Electronics Devices & Circuits

Chapter 2 : BIPOLAR TRANSISTOR

Complete Engineering Notes

Theory • Diagrams • Tables • Solved Examples • 15 MCQs with Answer Key • 10 Broad Questions

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Topics Covered

- **2.1** Construction and operation of NPN and PNP transistors; V-I characteristics; active, saturation and cut-off regions; CE, CB, CC configurations and their differences
- **2.2** Definitions of current gains and their relationship; concept of Q-point; AC and DC load line; stabilization and stability factor; types of biasing: base bias, collector feedback bias, emitter feedback bias, potential divider bias
- **2.3** Transistor as a simple small signal amplifier and oscillator, and their simple applications

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Chapter 2 : Bipolar Transistor

Chapter Overview

The **bipolar junction transistor (BJT)** is the most important active device of analog electronics. Invented in 1947, it replaced the vacuum tube and made small, reliable amplifiers, switches and oscillators possible. A transistor can take a very small input signal and control a much larger output current, which is the basis of **amplification**. In this chapter we study how a transistor is built and how it works, how its characteristics are obtained in the CB, CE and CC configurations, how a stable DC operating point is fixed by biasing, and finally how the transistor is used as an amplifier and as an oscillator.

After studying this chapter you will be able to:

- Describe the construction and working of NPN and PNP transistors and identify the active, saturation and cut-off regions.
- Draw and explain the input and output characteristics of CE and CB configurations and compare CB, CE and CC.
- Define α, β and γ and use the relations between them.
- Draw the DC and AC load lines, locate the Q-point and explain its effect on distortion.
- Explain the need for stabilization, define stability factor and analyse the four biasing circuits.
- Explain the working of a CE amplifier and of LC and RC oscillators, and list their applications.

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2.1 Construction and Operation of NPN and PNP Transistors, Characteristics and Configurations

2.1.1 Introduction to the Bipolar Junction Transistor

A **bipolar junction transistor** is a three-layer, three-terminal semiconductor device made by joining three doped regions in the order N-P-N or P-N-P. It contains **two PN junctions** placed back to back. The word *bipolar* is used because both types of charge carriers, **electrons and holes**, take part in conduction. The BJT is a **current-controlled device**: a small base current controls a large collector current.

Region (terminal)	Function	Doping	Physical size
Emitter (E)	Emits (injects) majority carriers into the base	Heavily doped	Medium
Base (B)	Very thin central layer; passes most carriers on to the collector	Lightly doped	Very thin (about 1 μm or less)
Collector (C)	Collects the carriers that have crossed the base	Moderately doped	Largest, because it dissipates the most heat

2.1.2 Construction of NPN and PNP Transistors

- **NPN transistor:** a thin P-type base is sandwiched between two N-type regions (emitter and collector).

- **PNP transistor:** a thin N-type base is sandwiched between two P-type regions.
- The junction between emitter and base is the **emitter-base junction (J_E)**; the junction between collector and base is the **collector-base junction (J_C)**.
- The emitter and collector are of the same type but are **not interchangeable**, since their doping and size are different.
- In the symbol, the **arrow is on the emitter** and shows the direction of conventional emitter current: **outward for NPN** and **inward for PNP**.

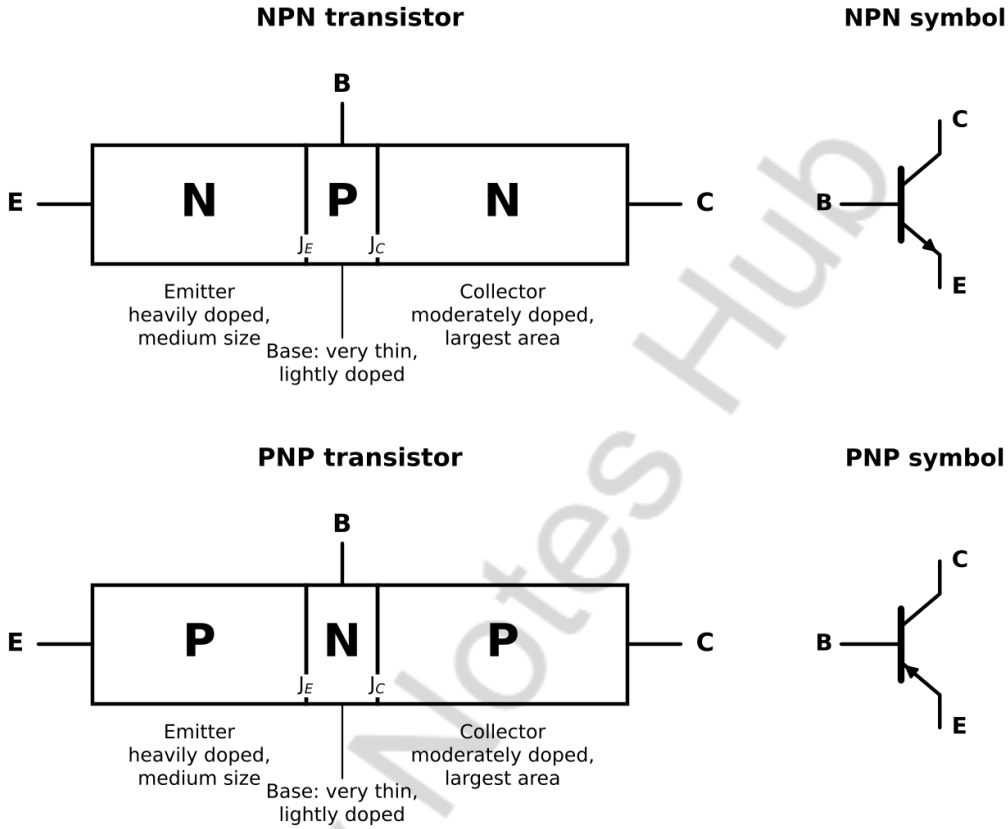


Fig. 2.1: Construction and symbols of NPN and PNP transistors

NPN versus PNP transistor

Feature	NPN transistor	PNP transistor
Emitter / collector type	N-type	P-type
Base type	P-type	N-type
Majority carriers carrying the current	Electrons	Holes
Collector supply polarity w.r.t. emitter	Positive	Negative
Direction of emitter arrow	Pointing outward	Pointing inward
Speed	Faster, because electron mobility is higher than hole mobility	Slower
Usage	More common in practice	Used as complement to NPN (e.g. push-pull stages)

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2.1.3 Operation of the Transistor

For normal amplifying action the emitter-base junction is **forward biased** and the collector-base junction is **reverse biased**. The working is explained below for an NPN transistor.

1. **Biasing:** a small battery V_{EE} forward biases J_E (emitter negative, base positive); a larger battery V_{CC} reverse biases J_C (collector positive with respect to base).
2. **Injection:** forward bias lowers the barrier at J_E, so a large number of electrons are injected from the heavily doped emitter into the base. The flow of holes from base to emitter is negligible because the base is lightly doped.
3. **Recombination in base:** since the base is very thin and lightly doped, only about 1 – 5 % of the electrons recombine with holes. The holes lost are replaced from the external circuit and this forms the small **base current I_B**.
4. **Collection:** the remaining 95 – 99 % of the electrons reach the collector junction, where the strong electric field of the reverse biased J_C sweeps them into the collector. They form the **collector current I_C**.
5. **Current relation:** by Kirchhoff's current law the emitter current is the sum of the other two: $\mathbf{I_E = I_B + I_C}$, with $I_C \approx 0.95 – 0.99\ I_E$.

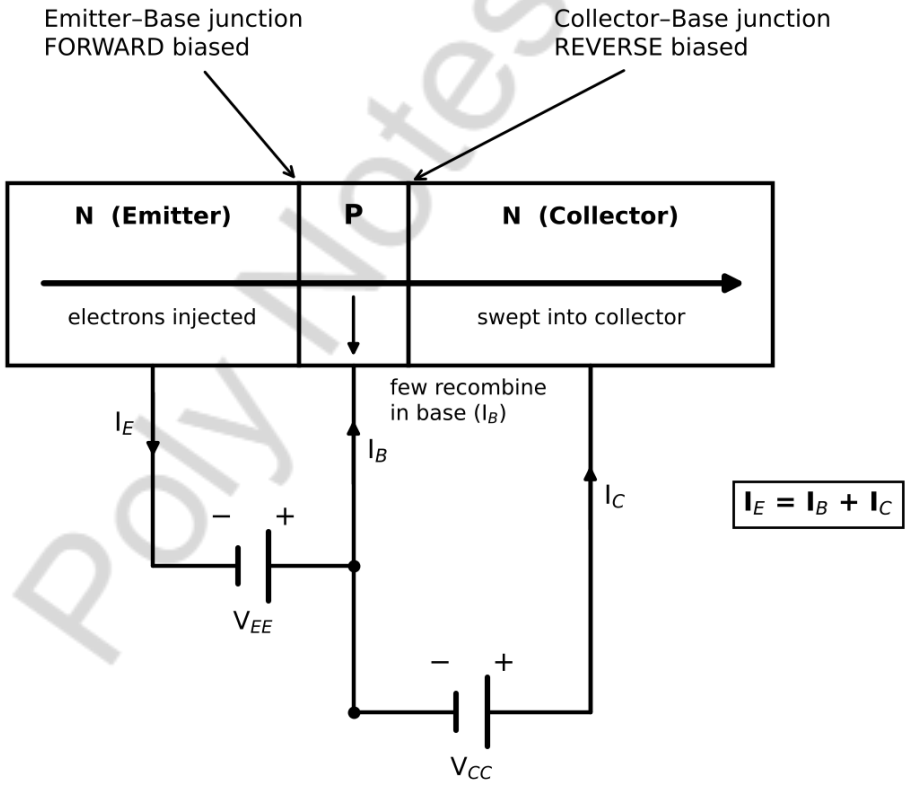


Fig. 2.2: Current flow in an NPN transistor biased in the active region

A very small **leakage current I_{CBO}** (due to minority carriers) also flows across the reverse biased collector junction even when the emitter is open.

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Operation of PNP transistor

The working of a PNP transistor is the same, with the roles of **holes and electrons interchanged** and all battery polarities and current directions reversed: the emitter is made positive with respect to base and the collector negative with respect to base. Holes are injected from the emitter into the base, a few recombine (giving I_B) and most are collected by the collector (giving I_C). Again $I_E = I_B + I_C$, but the conventional currents flow into the emitter and out of the base and collector.

2.1.4 Regions of Operation: Active, Saturation and Cut-off

According to the bias applied to the two junctions, a transistor works in one of the following regions.

Region	Emitter-base junction	Collector-base junction	Behaviour	Application
Active	Forward	Reverse	$V_{BE} \approx 0.7$ V (Si); $I_C = \beta I_B$; I_C is controlled by I_B	Amplifier
Saturation	Forward	Forward	$V_{CE(sat)} \approx 0.2$ V; I_C is maximum $\approx V_{CC}/R_C$ and no longer depends on I_B; transistor acts as a **closed switch (ON)**	Switch (ON state)
Cut-off	Reverse (or zero)	Reverse	$I_B \approx 0$; $I_C \approx I_{CEO}$ (very small); $V_{CE} \approx V_{CC}$; transistor acts as an **open switch (OFF)**	Switch (OFF state)
Reverse active	Reverse	Forward	Emitter and collector roles exchanged; very low gain	Rarely used

Thus in digital circuits the transistor is driven alternately between cut-off and saturation so that it works as an electronic switch, while in analog circuits it is kept in the active region so that the output is a faithful, amplified copy of the input.

2.1.5 Transistor Configurations

A transistor has three terminals, but a two-port network needs four (two for input and two for output). Therefore one terminal is made **common** to input and output, which gives three possible configurations.

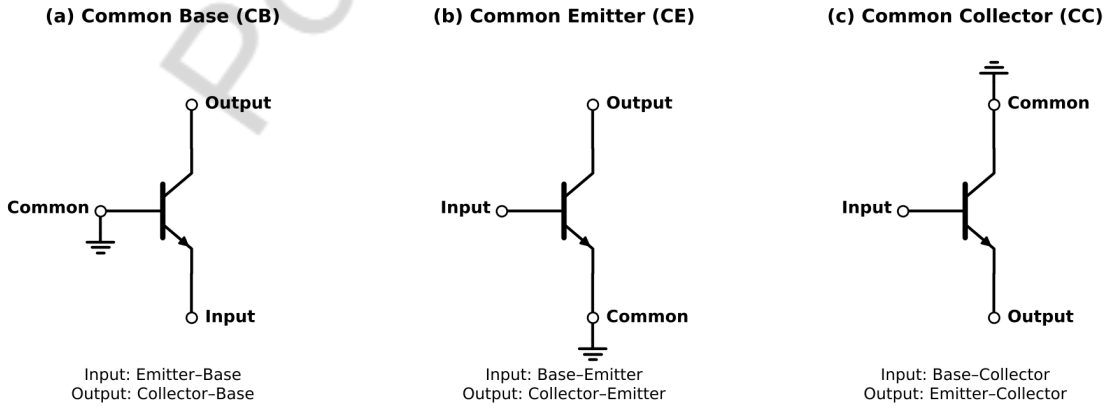


Fig. 2.3: Three configurations of a transistor

- **Common Base (CB):** base is common. Input is applied between emitter and base; output is taken between collector and base. Current gain is less than unity.

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- **Common Emitter (CE):** emitter is common. Input is applied between base and emitter; output is taken between collector and emitter. It is the most widely used configuration because it gives both current and voltage gain.
- **Common Collector (CC):** collector is common. Input is applied between base and collector; output is taken between emitter and collector. It is also called the **emitter follower**.

2.1.6 Common Emitter (CE) Configuration and Characteristics

In the CE configuration (Fig. 2.4) V_{BB} and R_B supply the base current I_B, and V_{CC} and R_C supply the collector current I_C. The characteristics are obtained by varying one voltage and noting the currents using meters in the input and output loops.

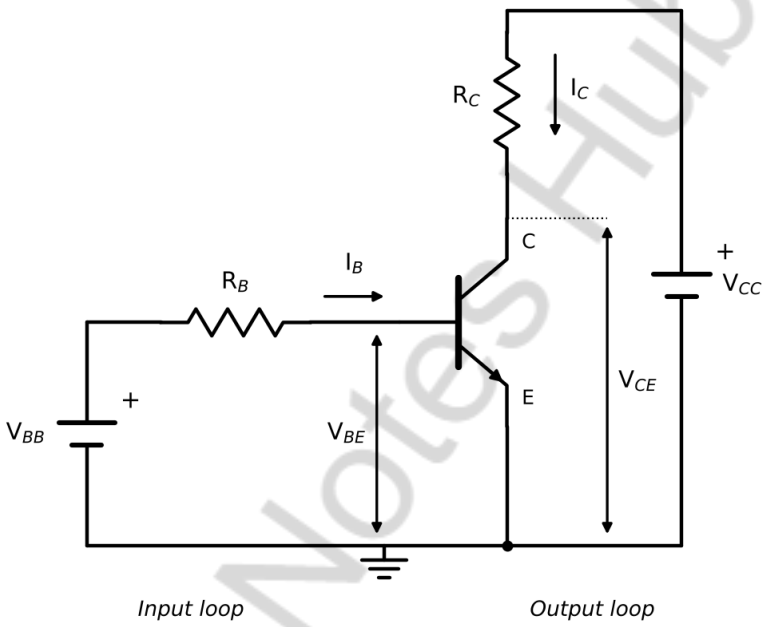


Fig. 2.4: Circuit for studying the CE characteristics (NPN)

(a) Input characteristics

The input characteristic is the plot of $\mathbf{I_B}$ **against** $\mathbf{V_{BE}}$ **at constant** $\mathbf{V_{CE}}$. It resembles the forward characteristic of a PN junction diode: the base current is negligible below the cut-in voltage (about 0.7 V for silicon) and then increases rapidly. When V_{CE} is raised, the curve shifts slightly to the right because the collector junction widens and draws more carriers, leaving less base current for the same V_{BE}.

Input resistance of the CE configuration: $r_i = \Delta V_{BE} / \Delta I_B$ (at constant V_{CE}); it is of the order of a few hundred ohms to a few kilo-ohms.

(b) Output characteristics

The output characteristic is the plot of $\mathbf{I_C}$ **against** $\mathbf{V_{CE}}$ **for constant values of** $\mathbf{I_B}$, giving a family of curves.

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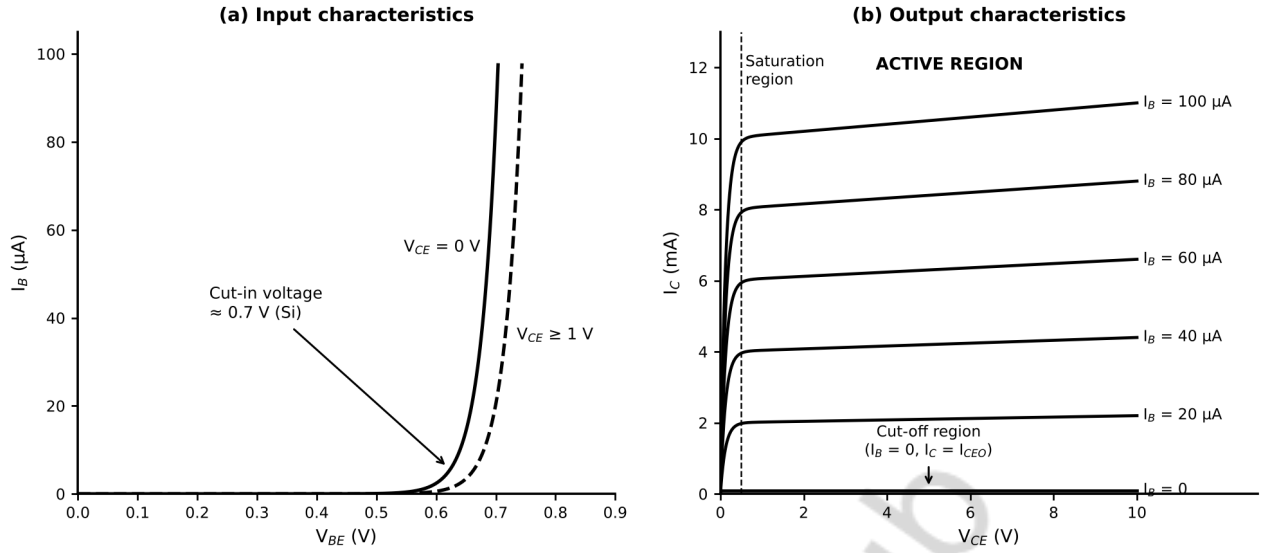


Fig. 2.5: Input and output characteristics of CE configuration

Region on the curves	Description
Active region	The curves are nearly flat (parallel to the V_{CE} axis); $I_C = \beta I_B$. The slight upward slope is due to the **Early effect** (base-width modulation).
Saturation region	Small V_{CE} (below about 0.2 – 0.5 V); both junctions are forward biased and I_C rises steeply with V_{CE}.
Cut-off region	Below the $I_B = 0$ curve; only the leakage current $\mathbf{I_{CEO}}$ flows, where $I_{CEO} = (1 + \beta)I_{CBO}$.
Breakdown region	At a high V_{CE} the collector junction breaks down by avalanche multiplication and I_C rises sharply; the transistor must not be operated here.

Output resistance: $r_o = \Delta V_{CE} / \Delta I_C$ (at constant I_B), which is the reciprocal of the slope of the flat portion; it is high (tens of kilo-ohms). **AC current gain:** $\beta_{ac} = \Delta I_C / \Delta I_B$ (at constant V_{CE}), obtained from the vertical spacing of the curves.

2.1.7 Common Base (CB) Configuration and Characteristics

- **Input characteristics:** plot of I_E against V_{EB} at constant V_{CB}. The curves look like a forward biased diode; a larger V_{CB} shifts the curve slightly to the left. **Input resistance** $r_i = \Delta V_{EB} / \Delta I_E$ is very small (typically 20 – 100 Ω).
- **Output characteristics:** plot of I_C against V_{CB} at constant I_E. In the active region $I_C \approx \alpha I_E$ and is almost independent of V_{CB}, so the curves are nearly horizontal. **Output resistance** $r_o = \Delta V_{CB} / \Delta I_C$ is very large (of the order of a megaohm).
- **Saturation region:** when V_{CB} becomes slightly negative (collector junction forward biased) I_C falls rapidly to zero.
- **Cut-off region:** for $I_E = 0$ only the leakage current $\mathbf{I_{CBO}}$ flows in the collector.
- **Current gain** $\alpha = \Delta I_C / \Delta I_E$ (at constant V_{CB}) is slightly less than 1, so CB gives no current amplification but gives voltage gain.

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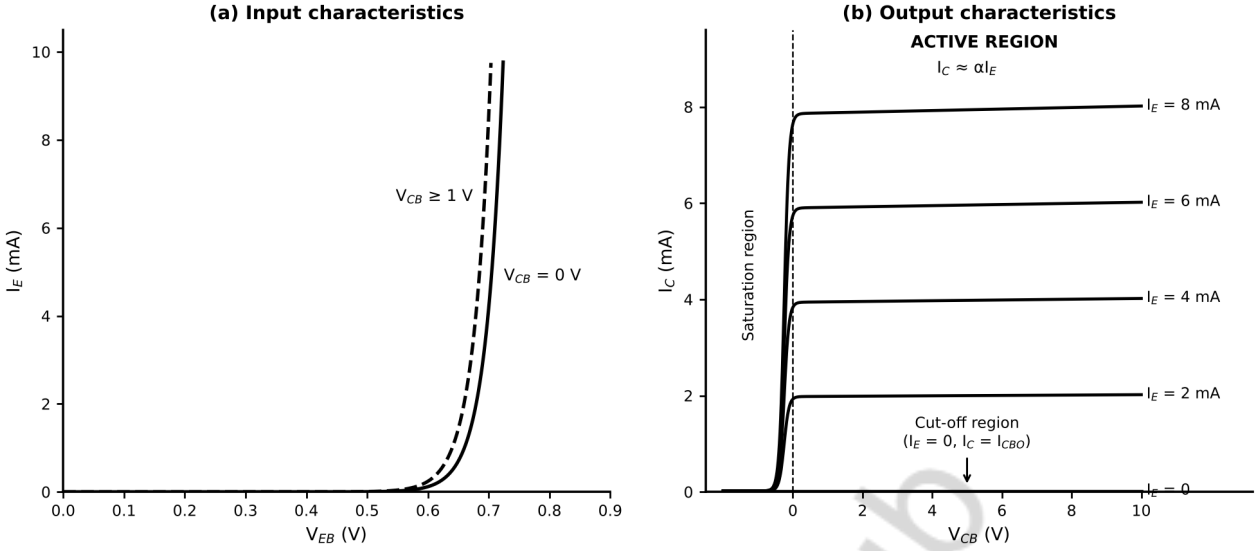


Fig. 2.6: Input and output characteristics of CB configuration

2.1.8 Common Collector (CC) Configuration

In the CC configuration the input is applied to the base and the output is taken from the emitter, so the load is connected in the emitter circuit and the collector is at AC ground. The output voltage follows the input voltage with a loss of about 0.7 V, so the voltage gain is **slightly less than 1** and there is **no phase shift**. The current gain is $\boldsymbol{\gamma = I_E/I_B = (1 + \beta)}$. Its input resistance is very high and its output resistance is very low, so it is used as a **buffer** (impedance-matching stage) between a high-impedance source and a low-impedance load. Its characteristics are similar to those of CE, with I_E plotted against V_{EC} for constant I_B.

2.1.9 Comparison of CB, CE and CC Configurations

Parameter	**Common Base (CB)**	**Common Emitter (CE)**	**Common Collector (CC)**
Common terminal	Base	Emitter	Collector
Input terminals	Emitter-Base	Base-Emitter	Base-Collector
Output terminals	Collector-Base	Collector-Emitter	Emitter-Collector
Input resistance	Very low (20 – 100 Ω)	Medium (about 1 kΩ)	Very high (about 100 kΩ or more)
Output resistance	Very high (about 1 MΩ)	High (about 50 kΩ)	Low (tens of ohms)
Current gain	α (less than 1)	β (20 – 500)	γ = 1 + β (high)
Voltage gain	High	Medium to high	Less than 1 (≈ 1)
Power gain	Medium	Highest	Low to medium
Phase shift between input and output	0° (in phase)	180° (inverted)	0° (in phase)
Leakage current	I_{CBO} (smallest)	$I_{CEO} = (1 + \beta)I_{CBO}$ (largest)	I_{CEO}
Typical applications	High frequency / RF amplifiers, current buffer	Audio and general purpose amplifiers, switching	Buffer, impedance matching, emitter follower

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The resistance and gain values above are typical approximate figures; actual values depend on the transistor and the circuit.

Solved Example 2.1

- **Problem:** In an NPN transistor, I_E = 5 mA and I_B = 0.1 mA. Find I_C, α and β.
- **Solution:** $I_C = I_E - I_B = 5 - 0.1 =$ **4.9 mA**
- $\alpha = I_C / I_E = 4.9 / 5 =$ **0.98**; $\beta = I_C / I_B = 4.9 / 0.1 =$ **49**

Solved Example 2.2 – Identifying the region

- **Problem:** A transistor with β = 100 has V_{CC} = 10 V and R_C = 1 kΩ. If I_B = 150 µA, is it in the active or saturation region? ($V_{CE(sat)}$ = 0.2 V)
- **Solution:** $I_{C(sat)} = (10 - 0.2) / 1\ k\Omega = 9.8$ mA. The base current needed for saturation is $I_{B(sat)} = 9.8\ mA / 100 = 98\ \mu A$.
- Since the actual I_B = 150 µA is greater than 98 µA, the transistor is **in saturation** (the collector current is limited to about 9.8 mA instead of βI_B = 15 mA).

Exam Tips – Section 2.1

- Always state the bias condition: **active = EB forward + CB reverse**; saturation = both forward; cut-off = both reverse.
- In the CE output characteristic label the axes (V_{CE} and I_C), the curves (I_B values) and the three regions.
- Remember the phase shifts: CE = 180°; CB and CC = 0°.

2.2 Current Gains, Q-point, Load Lines, Stabilization and Biasing

2.2.1 Definitions of Current Gains

Gain	Definition	Expression	Typical value
α_{dc} (DC current gain, CB)	Ratio of collector current to emitter current	$\alpha_{dc} = I_C / I_E$	0.95 – 0.99
α_{ac} (AC current gain, CB)	Ratio of change in I_C to change in I_E at constant V_{CB}	$\alpha_{ac} = \Delta I_C / \Delta I_E$	Nearly equal to α_{dc}
β_{dc} (h_{FE}, CE)	Ratio of collector current to base current	$\beta_{dc} = I_C / I_B$	20 – 500
β_{ac} (h_{fe}, CE)	Ratio of change in I_C to change in I_B at constant V_{CE}	$\beta_{ac} = \Delta I_C / \Delta I_B$	Close to β_{dc}
γ (CC)	Ratio of emitter current to base current	$\gamma = I_E / I_B$	1 + β

2.2.2 Relationship between α, β and γ

Start from the basic current relation $I_E = I_B + I_C$. Dividing throughout by I_C:

$$I_E / I_C = I_B / I_C + 1 \Rightarrow 1/\alpha = 1/\beta + 1$$

Solving this equation gives the following relations.

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Relation	Expression
α in terms of β	$\alpha = \beta / (1 + \beta)$
β in terms of α	$\beta = \alpha / (1 - \alpha)$
γ in terms of β	$\gamma = I_E / I_B = 1 + \beta$
γ in terms of α	$\gamma = 1 / (1 - \alpha)$
Collector current (with leakage)	$I_C = \alpha I_E + I_{CBO}$
Collector current in CE	$I_C = \beta I_B + I_{CEO}$, where $I_{CEO} = (1 + \beta) I_{CBO}$

Derivation of I_{CEO}: $I_C = \alpha I_E + I_{CBO} = \alpha(I_C + I_B) + I_{CBO}$. Hence $I_C(1 - \alpha) = \alpha I_B + I_{CBO}$, or $I_C = [\alpha/(1 - \alpha)]I_B + [1/(1 - \alpha)]I_{CBO} = \beta I_B + (1 + \beta) I_{CBO}$.

α	0.90	0.95	0.98	0.99	0.995
$\beta = \alpha/(1 - \alpha)$	9	19	49	99	199

A very small change in α produces a very large change in β; therefore β varies widely between transistors of the same type and also with temperature.

Solved Example 2.3

- **Problem:** A transistor has α = 0.98 and I_E = 10 mA. Find I_C, I_B and β.
- **Solution:** $I_C = \alpha I_E = 0.98 \times 10 =$ **9.8 mA**; $I_B = I_E - I_C =$ **0.2 mA**; $\beta = 0.98 / 0.02 =$ **49**

Solved Example 2.4

- **Problem:** For a transistor with β = 150, I_B = 30 µA. Find I_C, I_E and α.
- **Solution:** $I_C = \beta I_B = 150 \times 30$ µA = **4.5 mA**; $I_E = (1 + \beta) I_B = 151 \times 30$ µA = **4.53 mA**; α = 150/151 = **0.9934**

Solved Example 2.5 – Effect of leakage

- **Problem:** A transistor has β = 100 and I_{CBO} = 2 µA. Find I_{CEO} and the collector current for I_B = 40 µA.
- **Solution:** $I_{CEO} = (1 + \beta) I_{CBO} = 101 \times 2$ µA = **202 µA**; $I_C = \beta I_B + I_{CEO} = 4$ mA + 0.202 mA = **4.202 mA**

2.2.3 Concept of Q-Point (Operating Point)

To amplify an AC signal without distortion, the transistor must be kept in the active region at all instants of the signal. This is done by applying suitable DC voltages and currents, which is called **biasing**. The **Q-point (quiescent point or operating point)** is the point on the output characteristics defined by the DC collector current I_{CQ} and the DC collector-emitter voltage V_{CEQ} when **no signal is applied**. When the signal is applied, the operating point moves up and down about the Q-point along the load line.

2.2.4 DC Load Line

Applying Kirchhoff's voltage law to the output loop of a CE circuit (Fig. 2.4) gives $V_{CC} = I_C R_C + V_{CE}$ (and with an emitter resistor, $V_{CC} = I_C R_C + V_{CE} + I_E R_E$). Therefore

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$$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

This is a straight line when drawn on the output characteristics. It is called the **DC load line** and its slope is $-1/(R_C + R_E)$. It is drawn using its two end points:

1. **Saturation point (A):** put $V_{CE} = 0$, then $I_{C(sat)} = V_{CC} / (R_C + R_E)$. Mark this point on the I_C axis.
2. **Cut-off point (B):** put $I_C = 0$, then $V_{CE(cut\text{-}off)} = V_{CC}$. Mark this point on the V_{CE} axis.
3. Join A and B by a straight line. The **Q-point** is the point where this line cuts the output curve for the I_B fixed by the bias circuit.

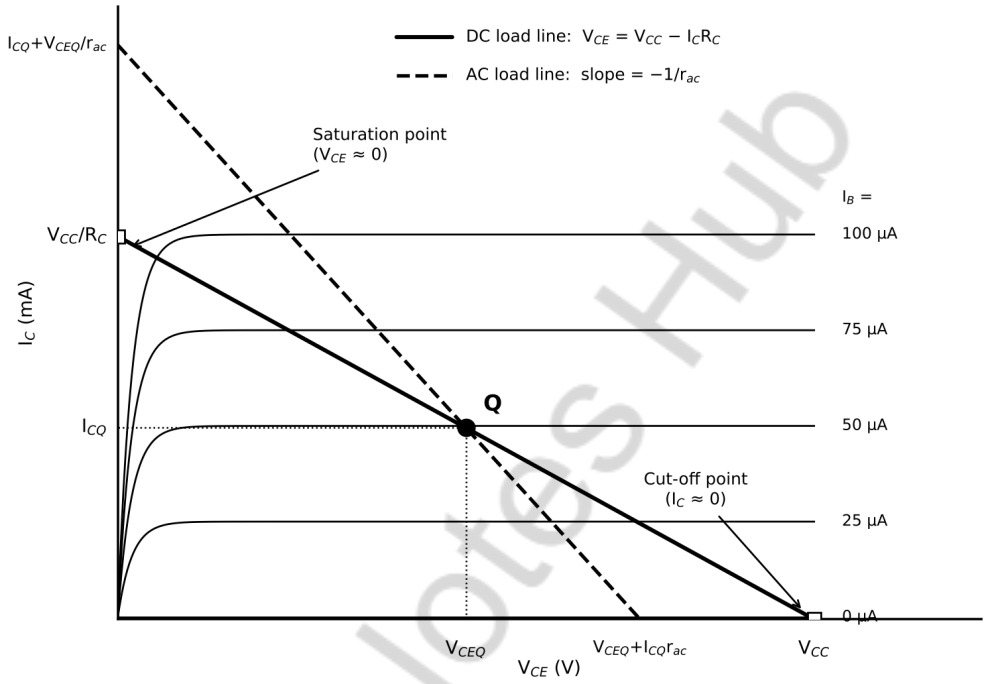


Fig. 2.7: DC load line, AC load line and Q-point on the output characteristics

Position of the Q-point and distortion

Position of Q-point	Effect on the output signal
Near the saturation point	The positive swing of base current drives the transistor into saturation; the **negative peak of the output is clipped**.
Near the cut-off point	The negative swing of base current drives the transistor into cut-off; the **positive peak of the output is clipped**.
Near the middle of the load line	Maximum undistorted output swing in both directions – **best position** for a class-A amplifier.

2.2.5 AC Load Line

For the DC conditions the total load is $R_C + R_E$. For AC signals, however, the coupling capacitor C_2 connects the load R_L in parallel with R_C and the bypass capacitor C_E short-circuits R_E. The AC load seen by the transistor is therefore

$$r_{ac} = R_C \,||\, R_L = R_C R_L / (R_C + R_L)$$

The **AC load line** is a line of slope $-1/r_{ac}$ drawn **through the Q-point**. Because $r_{ac} < R_C$, it is **steeper** than the DC load line. Its end points are $V_{CE(max)} = V_{CEQ} + I_{CQ} r_{ac}$ and $I_{C(max)} = I_{CQ} + V_{CEQ}/r_{ac}$. The signal swings along the AC load line, so the maximum undistorted peak output is

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the smaller of $I_{CQ}r_{ac}$ and V_{CEQ}.

Feature	DC load line	AC load line
Load considered	$R_C + R_E$ (DC conditions)	$r_{ac} = R_C \parallel R_L$ (signal conditions)
Slope	$-1/(R_C + R_E)$	$-1/r_{ac}$ (steeper)
Passes through	V_{CC} on V_{CE}-axis and $V_{CC}/(R_C + R_E)$ on I_C-axis	Q-point
Used to find	Q-point (I_{CQ}, V_{CEQ})	Maximum output swing and clipping

Solved Example 2.6

- **Problem:** A CE amplifier has V_{CC} = 12 V, R_C = 2 kΩ (R_E bypassed, neglect its DC drop), Q-point at I_{CQ} = 3 mA and V_{CEQ} = 6 V, and load R_L = 2 kΩ. Find the DC and AC load line end points and the maximum undistorted output.
- **DC load line:** $I_{C(sat)}$ = 12 / 2 kΩ = **6 mA**; $V_{CE(cut\text{-}off)}$ = **12 V**.
- **AC load line:** r_{ac} = 2k || 2k = 1 kΩ. $V_{CE(max)}$ = 6 + 3 mA × 1 kΩ = **9 V**; $I_{C(max)}$ = 3 + 6 / 1 kΩ = **9 mA**.
- **Maximum swing:** peak output = smaller of $I_{CQ}r_{ac}$ = 3 V and V_{CEQ} = 6 V, i.e. **3 V peak (6 V peak-to-peak)**.

2.2.6 Need for Stabilization and Stability Factor

The Q-point must remain fixed for proper amplification. In practice it shifts because the collector current depends on three quantities that change with temperature and from one transistor to another:

- **Leakage current I_{CBO}**, which approximately doubles for every 10 °C rise in temperature.
- **Base-emitter voltage V_{BE}**, which decreases by about 2 – 2.5 mV for every 1 °C rise.
- **Current gain β**, which increases with temperature and differs widely between transistors of the same type number.

A rise in I_C heats the junction, which increases I_{CBO}, which increases I_C again. This cumulative process is called **thermal runaway** and can destroy the transistor. **Stabilization** is the process of keeping the Q-point (and hence I_C) almost constant in spite of these changes, by using suitable bias circuits.

Stability factors

Stability factor	Definition	Meaning
S	$S = \partial I_C / \partial I_{CBO}$ (V_{BE} and β constant)	Change in I_C for unit change in leakage current
S'	$S' = \partial I_C / \partial V_{BE}$ (I_{CBO} and β constant)	Change in I_C for unit change in V_{BE}
S''	$S'' = \partial I_C / \partial \beta$ (I_{CBO} and V_{BE} constant)	Change in I_C for change in β

Starting with $I_C = \beta I_B + (1 + \beta)I_{CBO}$ and differentiating with respect to I_C gives the general expression

$$S = (1 + \beta) / [\ 1 - \beta\ (\partial I_B / \partial I_C)\ ]$$

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- The **ideal value of S is 1** (I_C does not change at all). The **smaller the value of S, the better the stability**.
- The larger the S, the more the Q-point shifts with temperature, and the greater the risk of thermal runaway.
- Stability is improved by making $\partial I_B/\partial I_C$ negative, i.e. by using **negative feedback**: when I_C tends to increase, the circuit automatically reduces I_B.

Methods of stabilization

Method	Principle
Emitter resistor R_E	Negative (DC) feedback: an increase in I_E raises V_E and reduces V_{BE} and I_B.
Potential divider bias	Fixes the base voltage firmly; the emitter current is then set by R_E almost independent of β.
Collector feedback	A rise in I_C lowers V_{CE}, which reduces I_B fed from the collector.
Compensation techniques	Use of a diode, thermistor or sensistor in the bias network whose characteristics track the change of V_{BE} or I_{CBO} with temperature.
Heat sink	Reduces the junction temperature rise and hence the thermal runaway.

2.2.7 Types of Biasing

The four standard biasing circuits are shown in Fig. 2.8. In all of them the aim is to forward bias the emitter junction and reverse bias the collector junction from a single supply V_{CC}. V_{BE} is taken as 0.7 V for silicon.

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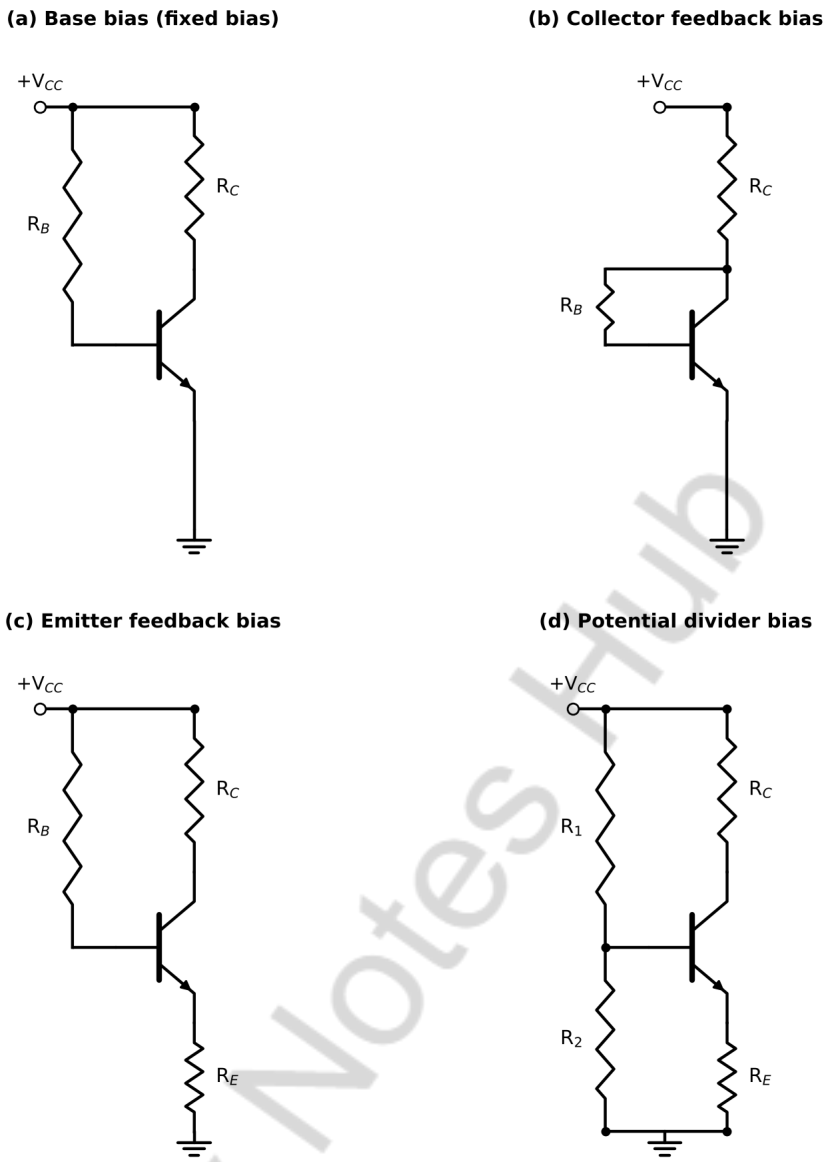


Fig. 2.8: (a) Base bias (b) Collector feedback bias (c) Emitter feedback bias (d) Potential divider bias

(a) Base bias (fixed bias)

A single resistor R_B connects V_{CC} to the base. Applying KVL to the base loop: $V_{CC} = I_B R_B + V_{BE}$.

- $I_B = (V_{CC} - V_{BE}) / R_B$ – fixed by V_{CC} and R_B; $I_C = \beta I_B$; $V_{CE} = V_{CC} - I_C R_C$
- **Stability factor:** $S = 1 + \beta$ (very poor, since I_B does not change when I_C changes).
- **Advantages:** very simple, few components, easy to design. **Limitations:** Q-point depends directly on β and shifts with temperature; thermal runaway is possible; not used in practical amplifiers.

(b) Collector feedback bias

R_B is connected between the **collector and the base** instead of V_{CC}. If I_C increases, V_{CE} falls, I_B through R_B falls and I_C is brought back – this is **negative feedback**. KVL: $V_{CC} = (I_C + I_B)R_C + I_B R_B + V_{BE}$, and with $I_C + I_B = (1 + \beta)I_B$:

- $I_B = (V_{CC} - V_{BE}) / [\, R_B + (1 + \beta)R_C \,]$; $I_C = \beta I_B$; $V_{CE} = V_{CC} - (I_C + I_B)R_C$

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- **Stability factor:** $S = (1 + \beta)(R_B + R_C) / [\ R_B + (1 + \beta)R_C\ ]$ – less than $(1 + \beta)$, so better than fixed bias.
- **Advantages:** simple and self-stabilizing. **Limitations:** the same feedback also acts on the AC signal, which reduces the voltage gain; stability is only moderate.

(c) Emitter feedback bias

A resistor R_E is placed in the emitter lead, in addition to R_B from V_{CC} to the base. KVL of the base loop: $V_{CC} = I_B R_B + V_{BE} + I_E R_E$. An increase in I_E increases the drop across R_E, which reduces V_{BE} and I_B.

- $I_B = (V_{CC} - V_{BE}) / [\ R_B + (1 + \beta)R_E\ ]$; $I_C = \beta I_B$; $V_{CE} = V_{CC} - I_C R_C - I_E R_E$
- **Stability factor:** $S = (1 + \beta)(R_B + R_E) / [\ R_B + (1 + \beta)R_E\ ]$
- **Advantages:** better stability than (a) and (b). **Limitations:** R_E gives AC feedback and lowers the gain unless it is bypassed by a capacitor; the Q-point still depends on β.

(d) Potential divider bias (voltage divider bias)

This is the most widely used circuit. Resistors R_1 and R_2 form a voltage divider across V_{CC} and fix the base voltage; R_E provides emitter feedback. Using Thevenin's theorem at the base:

- $V_{th} = V_{CC} R_2 / (R_1 + R_2)$; $R_{th} = R_1 \parallel R_2 = R_1 R_2 / (R_1 + R_2)$
- **Exact:** $I_B = (V_{th} - V_{BE}) / [\ R_{th} + (1 + \beta)R_E\ ]$; $I_C = \beta I_B$; $V_{CE} = V_{CC} - I_C R_C - I_E R_E$
- **Approximate (design) method:** if the divider is 'stiff', i.e. $R_{th} \gg \beta R_E$ (rule of thumb $R_2 \leq 0.1\beta R_E$), then $V_B \approx V_{th}$, $V_E = V_B - V_{BE}$, $I_C \approx I_E = V_E / R_E$, which is **independent of β**.
- **Stability factor:** $S = (1 + \beta)(1 + R_{th}/R_E) / (1 + \beta + R_{th}/R_E) \approx 1 + R_{th}/R_E$ – can be made very small by choosing a small R_{th}.
- **Advantages:** excellent stability, Q-point almost independent of β and temperature, needs only one supply. **Limitations:** more components; R_1 and R_2 load the input and draw some current from the supply.

Comparison of biasing circuits

Feature	Base bias	Collector feedback	Emitter feedback	Potential divider
Components	R_B, R_C	R_B, R_C	R_B, R_C, R_E	R_1, R_2, R_C, R_E
Stability factor S	1 + β (highest)	Less than 1 + β	Less than 1 + β	$\approx 1 + R_{th}/R_E$ (lowest)
Dependence on β	Very strong	Moderate	Moderate	Very weak
Thermal runaway	Possible	Reduced	Reduced	Practically avoided
Type of feedback	None	Negative (from collector)	Negative (from emitter)	Negative (from emitter)
Use	Switching, simple circuits	Simple amplifiers	Simple amplifiers	Most practical amplifiers

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Solved Example 2.7 – Base bias

- **Problem:** V_{CC} = 12 V, R_B = 470 kΩ, R_C = 2 kΩ, β = 100, V_{BE} = 0.7 V. Find I_B, I_C, V_{CE}.
- **Solution:** I_B = (12 − 0.7) / 470 kΩ = **24.04 µA**; I_C = 100 × 24.04 µA = **2.404 mA**; V_{CE} = 12 − 2.404 mA × 2 kΩ = **7.19 V**
- The transistor is in the active region. If β changes to 200, I_C doubles to 4.81 mA and V_{CE} falls to 2.4 V – showing the poor stability.

Solved Example 2.8 – Collector feedback bias

- **Problem:** V_{CC} = 12 V, R_B = 100 kΩ, R_C = 2 kΩ, β = 100, V_{BE} = 0.7 V. Find the Q-point.
- **Solution:** I_B = (12 − 0.7) / [100 k + 101 × 2 k] = 11.3 / 302 kΩ = **37.4 µA**; I_C = **3.74 mA**; I_E = 3.78 mA
- $V_{CE} = 12 - I_E R_C = 12 - 3.78 \times 2 =$ **4.44 V**

Solved Example 2.9 – Potential divider bias

- **Problem:** V_{CC} = 12 V, R_1 = 40 kΩ, R_2 = 10 kΩ, R_C = 2.2 kΩ, R_E = 1 kΩ, β = 100, V_{BE} = 0.7 V. Find I_C and V_{CE}.
- **Solution:** V_{th} = 12 × 10 / 50 = 2.4 V; R_{th} = 40 k || 10 k = 8 kΩ
- I_B = (2.4 − 0.7) / [8 k + 101 × 1 k] = 1.7 / 109 kΩ = **15.6 µA**; I_C = **1.56 mA**; I_E = 1.575 mA
- V_{CE} = 12 − 1.56 mA × 2.2 k − 1.575 mA × 1 k = 12 − 3.43 − 1.58 = **7.0 V**

Solved Example 2.10 – Comparing stability factors

- **Problem:** Find S for β = 100 for: (a) base bias, (b) collector feedback with R_B = 100 kΩ, R_C = 2 kΩ, (c) emitter feedback with R_B = 100 kΩ, R_E = 1 kΩ, (d) potential divider with R_{th} = 8 kΩ, R_E = 1 kΩ.
- (a) S = 1 + β = **101**
- (b) S = 101 × (100 + 2) / [100 + 101 × 2] = 10302 / 302 = **34.1**
- (c) S = 101 × (100 + 1) / [100 + 101 × 1] = 10201 / 201 = **50.8**
- (d) S = 101 × (8 + 1) / [8 + 101 × 1] = 909 / 109 = **8.3** → the potential divider circuit is by far the most stable.

Key Points – Section 2.2

- $\beta = \alpha/(1-\alpha)$, $\alpha = \beta/(1+\beta)$, $\gamma = 1 + \beta$, $I_{CEO} = (1+\beta)I_{CBO}$.
- Q-point = (V_{CEQ}, I_{CQ}) with no signal; it lies on the DC load line $V_{CE} = V_{CC} - I_C(R_C + R_E)$.
- The AC load line passes through Q and is steeper, with slope $-1/(R_C \parallel R_L)$.
- Stability factor $S = \partial I_C/\partial I_{CBO}$; ideal S = 1; smaller S means better stability.
- Potential divider bias gives the best stability and is the standard method in amplifiers.

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2.3 Transistor as a Small Signal Amplifier and Oscillator, and Their Applications

2.3.1 Transistor as a Small Signal Amplifier

An **amplifier** increases the voltage, current or power of a signal without changing its shape or frequency. The extra energy comes from the DC supply; the transistor only controls how this energy is delivered to the load. In a **small signal amplifier** the AC signal is so small compared with the DC bias values that the transistor works on the nearly linear portion of its characteristic around the Q-point, so the output is a faithful magnified copy of the input. The most common arrangement is the **CE amplifier** with potential divider bias.

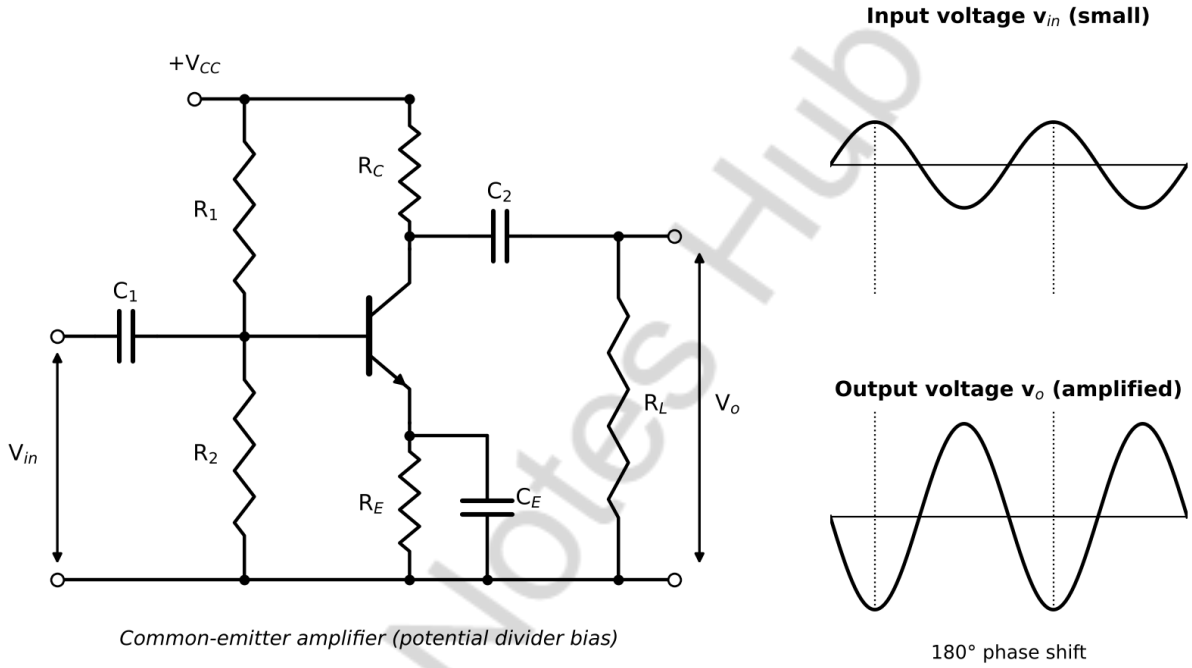


Fig. 2.9: Single stage CE amplifier and its input and output waveforms

Functions of the components

Component	Function
R_1, R_2	Potential divider that fixes the base bias voltage and the Q-point.
R_C	Collector load; converts the varying collector current into a varying output voltage.
R_E	Emitter resistor for DC stabilization of the Q-point (negative feedback).
C_E (bypass capacitor)	Short-circuits R_E for AC so that the voltage gain is not reduced, while R_E still stabilizes the DC.
C_1 (input coupling capacitor)	Passes the AC signal to the base and blocks the DC of the source so the bias is not disturbed.
C_2 (output coupling capacitor)	Passes the amplified AC to the load and blocks the DC component of the collector voltage.
R_L	Load connected to the output.
V_{CC}	DC supply that provides biasing and the power delivered to the load.

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Working of the CE amplifier

1. With no signal, the bias circuit sets the Q-point (I_{CQ}, V_{CEQ}) in the middle of the active region.
2. The input signal v_{in} reaches the base through C_1 and is superimposed on the DC bias, so the base current becomes $I_{BQ} + i_b$.
3. A small change in base current causes a much larger change in collector current: $i_c = \beta i_b$.
4. The varying collector current flows through R_C (in parallel with R_L for the AC), producing the voltage change $v_{ce} = -i_c r_{ac}$.
5. When the input rises, i_c rises and the drop across R_C increases, so the collector voltage **falls**; when the input falls, the collector voltage rises. Hence the output is **180° out of phase** with the input.
6. C_2 blocks the DC part of V_{CE} and delivers only the amplified AC signal to the load.

Small signal performance (mid-frequency, C_E connected)

Quantity	Expression	Remark
Dynamic emitter resistance	$r_e = 26\ mV / I_E$	I_E in mA gives r_e in ohms
Input resistance at the base	$r_{in(base)} \approx \beta r_e$	Seen looking into the base
Amplifier input resistance	$Z_{in} = R_1 \parallel R_2 \parallel \beta r_e$	Bias resistors are in parallel with the base
Output resistance	$Z_{out} \approx R_C$	
Voltage gain	$A_v = -r_{ac} / r_e$, $r_{ac} = R_C \parallel R_L$	Negative sign = 180° phase shift
Voltage gain without C_E	$A_v \approx -r_{ac} / (r_e + R_E)$	Gain is reduced but is more stable and less distorted
Current gain	$A_i \approx \beta$ (reduced by the bias dividers and load)	
Power gain	$A_p = A_v \times A_i$	Highest in CE

Solved Example 2.11 – Voltage gain

- **Problem:** For the biased circuit of Example 2.9 ($I_E = 1.575$ mA, $R_C = 2.2$ kΩ) a load $R_L = 4.7$ kΩ is connected through C_2, and R_E is bypassed. Find the voltage gain and input resistance.
- **Solution:** $r_e = 26\ mV / 1.575\ mA =$ **16.5 Ω**; $r_{ac} = 2.2\ k \parallel 4.7\ k =$ **1.5 kΩ**
- $A_v = -r_{ac} / r_e = -1500 / 16.5 \approx$ **−91** (magnitude 91, with 180° phase shift)
- $\beta r_e = 100 \times 16.5 = 1.65$ kΩ; $Z_{in} = 8\ k \parallel 1.65\ k =$ **1.37 kΩ**

Frequency response and classification

- **Mid-frequency band:** the gain is constant; the capacitors act as short circuits and the junction capacitances are negligible.
- **Low frequencies:** gain falls because the reactances of C_1, C_2 and C_E become large.
- **High frequencies:** gain falls because of the internal junction capacitances and the transit time of carriers. The range between the two half-power frequencies is the **bandwidth**.

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Basis of classification	Types
Signal level	Small signal (voltage) amplifiers; large signal (power) amplifiers
Frequency	Audio frequency (AF) amplifiers; radio frequency (RF) amplifiers
Coupling between stages	RC coupled; transformer coupled; direct coupled
Configuration	CE, CB and CC amplifiers

2.3.2 Transistor as an Oscillator

An **oscillator** is a circuit that **generates a continuous AC output of constant amplitude and frequency without any external AC input**; it converts DC power from the supply into AC power. It consists of an amplifier together with a **positive feedback network** that returns a part of the output to the input in phase with it.

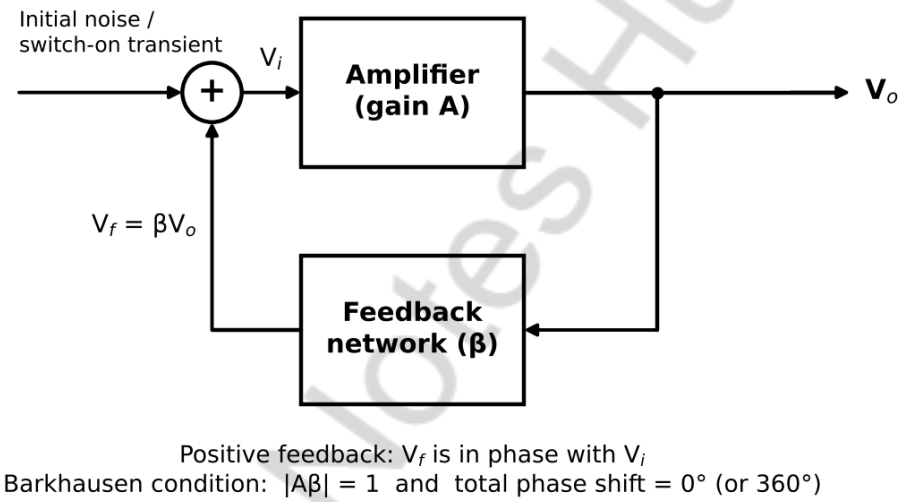


Fig. 2.10: Block diagram of a feedback oscillator

Barkhausen criteria

1. The magnitude of the loop gain must be unity: **|Aβ| = 1**.
2. The total phase shift around the loop must be **0° or 360°**, so that the feedback is positive.

- **Starting of oscillations:** at switch-on, noise and the switching transient contain a small signal of every frequency. The circuit selects the frequency at which the phase condition is met. Initially |Aβ| is made **slightly greater than 1**, so the oscillation builds up.
- **Amplitude limiting:** as the amplitude grows, the transistor gain falls because of non-linearity (it enters saturation and cut-off) until |Aβ| becomes exactly 1, and the amplitude then stays constant.
- **Frequency determination:** the frequency of oscillation is set by the frequency-determining network (an LC tank, RC network or crystal).

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Types of oscillators

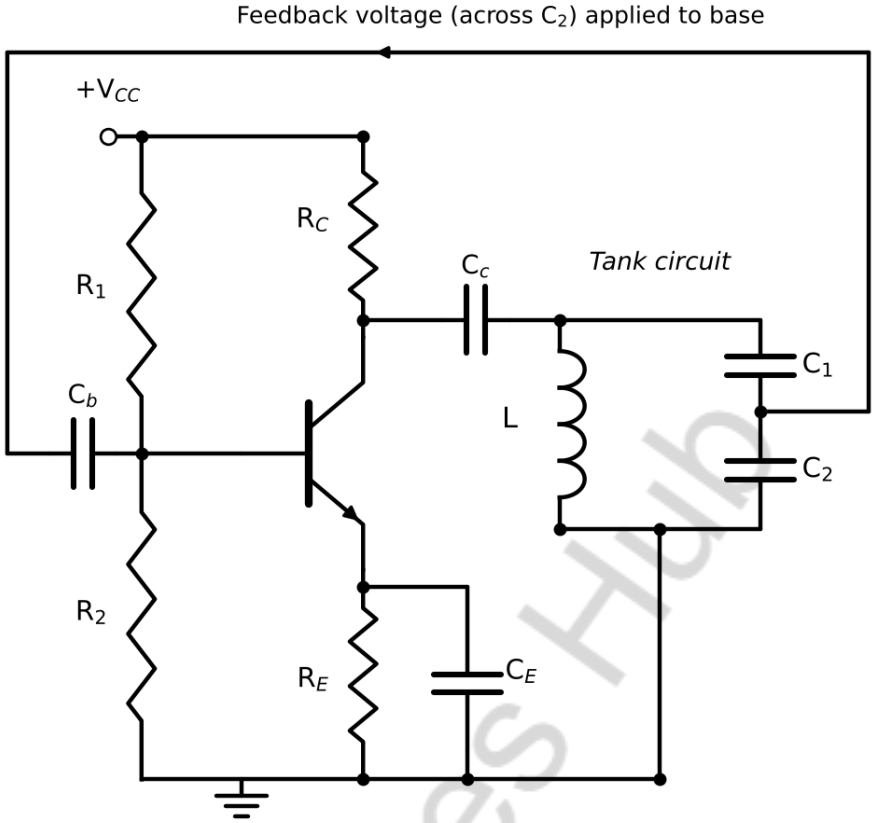
Type	Frequency-determining network	Frequency of oscillation	Range / remark
Hartley (LC)	Two inductors L_1, L_2 and capacitor C	$f = 1 / [2\pi\sqrt{((L_1 + L_2 + 2M)C)}]$	RF, up to hundreds of MHz
Colpitts (LC)	Inductor L and two capacitors C_1, C_2	$f = 1 / [2\pi\sqrt{(L\, C_{eq})}]$, $C_{eq} = C_1C_2/(C_1 + C_2)$	RF; very popular
Tuned collector (LC)	Tank circuit in the collector with transformer feedback	$f = 1 / (2\pi\sqrt{(LC)})$	RF
RC phase shift	Three RC sections giving 180° shift	$f = 1 / (2\pi\sqrt{6}\, RC)$	Audio frequencies; needs amplifier gain ≥ 29
Wien bridge	RC series-parallel network	$f = 1 / (2\pi RC)$	Audio; good waveform
Crystal	Quartz crystal	Series resonant frequency of the crystal	Very high frequency stability

Colpitts oscillator

In the Colpitts oscillator (Fig. 2.11) the CE transistor is biased by R_1, R_2, R_E. The **tank circuit** is formed by the inductor L in parallel with the series combination of C_1 and C_2, coupled to the collector through C_c. The **voltage across C_2 is fed back to the base** through C_b.

- The CE transistor produces a phase shift of 180° and the capacitive divider (C_1, C_2), whose centre point is grounded for AC, produces another 180°, so the total is 360° (positive feedback).
- The feedback factor is $\beta \approx C_1/C_2$, so the amplifier gain must satisfy $A \geq C_2/C_1$.
- Frequency: **$f = 1 / (2\pi\sqrt{(L\, C_{eq})})$** with $C_{eq} = C_1C_2/(C_1 + C_2)$; the frequency is varied by changing the capacitors.

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$f = 1 / [\ 2\pi\sqrt{(\ L \cdot C_1C_2/(C_1+C_2)\ )}\ ]$

Fig. 2.11: Transistor Colpitts oscillator

Solved Example 2.12 – Colpitts oscillator

- **Problem:** A Colpitts oscillator uses L = 100 µH, $C_1 = C_2 = 200$ pF. Find the frequency of oscillation.
- **Solution:** $C_{eq} = (200 \times 200) / (200 + 200) = 100$ pF $= 10^{-10}$ F
- $f = 1 / [2\pi\sqrt{(100 \times 10^{-6} \times 10^{-10})}] = 1 / (2\pi \times 10^{-7}) \approx$ **1.59 MHz**

Solved Example 2.13 – RC phase shift oscillator

- **Problem:** An RC phase shift oscillator uses R = 10 kΩ and C = 0.01 µF in each section. Find the frequency.
- **Solution:** $f = 1 / (2\pi\sqrt{6}\ RC) = 1 / (2\pi \times 2.449 \times 10 \times 10^3 \times 0.01 \times 10^{-6}) \approx$ **650 Hz**

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Amplifier versus oscillator

Feature	Amplifier	Oscillator
External input signal	Required	Not required
Feedback	Usually none or negative	Positive feedback
Loop gain |Aβ|	Less than 1 (for stability)	Equal to 1
Purpose	Increase the magnitude of a signal	Generate a signal of fixed frequency
Frequency-determining network	Not required	Required (LC, RC or crystal)

2.3.3 Simple Applications

Circuit	Applications
Small signal amplifier	Pre-amplifier for microphones, pick-ups and sensors (temperature, light, strain) • audio amplifiers in radios, TVs and music systems • RF and IF amplifiers in receivers • amplification of the weak signal from an antenna • stages of instruments and measuring equipment
Oscillator	Carrier-wave generation in radio and TV transmitters • local oscillator in a superheterodyne receiver • clock-pulse generation for digital circuits and microprocessors • signal and function generators in laboratories • alarms, buzzers and remote controls • metal detectors • timers and electronic watches (crystal oscillator)
Transistor as a switch	Driving relays, LEDs and lamps • logic gates and digital ICs • inverters and chopper circuits • interface between low-power electronics and heavy loads
Emitter follower (CC)	Buffer stage between a high-impedance source and a low-impedance load • impedance matching • output stages of voltage regulators

Chapter Summary

- A BJT has an emitter, a thin base and a collector forming two junctions; it works in the active region with EB forward and CB reverse biased, and $I_E = I_B + I_C$.
- CB has current gain $\alpha < 1$; CE gives the highest power gain with 180° phase shift; CC (emitter follower) has gain ≈ 1, high input and low output resistance.
- $\beta = \alpha/(1 - \alpha)$; $I_C = \beta I_B + (1 + \beta) I_{CBO}$.
- The Q-point on the DC load line should be near the centre; the AC load line through Q is steeper and decides the undistorted swing.
- The stability factor $S = \partial I_C / \partial I_{CBO}$ should be as small as possible; potential divider bias gives the best stabilization.
- A CE amplifier has a gain of about $-r_{ac}/r_e$; an oscillator is an amplifier with positive feedback satisfying $|A\beta| = 1$ and 0°/360° phase shift.

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Multiple Choice Questions (15 MCQs)

Choose the correct option. The answer key is given after the questions.

Q1. In an NPN transistor, the majority carriers in the emitter are:

(a) holes
(b) free electrons
(c) positive ions
(d) protons

Q2. The region of a transistor that is very thin and lightly doped is the:

(a) emitter
(b) collector
(c) base
(d) substrate

Q3. For a transistor to work in the active region, the junctions must be biased as:

(a) both forward
(b) both reverse
(c) emitter-base forward and collector-base reverse
(d) emitter-base reverse and collector-base forward

Q4. A transistor with both junctions forward biased operates in the:

(a) cut-off region
(b) active region
(c) reverse active region
(d) saturation region

Q5. The correct relation among the three currents of a transistor is:

(a) $I_E = I_B + I_C$
(b) $I_C = I_B + I_E$
(c) $I_B = I_C + I_E$
(d) $I_E = I_B - I_C$

Q6. If $\alpha = 0.98$, the value of β is:

(a) 0.02
(b) 49
(c) 98
(d) 51

Q7. A transistor has $\beta = 100$ and $I_B = 40\ \mu A$. The collector current is:

(a) 0.4 mA
(b) 2.5 mA
(c) 4 mA
(d) 40 mA

Q8. The phase difference between input and output voltages of a CE amplifier is:

(a) 0°
(b) 45°
(c) 90°
(d) 180°

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Q9. The configuration having the highest input resistance and lowest output resistance is:

(a) common collector
(b) common base
(c) common emitter
(d) none of these

Q10. The configuration whose current gain is less than unity is:

(a) common emitter
(b) common base
(c) common collector
(d) all of these

Q11. The quiescent (Q) point of an amplifier is defined by:

(a) the peak values of the AC signal
(b) V_{CC} and R_C only
(c) the DC values of I_C and V_{CE} with no signal applied
(d) the cut-off and saturation points only

Q12. The biasing circuit giving the best stability of the operating point is:

(a) base bias
(b) collector feedback bias
(c) emitter feedback bias
(d) potential divider bias

Q13. The stability factor S of a fixed (base) bias circuit is:

(a) $1 + \beta$
(b) 1
(c) β
(d) $1 - \beta$

Q14. According to the Barkhausen criteria, sustained oscillations require:

(a) $|A\beta| < 1$ and phase shift 180°
(b) $|A\beta| = 1$ and total phase shift 0° (or 360°)
(c) $|A\beta| = 0$
(d) $|A\beta| = 1$ and phase shift 90°

Q15. In a Colpitts oscillator, the feedback voltage is obtained from:

(a) a tapped inductor
(b) an RC network
(c) a capacitive voltage divider (C_1 and C_2)
(d) a quartz crystal

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Answer Key – MCQs

Q	Ans	Q	Ans	Q	Ans	Q	Ans	Q	Ans
1	**(b)**	4	**(d)**	7	**(c)**	10	**(b)**	13	**(a)**
2	**(c)**	5	**(a)**	8	**(d)**	11	**(c)**	14	**(b)**
3	**(c)**	6	**(b)**	9	**(a)**	12	**(d)**	15	**(c)**

Broad Questions (10 Questions)

Q1. Explain the construction of NPN and PNP transistors with neat sketches and symbols. Why are the emitter, base and collector doped and sized differently?

Q2. Explain with a neat diagram the operation of an NPN transistor in the active region. Show how the emitter, base and collector currents are related. How does the working of a PNP transistor differ?

Q3. Explain the active, saturation and cut-off regions of a transistor in terms of junction bias conditions. How is the transistor used as a switch?

Q4. Draw the circuit for obtaining the characteristics of a transistor in CE configuration. Draw and explain the input and output characteristics and mark the different regions. Define input and output resistance.

Q5. Draw and explain the input and output characteristics of a transistor in CB configuration. Define α and explain why the current gain is less than unity.

Q6. Distinguish between CB, CE and CC configurations in a tabular form with respect to input and output resistance, current gain, voltage gain, phase shift and applications.

Q7. Define α, β and γ and derive the relations $\beta = \alpha/(1 - \alpha)$ and $I_C = \beta I_B + (1 + \beta) I_{CBO}$. A transistor has $\alpha = 0.99$; find β and γ, and find I_C and I_B if $I_E = 5$ mA.

Q8. What is a Q-point? Explain the DC and AC load lines with a diagram. Describe the effect of the position of the Q-point on the output waveform. Why is the AC load line steeper than the DC load line?

Q9. What is meant by stabilization? Define stability factor and explain thermal runaway. With a circuit diagram explain the potential divider bias, derive the expression for I_C and find I_C and V_{CE} if $V_{CC} = 12$ V, $R_1 = 40$ kΩ, $R_2 = 10$ kΩ, $R_C = 2.2$ kΩ, $R_E = 1$ kΩ, $\beta = 100$.

Q10. Explain the working of a single stage CE amplifier with a circuit diagram and state the function of each component. Also explain the Barkhausen criteria, the working of a Colpitts oscillator and list three applications each of amplifiers and oscillators.

Best of luck!

- Revise the diagrams (Fig. 2.1 to Fig. 2.11), the stability-factor formulas and the solved examples before the examination.
- For more engineering notes, visit www.polynoteshub.co.in

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