Chapter Nine (2^{nd} Semester)
Power Amplifiers

9.1: Introduction

Power amplifiers are large-signal amplifiers. This generally means that a **much larger portion of the load line** is used during signal operation than in a **small-signal amplifier**.
In this chapter, we will cover **four classes of power amplifiers**: **class A**, **class B**, **class AB**, and **class C**.
These amplifier classifications are **based on the percentage of the input cycle for which the amplifier operates in its linear region**.
Each class has a **unique circuit** configuration because of the way it must be operated.
The emphasis is on power amplification.
Power amplifiers are normally **used as the final stage of a communications receiver** or **transmitter** to **provide signal power** to **speakers** or to a **transmitting antenna**.
BJTs are used to illustrate power amplifier principles.

9.2: Class A Power Amplifier

When an amplifier is biased such that, **the amplifier always operates in the linear region** where the **output signal is an amplified replica of the input signal**, it is a **class A amplifier**.
The discussion of amplifiers in the previous chapters applies to class A operation.
Power amplifiers are those amplifiers that have the **objective of delivering power to a load**.
This means that **components must be considered** in terms of their **ability to dissipate heat**.

After completing this section, you should be able to
❏ Explain and analyze the operation of class A amplifiers
❏ Discuss transistor heat dissipation
❏ Discuss the importance of a centered $Q-point$
❏ Determine power gain
❏ Define dc quiescent power
❏ Discuss and determine output signal power
❏ Define and determine the efficiency of a power amplifier

9.2.1: Operation of Class A amplifiers

In a small-signal amplifier, the *ac* signal **moves** over a **small percentage** of the total *ac* load line.
When the output signal is larger and approaches the limits of the *ac* load line, **the amplifier is a large-signal type**.
Both large-signal and small-signal amplifiers are considered to be **class A** if they operate in the linear region at all times, as illustrated in Figure (9.1).

Class A power amplifiers are large-signal amplifiers with the objective of providing power (rather than voltage) to a load. As a **rule of thumb**, an amplifier may be considered to be a power amplifier **if it is rated for more than 1 W** and **it is necessary to consider the problem of heat dissipation in components**.

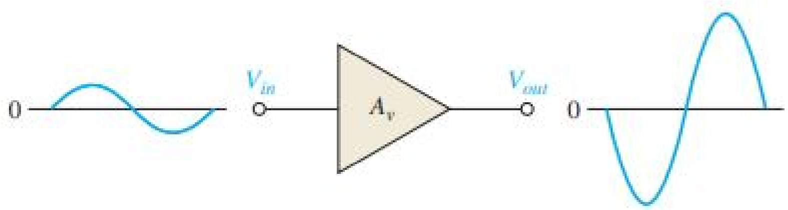


Figure (9.1): Basic class A amplifier operation. Output is shown 180° out of phase with the input (inverted).

9.2.2: Heat Dissipation

Power transistors (and other power devices) must **dissipate a large amount of internally generated heat**.
For BJT power transistors, the **collector terminal is the critical junction**; for this reason, **the transistor's case is always connected to the collector terminal**.
The case of **all power transistors is** designed to **provide a large contact area between it and an external heat sink**.
Heat from the transistor flows through the case to the heat sink and then dissipates in the surrounding air.
Heat sinks vary in **size**, **number of fins**, and **type of material**.
Their **size** depends on the **heat dissipation requirement** and the **maximum ambient temperature** in which the transistor is to operate.
In high-power applications (**a few hundred watts**), a **cooling fan may be necessary**.

9.2.3: Centered $Q - Point$

Recall that **the dc and ac load lines intersect at the $Q - point$**.
When the $Q - point$ is **at the center** of the ac load line, a **maximum class A signal** can be obtained.

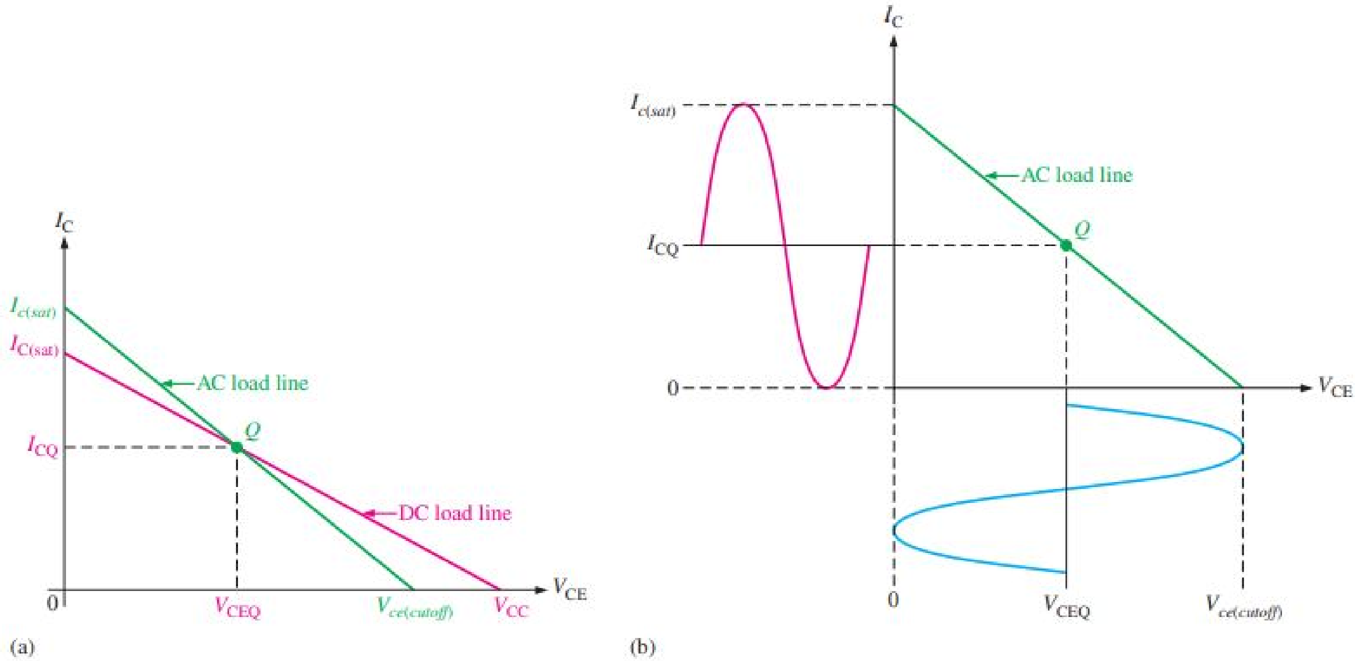


Figure (9.2): Maximum class A output occurs when the $Q - point$ is centered on the ac load line.

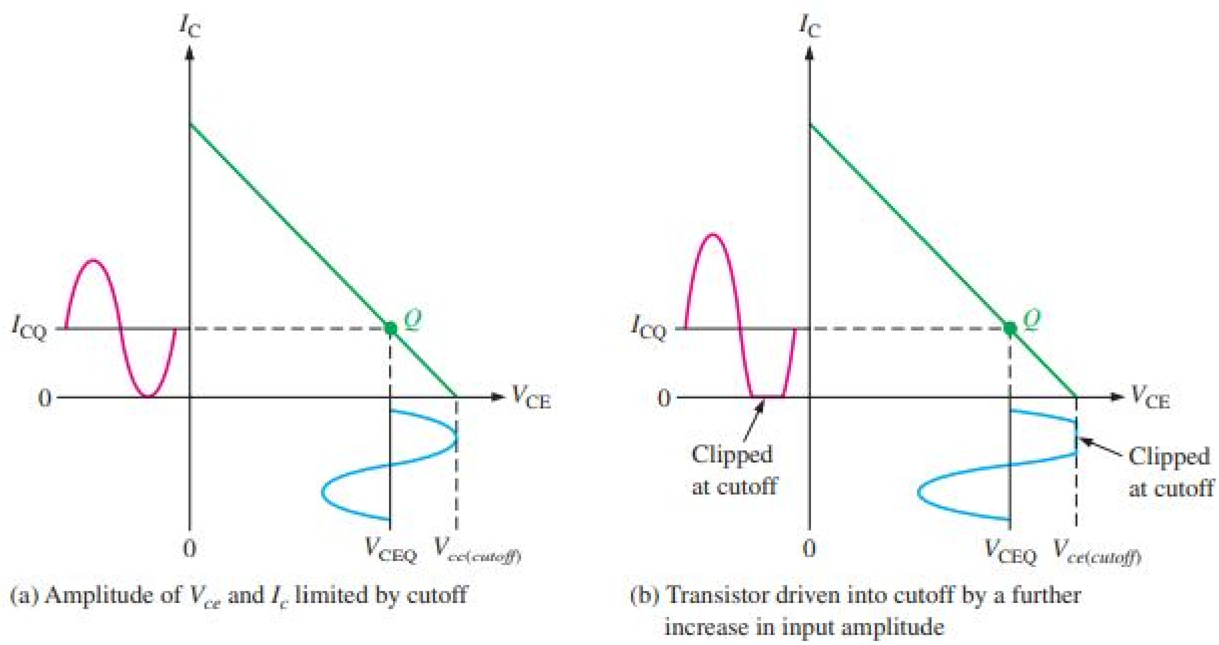
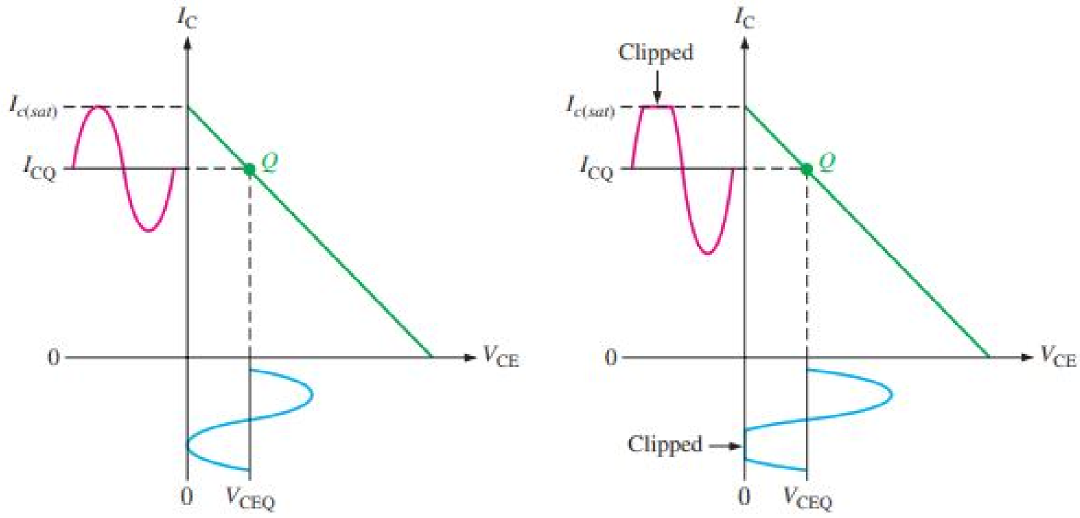


Figure (9.3): $Q - point$ closer to cutoff.



(a) Amplitude of V_{ce} and I_c limited by saturation
(b) Transistor driven into saturation by a further increase in input amplitude

Figure (9.4): $Q - point$ closer to saturation.

9.2.4: Power Gain

A power amplifier delivers power to a load. The **power gain** of an amplifier **is the ratio of the output power (power delivered to the load) to the input power**.
In general, power gain is:

$$A_p = \frac{P_L}{P_{in}} \quad \dots (1)$$

where A_p is the power gain, P_L is signal power delivered to the load, and P_{in} is signal power delivered to the amplifier.
The power gain can be computed by any of **several formulas**, depending on what is known.

For ac power, the voltage is expressed as rms. The **output power delivered to the load** is:

$$P_L = \frac{{V_L}^2}{R_L}$$

The **input power delivered to the amplifier** is:

$$P_{in} = \frac{{V_{in}}^2}{R_{in}}$$

By substituting into Equation (1), the following useful relationship is produced:

$$A_p = \frac{P_L}{P_{in}} = \frac{{V_L}^2}{{V_{in}}^2}\left(\frac{R_{in}}{R_L}\right) = \left(\frac{V_L}{V_{in}}\right)^2\left(\frac{R_{in}}{R_L}\right) = {A_v}^2\left(\frac{R_{in}}{R_L}\right) \dots (2) \quad since\ A_v = \frac{V_L}{V_{in}}$$

Equation (2) shows that the power gain of an amplifier is the voltage gain squared times the ratio of the input resistance to the output load resistance.
The formula can be applied to any amplifier.

Recall from Chapter 7 that for a voltage-divider biased amplifier,

$$R_{in\,(tot)} = R_1 \parallel R_2 \parallel R_{in\,(base)}$$

and that for a CE or CC amplifier,

$$R_{in\,(base)} = \beta_{ac}\, R_e$$

For example, assume a common-collector (CC) amplifier has an input resistance of $5K\Omega$ and a load resistance of 100Ω. Since a CC amplifier has a voltage gain of approximately 1, the power gain is:

$$A_p = {A_v}^2 \left(\frac{R_{in}}{R_L}\right) = 1^2 \left(\frac{5000}{100}\right) = 50$$

For a CC amplifier, A_p is just the ratio of the input resistance to the output load resistance.

9.2.5: DC Quiescent Power

The **power dissipation of a transistor** with **no signal input** is the product of its $Q-point$ current and voltage is:

$$P_{DC} = I_{CQ}V_{CEQ} \quad \ldots (3)$$

The only way **a class A power amplifier can supply power to a load** is to maintain a **quiescent current** that is **at least as large** as the **peak current requirement for the load current**.

A **signal will not increase the power dissipated by the transistor** but **actually causes less total power to be dissipated**.

The ***dc* quiescent power**, given in Equation (3), is the **maximum power that a class A amplifier** must **handle**. **The transistor's power rating** must **exceed this value**.

9.2.6: Output Signal Power

In general, the **output signal power is the product of the rms load current and the rms load voltage**.

The maximum unclipped ac signal **occurs** when the $Q - point$ is centered on the ac load line.

For a CE amplifier with a centered $Q - point$, the **maximum peak voltage swing** is:

$$V_{c(max)} = I_{CQ}\, R_c$$

The rms value of voltage is: $V_{c(rms)} = \frac{V_{c(max)}}{\sqrt{2}}$.

The **maximum peak current swing** is:

$$I_{c(max)} = \frac{V_{CEQ}}{R_c}$$

The rms value of current is: $I_{c(rms)} = \frac{I_{c(max)}}{\sqrt{2}}$.

The **maximum power out from a class A amplifier** is:

$$P_{out\,(max)} = V_{c(rms)}\, I_{c(rms)} = \frac{V_{c(max)}}{\sqrt{2}} \frac{I_{c(max)}}{\sqrt{2}} = \frac{I_{CQ}\, \cancel{R_c} \cdot \frac{V_{CEQ}}{\cancel{R_c}}}{2} = 0.5\, I_{CQ} V_{CEQ} \; \dots (4)$$

9.2.7: Efficiency

The efficiency of any amplifier **is the ratio of the output signal power supplied to a load to the total power from the dc supply**.

The **maximum output signal power** that can be obtained is given by Equation (4).

The **average power** supply current I_{CC} is equal to I_{CQ} and the supply **voltage is at least $2V_{CEQ}$**. Therefore, the **total dc power** is:

$$P_{DC} = I_{CC}V_{CC} = 2\,I_{CQ}V_{CEQ}$$

The **maximum efficiency η_{max}** of a capacitively coupled class A amplifier is

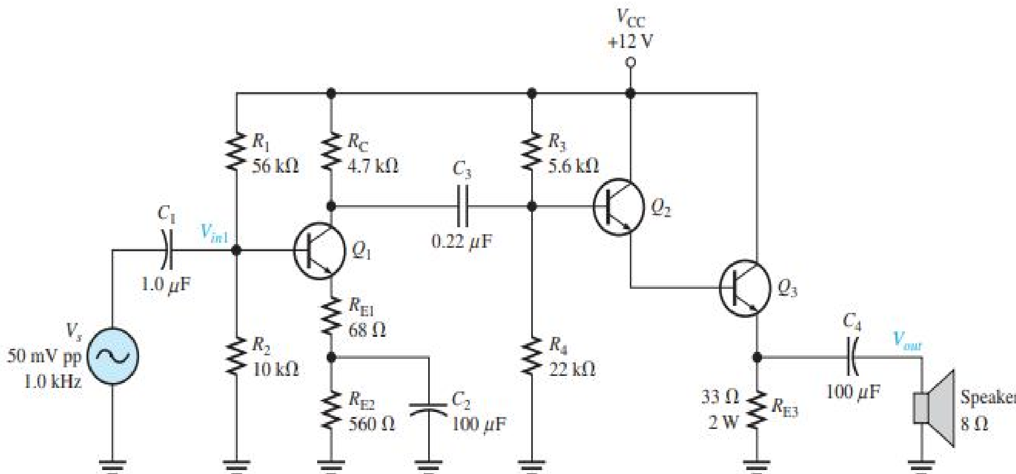
$$\eta_{max} = \frac{P_{out}}{P_{DC}} = \frac{0.5\,I_{CQ}V_{CEQ}}{2\,I_{CQ}V_{CEQ}} = 0.25 = 25\%$$

The **maximum efficiency** of a capacitively coupled class A amplifier **cannot be higher than 0.25, or 25%**, and **in practice**, is usually considerably **less** (**about 10%**).

Although the **efficiency can be made higher** by **transformer coupling** the signal to the load, there are drawbacks to transformer coupling. These drawbacks include the size and cost of transformers as well as potential distortion problems when the transformer core begins to saturate.

In general, the **low efficiency of class A amplifiers** limits their usefulness to **small power applications that require usually less than 1 W**.

Example 1: Determine the voltage gain and the power gain of the class A power amplifier in this figure. Assume $\boldsymbol{\beta_{ac} = 200}$ for all transistors. Determine the efficiency of the power amplifier in this figure.



Solution:

Notice that the first stage (Q_1) is a voltage-divider biased common-emitter with a swamping resistor (R_{E1}). The second stage (Q_2 and Q_3) is a Darlington voltage-follower configuration. The speaker is the load.

First stage: The ac collector resistance of the first stage is R_C in parallel with the input resistance to the second stage.

$$R_{c1} \cong R_C \parallel (R_3 \parallel R_4) = 4.7\,k\Omega \parallel 5.6\,k\Omega \parallel 22\,k\Omega = 2.29\,k\Omega$$

The voltage gain of the first stage is the ac collector resistance, R_{c1}, divided by the ac emitter resistance, which is the sum of $R_{E1} + r'_{e(Q1)}$. The approximate value of $r'_{e(Q1)}$ is determined by first finding I_E.

$$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{10\,k\Omega}{66\,k\Omega}\right)12\,V = 1.82\,V$$

$$I_E = \frac{V_B - 0.7\,V}{R_{E1} + R_{E2}} = \frac{1.82\,V - 0.7\,V}{628\,\Omega} = 1.78\,mA$$

$$r'_{e(Q1)} = \frac{25\,mV}{I_E} = \frac{25\,mV}{1.78\,mA} = 14\,\Omega$$

Using the value of r'_e, determine the voltage gain of the first stage with the loading of the second stage taken into account.

$$A_{v1} = -\frac{R_{c1}}{R_{E1} + r'_{e(Q1)}} = -\frac{2.29\,k\Omega}{68\,\Omega + 14\,\Omega} = -27.9$$

The negative sign is for inversion.

The total input resistance of the first stage is equal to the bias resistors in parallel with the ac input resistance at the base of Q_1.

$$R_{in(tot)1} = R_1 \parallel R_2 \parallel \beta_{ac(Q1)}(R_{E1} + r'_{e(Q1)})$$
$$= 56\,k\Omega \parallel 10\,k\Omega \parallel 200(68\,\Omega + 14\,\Omega) = 8.4\,k\Omega$$

Second stage: The voltage gain of the darlington emitter-follower is approximately equal to 1.

$$A_{v2} \cong 1$$

Overall amplifier: The overall voltage gain is the product of the first and second stage voltage gains. Since the second stage has a gain of approximately 1, the overall gain is approximately equal to the gain of the first stage.

$$A_{v(tot)} = A_{v1}A_{v2} = (-27.9)(1) = -27.9$$

Power gain: The power gain of the amplifier can be calculated using Equation 2.

$$A_p = A_{v(tot)}^2\left(\frac{R_{in(tot)1}}{R_L}\right) = (-27.9)^2\left(\frac{8.4\ \text{k}\Omega}{8\ \Omega}\right) = \mathbf{817{,}330}$$

The efficiency is the ratio of the signal power in the load to the power supplied by the dc source. The input voltage is 50 mV peak-to-peak which is 35.4 mV rms. The input power is, therefore,

$$P_{in} = \frac{V_{in}^2}{R_{in}} = \frac{(35.4\ \text{mV})^2}{8.4\ \text{k}\Omega} = 149\ \text{nW}$$

The output power is

$$P_{out} = P_{in}A_p = (149\ \text{nW})(817{,}330) = 122\ \text{mW}$$

Most of the power from the dc source is supplied to the output stage. The current in the output stage can be computed from the dc emitter voltage of Q_3.

$$V_{E(Q3)} \cong \left(\frac{22\ \text{k}\Omega}{27.6\ \text{k}\Omega}\right)12\ \text{V} - 1.4\ \text{V} = 8.2\ \text{V}$$

$$I_{E(Q3)} = \frac{V_{E(Q3)}}{R_E} = \frac{8.2\ \text{V}}{33\ \Omega} = 0.25\ \text{A}$$

Neglecting the other transistor and bias currents, which are very small, the total dc supply current is about 0.25 A. The power from the dc source is

$$P_{DC} = I_{CC}V_{CC} = (0.25\ \text{A})(12\ \text{V}) = 3\ \text{W}$$

Therefore, the efficiency of the amplifier for this input is

$$\eta = \frac{P_{out}}{P_{DC}} = \frac{122\ \text{mW}}{3\ \text{W}} \cong \mathbf{0.04}$$

This represents an efficiency of 4% and illustrates why class A is not a good choice for a power amplifier.

9.3: Class B and Class AB Push-Pill Power Amplifiers

When an **amplifier is biased at cutoff** so that **it operates in the linear region for 180° of the input cycle** and is in cutoff for it is a **class B amplifier**.
Class AB amplifiers are biased to conduct for **slightly more than 180°**.
The primary **advantage** of a class B or class AB amplifier over a class A amplifier is that **either one is more efficient than a class A amplifier**; you can **get more output power** *for a given amount of* **input power**.
A **disadvantage** of class B or class AB is that it is **more difficult to implement (apply) the circuit** in order to *get a linear reproduction of the input waveform*.
The term **push-pull refers to a common type of class B or class AB amplifier** circuit **in which two transistors** are **used on alternating half-cycles** *to reproduce the input waveform at the output*.

After completing this section, you should be able to:

❑ Explain and analyze the operation of class B and class AB amplifiers

❑ Describe class B operation
- ◆ Discuss $Q-point$ location

❑ Describe class B push-pull operation

❑ Bias a push-pull amplifier for class AB operation
- ◆ Define class AB
- ◆ Explain class AB ac signal operation

❑ Describe a single-supply push-pull amplifier

❑ Discuss class B/AB power
- ◆ Calculate maximum output power
- ◆ Calculate dc input power
- ◆ Determine efficiency

❑ Determine the ac input resistance of a push-pull amplifier

9.3.1: Class B Operation

The class B operation is illustrated in Figure (9.5), where the output waveform is shown relative to the input in terms of time (t).

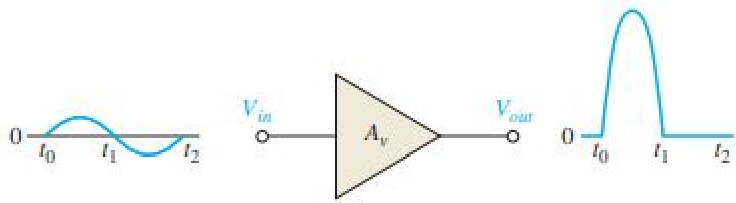


Figure (9.5): Basic class B amplifier operation (noninverting).

The $Q - Point$ is at Cutoff:

The **class B amplifier is biased at the cutoff point** so that: $I_{CQ} = 0$ and $V_{CEQ} = V_{CE(cutoff)}$.
It is brought out of cutoff and operates in its linear region when the input signal drives the transistor into conduction. This is illustrated in Figure (9.6) with an emitter-follower circuit where the output is not a replica of the input.

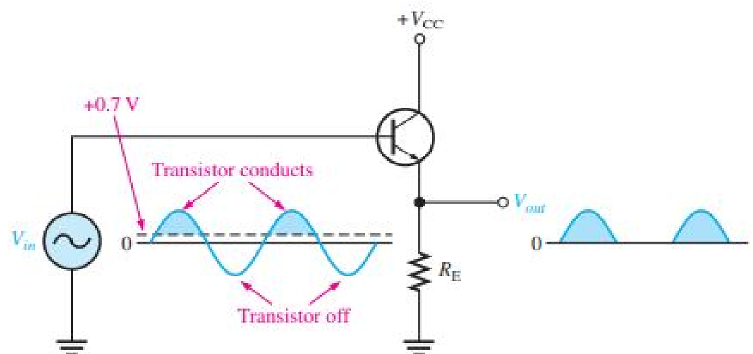


Figure (9.6): Common-collector class B amplifier.

9.3.2: Class B Push-Pull Operation

As you can see, the circuit in Figure (9.6) **only conducts** <u>for</u> **the positive half of the cycle**. *To amplify the entire cycle*, it is <u>necessary to **add**</u> **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** <u>to</u> *reproduce the entire waveform*. The **first** approach uses **transformer coupling**. The **second** uses **two complementary symmetry transistors**; these are a matching **pair of *npn*/*pnp* BJTs**.

9.3.3: 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**; this results in a modified form of operation called **class AB**.

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 in Figure (9.7).

When the diode characteristics of D_1 and D_2 are closely matched to the characteristics of the transistor base-emitter junctions, **the current in the diodes and the current in the transistors are the same**; this is called a **current mirror**.

This **current mirror** produces the desired **class AB operation** and **eliminates** crossover distortion.

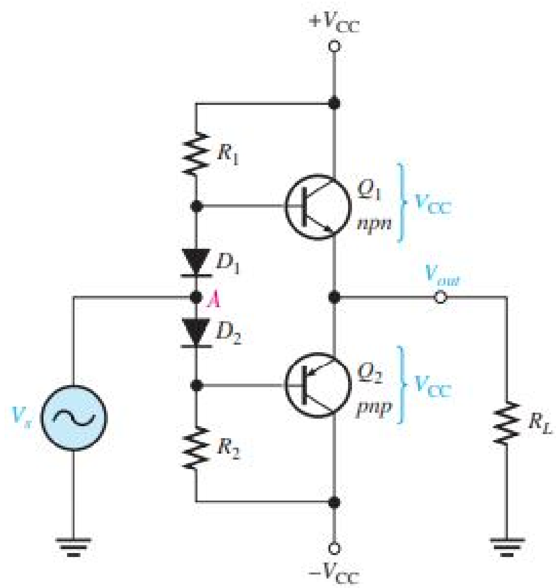


Figure (9.7): Biasing the push-pull amplifier with current-mirror diode bias to eliminate crossover distortion. The transistors form a complementary pair (one *npn* and one *pnp*).

In the bias path of the circuit in Figure (9.7), R_1 **and** R_2 **are of equal value**, as **are the positive and negative supply voltages**. This forces the **voltage at point A** (between the diodes) to equal **0 V** and **eliminates** the need for an **input coupling capacitor**. The ***dc* voltage on the output is also 0 V**. Assuming that **both diodes** and **both complementary transistors** are **identical**, the *drop across* D_1 *equals the* V_{BE} *of* Q_1, and the *drop across* D_2 *equal the* V_{BE} *of* Q_2. Since they are **matched**, the **diode current** will be the **same as I_{CQ}**. The **diode current and I_{CQ}** can be found by applying Ohm's law to either R_1 or R_2 as follows:

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

This **small current required of class AB operation** eliminates the crossover distortion **but** has the potential for **thermal instability** ***if* the transistor's V_{BE} drops are not matched to the diode drops** or ***if* the diodes are not in thermal equilibrium with the transistors**.

Heat in the power transistors **decreases** **the base-emitter voltage** and tends to **increase current**. ***If*** the **diodes are warmed the same amount**, the **current is stabilized**; ***but if*** the **diodes are in a cooler environment, they cause I_{CQ} to increase even more**.

More heat is produced in an unrestrained cycle known as thermal runaway. To keep this from happening, the **diodes should have the same thermal environment as the transistors**.

In some cases, a **small resistor in the emitter of each transistor** **can** **alleviate (decrease) thermal runaway**.

AC Operation:

Consider the ac load line for Q_1 of the class AB amplifier in Figure (9.7). The $\boldsymbol{Q-point}$ **is slightly above cutoff**. (*In a true class B amplifier, the $Q - point$ is at cutoff.*)

The ac cutoff voltage for a two-supply operation is at V_{CC} with an I_{CQ} as given earlier.

The ***ac* saturation current for a two-supply operation with a push-pull amplifier is**:

$$\boldsymbol{I_{C(sat)} = \frac{V_{CC}}{R_L}} \quad \dots (5)$$

The ac load line for the npn transistor is as shown in Figure (9.8). The ***dc* load line** can be found by **drawing a line** that passes through $\boldsymbol{V_{CEQ}}$ and the ***dc* saturation current $\boldsymbol{I_{C(sat)}}$**.

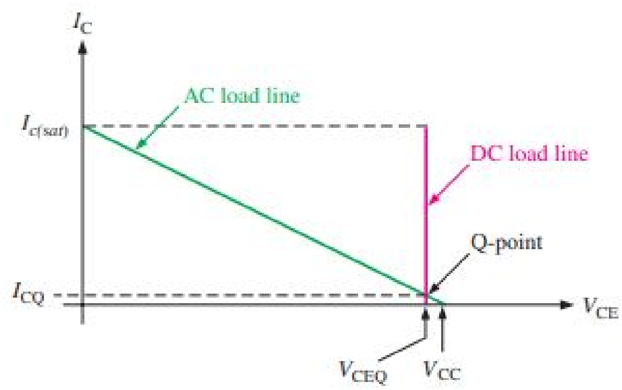
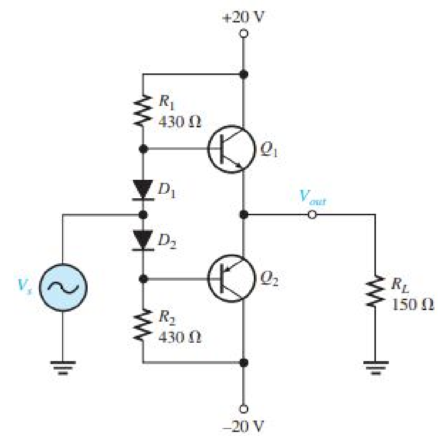


Figure (9.8): Load lines for a complementary symmetry push-pull amplifier. Only the load lines for the $\boldsymbol{npn}$ transistor are shown.

However, the saturation current for dc is the current **if the collector to emitter is shorted on both transistors**! This assumed short across the power supplies obviously would **cause maximum current** *from* the supplies and implies the dc load line passes **almost vertically** through the cutoff as shown. **Operation along the *dc* load line, such as caused by thermal runaway, could produce such a high current that the transistors are destroyed**.

Example 2: Determine the ideal maximum peak output voltage and current for the circuit shown in this figure.



Solution:

The ideal maximum peak output voltage is:

$$V_{out(peak)} \cong V_{CEQ} \cong V_{CC} = \mathbf{20\ V}$$

The ideal maximum peak current is:

$$I_{out(peak)} \cong I_{c(sat)} \cong \frac{V_{CC}}{R_L} = \frac{20\text{ V}}{150\ \Omega} = \mathbf{133\ mA}$$

The actual maximum values of voltage and current are slightly smaller.

9.3.4: Single-Supply Push-Pull Amplifier

Push-pull amplifiers using complementary **symmetry transistors** can be **operated from a single voltage source** as shown in Figure (9.9). The circuit operation is the same as that described previously, **except the bias is set** to force the **output emitter voltage to be** $\frac{V_{CC}}{2}$ **instead of zero volts** used with two supplies. Because the **output is not biased at** zero volts, **capacitive coupling** for the **input and output** is **necessary** *to block the bias voltage from the source and the load resistor*. **Ideally**, the **output voltage can swing from zero to V_{CC}**, ***but in practice***, **it does not quite reach these ideal values**.

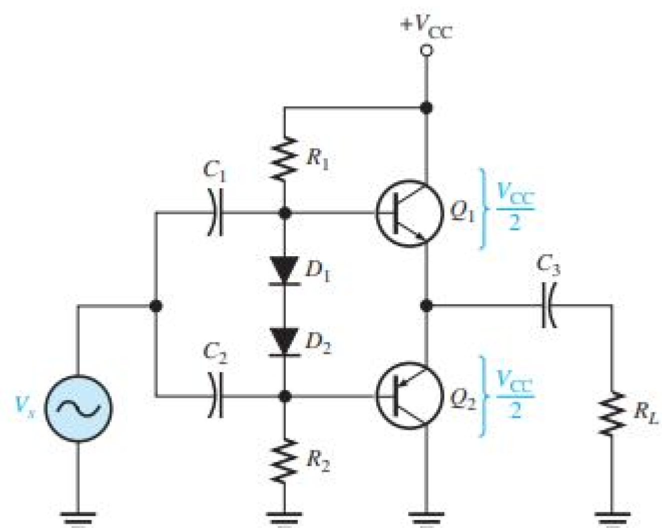
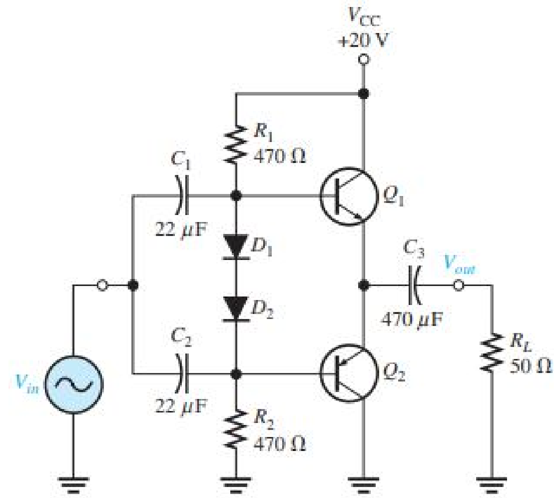


Figure (9.9): Single-ended push-pull amplifier.



Example 3: Determine the maximum ideal peak values for the output voltage and current in this figure.

Solution:

The maximum peak output voltage is:

$$V_{out(peak)} \cong V_{CEQ} = \frac{V_{CC}}{2} = \frac{20\text{ V}}{2} = \mathbf{10\text{ V}}$$

The maximum peak output current is:

$$I_{out(peak)} \cong I_{c(sat)} = \frac{V_{CEQ}}{R_L} = \frac{10\text{ V}}{50\ \Omega} = \mathbf{200\text{ mA}}$$

9.3.5: Class B/AB Power

Maximum Output Power:

You have seen that the ideal maximum peak output current for both dual-supply and single-supply push-pull amplifiers is approximately $I_{c(sat)}$, and the maximum peak output voltage is approximately V_{CEQ}. Ideally, **the maximum average output power** is, therefore,

$$\boldsymbol{P_{out} = I_{out(rms)}\, V_{out(rms)}}$$

Since

$$I_{out(rms)} = 0.7071\, I_{out(peak)} = 0.7071\, I_{c(sat)}$$

and

$$V_{out(rms)} = 0.7071\, V_{out(peak)} = 0.7071\, V_{CEQ}$$

then

$$P_{out} = 0.5\, I_{c(sat)}\, V_{CEQ}$$

Substituting $V_{CC}/2$ for V_{CEQ}, the maximum average output power is:

$$\boldsymbol{P_{out} = 0.25\, I_{c(sat)}\, V_{CC}} \quad \dots \mathbf{(6)}$$

DC Input Power:

The ***dc* input power** comes from the V_{CC} supply and is:

$$P_{DC} = I_{CC}\, V_{CC}$$

Since each transistor draws current for a half-cycle, the current is a half-wave signal with an average value of

$$I_{CC} = \frac{I_{c(sat)}}{\pi}$$

So,

$$P_{DC} = \frac{I_{c(sat)}V_{CC}}{\pi} \quad \dots (7)$$

Efficiency:

An advantage of push-pull class B and class AB amplifiers over class A is a much higher efficiency. This advantage usually overrides the difficulty of biasing the class AB push-pull amplifier to eliminate crossover distortion. Recall that **efficiency**, η is defined as the ratio of ac output power to dc input power:

$$\eta = \frac{P_{out}}{P_{DC}}$$

The **maximum efficiency**, for a class B amplifier (class AB is slightly less) is developed as follows, starting with Equation 6.

$$\eta_{max} = \frac{0.25\, I_{c(sat)}\, V_{CC}}{\frac{I_{c(sat)}V_{CC}}{\pi}} = 0.25\,\pi = 0.79 = 79\%$$

Recall that the maximum efficiency for class A is 0.25 (25 percent).

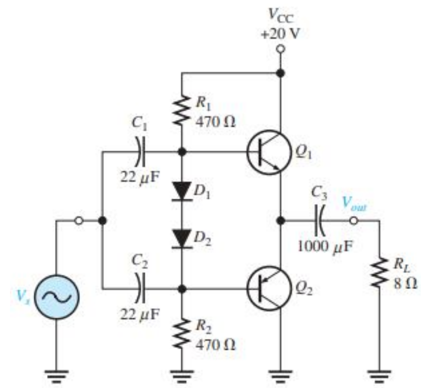
Input Resistance:

The complementary push-pull configuration used in class B/class AB amplifiers is, in effect, two emitter-followers. The **input resistance for the emitter-follower**, where R_1 and R_2 are the bias resistors, is:

$$R_{in} = \beta_{ac}(r'_e + R_E) \parallel R_1 \parallel R_2$$

Since $R_E = R_L$, the formula is:

$$R_{in} = \beta_{ac}(r'_e + R_L) \parallel R_1 \parallel R_2 \quad \dots (8)$$



Example 4: Find the maximum *ac* output power and the *dc* input power of the amplifier in this figure.

Solution:

The ideal maximum peak output voltage is

$$V_{out(peak)} \cong V_{CEQ} = \frac{V_{CC}}{2} = \frac{20\text{ V}}{2} = 10\text{ V}$$

The maximum peak output current is

$$I_{out(peak)} \cong I_{c(sat)} = \frac{V_{CEQ}}{R_L} = \frac{10\text{ V}}{8\ \Omega} = 1.25\text{ A}$$

The ac output power and the dc input power are

$$P_{out} = 0.25 I_{c(sat)} V_{CC} = 0.25(1.25\text{ A})(20\text{ V}) = \mathbf{6.25\ W}$$

$$P_{DC} = \frac{I_{c(sat)} V_{CC}}{\pi} = \frac{(1.25\text{ A})(20\text{ V})}{\pi} = \mathbf{7.96\ W}$$

H.W: Q1: Determine the maximum *ac* output power and the *dc* input power in above figure for $V_{CC} = 15\ V$ and $R_L = 16\ \Omega$.

Solution:

Example 5: Assume that a preamplifier stage with an output signal voltage of 3 V rms and an output resistance of 50 Ω is driving the push-pull power amplifier in above figure (Example 4). Q_1 and Q_2 in the power amplifier have a β_{ac} of 100 and an r'_e of 1.6 Ω. Determine the loading effect that the power amplifier has on the preamp stage.

Solution:

The *ac* input resistance of the power amplifier is:

$$R_{in} = \beta_{ac}(r'_e + R_L) \parallel R_1 \parallel R_2 = 100(9.6\ \Omega) \parallel 470\ \Omega \parallel 470\ \Omega = 188\ \Omega$$

Obviously, this will have an effect on the preamp driver stage. The output resistance of the preamp stage and the input resistance of the power amp effectively form a voltage divider that reduces the output signal from the preamp. The actual signal at the power amp is:

$$V_{in} = \left(\frac{R_{in}}{R_s + R_{in}}\right)V_s = \left(\frac{188\ \Omega}{238\ \Omega}\right)3\text{ V} = 2.37\text{ V}$$

9.4: 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 or push-pull class B and class AB, which means that **more output power** can be obtained from class C operation.
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 circuits, such as oscillators, that have a constant output amplitude, and modulators, where a high-frequency signal is controlled by a low-frequency signal.

After completing this section, you should be able to:

- ❑ Explain and analyze the operation of class C amplifiers
- ❑ Describe basic class C operation
    - ◆ Discuss the bias of the transistor
- ❑ Discuss class C power dissipation
- ❑ Explain tuned operation
- ❑ Determine maximum output power
- ❑ Explain clamper bias for a class C amplifier

9.4.1: Basic Class C Operation

The basic concept of class C operation is illustrated in Figure (9.10). A common-emitter class C amplifier with a resistive load is shown in Figure (9.11a). 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. It is biased below cutoff with the negative V_{BB} supply.

The ***ac*** **source voltage** has **a peak value** that is **slightly greater than** so that the **base voltage** exceeds the barrier potential of the base-emitter junction for a short time near the positive peak of each cycle, as illustrated in Figure (9.11b).

During this short interval, the **transistor is turned on**. When the entire ***ac*** **load line is used**, as shown in Figure (9.11c), the **ideal maximum collector current is $I_{c(sat)}$**, and the **ideal minimum collector voltage is $V_{ce(sat)}$**.

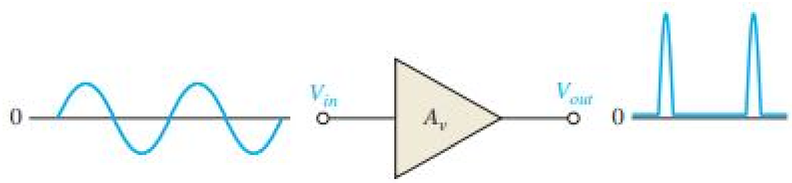


Figure (9.10): Basic class C amplifier operation (noninverting).

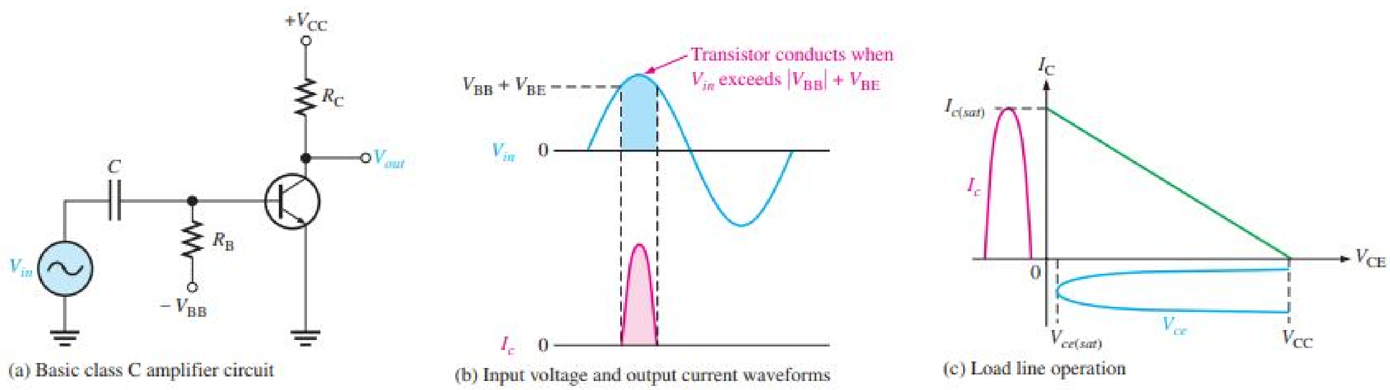


Figure (9.11): Basic class C operation.

9.4.2: Power Dissipation

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**. Figure (9.12a) shows the collector current pulses.

The **time** between the pulses is the period (T) of the *ac* input voltage. The collector current and the collector voltage during the on **time** of the transistor are shown in Figure (9.12b).

To avoid complex mathematics, we will assume ideal pulse approximations. Using this simplification, if the output swings over the entire load, the **maximum current amplitude is**

$I_{c(sat)}$ and the **minimum voltage amplitude is $V_{ce(sat)}$** during the time the **transistor is on**. **The power dissipation during the on time is**, therefore,

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

The transistor is on for a short time, ton, and off for the rest of the input cycle. Therefore, assuming the entire load line is used, **the power dissipation averaged over the entire cycle is**:

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

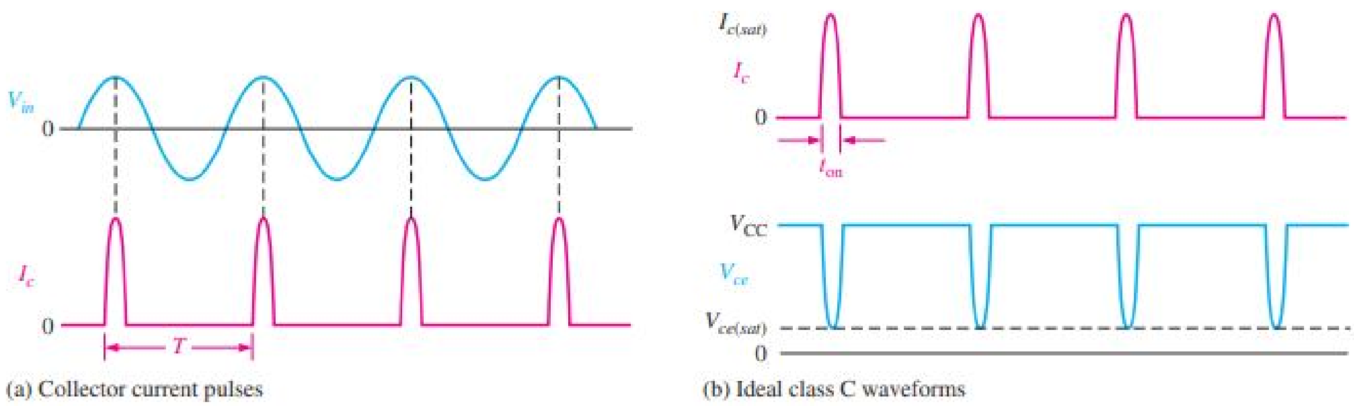


Figure (9.12): Class C waveforms.

Example 5: A class C amplifier is driven by a 200 kHz signal. The transistor is on for 1 µs and the ms, amplifier is operating over 100 percent of its load line. If $I_{c(sat)} = 100\ mA$ and $V_{ce(sat)} = 0.2\ V$, what is the average power dissipation of the transistor?

Solution:

The period is:

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

Therefore,

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

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.

H.W: Q2: 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?

Solution:

9.4.3: Tuned 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 in Figure (9.13a).

The **resonant frequency** of the tank circuit is **determined** by the formula $f_r = \frac{1}{2\pi\sqrt{LC}}$.

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, as illustrated in Figure (9.13b). The **tank circuit has high impedance only near the resonant frequency**, so the **gain is large only at this frequency**.

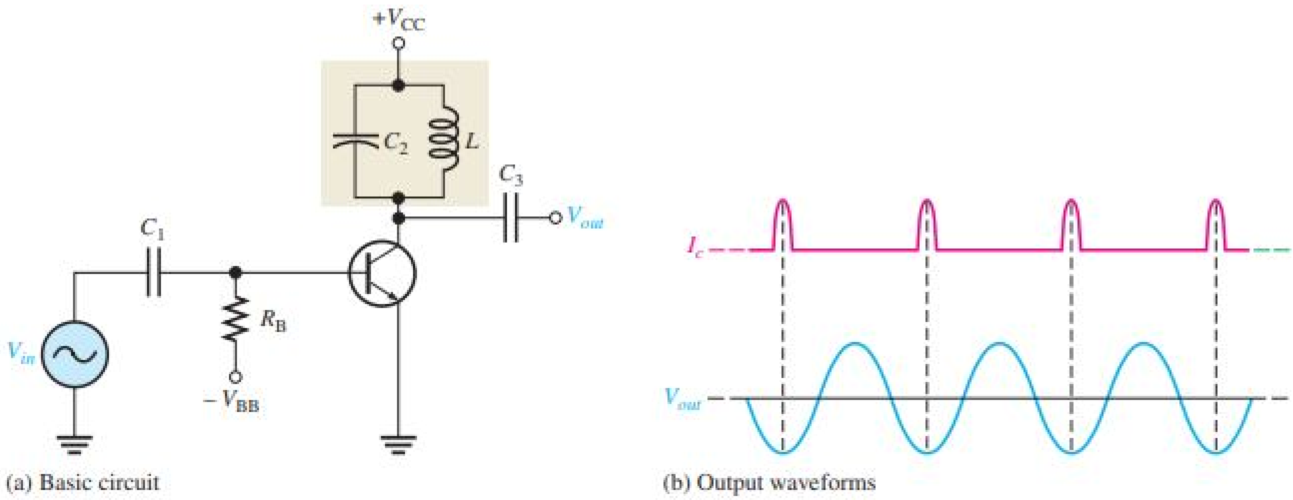


Figure (9.13): Tuned class C amplifier.

The current pulse charges the capacitor to approximately $+V_{CC}$, as shown in Figure (9.14a). After the pulse, the capacitor quickly discharges, thus charging the inductor. Then, after the capacitor completely discharges, the inductor's magnetic field collapses and then quickly recharges C to near V_{CC} in a direction opposite to the previous charge. This completes one half-cycle of the oscillation, as shown in parts (b) and (c) of Figure (9.14). Next, the capacitor discharges again, increasing the inductor's magnetic field. The inductor then quickly recharges the capacitor back to a positive peak slightly less than the previous one, due to energy loss in the winding resistance. This completes one full cycle, as shown in parts (d) and (e) of Figure (9.14).

The **peak-to-peak output voltage** is therefore approximately equal to $2V_{CC}$.

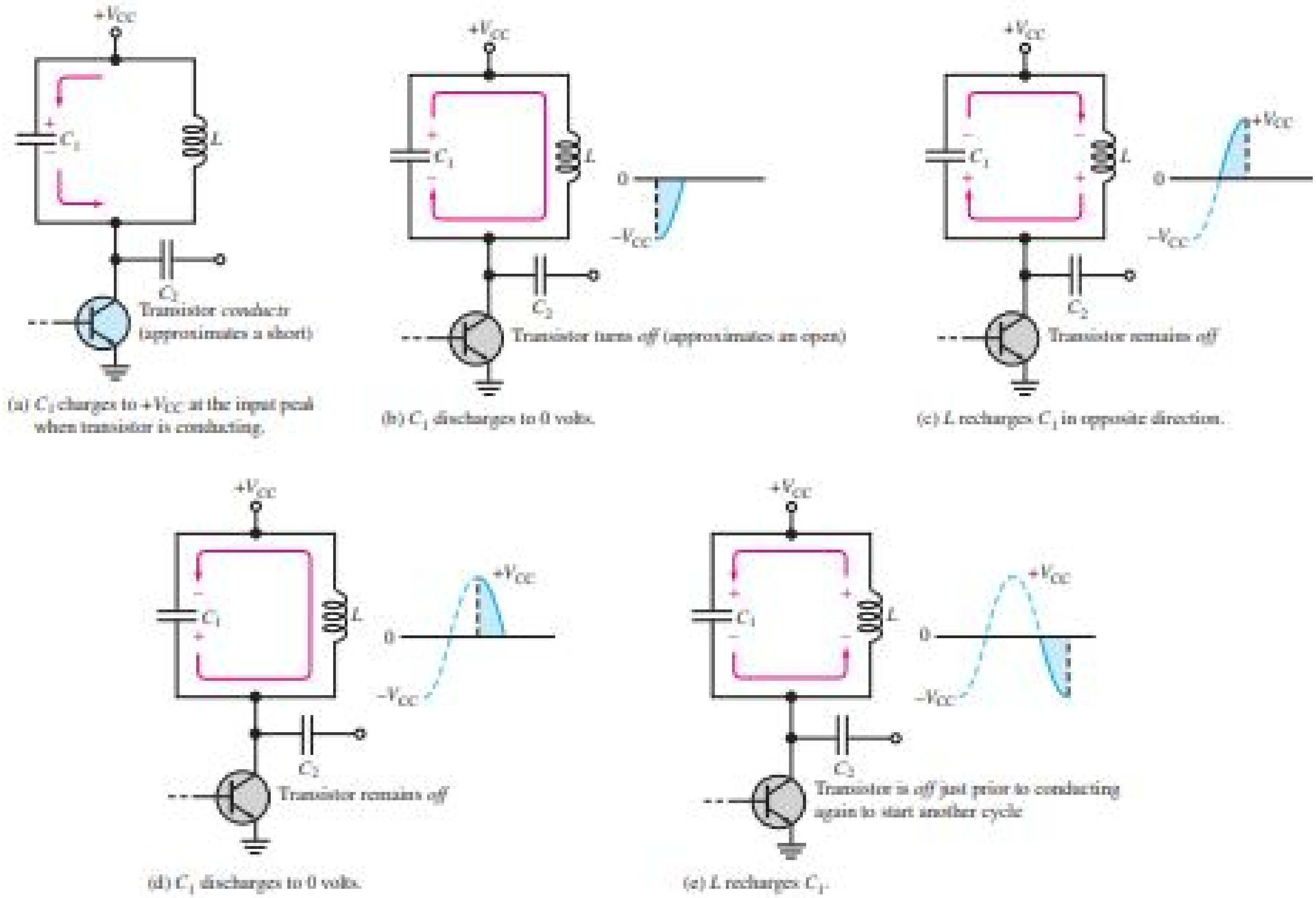
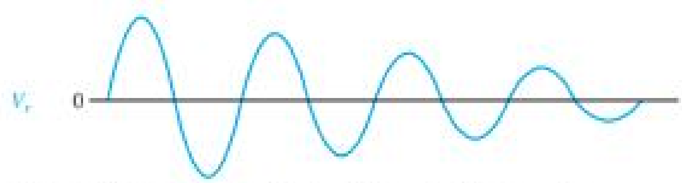


Figure (9.14): Resonant circuit action.

The amplitude of each successive cycle of the oscillation will be less than that of the previous cycle because of energy loss in the resistance of the tank circuit, as shown in Figure (9.15a), and the oscillation will eventually die out. However, the regular recurrences of the collector current pulse re-energize the resonant circuit and sustains the oscillations at a constant amplitude. When the tank circuit is tuned to the frequency of the input signal (fundamental), reenergizing occurs on each cycle of the tank voltage $\boldsymbol{V_r}$, as shown in Figure (9.15b). When the tank circuit is tuned to the second harmonic of the input signal, re-energizing occurs on alternate cycles as shown in Figure (9.15c). In this case, a class C amplifier operates as a frequency multiplier ($\times 2$). By tuning the resonant tank circuit to higher harmonics, further frequency multiplication factors are achieved.



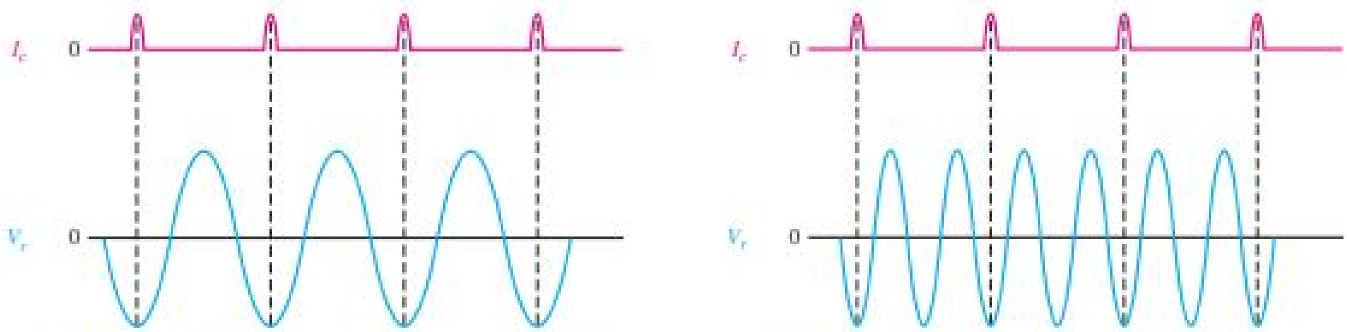


Figure (9.15): Tank circuit oscillations. V_r is the voltage across the tank circuit.

9.4.4: 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:

$$P_{out} = \frac{V^2{}_{rms}}{R_c} = \frac{(0.707V_{CC})^2}{R_c} \rightarrow P_{out} = \frac{0.5\,V^2{}_{CC}}{R_c} \quad \dots (9)$$

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**:

$$\eta = \frac{P_{out}}{P_{out} + P_{D(avg)}} \quad \dots (10)$$

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

Example 6: Suppose the class C amplifier described in **Example (5)** has a V_{CC} equal to 24 V and the R_c is 100Ω. Determine the efficiency.

Solution:

From Example **5**, $P_{D(avg)} = 4\text{ mW}$.

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

Therefore,

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

or, as a percentage, 99.9%.

9.4.5: Clamper Bias for a Class C Amplifier

Figure (9.16) shows a class C amplifier with a base bias clamping circuit. The base-emitter junction functions as a diode.

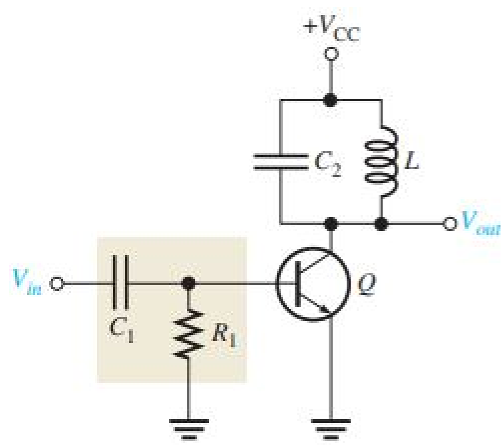


Figure (9.16): Tuned class C amplifier with clamper bias.

When the input signal goes positive, capacitor C_1 is charged to the peak value with the polarity shown in Figure (9.17a). This action produces an average voltage at the base of approximately $-V_p$. This places the transistor in cutoff except at the positive peaks, when the transistor conducts for a short interval. For good clamping action, the R_1C_1 time constant of the clamping circuit must be much greater than the period of the input signal. Parts (b) through (f) of Figure (9.17) illustrate the bias clamping action in more detail. During the time up to the positive peak of the input (t_0 to t_1), the capacitor charges to $V_p - 0.7\ V$ through the base-emitter diode, as shown in part (b). During the time from t_1 to t_2, as shown in part (c), the capacitor discharges very little because of the large RC time constant. The capacitor, therefore, maintains an average charge slightly less than $V_p - 0.7\,V$.

Since the dc value of the input signal is zero (positive side of C_1), the dc voltage at the base (negative side of C_1) is slightly more positive than $-(V_p - 0.7\,V)$, as indicated in Figure (9.17d). As shown in Figure (9.17e), the capacitor couples the ac input signal through to the base so that the voltage at the transistor's base is the ac signal riding on a dc level slightly more positive than $-(V_p - 0.7\,V)$. Near the positive peaks of the input voltage, the base voltage goes slightly above $0.7\,V$ and causes the transistor to conduct for a short time, as shown in Figure (9.17f).

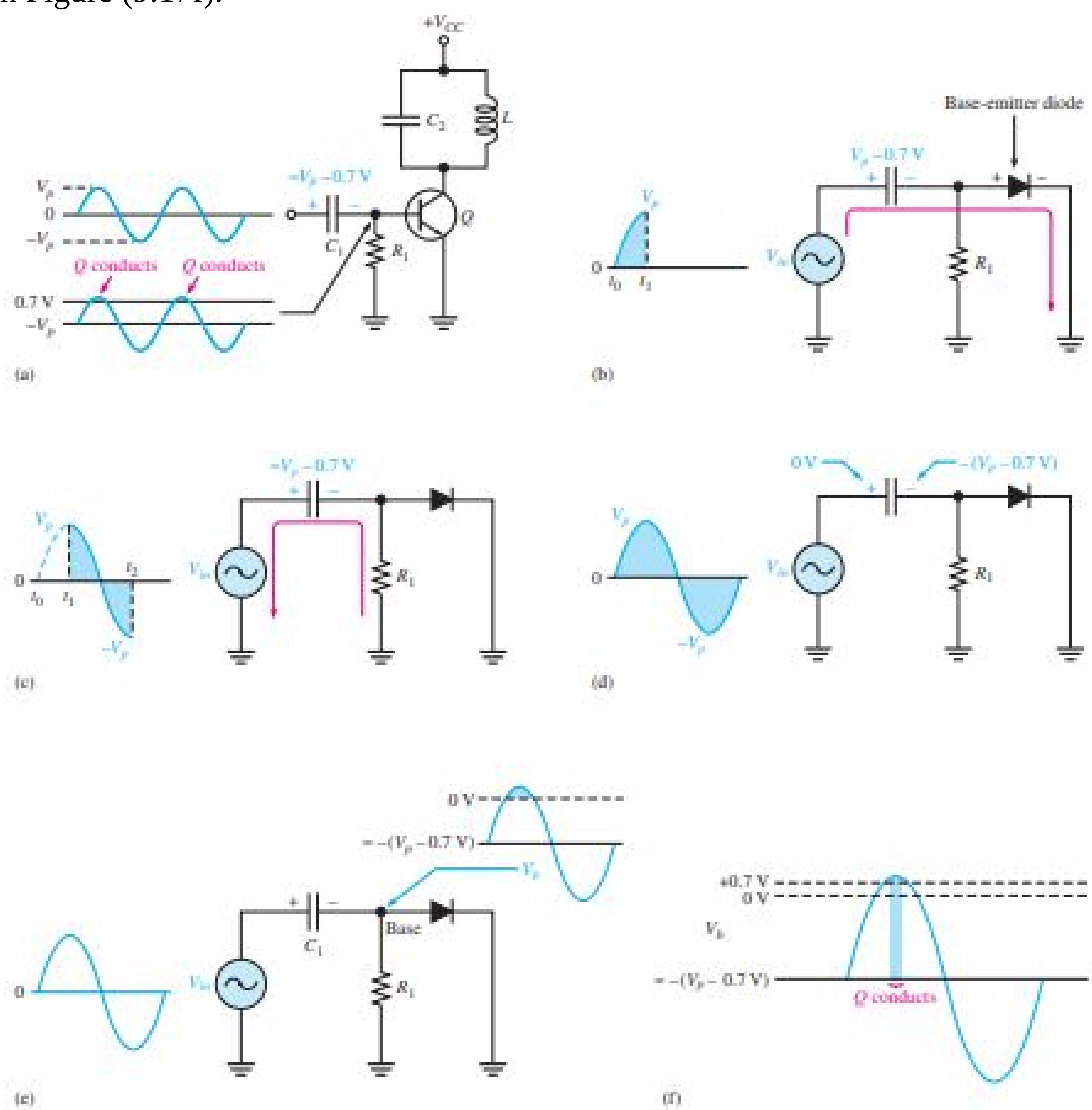
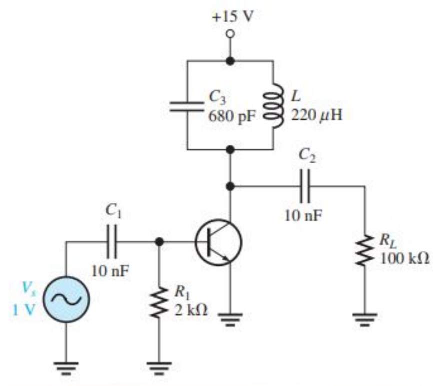


Figure (9.17): Clamper bias action.

Example 6: Determine the voltage at the base of the transistor, the resonant frequency, and the peak-to-peak value of the output signal voltage for the class C amplifier in this figure.



Solution:

$$V_{s(p)} = (1.414)(1\text{ V}) \cong 1.4\text{ V}$$

The base is clamped at

$$-(V_{s(p)} - 0.7) = \mathbf{-0.7\ V\ dc}$$

The signal at the base has a positive peak of +0.7 V and a negative peak of

$$-V_{s(p)} + (-0.7\text{ V}) = -1.4\text{ V} - 0.7\text{ V} = \mathbf{-2.1\ V}$$

The resonant frequency is

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

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

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

KEY TERMS:

Class A: A type of amplifier that operates entirely in its linear (active) region.
Class AB: A type of amplifier that is biased into slight conduction.
Class B: A type of amplifier that operates in the linear region for of the input cycle because it is biased at cutoff.
Class C: A type of amplifier that operates only for a small portion of the input cycle.
Efficiency: The ratio of the signal power delivered to a load to the power from the power supply of an amplifier.
Power gain: The ratio of output power to input power of an amplifier.
Push-Pull: A type of class B amplifier with two transistors in which one transistor conducts for one half-cycle and the other conducts for the other half-cycle.

SUMMARY:

- A class A power amplifier operates entirely in the linear region of the transistor's characteristic curves. The transistor conducts during the full 360° of the input cycle.
- The Q-point must be centered on the load line for maximum class A output signal swing.
- The maximum efficiency of a class A power amplifier is 25 percent.

- A class B amplifier operates in the linear region for half of the input cycle and it is in cutoff for the other half.
- The Q-point is at cutoff for class B operation.
- Class B amplifiers are normally operated in a push-pull configuration in order to produce an output that is a replica of the input.
- The maximum efficiency of a class B amplifier is 79 percent.
- A class AB amplifier is biased slightly above cutoff and operates in the linear region for slightly more than of the input cycle.
- Class AB eliminates crossover distortion found in pure class B.

- A class C amplifier operates in the linear region for only a small part of the input cycle.
- The class C amplifier is biased below cutoff.
- Class C amplifiers are normally operated as tuned amplifiers to produce a sinusoidal output.
- The maximum efficiency of a class C amplifier is higher than that of either class A or class B amplifiers. Under conditions of low power dissipation and high output power, the efficiency can approach 100 percent.

SELF-TEST: https://www.chegg.com/homework-help/questions-and-answers/1-amplifier-operates-linear-region-times-class-b-class-mathrm-ab-c-class-b-d-class-c-2-cer-q111080477

More: https://www.sanfoundry.com/analog-circuits-questions-answers-comparison-amplifier-classes-1/

1. An amplifier that operates in the linear region at all times is
(a) Class A (b) Class AB (c) Class B (d) Class C
2. A certain class A power amplifier delivers 5 W to a load with an input signal power of 100 mW. The power gain is
(a) 100 (b) 50 (c) 250 (d) 5
3. The peak current a class A power amplifier can deliver to a load depends on the
(a) maximum rating of the power supply (b) quiescent current
(c) current in the bias resistors (d) size of the heat sink
4. For maximum output, a class A power amplifier must maintain a value of quiescent current that is
(a) one-half the peak load current (b) twice the peak load current
(c) at least as large as the peak load current (d) just above the cutoff value
5. A certain class A power amplifier has $V_{CEQ} = 12V$ and $I_{CQ} = 1A$. The maximum signal power output is
(a) 6 W (b) 12 W (c) 1 W (d) 0.707 W
6. The efficiency of a power amplifier is the ratio of the power delivered to the load to the
(a) input signal power (b) power dissipated in the last stage
(c) power from the dc power supply (d) none of these answers
7. The maximum efficiency of a class A power amplifier is
(a) 25% (b) 50% (c) 79% (d) 98%
8. The transistors in a class B amplifier are biased
(a) into cutoff (b) in saturation (c) at midpoint of the load line (d) right at cutoff
9. Crossover distortion is a problem for
(a) class A amplifiers (b) class AB amplifiers (c) class B amplifiers (d) all of these amplifiers
10. A BJT class B push-pull amplifier with no transformer coupling uses
(a) two npn transistors (b) two pnp transistors
(c) complementary symmetry transistors (d) none of these
11. A current mirror in a push-pull amplifier should give an I_{CQ} that is
(a) equal to the current in the bias resistors and diodes
(b) twice the current in the bias resistors and diodes
(c) half the current in the bias resistors and diodes

(d) zero

12. The maximum efficiency of a class B push-pull amplifier is

(a) 25% (b) 50% (c) 79% (d) 98%

13. The output of a certain two-supply class B push-pull amplifier has a V_{CC} of 20 V. If the load resistance is Ω, the value of $I_{c(sat)}$ is

(a) 5 mA (b) 0.4 A (c) 4 mA (d) 40 mA

14. The maximum efficiency of a class AB amplifier is

(a) higher than a class B (b) the same as a class B

(c) about the same as a class A (d) slightly less than a class B

15. The power dissipation of a class C amplifier is normally

(a) very low (b) very high (c) the same as a class B (d) the same as a class A

16. The efficiency of a class C amplifier is

(a) less than class A (b) less than class B

(c) less than class AB (d) greater than classes A, B, or AB

17. The transistor in a class C amplifier conducts for

(a) more than of the input cycle (b) one-half of the input cycle

(c) a very small percentage of the input cycle (d) all of the input cycle