Bipolar Junction Transistor Amplifier

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The Great Invention in 1948

Willium Shokley explaining their invention

Team : Willium Shokley, John Bardeen, Walter Brattain

Bell Laboratories, USA

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→ trend towards miniaturizing

The First-ever Transistor

World's First Transistor developed by Shokley, Bardeen and Brattain

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Early Developments

- 1948 The point-contact BJT is invented
- 1952 Junction field-effect transistor (JFET) is invented
- 1952 Single-crystal silicon is fabricated
- 1954 Oxide masking process is developed.

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* BJT is very small → To use in PCBs we need packages

* Package names and transistor names are different

Packages for BJT

- TO 18 , TO 39, TO 92, TO 99
- TO 5, TO247
- TO 3

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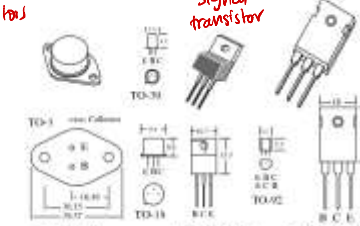
Package names imply standard dimensions

Packaging BJTs for practical use

Power transistors

Signal transistor

medium Power level transistor



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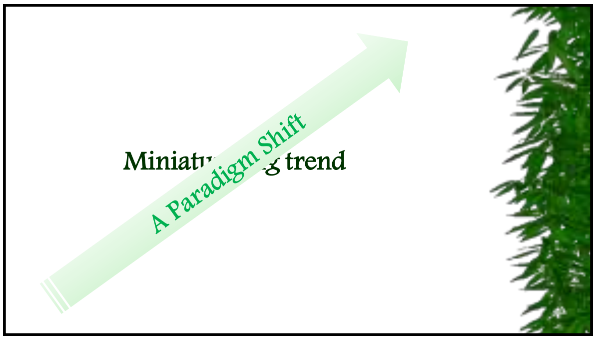

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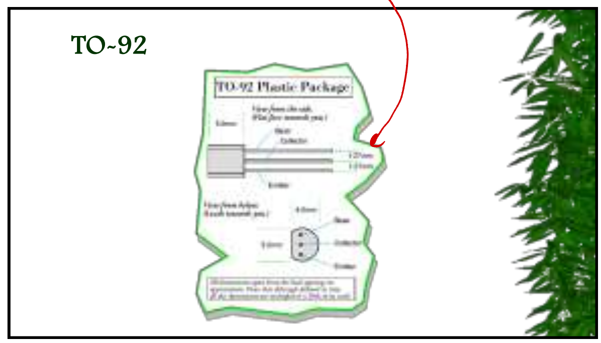
standardized (length between two pins)



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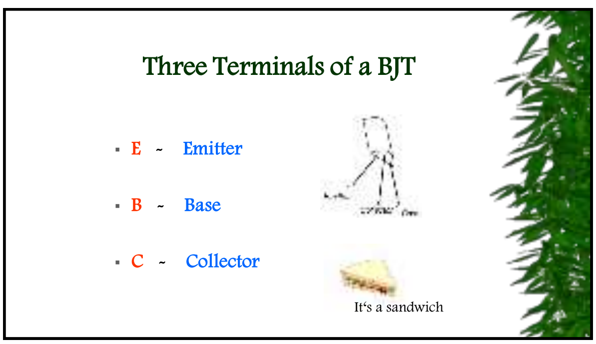

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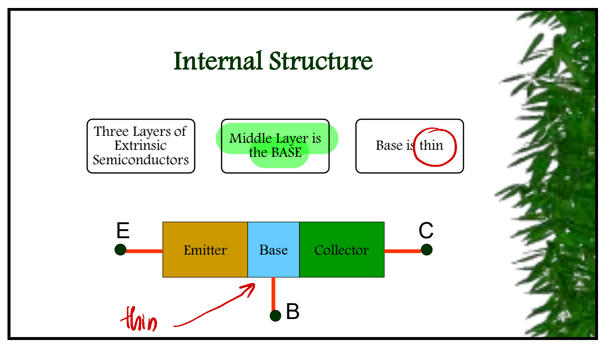

thin base

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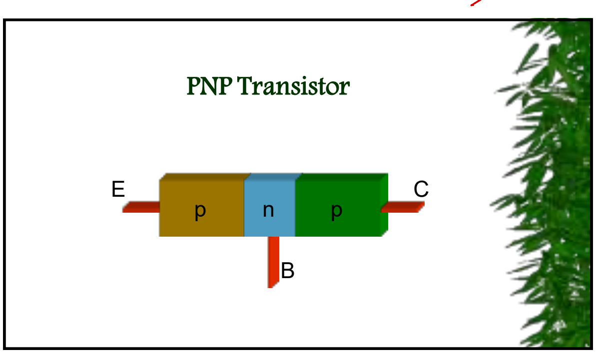
behavior is not exactly like this



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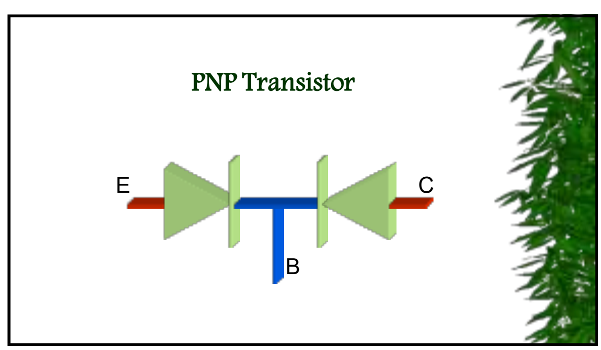

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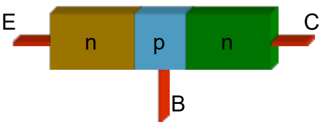
Why npn is popular?
npn majority carrier is electrons
electrons are faster than holes.

but can visualize as such.

How to check pnp/npn using multimeter?
Put multimeter to diode check mode and check E-B, BC junction

NPN Transistor



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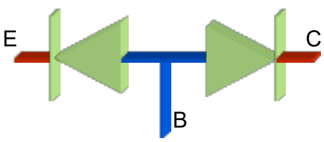
NPN Transistor



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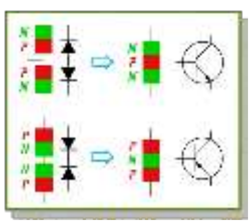
Operating modes
- Switching → digital
  - cut off state
  - saturation state
- Amplifying → analog
  - BE f. biased
  - BC r. biased
  - also called active state

Summary



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DC Bias & Operating Modes

According to DC bias

- Switching Mode (on off switch)
  - Cut-Off (OFF State)
  - Saturation (ON State)
- Amplifying Mode
  - BE Junction Forward Biased
  - BC Junction Reverse Biased

Active state

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Summary of Modes

Mode & State		BIAS	
		BE	BC
Switching	Cut-Off	Rev	Rev
	Saturation	Fwd	Fwd
Amplifying	Active	Fwd	Rev

our study is on this

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Analog & Digital

Analog Electronics	Digital Electronics
we study how transistors are used as amplifiers	we study how they are used as switching devices

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BJT as an Amplifier

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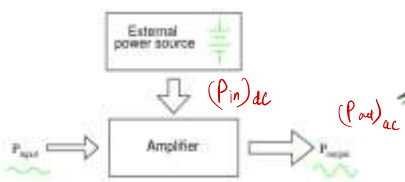
External power source is always needed!

Amplification



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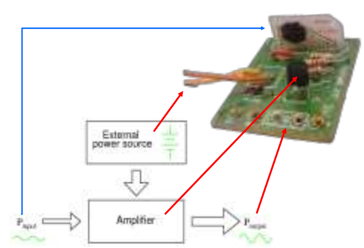
Power efficiency $= \eta = \dfrac{(P_o)_{signal}}{(P_{in})_{dc}}$

Amplification



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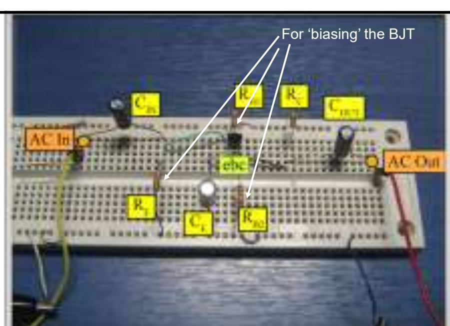

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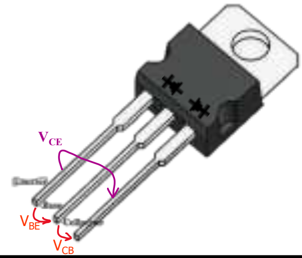
Biasing an NPN BJT for Amplifying Mode



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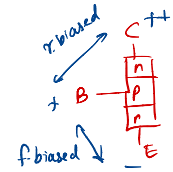
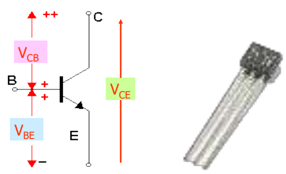
Why can't we give AC power for BJT amplifier?
— Can't forward bias using AC signals. DC bias is needed.



Biasing an NPN BJT for Amplifying Mode

B-E – f.b
C-B- r.b



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NPN BJT Biasing

- The Base must be more positive than the Emitter
- The Collector must be even more positive than the Base

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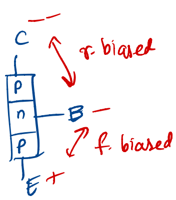
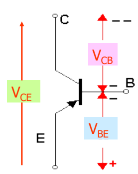
Biasing the PNP BJT





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Activity

If a PNP transistor is selected, The base terminal must be more negative than the emitter terminal in order to forward bias the B-E junction.

The collector terminal must be even more negative than the base terminal in order to reverse bias the B-C junction.

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3 voltages | 3 currents

Solution

If a PNP transistor is selected, The base terminal must be more NEGATIVE than the emitter terminal in order to forward bias the B-E junction.

The collector terminal must be even MORE NEGATIVE than the base terminal in order to reverse bias the B-C junction.

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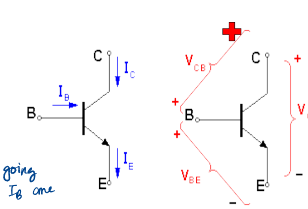
External Voltages and Currents



If I_E is going out I_C and I_B are coming in.

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Kirchoff's Current Law

$$I_E = I_B + I_C$$

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Internal Operation of BJT

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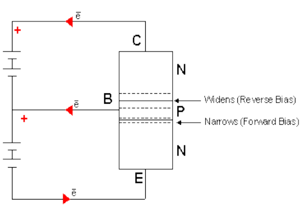
Junctions Biased by External DC sources



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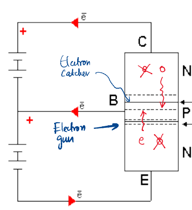
Junctions Biased by External DC sources



BC junction is reverse biased
Electric field exists in the depletion layer
Only the Minority carriers can cross it

BE Junction is forward biased
Majority carriers can cross BE junction

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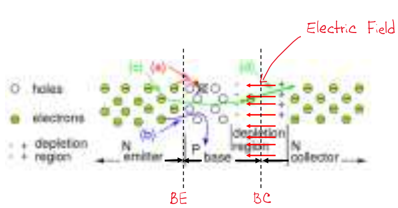
Behaviour of Current Carriers



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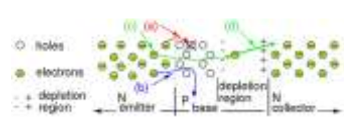
Transistor Action



- Majority carriers from emitter gets injected to the base at high velocity
- But the Base is thin
- Therefore most of them get caught in the electric field of BC junction
- They are swept to the Collector

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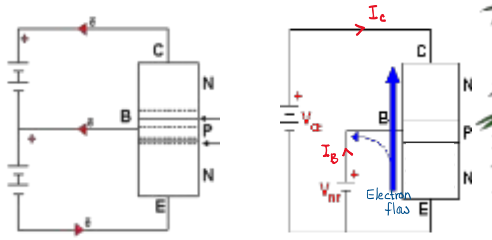
What's wrong?
No common ground
One battery is dependent on the other

Rearranging the Bias Supplies



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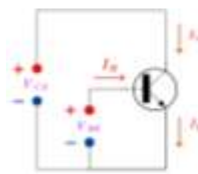
This arrangement is better.
Has common reference

Replacing BJT with its Symbol…



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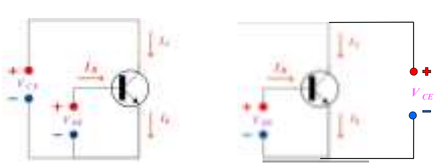
Cannot self limit currents ⇒ install series R

Separating Input and Output Terminals…



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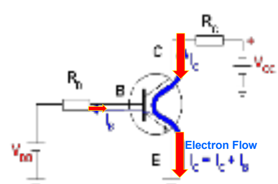
Limiting Currents with External Resistors



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Biasing → Before we amplify a A/c signal we need to put (B) to the correct mode of amplification

BJT Current Relationships

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Static Current Gain Concept

- Ratio between static output current and static input current.
- Also given as h_{FE} (for common emitter)

$$\beta = h_{FE} = I_C/I_B$$

Static current gain

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$$\alpha = h_{FB} = I_C/I_E$$

Alpha (α) = $\frac{I_C}{I_E}$ and Beta (β) = $\frac{I_C}{I_B}$

$\therefore I_C = \alpha . I_E = \beta . I_B$

as: $\alpha = \frac{\beta}{\beta + 1}$ $\beta = \frac{\alpha}{1 - \alpha}$

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$\alpha = \frac{\beta}{\beta+1}$ $\beta = \frac{\alpha}{1-\alpha}$

$$\boxed{\frac{1}{\alpha} = \frac{1}{\beta} + 1}$$

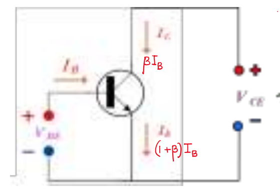
Current Relations

$I_C = \beta I_B$

$I_E = I_B + I_C$

$I_E = I_B + \beta I_B$

$I_E = (1 + \beta) I_B$



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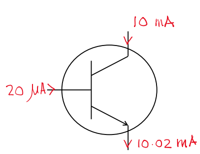
Example

- BC 109C BJT
- H_{FE} = 500 (Typ.)
- Find currents in the three terminals when the Base current is 20 μA ?



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Generating a Higher Force…

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Keyword – control

Current Control Concept

- Using a small current to *control* a larger current
- Collector current is determined by the base current.
- BJT is a current-controlled device.
- Controlling + Controlled =Emitter current

usually the base current

usually the collector current

- Current means; electron and hole movement

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* One current controls
One current is being controlled.

$I_C = \beta I_B$

controlled

controlling

Current = electron + holes

BJT Amplifier Configurations

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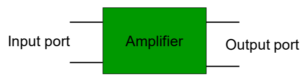
Microwave engineering - diods can amplify GHz range frequencies

An Amplifier

- An amplifier should have an input port and an output port (Four wires).



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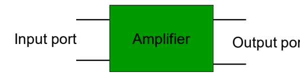
Two Ports from Three Terminals ?



- BJT is a three terminal device !
- Solution : Take one of it's terminals as a common terminal for both ports.

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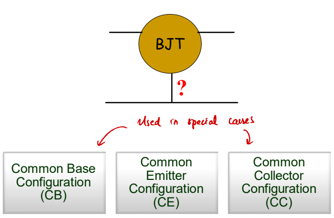
Three Amplifier Configurations



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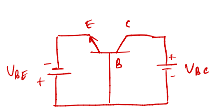
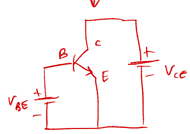
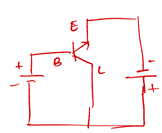
More popular







* Even though theoretical gain is possible it is not favourable because noise problems / interference can happ
Solution → Use one amplifier to another
(Cascading amplifiers)

one of the V/I gains is <1

Configuration	CE	CC	CB
Voltage Gain	High	<1	HIgh
Current Gain	High	High	<1
Power Gain	High	Moderate	Moderate
Phase Inversion	Yes	No	No
Input Impedance	Moderate (≈1K)	High (≈300K)	Low (≈50 Ohm)
Output Impedance	Moderate (≈50K)	Low (≈300 Ohm)	High (≈1M)

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Most common

Special occasions
eg: The first amplifier in mobile phones

BJT Characteristics

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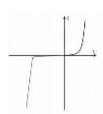
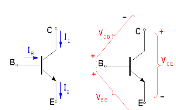
By taking one terminal common we can reduce the no. of variables

Number of Variables involved

- Diode
  - One current and one voltage



- BJT
  - Three currents and three voltages!
  - They are interdependent
  - How many characteristic graphs?



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Variables in an Amplifier Configuration

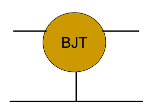
dependent

Input voltage

Input current

independent Variable

Because BJT is a current controlled device.



Independent Variable

Output voltage

Output current

dependent Variable

Four Variables
V_i, I_i, V_o, I_o

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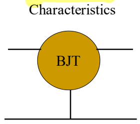
Static – because we're studying DC behaviour

Characteristics of a BJT

Mutual characteristics (also called)

Static Transfer Characteristics

Static Input Characteristics



Static Output Characteristics

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Three Characteristics of a BJT in a given Amplifier Configuration

We need this the most

- ☑ Static Output Characteristics
- Static Input Characteristics
- Static Transfer Characteristics
  - Mutual Characteristics

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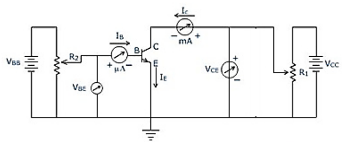
Test Circuit for CE Configuration



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Since we have 2 independent variable to plot V_E against I_E we have to keep V_0 constant.

Static Input Characteristics

- The plot of input current against input voltage
  - Keep the output voltage constant
  - Multiple curves for each constant value

Which value?

Separate graphs for each V_0 value we will get multiple curves

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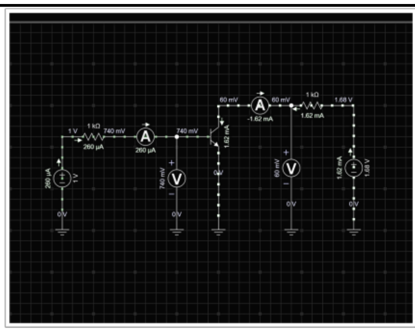
Output voltage is V_{CE} – constant



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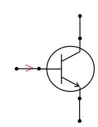
Static Input Characteristics for CE Configuration

- For CE configuration it is the plot of Base current vs Base voltage
  - Collector voltage is kept constant
  - Remember diode characteristics

Because it is a pn junction



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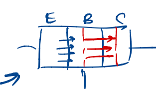
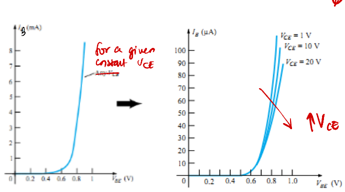
Why curve shifts down when V_{CE}↑ ?
V_{CE}↑ means widening the depletion layer
So more electrons would flow to the collector, reducing I_B current.



Basically we are plotting V/I characteristics of a diode

Static Input Characteristics



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* Everytime we change I_B V_{CE} will change. So we have to change V_{cc} so that V_{CE} will be the same value

Static Output Characteristics

- The plot of output current against output voltage
  - Keep the input current constant
  - Multiple curves for each constant value

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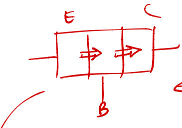
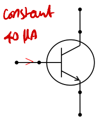


Collector current will saturate at one point. This is due to limited number of electrons.

Static Output Characteristics

- For CE configuration it is the plot of Collector current vs Collector voltage
  - Base current is kept constant

constant 40 μA



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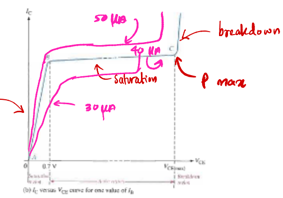
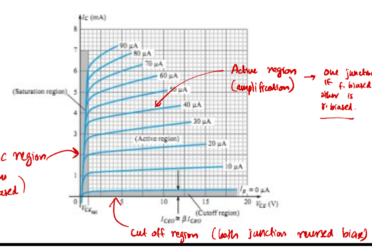
Static Output Characteristics



67 To increase the saturation level → increase the base bias (current)

Static Output Characteristics



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Static Transfer Characteristics

- The plot of output current against input current
  - Keep the output voltage constant → keep V_{CE} constant
  - Multiple curves for each constant value
- For CE configuration it is the plot of Collector current vs Base current
  - Collector voltage is kept constant
  - Linear behaviour

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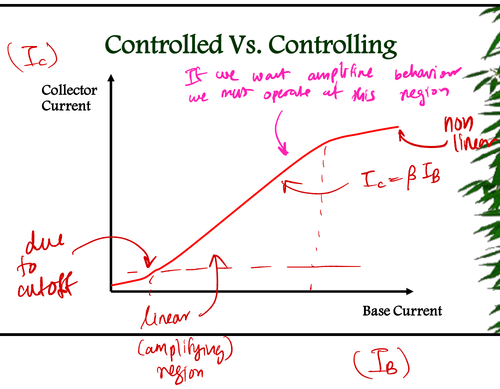
Controlled Vs. Controlling



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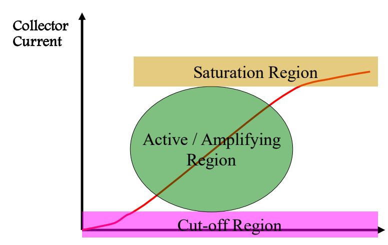
Controlled Vs. Controlling



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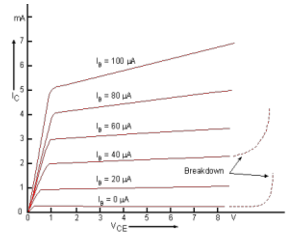
Typical Static Output Characteristics for CE



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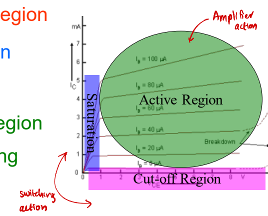
Three Regions

- Cut-off Region
- Saturation Region
- Active Region (Amplifying Region)



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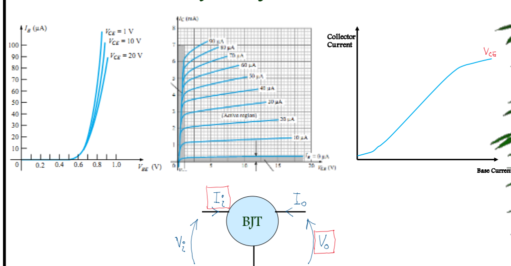
Summary of BJT Characteristics



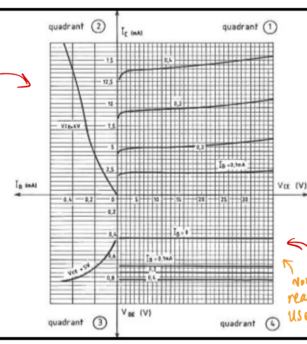
74

Manufacturers give all 3 graphs in one)

All Characteristics in one diagram

transfer

Input



output

Not really useful

75

Acts like a character certificate

BJT in Common Emitter Amplifier Configuration

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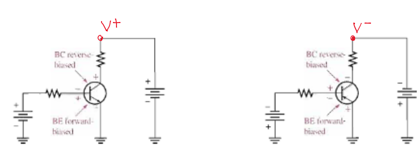
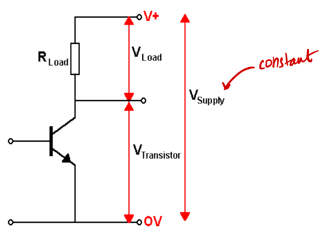
Biasing in CE Configuration



Have to put the ⓑ in amplifying region by choosing I_B

77

Output Side is a Potential Divider…



78

Kirchoff's Voltage Law

$$V_{LOAD} + V_{TRANSISTOR} = V_{SUPPLY}$$

constant

constant

$V_T \downarrow$ $V_{load} \uparrow$

$V_T \uparrow$ $V_{load} \downarrow$

79

Any device which display negative resistance can amplify.

increasing I decreases V and vice versa

($I_B \uparrow$ $V_{ce} \downarrow$)

A Negative Resistance ?

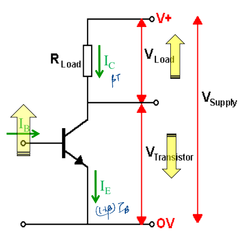
when $I_B \uparrow$ $I_C \uparrow$

$V_{load} \uparrow$

Then $V_{CE} \downarrow$

↓

negative resistance



80

Activity

When collector current is increased voltage across ……………… rises and voltage across ……………… decreases. When the input voltage increases, collector current ………………, and the voltage across the load …………………… . The output voltage is the C-E voltage across the transistor. It ………, as a result of the increase in load voltage.

81

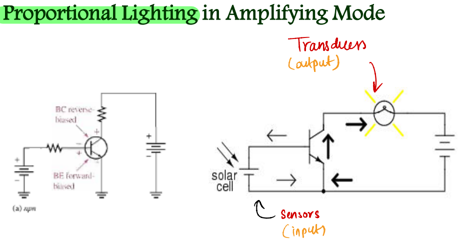
Answer

When collector current is increased voltage across the LOAD rises and voltage across TRANSISTOR decreases. When the input voltage increases, collector current RISES, and the voltage across the load RISES AS A RESULT. The output voltage is the C-E voltage across the transistor. It DROPS, as a result of the increase in load voltage.

82

Conceptualizing …

Proportional Lighting in Amplifying Mode



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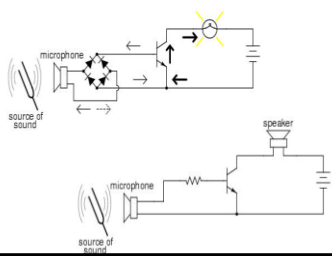
Lighting Proportional to Sound



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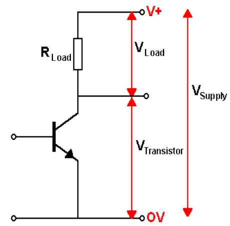
Plotting DC Load Line

85

DC Load Line



$V_{Load} = I_C \times R_L$

$V_{Transistor} = V_{CE}$

$V_{Supply} = V^{+} = V_{CC}$

Using Kirchoff's Voltage Law …

$V_{CE} + I_C \times R_L = V_{CC}$

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DC Load Line

$V_{CE} + I_C \times R_L = V_{CC}$

$I_C \times R_L = -(V_{CE}) + V_{CC}$

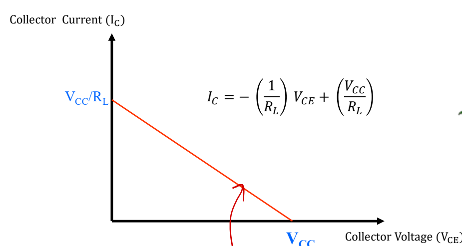
$$I_C = -\left(\frac{V_{CE}}{R_L}\right) + \left(\frac{V_{CC}}{R_L}\right)$$

$$I_C = -\left(\frac{1}{R_L}\right) V_{CE} + \left(\frac{V_{CC}}{R_L}\right)$$

$Y = m \cdot X + C$

87

DC Load Line is KVL in Graphical Form



$$I_C = -\left(\frac{1}{R_L}\right) V_{CE} + \left(\frac{V_{CC}}{R_L}\right)$$

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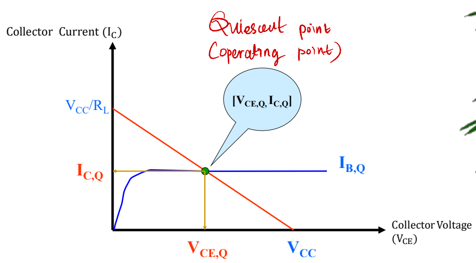
represent Kirchoff' law (as a graphical model)

Q-point can be marked on any of the three characteristics

Operating Point (Q Point)

Quiescent point (Operating point)



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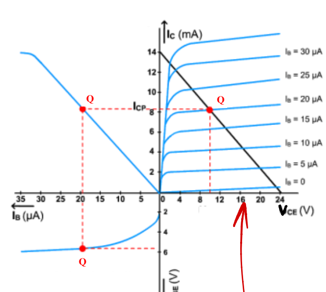
Operating Point (Q Point)



90

This quadrant is enough for analysis

BJT Biasing Techniques

1. Base Bias
2. Fixed Bias
3. Collector feedback bias
4. Potential divider bias

in 4th semester

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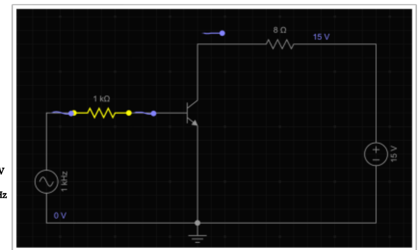
A Common Emitter BJT Amplifier ?

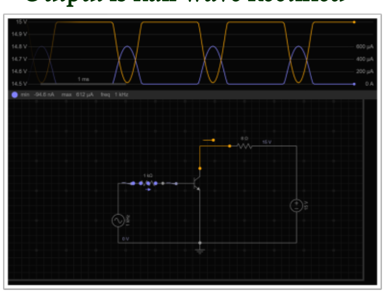
Amplitude 1.5 V
Frequency 1 kHz



92

No base bias.
(distorted audio)

Output is half wave Rectified



93

DC Bias on Terminals

- Transistor must be in its active mode throughout the entire cycle of the input AC signal. This is called 'Class A' operation.
- Solution :
- Superimpose the small input AC signal on a DC voltage.

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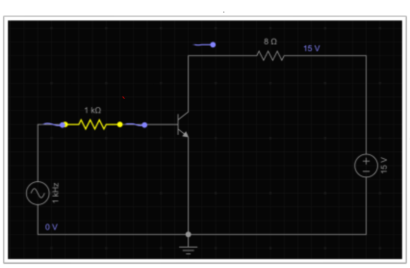
The Base Bias

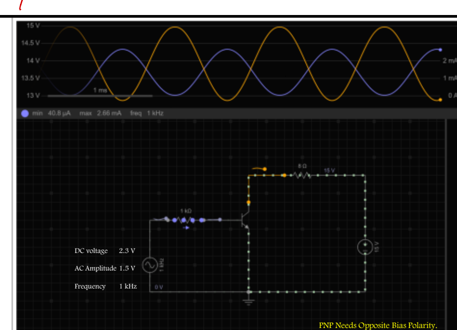
DC bias 2.3 V
Amplitude 1.5
Frequency 1 kHz



96

Not used in industry → Because we need 2 power supplys.
Not cost effective

This process is called base bias



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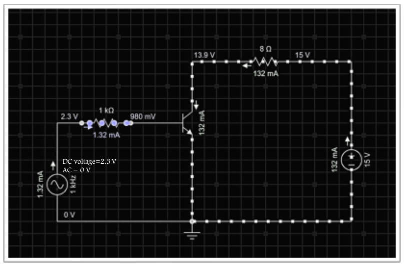
DC Analysis



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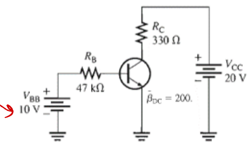
Ex. Base Bias Example

Let us analyze this circuit

Base Bias Power Supply



$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10\text{ V} - 0.7\text{ V}}{47\text{ k}\Omega} = 198\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = (200)(198\ \mu\text{A}) = \mathbf{39.6\ mA}$$

$$V_{CE} = V_{CC} - I_C R_C = 20\text{ V} - 13.07\text{ V} = \mathbf{6.93\ V}$$

$$I_B = \frac{10 - 0.7}{4.7}\ mA$$

$$I_C = \frac{10-0.7}{4.7} \times 200\ mA$$

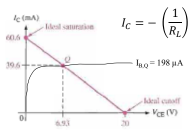
$$V_{CE} = 20 - \frac{10-0.7}{4.7} \times 200 \times 330 \times 10^{-3}$$

$$= 20 - \frac{10-0.7}{4.7} \times 66$$

Q point = [6.93V, 39.6 mA]

103

Maximum theoretical drive possible



$$I_C = -\left(\frac{1}{R_L}\right) V_{CE} + \left(\frac{V_{CC}}{R_L}\right)$$

$$I_{C(sat)} - I_{CQ} = 60.6\text{ mA} - 39.6\text{ mA} = 21\text{ mA}$$

$$I_{b(peak)} = \frac{I_{c(peak)}}{\beta_{DC}} = \frac{21\text{ mA}}{200} = \mathbf{105\ \mu A}$$

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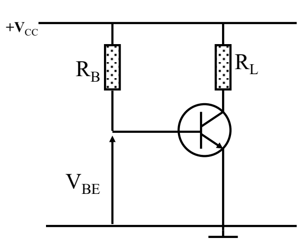
The Fixed Bias

105

Same power supply (economical)

But sacrificing certain amount of power wastage → reduce by using ↑R resistor

Fixed Bias Circuit



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Apply KVL

$V_{BE} + I_B.R_B = V_{CC}$

Analysis

$V_{BE} + I_B.R_B = V_{CC}$

$I_B.R_B = V_{CC} - V_{BE}$ — 0.7 V Typical

$I_{B,Q} = (V_{CC} - V_{BE,Q}) / R_B$

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Apply KVL

$V_{BE} + I_B.R_B = V_{CC}$

Designing

$V_{BE} + I_B.R_B = V_{CC}$

$I_B.R_B = V_{CC} - V_{BE}$ 0.7 V Typical

$R_B = (V_{CC} - V_{BE,Q}) / I_{B,Q}$

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Plotting DC Load Line

Selecting Static Output Characteristics

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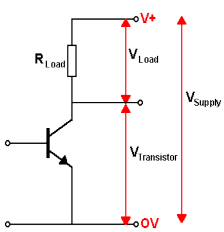
DC Load Line



$V_{Load} = I_C \times R_L$

$V_{Transistor} = V_{CE}$

$V_{Supply} = V^+ = V_{CC}$

Using Kirchoff's Voltage Law …

$V_{CE} + I_C \times R_L = V_{CC}$

110

DC Load Line

$V_{CE} + I_C \times R_L = V_{CC}$

$I_C \times R_L = -(V_{CE}) + V_{CC}$

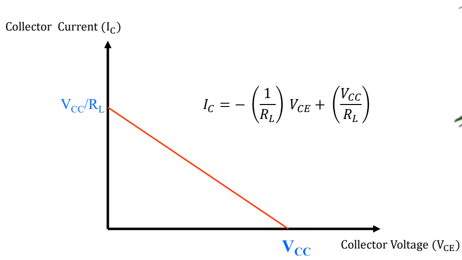
$$I_C = -\left(\frac{V_{CE}}{R_L}\right) + \left(\frac{V_{CC}}{R_L}\right)$$

$$I_C = -\left(\frac{1}{R_L}\right) V_{CE} + \left(\frac{V_{CC}}{R_L}\right)$$

$Y = m . X + C$

111

DC Load Line is KVL in Graphical Form



$$I_C = -\left(\frac{1}{R_L}\right) V_{CE} + \left(\frac{V_{CC}}{R_L}\right)$$

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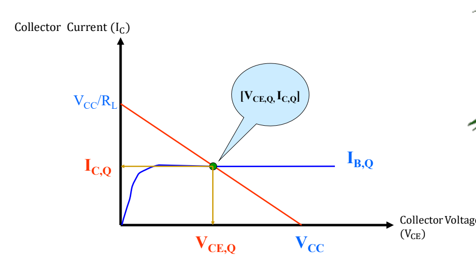
Operating Point (Q Point)



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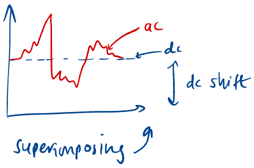

Feeding the Input

- Input signal is a small a.c. signal
  - Eg. Audio from a microphone
- Should ride on d.c. bias levels. This is known as superimposing.
- Use coupling capacitors
- Input coupling capacitor can superimpose small a.c. signal on base bias.

Watch this Video…
https://youtu.be/eF8e-FmtDh4

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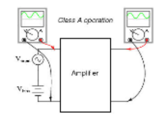
Signal to Ride on D.C.



- Input signal is elevated to level $V_{BE,Q}$
- Output DC level ($V_{CE,Q}$) is removed by output coupling capacitor

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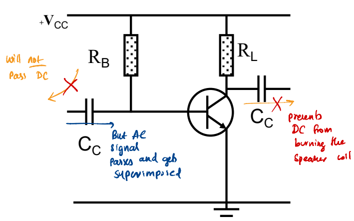
Common Emitter Amplifier with Fixed Bias



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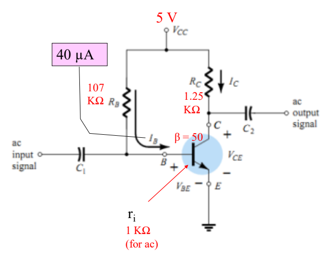
An Example Design



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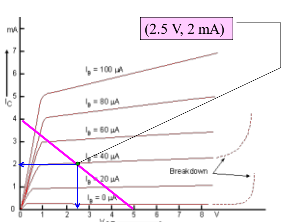
Load Line on Static Output Characteristics



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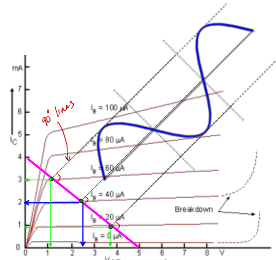
Load Line on Output Characteristics (Cont.)



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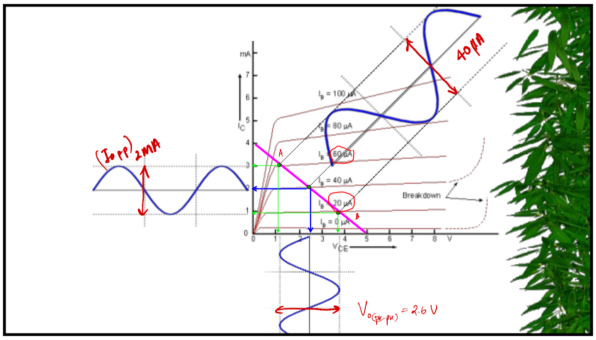
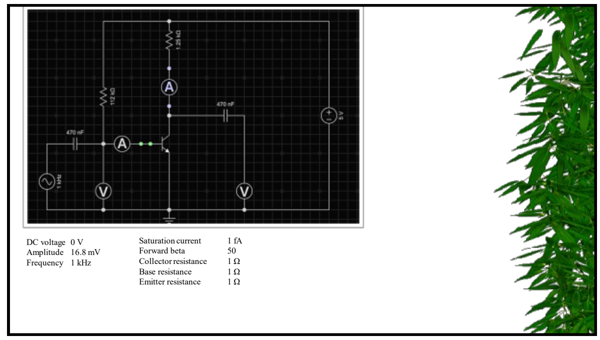
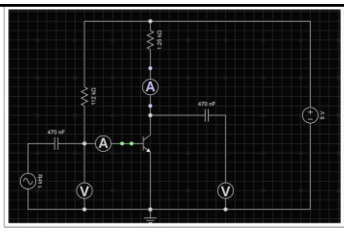
Q point will oscillate between
A and B



120



121



DC voltage 0 V
Amplitude 16.8 mV
Frequency 1 kHz

Saturation current	1 fA
Forward beta	50
Collector resistance	1 Ω
Base resistance	1 Ω
Emitter resistance	1 Ω

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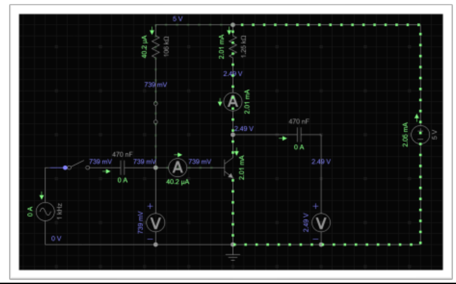
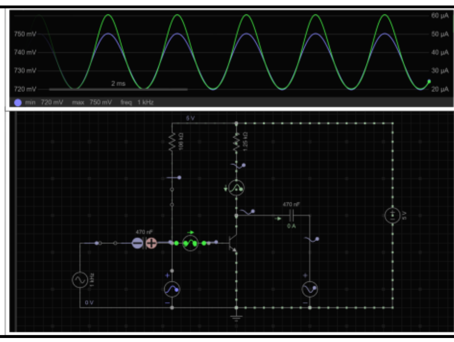
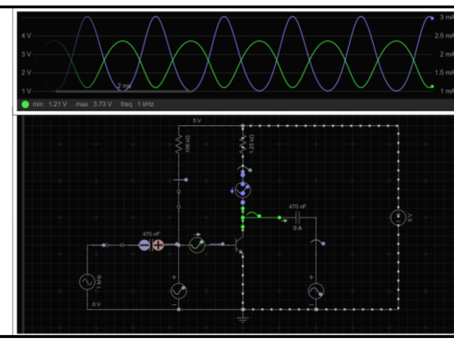
DC Analysis



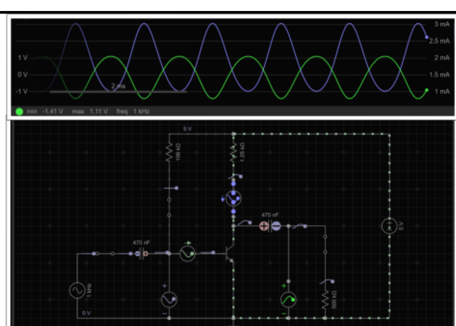
123



124



125



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Gain of an Amplifier

- Ratio between an output parameter and the corresponding input parameter
- Gain is specified in three ways
  - Power Gain (G)
  - Voltage Gain (A_v)
  - Current Gain (A_i)

127

$A_i = \frac{3-1 \ mA}{60-20 \ \mu A} = 50$

Current Gain of an Amplifier

- Ratio between the peak-peak output current variation and the peak-peak input current variation

* we only consider AC signal because we are amplifying that signal

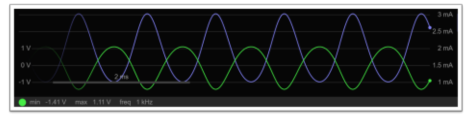
collector

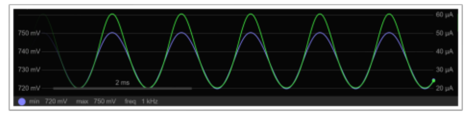
$$A_i = \frac{I_{o,(pk-pk)}}{I_{i,(pk-pk)}}$$

base

Ex. Find the current gain of the circuit

128





$$A_i = \frac{I_{o,(pk-pk)}}{I_{i,(pk-pk)}}$$

129

Voltage Gain of an Amplifier

- Ratio between the peak-peak output voltage variation and the peak-peak input voltage variation

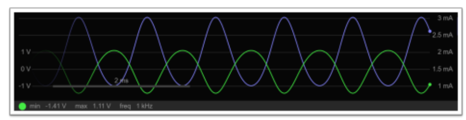
collector voltage

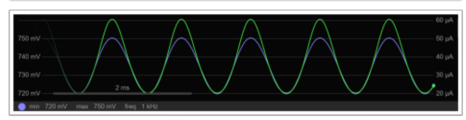
$$A_v = \frac{V_{o,(pk-pk)}}{V_{i,(pk-pk)}}$$

base voltage

Ex. Find the voltage gain of the circuit. Assume input resistance as 1 KΩ

130





$$A_v = \frac{V_{o,(pk-pk)}}{V_{i,(pk-pk)}}$$

131

$A_v = \frac{-2.41 V}{40 \times 10^{-6} \times 10^3} = -65$

input current pk-pk

input resistance

Power Gain of an Amplifier

- Ratio between the output signal power and the input signal power

$$G = \frac{P_o}{P_i}$$

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Power Gain of an Amplifier

Power = voltage x current

$$G = \frac{V_o . I_o}{V_i . I_i} = \left(\frac{V_o}{V_i}\right) . \left(\frac{I_o}{I_i}\right) = |A_v| . |A_i|$$

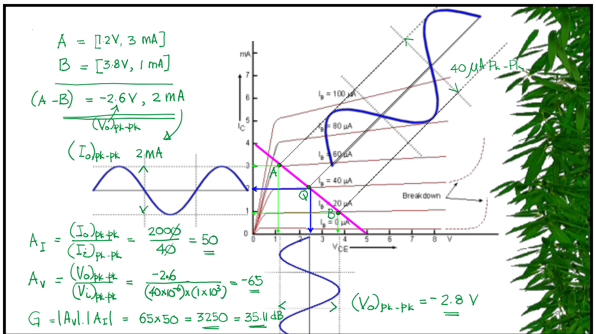
$$G = |A_v| . |A_i|$$

we don't consider the sign

Ex. Find the power gain of the circuit

133

$G = |50| \times |-65| = 3250$



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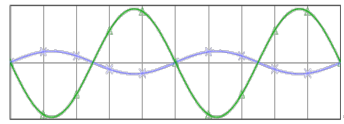
→ $10 \log_{10} |G|$ dB

When taking power gain from current/voltage use } $20 \log_{10} |A_i|$ eg: $20 \log |50|$

$20 \log_{10} |V_i|$ eg: $20 \log |-65|$

Input voltage vs. Output voltage



135

Phase Inversion

- Output voltage measured between emitter and collector on a common-emitter amplifier, is 180 degrees out of phase with the input voltage waveform.
- Common-emitter amplifier is called an *inverting* amplifier circuit.

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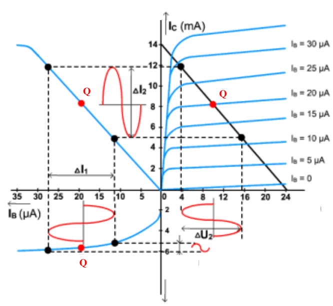
* Phase inversion is NOT an issue for audio amplification



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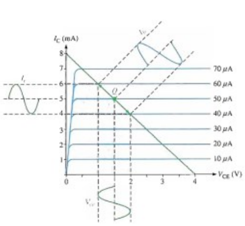
Ex. Calculate A_v, A_i and G



Assume R_i = 1 KΩ for BE junction

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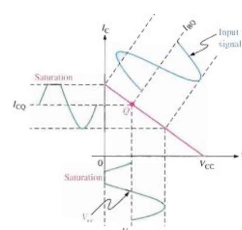
Incorrect Q Point



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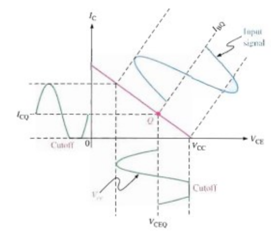
Important –
1. Location of the Q point
2. Drive level.

Incorrect Q Point

drive signal



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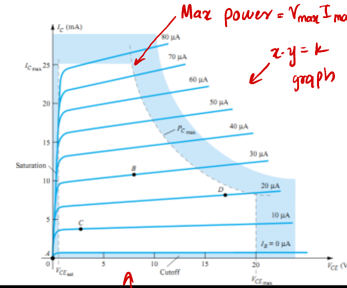
Q Point

Max power = $V_{max} I_{max}$

$x \cdot y = k$ graph

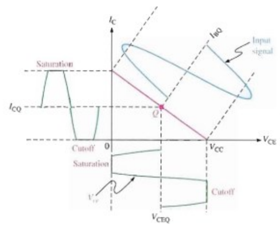


141

B is ideal.

Collector is physically larger

Too much drive…



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Thermal Runaway

- Power is dissipated in the collector and hence it is made physically larger than the emitter and base region.
- As the power is dissipated the collector base junction temperature increase. → reverse biased (leakage)
- The reverse leakage current I_{CBO} increases due to the flow of thermally generated minority carriers

$$\uparrow I_C = \alpha I_E + I_{CBO} \uparrow$$

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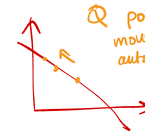
* Positive feedback loop

leakage current

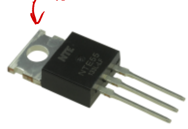


Q point moves upward automatically

Thermal Runaway

Manufac. heat sink

- Process is cumulative leading eventually to the destruction of the transistor.
- Thermal runaway can be prevented by using a heat sink.
- Emitter degenerative feedback can also be used.



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external heat sink

Emitter Degeneration with degenerative feedback

additional component

* We need stability of Q point

$\approx I_C$

$I_E R_E + V_{CE} + I_C R_C = V_{CC}$

$V_{CE} + I_C (R_C + R_E) \approx V_{CC}$ — ①

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

$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E}$

$(1+\beta) I_B$

$I_E R_E + V_{BE} + I_B R_B = V_{CC}$

$I_B \left[(1+\beta) R_E + R_B\right] = V_{CC} - V_{BE}$

$I_B = \frac{V_{CC} - V_{BE}}{(1+\beta) R_E + R_B}$

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When temp ↑, Voltage across R_E ↑

V_{BE} → V_{BE} ↓ → I_B ↓ → I_C ↓

same rise

Problem: voltage gain is reduced!

Solution: put an emitter bypass capacitor →

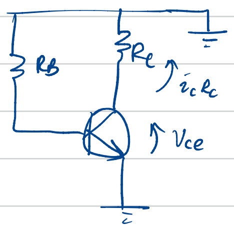
$X_C \lll R_E$

$\frac{1}{\omega C} \lll R_E$ → AC will flow through capacitor instead of R_E

* But now since AC goes through a different path we cannot use DC load line to get AC behaviour (gain calculations)
DC analysis and AC analysis are seperate.

Consider an a.c. load line

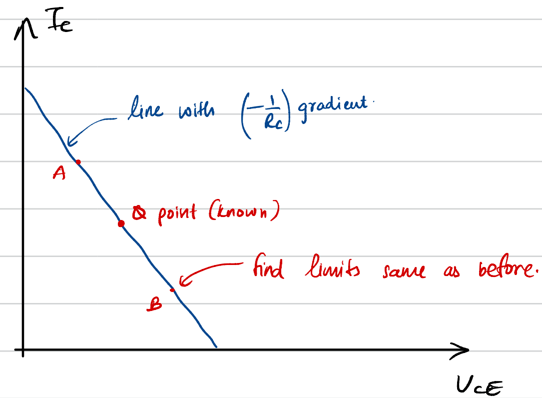
AC equivalent circuit →



$V_{ce} + i_c R_c = 0$

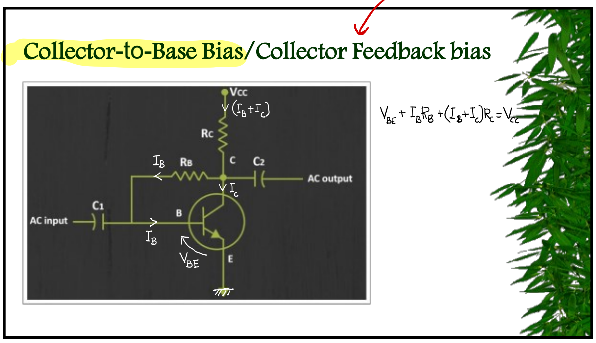
$i_c = -\frac{1}{R_c} V_{ce}$

gradient different



Another approach to stabilization

Name of the circuit changes



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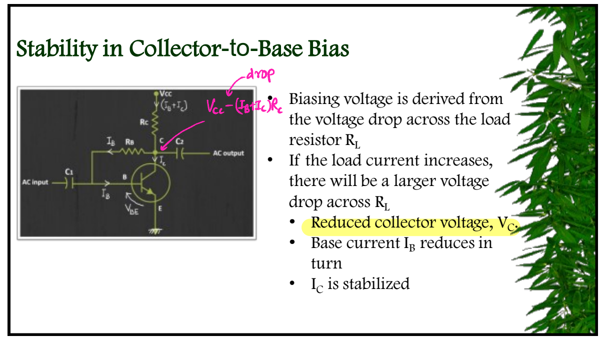
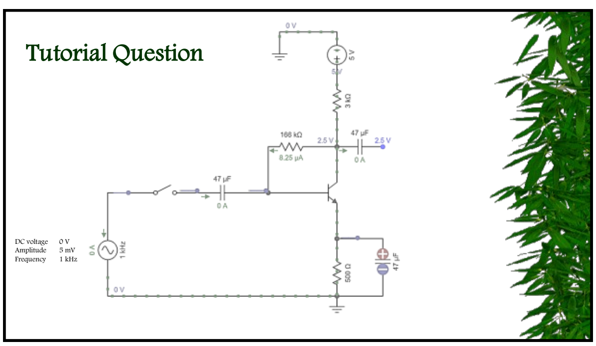
* 3 solutions to thermal runaway

1. heat sinks
2. Emitter degeneration
3. Collector-to-Base bias



147 $\theta\uparrow \rightarrow I_C\uparrow \rightarrow V_C\downarrow \rightarrow I_B\downarrow \rightarrow I_C\downarrow$



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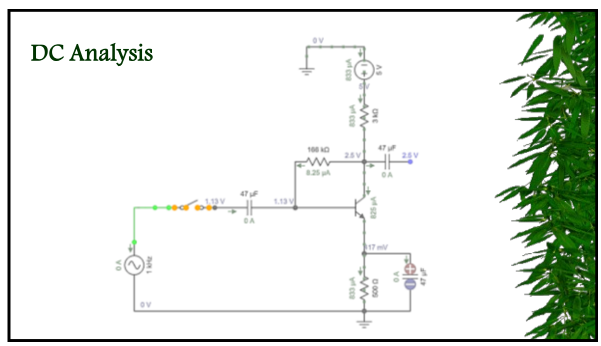

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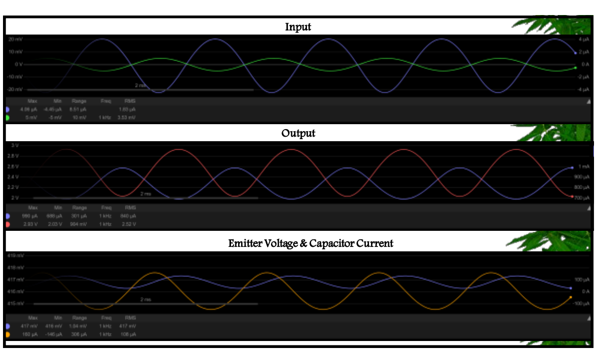

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