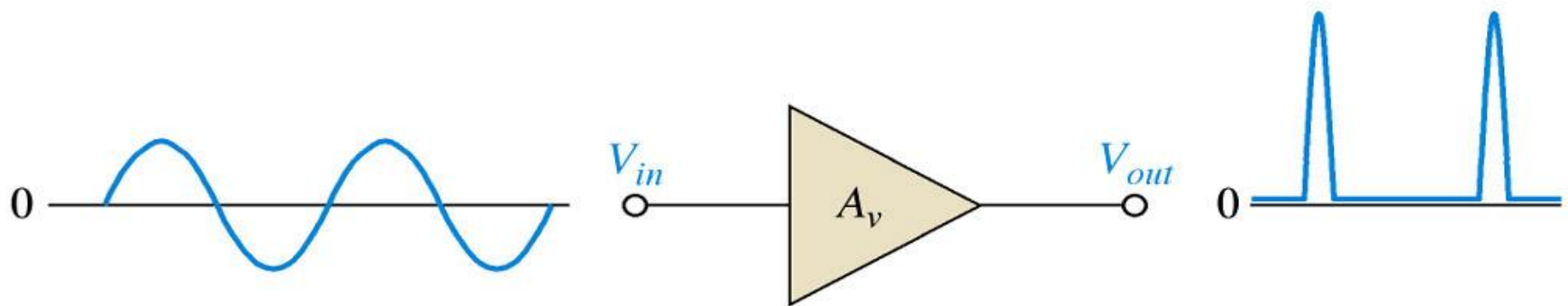
A Darlington class AB push-pull amplifier.



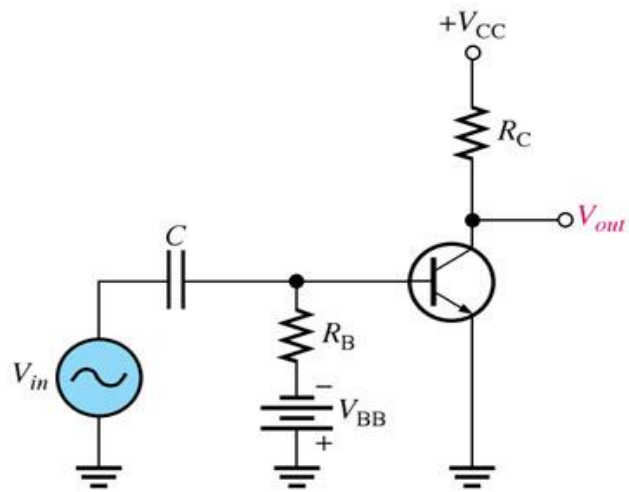
Class C

- Class C amps are **never used for audio circuits.**
- They are commonly **used in RF circuits.**
- Class C amplifiers operate the output transistor in a state that results in **tremendous distortion** (it would be totally unsuitable for audio signal reproduction).

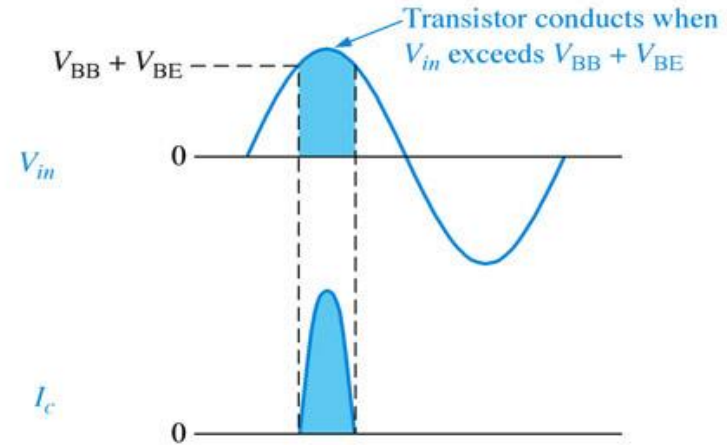
Basic class C amplifier operation (non inverting).



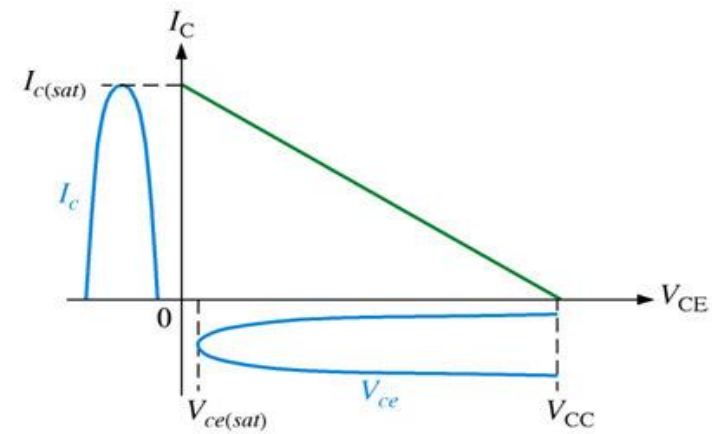
Basic class C operation.



(a) Basic class C amplifier circuit

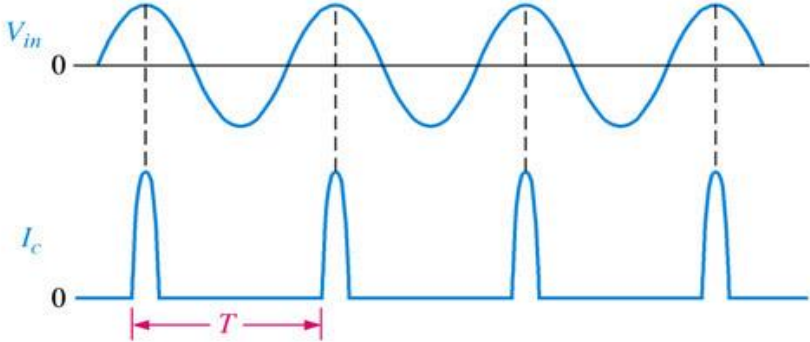


(b) Input voltage and output current waveforms

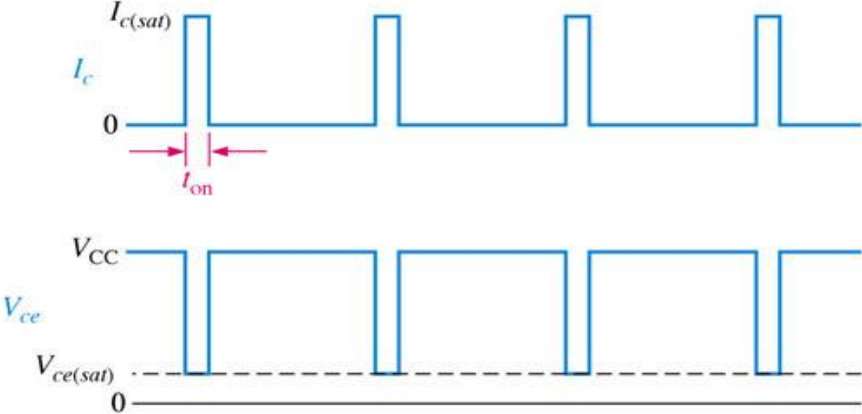


(c) Load line operation

Class C waveforms.



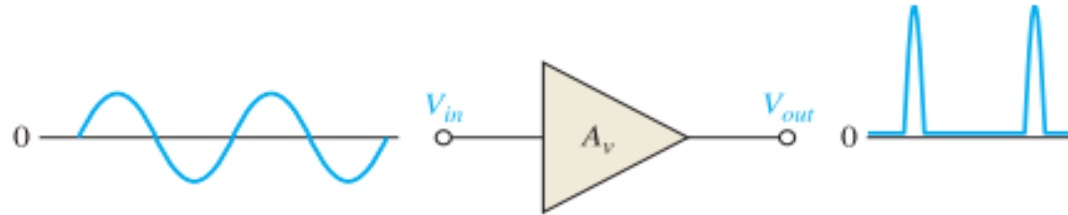
(a) Collector current pulses



(b) Ideal class C waveforms

Class C amplifiers

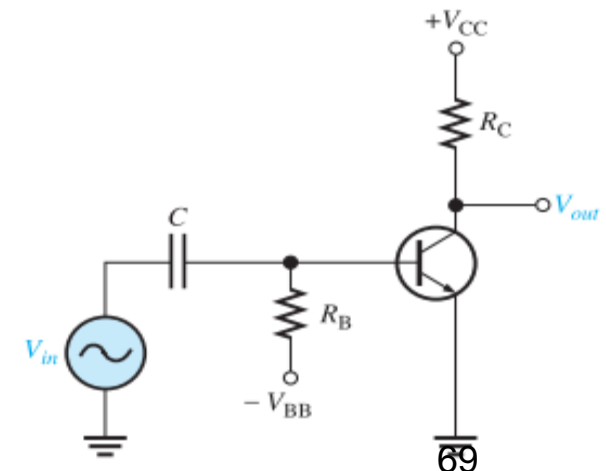
- Class C amplifiers are biased so that conduction occurs for much less than 180°
 - Class C amplifiers are more efficient than either class A, B, or AB



- The output amplitude is a nonlinear function of the input, so class C amplifiers are not used for linear amplification.
 - They are generally used in radio frequency (RF) applications, including resonance circuits

Basic Class C Operation

- A class C amplifier is normally operated with a resonant circuit load, so the resistive load is used only for the purpose of illustrating the concept.
 - The ac source voltage has a peak value that exceeds the barrier potential of the base-emitter junction for a short time near the positive peak of each cycle,



(a) Basic class C amplifier circuit

Class C amplifiers

Basic Class C Operation

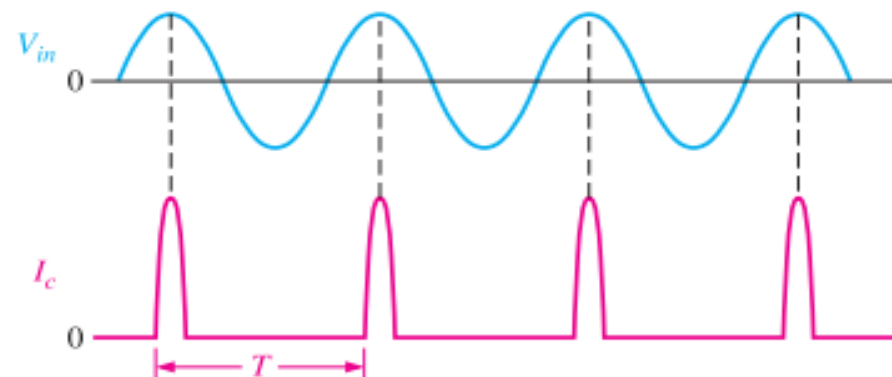
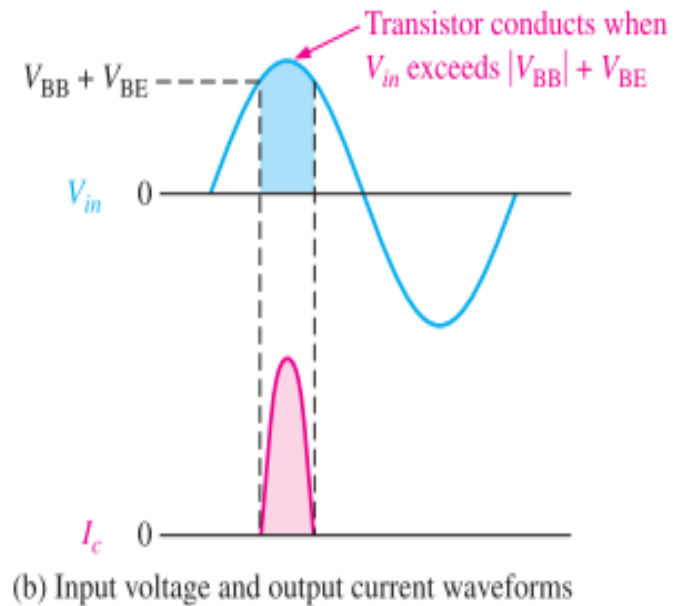
- During this short interval, the transistor is turned on.
- The power dissipation of the transistor in a class C amplifier is low because it is on for only a small percentage of the input cycle
- The power dissipation during the on time is

$$P_{D(\text{on})} = I_{c(\text{sat})} V_{ce(\text{sat})}$$

- The power dissipation averaged over the entire cycle is

$$P_{D(\text{avg})} = \left(\frac{t_{\text{on}}}{T}\right) P_{D(\text{on})} = \left(\frac{t_{\text{on}}}{T}\right) I_{c(\text{sat})} V_{ce(\text{sat})}$$

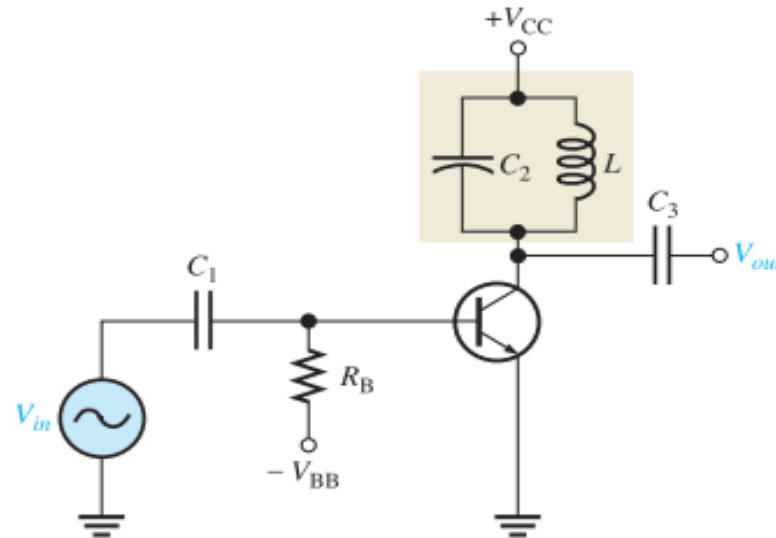
Check EXAMPLE 7-7 (Floyde)



Tuned Class C Operation

- Because the collector voltage (output) is not a replica of the input, the resistively loaded class C amplifier alone is of no value in linear applications.
- It is therefore necessary to use a class C amplifier with a parallel resonant circuit (tank), as shown

- The short pulse of collector current on each cycle of the input initiates and sustains the oscillation of the tank circuit so that an output sinusoidal voltage is produced



(a) Basic circuit

Cass-C operation

Transistor conducts for less than half a cycle of input signal



- Tuned circuit is required.
- Used for RF amplifier.
- Efficiency $> 78.5\%$

B – E junction is reverse-biased to obtain Q-point beyond cut-off.

Maximum Output Power

Since the voltage developed across the tank circuit has a peak-to-peak value of approximately $2V_{CC}$, the maximum output power can be expressed as

$$P_{out} = \frac{V_{rms}^2}{R_c} = \frac{(0.707V_{CC})^2}{R_c}$$
$$P_{out} = \frac{0.5V_{CC}^2}{R_c}$$

R_c is the equivalent parallel resistance of the collector tank circuit at resonance and represents the parallel combination of the coil resistance and the load resistance. It usually has a low value. The total power that must be supplied to the amplifier is

$$P_T = P_{out} + P_{D(avg)}$$

Therefore, the efficiency is

$$\eta = \frac{P_{out}}{P_{out} + P_{D(avg)}}$$

When $P_{out} \gg P_{D(avg)}$, the class C efficiency closely approaches 1 (100 percent).

A class C amplifier is driven by a 200 kHz signal. The transistor is on for 1 μs , and the amplifier is operating over 100 percent of its load line. If $I_{c(sat)} = 100 \text{ mA}$ and $V_{ce(sat)} = 0.2 \text{ V}$, what is the average power dissipation of the transistor?

Solution The period is

$$T = \frac{1}{200 \text{ kHz}} = 5 \mu\text{s}$$

Therefore,

$$P_{D(\text{avg})} = \left(\frac{t_{\text{on}}}{T} \right) I_{c(sat)} V_{ce(sat)} = (0.2)(100 \text{ mA})(0.2 \text{ V}) = 4 \text{ mW}$$

The low power dissipation of the transistor operated in class C is important because, as you will see later, it leads to a very high efficiency when it is operated as a tuned class C amplifier in which relatively high power is achieved in the resonant circuit.

Problem If the frequency is reduced from 200 kHz to 150 kHz with the same *on* time, what is the average power dissipation of the transistor?

Suppose the class C amplifier described in Example 7-7 has a V_{CC} equal to 24 V and the R_c is 100 Ω . Determine the efficiency.

Solution From Example 7-7, $P_{D(\text{avg})} = 4 \text{ mW}$.

$$P_{out} = \frac{0.5V_{CC}^2}{R_c} = \frac{0.5(24 \text{ V})^2}{100 \Omega} = 2.88 \text{ W}$$

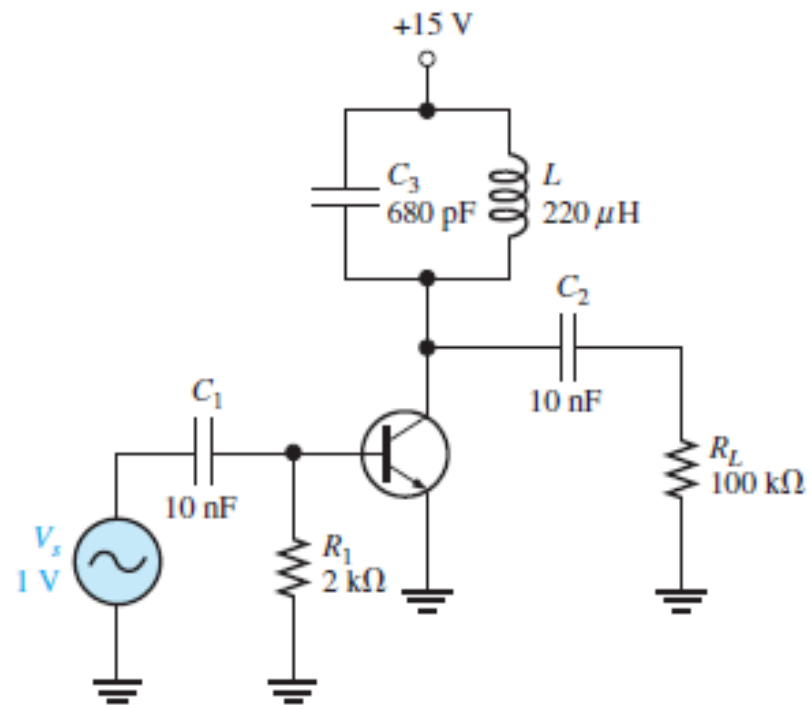
Therefore,

$$\eta = \frac{P_{out}}{P_{out} + P_{D(\text{avg})}} = \frac{2.88 \text{ W}}{2.88 \text{ W} + 4 \text{ mW}} = 0.999$$

or, as a percentage, 99.9%.

Problem What happens to the efficiency of the amplifier if R_c is increased?

► FIGURE 7-29



The resonant frequency is

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(220\ \mu\text{H})(680\ \text{pF})}} = 411\ \text{kHz}$$

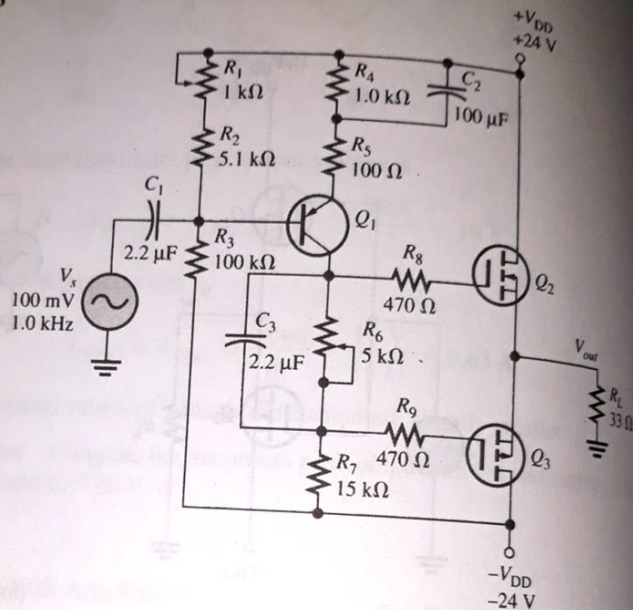
The output signal has a peak-to-peak value of

$$V_{pp} = 2V_{CC} = 2(15\ \text{V}) = 30\ \text{V}$$

EXAMPLE 5-9

The *n*-channel E-MOSFET shown in Figure 5-38 has a threshold voltage of +2.0 V. The *p*-channel E-MOSFET has a threshold voltage of -2.0 V. What resistance setting for R_6 will bias the transistors to class AB operation? At this setting, what power is delivered to the load if the input signal is 100 mV? Assume that potentiometer R_1 is set to 440 Ω .

FIGURE 5-38



Solution Start by computing the dc parameter for the CE amplifier. The base voltage is determined by the voltage divider composed of R_1 , R_2 , and R_3 . The standard voltage divider equation is modified to account for the fact that the divider is not referenced to ground.

$$V_B = V_{R3} - V_{DD} = \left(V_{DD} - (-V_{DD}) \right) \left(\frac{R_3}{R_1 + R_2 + R_3} \right) - V_{DD}$$

$$= (24 \text{ V} - (-24 \text{ V})) \left(\frac{100 \text{ k}\Omega}{440 \Omega + 5.1 \text{ k}\Omega + 100 \text{ k}\Omega} \right) - 24 \text{ V} = 21.5 \text{ V}$$

The emitter voltage is one diode drop higher than the base voltage (because the transistor is a *pnp* type).

$$V_E = V_B + 0.7 \text{ V} = 21.5 \text{ V} + 0.7 \text{ V} = 22.2 \text{ V}$$

Calculate the emitter current from Ohm's law.

$$I_E = \frac{V_{DD} - V_E}{R_4 + R_5} = \frac{24 \text{ V} - 22.2 \text{ V}}{1.1 \text{ k}\Omega} = 1.64 \text{ mA}$$

The required drop across R_6 is the difference in the threshold voltages.

$$V_{R6} = V_{TH(Q1)} - V_{TH(Q2)} = 2.0 \text{ V} - (-2.0 \text{ V}) = 4.0 \text{ V}$$

Use Ohm's law to determine the required setting for R_6 .

$$R_6 = \frac{V_{R6}}{I_{R6}} = \frac{4.0 \text{ V}}{1.64 \text{ mA}} = 2.4 \text{ k}\Omega$$

This setting produces class AB operation, so the output voltage replicates the input of the MOSFET (less a small drop across the internal MOSFET resistance). Determine the gain of the CE amplifier using the ratio of unypassed collector resistance (R_7) to the unypassed emitter resistance (R_5) and r'_e .

$$r'_e = \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{1.64 \text{ mA}} = 15.2 \Omega$$

and

$$A_v = \frac{R_7}{R_5 + r'_e} = \frac{15 \text{ k}\Omega}{100 \Omega + 15.2 \Omega} = 130$$

Assuming no internal drop in the MOSFETs, the output voltage is

$$V_{out} = A_v V_{in} = (130)(100 \text{ mV}) = 13 \text{ V}$$

The power out is

$$P_L = \frac{V_{out}^2}{R_L} = \frac{13 \text{ V}^2}{33 \Omega} = 5.1 \text{ W}$$

Practice Exercise Compute the setting of R_6 if the threshold voltages for the MOSFETs are +1.5 V and -1.5 V.

6 REVIEW QUESTIONS

1. What is the advantage to two-supply operation with a class B complementary symmetry amplifier?
2. What is crossover distortion and how is it avoided?
3. What is the maximum theoretical efficiency for a class B amplifier?
4. Where should an E-MOSFET, operating as a class AB amplifier, be biased?

Heat Sink

As power transistors handle large currents, they always heat up during operation. Since transistor is a temperature dependent device, the heat generated must be dissipated to the surroundings in order to keep the temperature within permissible limits. Generally, the transistor is fixed on a metal sheet (usually aluminium) so that additional heat is transferred to the *Al sheet*. *The metal sheet that serves to dissipate the additional heat from the power transistor is known as **heat sink**.*

Most of the heat within the transistor is produced at the ****collector base junction**.

The heat sink increases the surface area and allows heat to escape from the collector junction easily. The result is that temperature of the transistor is sufficiently lowered. Thus heat sink is a direct practical means of combating the undesirable thermal effects *e.g. **thermal runaway***.

It may be noted that the ability of any heat sink to transfer heat to the surroundings depends upon its *material, volume, area, shape, contact between case and sink and movement of air around the sink*. Finned aluminium heat sinks yield the best heat transfer per unit cost. It should be realised that the use of heat sink alone may not be sufficient to prevent thermal runaway under all conditions. In designing a transistor circuit, consideration should also be given to the choice of *(i) operating point (ii) ambient temperatures which are likely to be encountered and (iii) the type of transistor e.g. metal case transistors are more readily cooled by conduction than plastic ones*. Circuits may also be designed to compensate automatically for temperature changes and thus stabilise the operation of the transistor components.

The permissible power dissipation of the transistor is very important item for power transistors. The permissible power rating of a transistor is calculated from the following relation :

$$P_{total} = \frac{T_{Jmax} - T_{amb}}{\theta}$$

where

P_{total} = total power dissipated within the transistor

T_{Jmax} = maximum junction temperature. It is 90°C for *germanium* transistors and 150°C for *silicon* transistors.

T_{amb} = ambient temperature *i.e.* temperature of surrounding air

θ = *thermal resistance *i.e.* resistance to heat flow from the junction to the surrounding air

The unit of θ is °C/ watt and its value is always given in the transistor manual. A low thermal resistance means that it is easy for heat to flow from the junction to the surrounding air. The larger the transistor case, the lower is the thermal resistance and *vice-versa*. It is then clear that by using heat sink, the value of θ can be decreased considerably, resulting in increased power dissipation.

Example 12.15. A power transistor dissipates 4 W. If $T_{Jmax} = 90^\circ\text{C}$, find the maximum ambient temperature at which it can be operated. Given $\theta = 10^\circ\text{C/W}$.

Solution.

$$P_{total} = 4 \text{ W}$$

$$T_{Jmax} = 90^\circ\text{C}$$

$$\theta = 10^\circ\text{C/W}$$

$$\text{Now } P_{total} = \frac{T_{Jmax} - T_{amb}}{\theta}$$

$$\text{or } 4 = \frac{90 - T_{amb}}{10}$$

$$\therefore \text{ Ambient temperature, } T_{amb} = 90 - 40 = 50^\circ\text{C}$$

The above example shows the effect of ambient temperature on the permissible power dissipation in a transistor. The lower the ambient temperature, the greater is the permissible power dissipation. Thus, a transistor can pass a higher collector current in winter than in summer.