Bipolar Junction Transistors (BJTs)

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Outline

✓ Bipolar Junction Transistor (BJT)

- Introduction – Forward-Active Mode Operation
- CE Current-Voltage Characteristics
- DC Analysis of Transistor Circuits

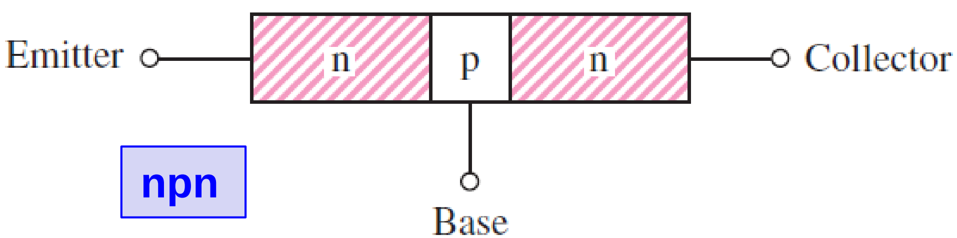
✓ Basic BJT Amplifiers

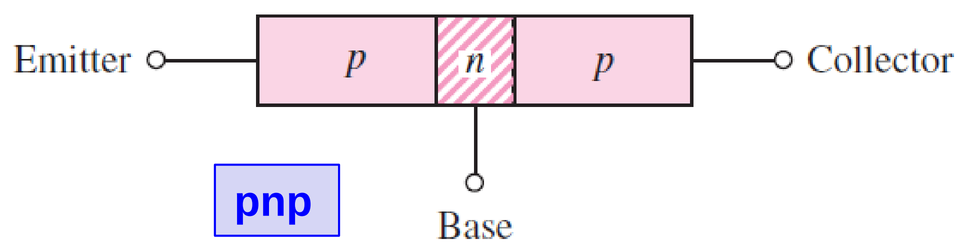
- Introduction – Analog Signals & Linear Amplifiers
- Small-Signal Hybrid–π Equivalent Circuit
- Small-Signal Voltage Gain
- Hybrid–π Equivalent Circuit, including Early Effect

Basic Bipolar Junction Transistor (BJT)

Transistor principle is that *the voltage between two terminals controls the current through the third terminal*.

- ✓ BJT has 3 separately doped regions & contains 2 pn junctions. A single pn junction has two modes of operation – forward and reverses biases.
- ✓ Bipolar transistor with 2 pn junctions, therefore has 4 possible modes of operation, which is one reason for the versatility of the device.
- ✓ With 3 separately doped regions, the bipolar transistor is a 3 terminal device. Current in the transistor is due to the flow of both electrons and holes, hence the name *bipolar*.



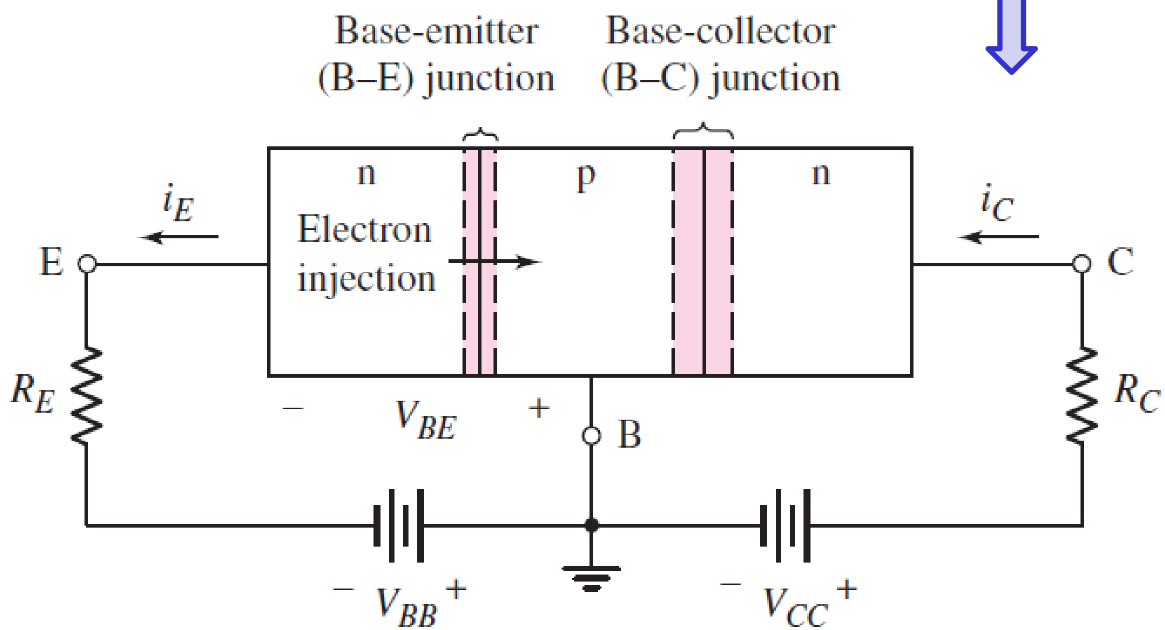


Forward-Active Mode Operation

- ✓ Since the transistor has 2 pn junctions, 4 possible bias combinations may be applied to the device, depending on whether a forward or reverse bias is applied to each junction.

- ✓ For example, if the transistor is used as an amplifying device, the **base-emitter (B-E) junction** is forward biased and the **base-collector (B-C) junction** is reverse biased, in a configuration called *forward-active operating mode,* or simply called the *active region*.

Since B-E junction is forward-biased, electrons from the emitter are injected across B-E junction into the base, creating excess minority carrier concentration in base. Since B-C junction is reverse-biased, the electron concentration at the edge of junction is 0.



Forward-Active Mode Operation

Emitter Current:

Since the B-E junction is forward biased, it is expected that the current through this junction is to be an exponential function of B-E voltage.

$$i_E = I_{EO}\left[e^{v_{BE}/V_T} - 1\right] \cong I_{EO}e^{v_{BE}/V_T}$$

The (-1) term is usually neglected since $v_{BE} \gg V_T$ in most cases. The flow of negatively charged electrons is through the emitter into the base and is opposite to the conventional current direction. The conventional emitter current direction is therefore out of the emitter terminal.

The multiplying constant I_{EO} contains electrical parameters of the junction, but is directly proportional to the active B-E cross-sectional area. Typical values of I_{EO} are in the range of $10^{-12} \sim 10^{-16}\ A$.

Forward-Active Mode Operation

Collector Current:

Since the doping concentration in the emitter is much larger than that in the base region, the vast majority of emitter current is due to injection of electrons into the base – these *injected electrons reach the collector*. The number of electrons reaching collector/unit time is proportional to function of B-E voltage.

$$i_C = I_S \, e^{v_{BE}/V_T}$$

- ✓ The collector current is controlled by the B-E voltage.
- ✓ The collector current is slightly smaller than the emitter current. Their relation can be shown as $i_C = \alpha i_E$.
- ✓ The coefficients can also be written as $I_S = \alpha I_{EO}$.
- ✓ The parameter α is called *common-base current gain*, always < 1.

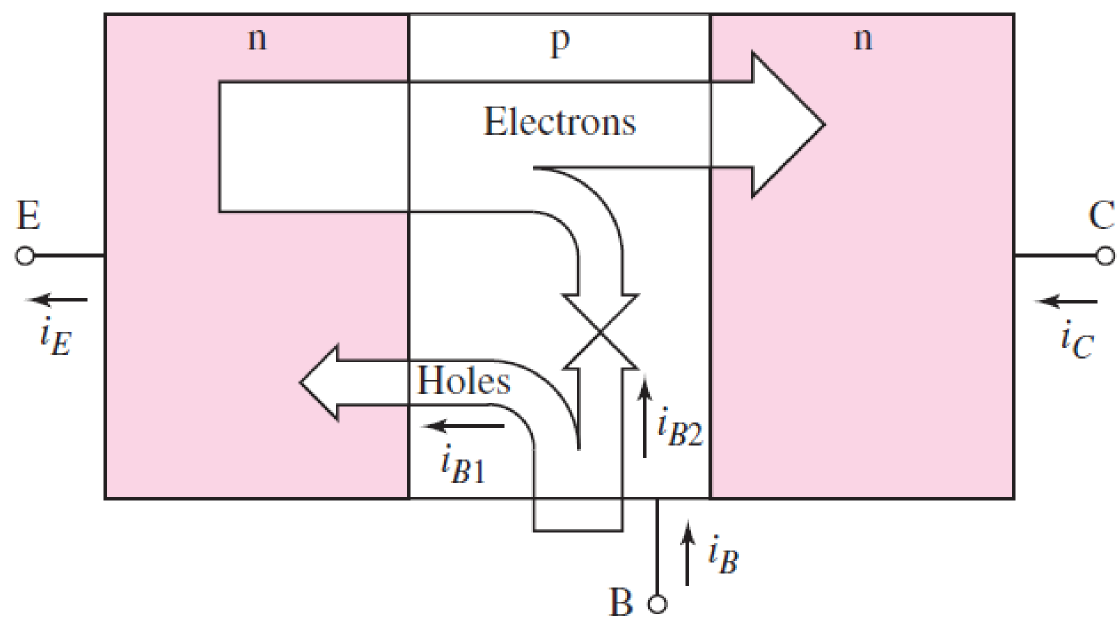
Forward-Active Mode Operation

Base Current:

Since the B–E junction is forward biased, holes from the base are injected across the B–E junction into the emitter. However, the flow of holes do not contribute to collector current & forms one component of base current, which is an exponential function of B-E voltage.

$$i_B \propto e^{v_{BE}/V_T}$$

$$i_B = i_{B1} + i_{B2}$$



Forward-Active Mode Operation

Common-Emitter (CE) Current Gain:

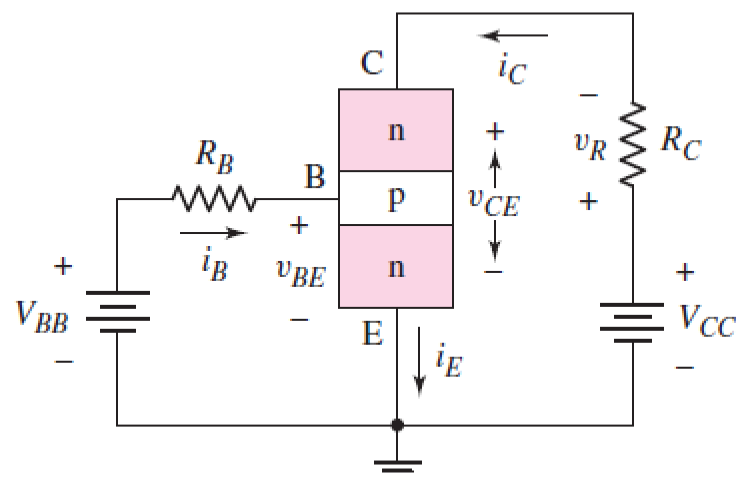
In the transistor, the rate of flow of electrons and the resulting collector current are an exponential function of the B–E voltage, as is the resulting base current – it means that the collector and base currents are linearly related.

$$\frac{i_C}{i_B} = \beta \rightarrow i_B = I_{BO} e^{v_{BE}/V_T} = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T}$$

The parameter β is *common-emitter current gain.*
It is considered as a constant, $50 < \beta < 300$.

✓ In the active region, B-E junction is forward biased and B-C junction is reverse biased.

✓ Base current is established by V_{BB} and R_B, and resulting collector current is $i_C = \beta i_B$.



Common-emitter configuration

$$V_{CC} = v_{CE} + i_C R_C$$

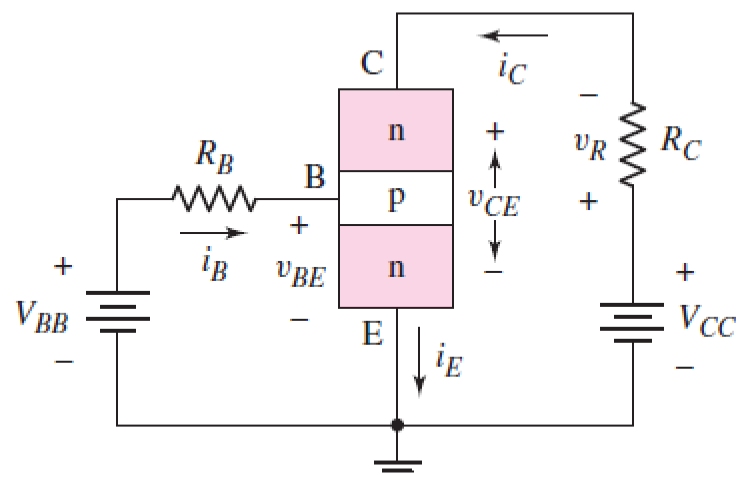
Forward-Active Mode Operation

Common-Emitter (CE) Current Gain:

- ✓ If bipolar transistor is considered as a single node, by using KCL, we get,

$$i_E = i_C + i_B$$

- ✓ If the transistor is biased in the forward-active mode, then $i_C = \beta i_B$.
- ✓ From the above equations, we can get the relationship, $i_E = (1+\beta)i_B$.
- ✓ Moreover, i_C & i_E are related as, $i_C = \left(\frac{\beta}{1+\beta}\right) i_E$
- ✓ Recall $i_C = \alpha i_E \rightarrow \alpha = \frac{\beta}{1+\beta}$



Common-emitter configuration

Forward-Active Mode Operation

Exercise–1: Assume a common-emitter (CE) current gain of $\beta = 150$ and a base current of $i_B = 15\ \mu A$. Moreover, assume that the transistor is biased in the forward-active mode. Calculate the collector current, emitter current, and common-base current gain.

Solution

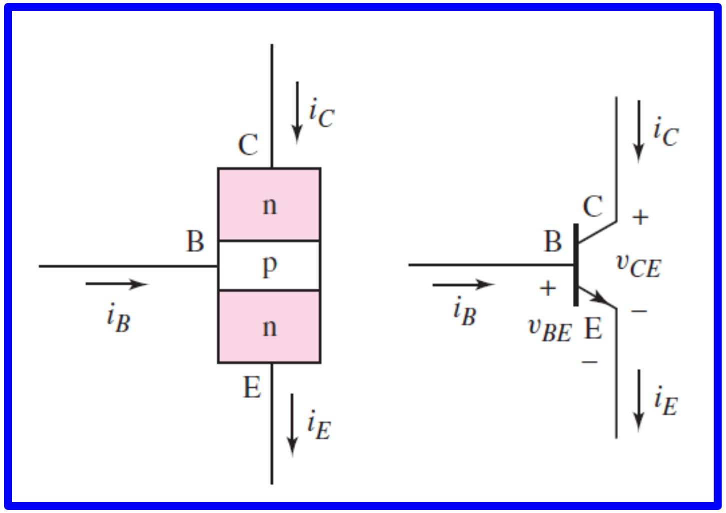
Collector current, $i_C = \beta i_B = 150 \times 15 = 2.25\ mA$.

Emitter current, $i_E = (1 + \beta) i_B = (1 + 150) \times 15 = 2.27\ mA$.

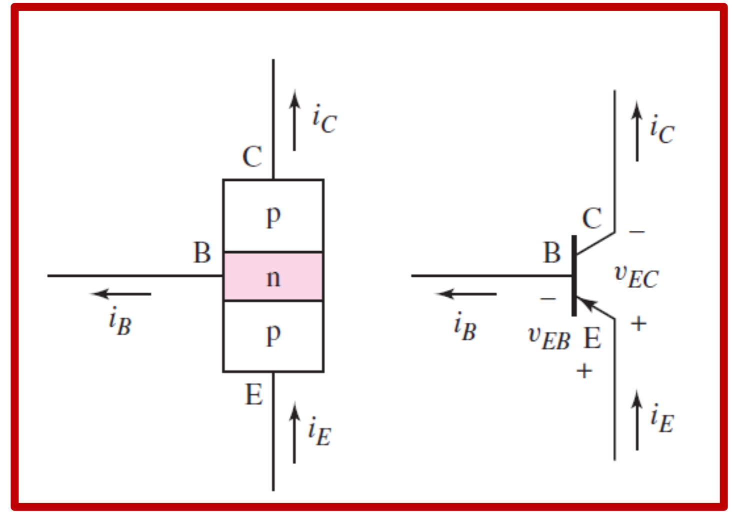
Common-base current gain, $\alpha = \frac{\beta}{1+\beta} = \frac{150}{1+150} = 0.9934$

BJT Symbols and Circuits

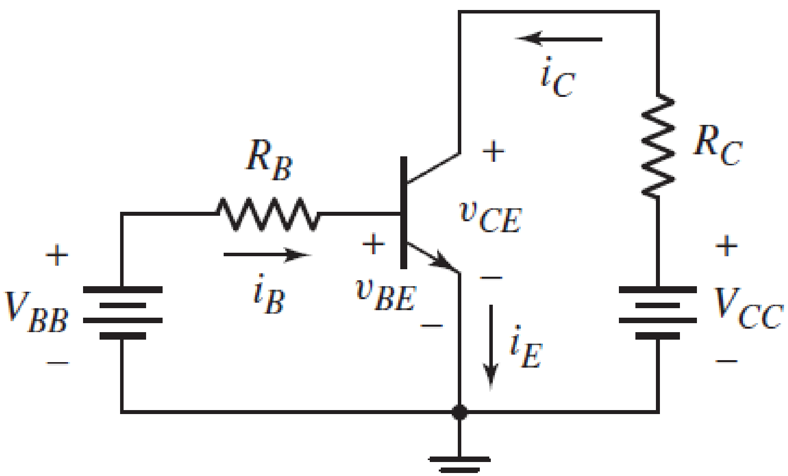
npn – transistor block diagram and symbol



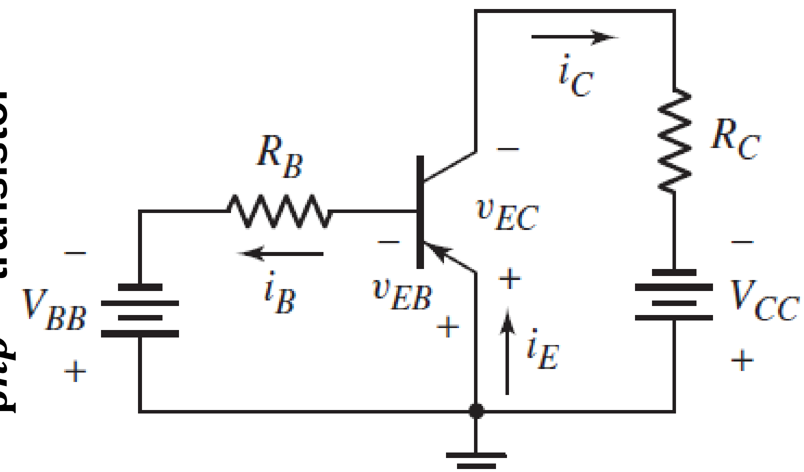
pnp – transistor block diagram and symbol



CE circuit with an *npn* – transistor

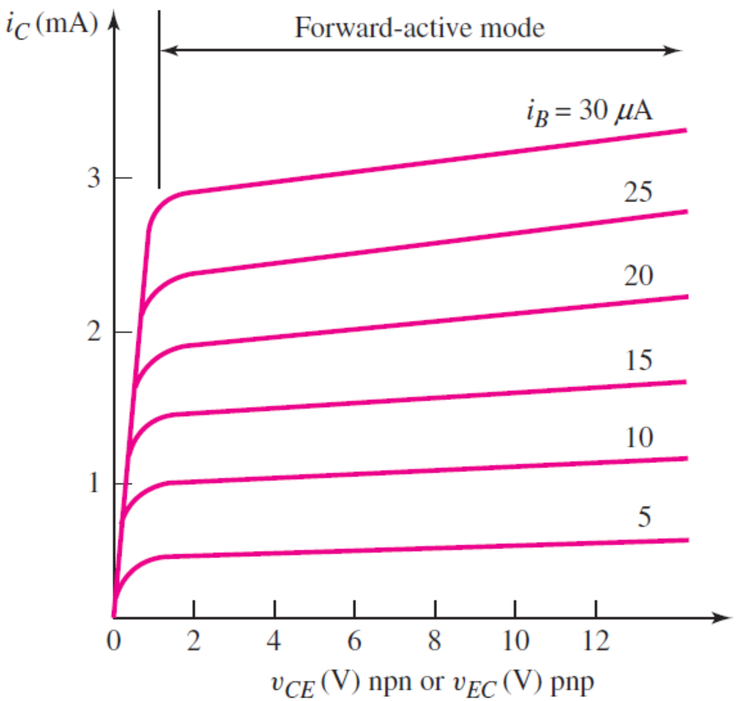


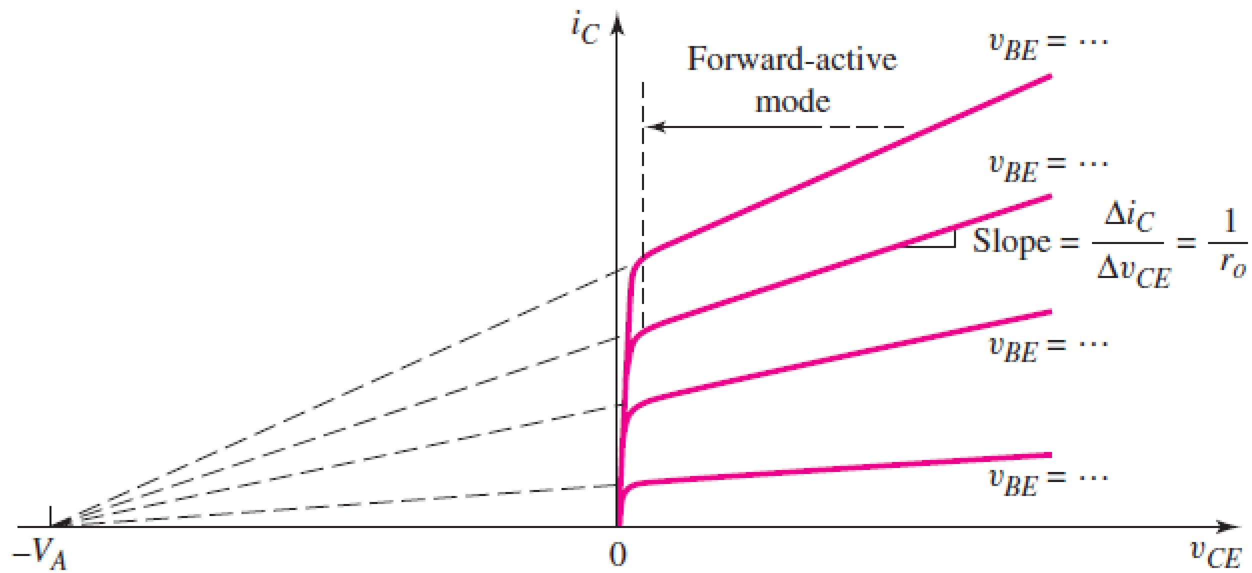
CE circuit with *pnp* – transistor



CE Circuit Current-Voltage Characteristics

The collector current is plotted against the collector–emitter voltage, for various constant values of the base current.





Exaggerated view plotted for constant values of B-E voltage

The slope in these characteristics is due to an effect called base-width modulation that was first analyzed by J. M. Early – called *Early effect*.

CE Circuit Current-Voltage Characteristics

- ✓ When the curves are extrapolated to zero current, they meet at a point on the negative voltage axis, at $v_{CE} = -V_A$. The voltage V_A is positive, called *Early voltage*. Typical values are in the range $50 < V_A < 300\ V$.

- ✓ The linear dependence of i_C vs v_{CE} in the forward-active mode can be as,

$$i_C = I_S\, e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$

- ✓ Non-zero slope of the curves indicates that the *output resistance* r_o looking into the collector is finite. This r_o is determined from, $\frac{1}{r_o} = \left.\frac{\partial i_C}{\partial v_{CE}}\right|_{v_{BE=Const}}$

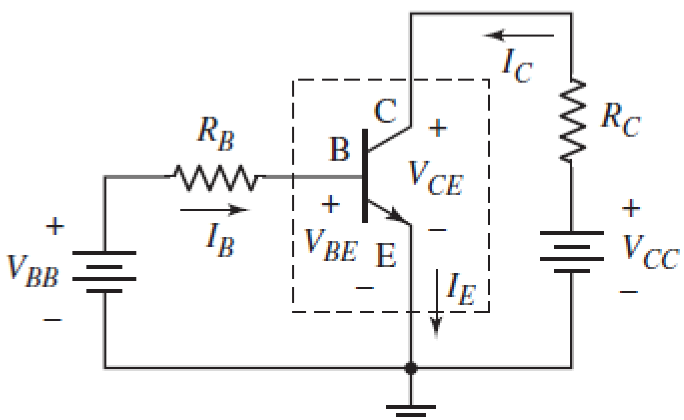
- ✓ Therefore, we can show that, $r_o \cong \frac{V_A}{I_C}$

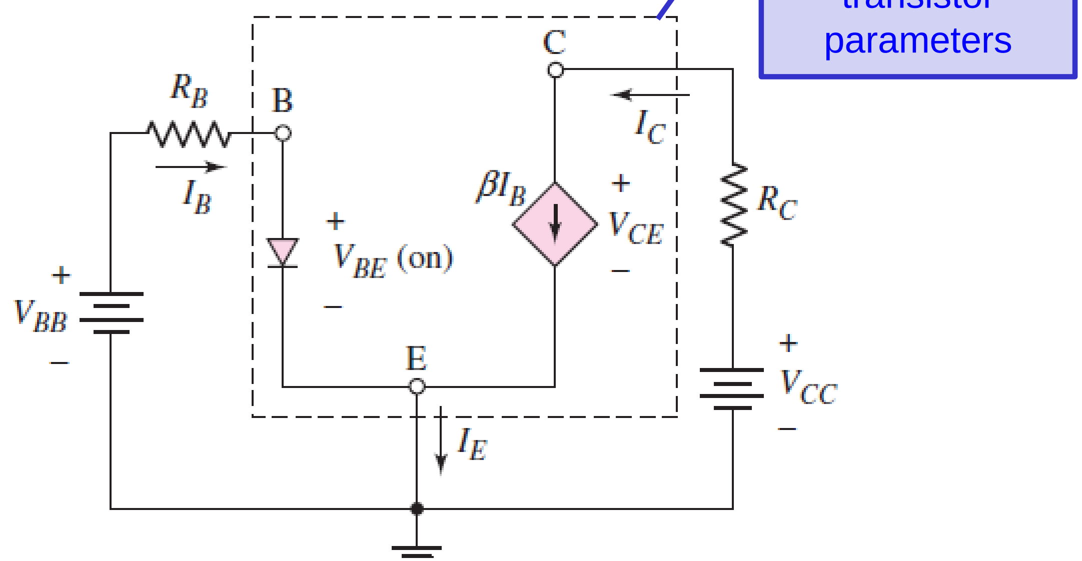
I_C is the quiescent collector current when v_{BE} is constant and $v_{CE} < v_A$.

DC Analysis of Transistor Circuits

- ✓ Now analyze and design the dc biasing of transistor circuits – an important part of designing bipolar amplifiers which is the focus of later syllabus.
- ✓ The *piecewise linear model of a pn junction* can be used for the dc analysis of bipolar transistor circuit.
- ✓ One of the basic transistor circuit configuration is *common-emitter (CE) circuit* – the *emitter terminal* is obviously at *ground potential*.

CE circuit with npn transistor





DC equivalent circuit

DC Analysis of Transistor Circuits

- ✓ Assume that the B-E junction is forward-biased so that the voltage drop across that junction is cut-in or turn-on voltage $V_{BE}(on)$.
- ✓ When the transistor is biased in forward-active mode, the *collector current* is represented as a dependent current source, function of base current.
- ✓ Neglect the reverse-biased junction leakage current and Early effect.

The base current is, $I_B = \frac{V_{BB}-V_{BE}(on)}{R_B}$

It is implicit that $V_{BB} > V_{BE}(on) \rightarrow I_B > 0$. If $V_{BB} < V_{BE}(on)$, transistor is cut off & $I_B = 0$.

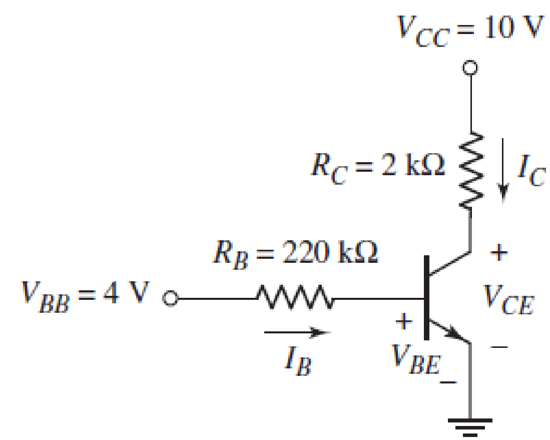
In the collector-emitter portion, we can write

$I_C = \beta I_B$, and $V_{CC} = I_C R_C + V_{CE}$ (or) $V_{CE} = V_{CC} - I_C R_C$

It is also implicit that $V_{CE} > V_{BE}(on)$, which means B-C junction is reverse biased and the transistor is biased in the forward-active mode.

DC Analysis of Transistor Circuits

Exercise–2: For the circuit shown below, the parameters are: $V_{BB} = 4\ V, R_B = 220\ k\mathbf{\Omega}, R_C = 2\ k\mathbf{\Omega}, V_{CC} = 10\ V, V_{BE}(on) = 0.7\ V\ \&\ \beta = 200$. Calculate the base, collector, and emitter currents and also CE voltage.



Solution

Base current, $I_B = \frac{V_{BB} - V_{BE}(on)}{R_B} = \frac{4 - 0.7}{220} = 15\ \mu A$.

Collector current, $I_C = \beta i_B = 200 \times 15 \times 10^{-6} = 3\ mA$

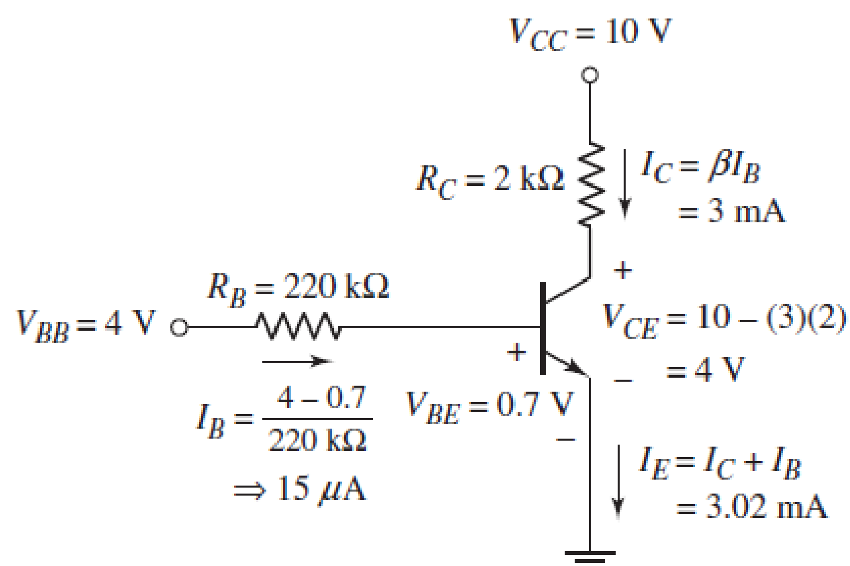
Emitter current, $I_E = (1 + \beta) i_B$

$$= (1 + 200) \times 15 \times 10^{-6}$$

$$= 3.02\ mA.$$

CE voltage, $V_{CE} = V_{CC} - I_C R_C$

$$= 10 - 3 \times 2 = 4\ V$$



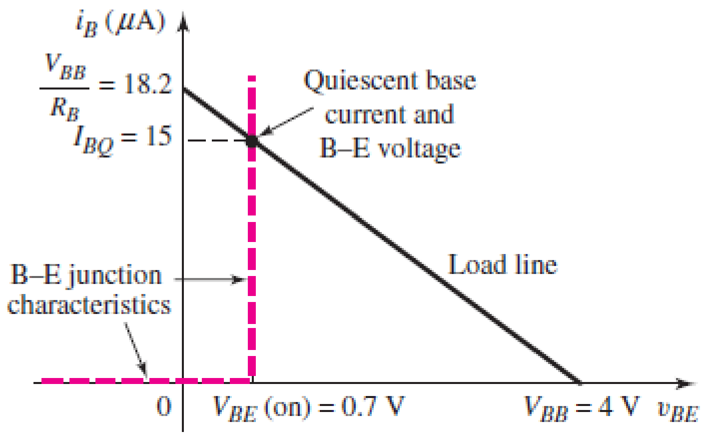
DC Analysis – Load Line & Modes of Operation

- ✓ Load line helps in visualizing the characteristics of a transistor circuit.
- ✓ For the CE circuit shown in the previous example: see the piecewise linear characteristics for the B-E junction and the input load line. Output load line from KVL around CE loop as $V_{CE} = V_{CC} - I_C R_C \rightarrow I_C = \frac{V_{CC}}{R_C} - \frac{V_{CE}}{R_C}$.

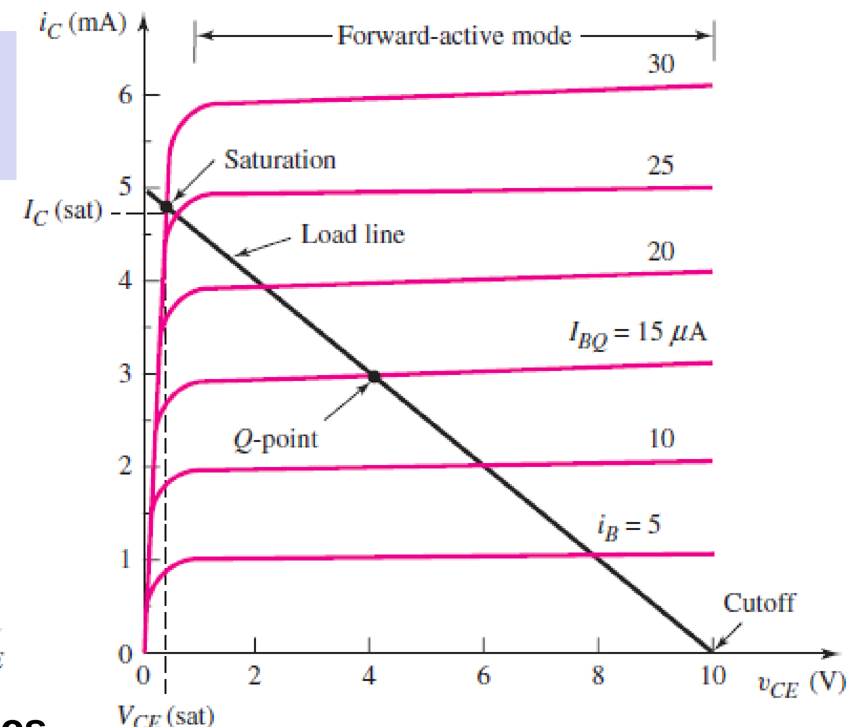
The *quiescent point* or *Q-point*, of the transistor is given by the dc collector currents & C-E voltage.

Input load line is obtained from KVL around BE loop as,

$$I_B = \frac{V_{BB}}{R_B} - \frac{V_{BE}}{R_B}$$



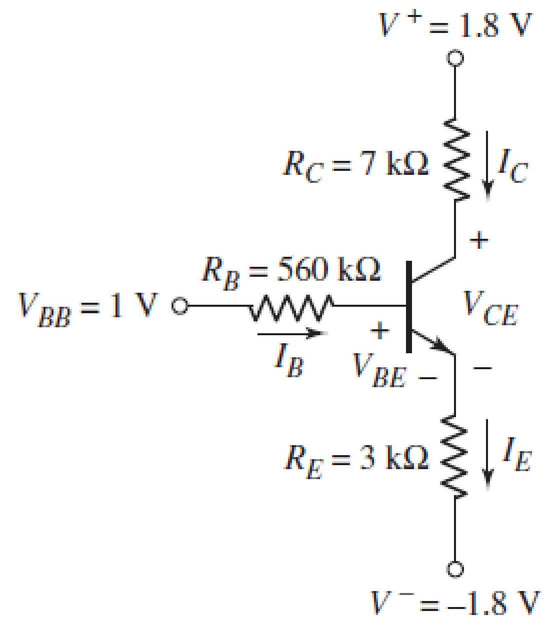
BE piecewise linear characteristics and input load line



CE characteristics and load line

Characteristics containing an emitter resistor

Exercise–3: For the circuit shown below, the parameters are: $V_{BE}(on) = 0.7\ V$ & $\beta = 75$. Calculate the characteristics of circuit including an emitter resistor. Note that the circuit has both positive & negative supply voltages.



Solution (Q –point values)

KVL around B-E loop, $V_{BB} = I_B R_B + V_{BE}(on) + I_E R_E + V^-$
Assume transistor is biased in forward-active mode and $I_E = (1+\beta) I_B$, we can then write base current as,

$$I_B = \frac{V_{BB} - V_{BE}(on) - V^-}{R_B + (1+\beta) R_E} = \frac{1 - 0.7 - (-1.8)}{560 + (76)(3)} = 2.665\ \mu A.$$

Collector current, $I_C = \beta i_B = 75 \times 2.66 \times 10^{-6} = 0.2\ mA$

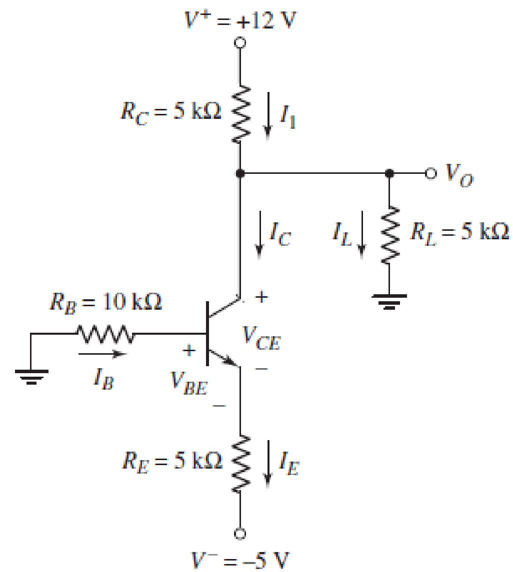
Emitter current, $I_E = (1+\beta) i_B = (1+75) \times 2.66 \times 10^{-6} = 0.203\ mA$

CE voltage, $V_{CE} = V^+ - I_C R_C - I_E R_E - V^- = 1.59\ V$

Characteristics containing an load resistance

Exercise–4: For the circuit shown below, the parameters are: $V_{BE}(on) = 0.7\ V$ & $\beta = 100$. Calculate the characteristics of circuit with a load resistance. Note that the load resistance can represent a second transistor stage.

Solution (Q –point values)



KVL around B-E loop, $I_B R_B + V_{BE}(on) + I_E R_E + V^- = 0$

Assume $I_E = (1+\beta) I_B$, then

$$I_B = \frac{-(V^- + V_{BE}(on))}{R_B + (1+\beta) R_E} = \frac{-(-5+0.7)}{10+(101)(5)} = 8.35\ \mu A.$$

Collector current, $I_C = \beta i_B = 100 \times 8.35 = 0.835\ mA$

Emitter current, $I_E = (1+\beta) i_B = (1+100) \times 8.35 = 0.843\ mA$

At collector node, $I_C = I_1 - I_L = \frac{V^+ - V_O}{R_C} - \frac{V_O}{R_L} \rightarrow 0.835 = \frac{12 - V_O}{5} - \frac{V_O}{5} \rightarrow V_O = 3.91$

CE voltage, $V_{CE} = V_O - I_E R_E - V^- = 4.7\ V$

Basic BJT Amplifiers (Introduction)

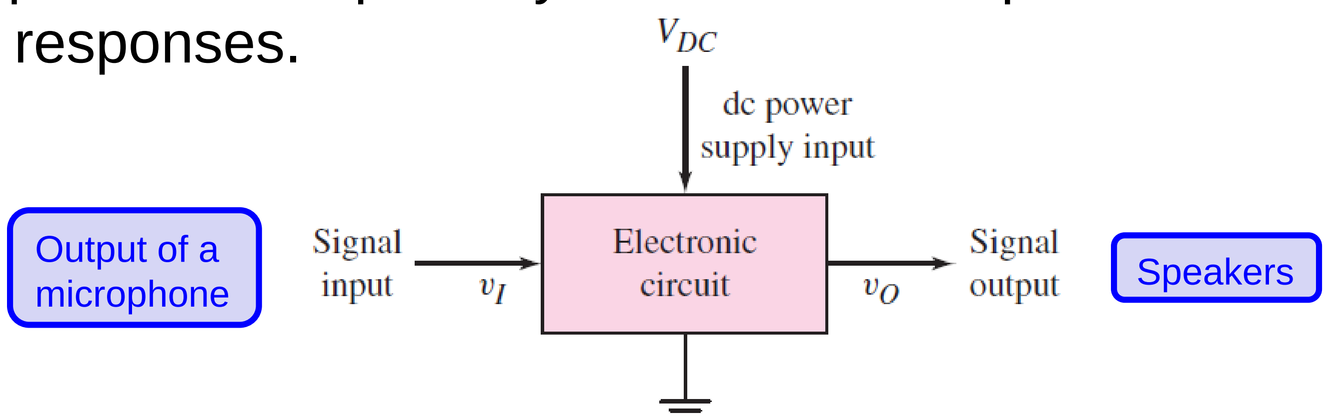
Introduction

- ✓ Electronic circuits that process analog signals – *analog circuits* (ex: linear amplifier). It *magnifies* an input signal and produces an output signal whose *magnitude is larger* and directly proportional to the input signal.

- ✓ **Time-varying signals** from a particular source very often need to be amplified before the signal is capable of being useful.

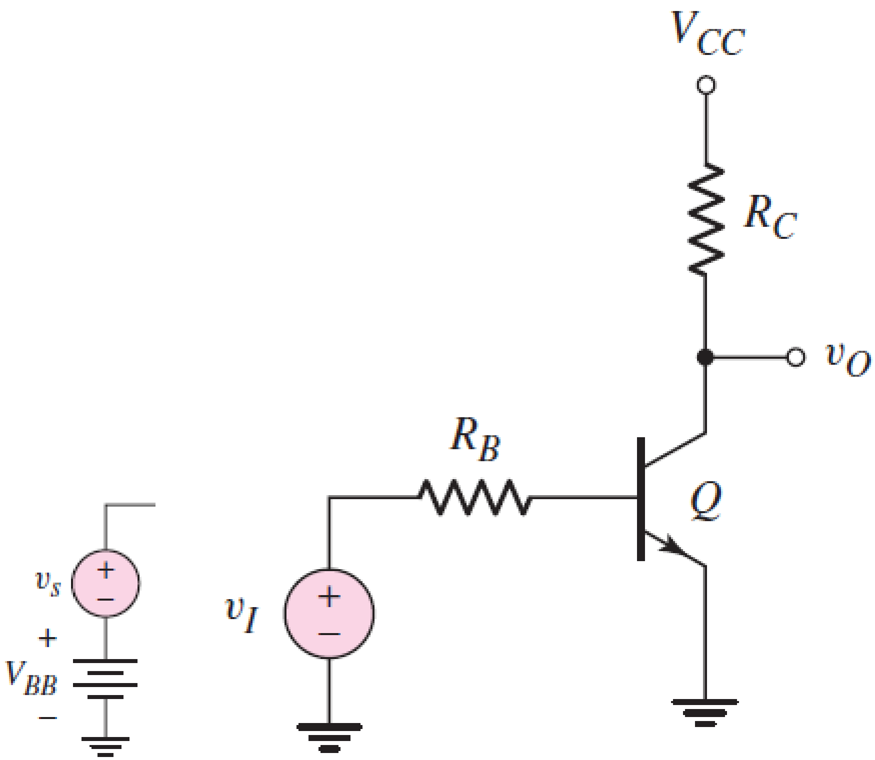
- ✓ Analyse & design linear amplifiers that use bipolar transistors as the amplifying device. **Small-signal –** linearizes the ac equivalent circuit.

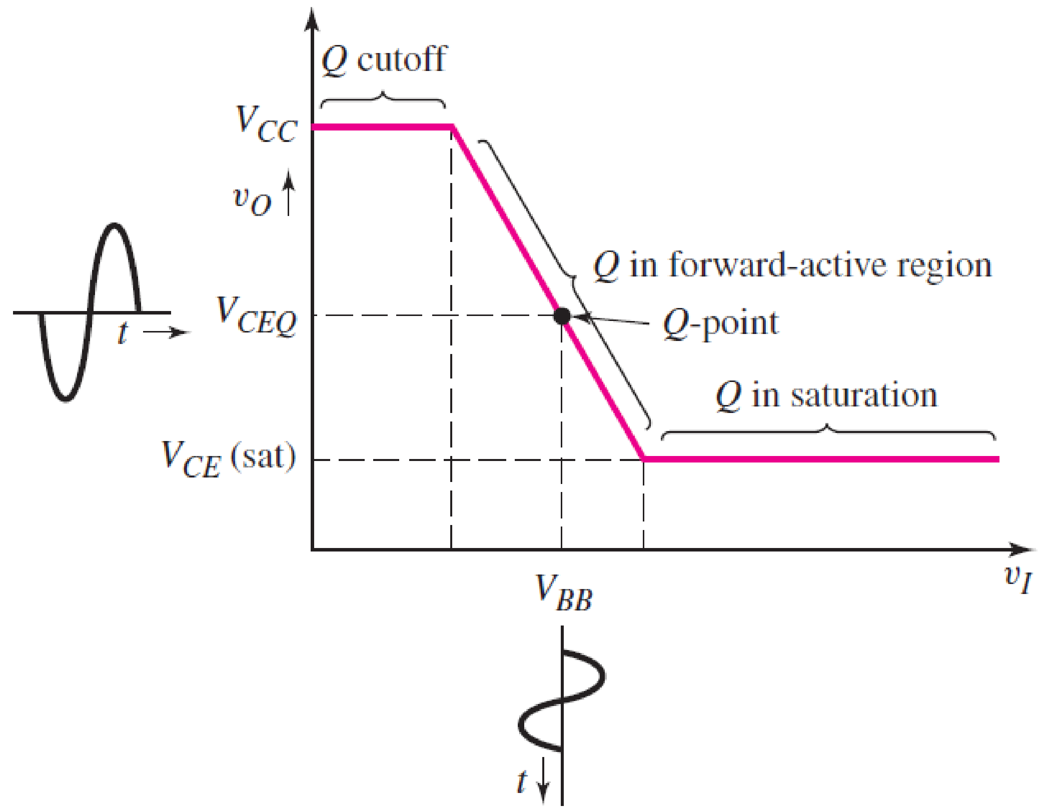
- ✓ *Linear amplifier* – use superposition so that the dc analysis & ac analysis of the circuits can be performed separately and the total response is the sum of two individual responses.



Bipolar Linear Amplifier

✓ Transistor is the heart of amplifier – Bipolar transistors have traditionally been used in linear amplifiers due to their high gain. V_{BB} is a dc voltage to bias the transistor at a particular Q –point & v_s is ac signal to be amplified.

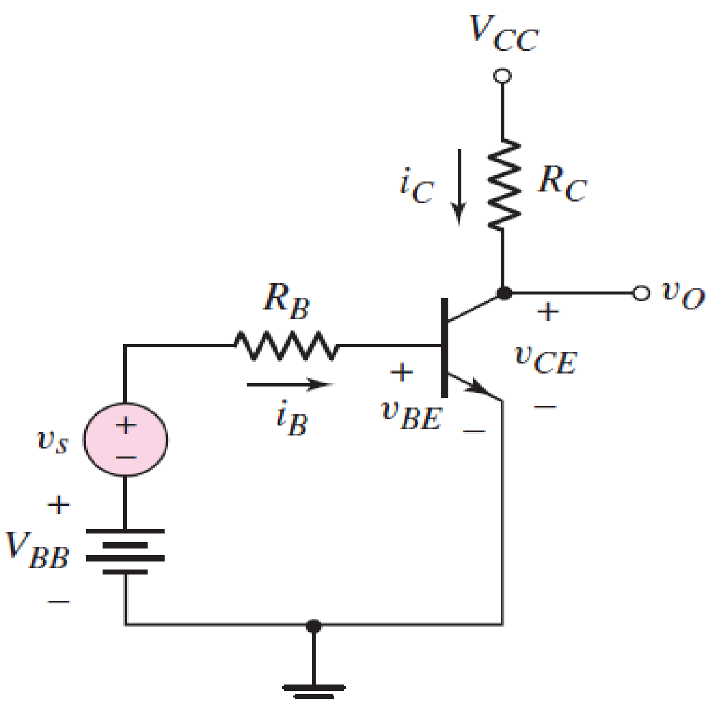


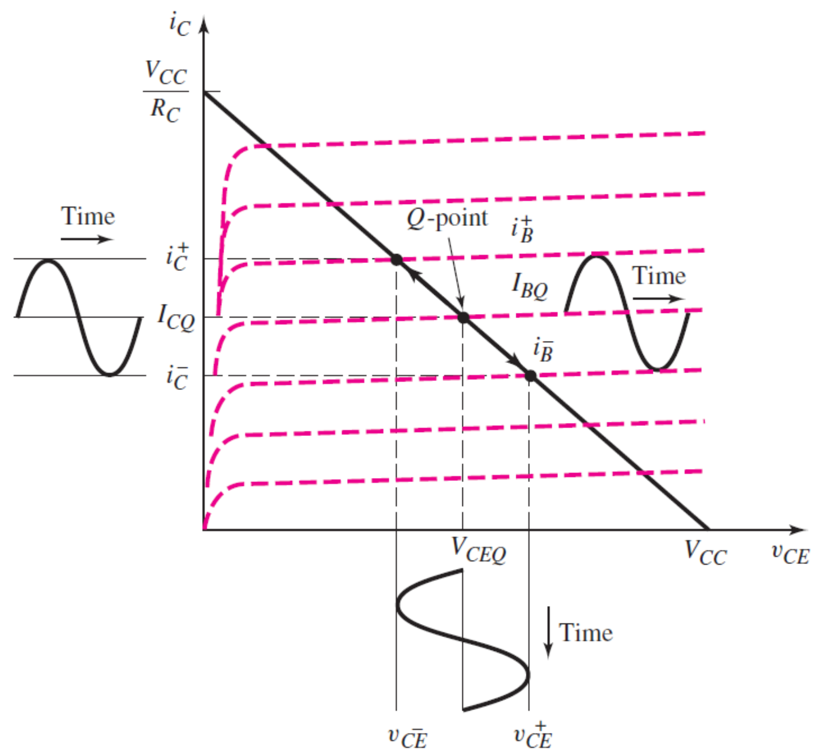


Voltage transfer characteristics

Bipolar Linear Amplifier – Common Emitter

✓ v_s will produce a time-varying or ac base current superimposed on the quiescent base current. The time-varying base current will induce ac collector current superimposed on quiescent collector current. The ac collector current then produces a time-varying voltage across R_C, which induces ac collector-emitter voltage – larger than v_s (*signal amplification*).





CE transistor characteristics

Bipolar Linear Amplifier – Common Emitter

- ✓ Need to develop a *mathematical method/model* for determining relationships between sinusoidal variations in currents and voltages.
- ✓ As mentioned, linear amplifier implies that *superposition applies* so that dc and ac analyses can be performed separately.
- ✓ The time-varying or ac signals must be small enough to ensure a linear relation between the ac signals – assumed to be *small signals*.
- ✓ Since time-varying v_s *generates* time-varying component of base current, there is also a *time-varying component of base-emitter voltage*.
- ✓ If the magnitudes of the time-varying signals that are superimposed on the dc quiescent point are small, then we can develop a linear relationship between the ac base–emitter voltage and ac base current – *this relationship corresponds to the slope of the curve at the Q-point*.

*Bipolar Linear Amplifier – **Small Signal***

Relation between base-emitter voltage and base current can be written as

$$i_B = \frac{I_S}{\beta}\left[e^{\left(\frac{v_{BE}}{V_T}\right)}\right]$$

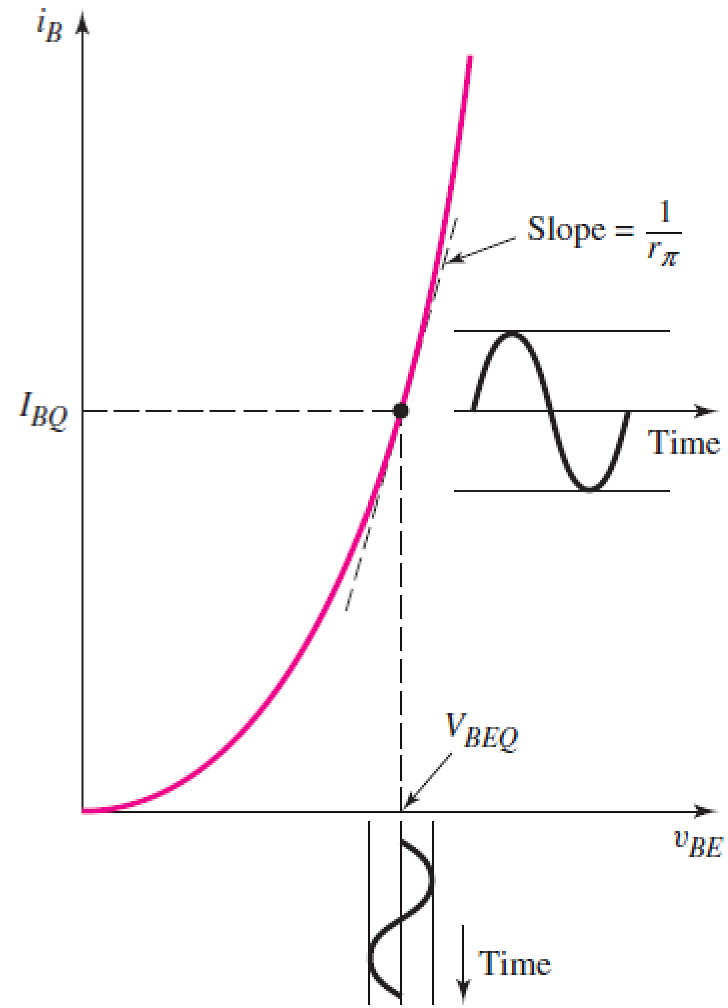
If v_{BE} is composed of a dc term with sinusoidal component superimposed, $v_{BE} = V_{BEQ} + v_{be}$

$$i_B = \frac{I_S}{\beta}\left[e^{\left(\frac{V_{BEQ}+v_{be}}{V_T}\right)}\right] = \frac{I_S}{\beta} \times \left[e^{\left(\frac{V_{BEQ}}{V_T}\right)}\right] \times \left[e^{\left(\frac{v_{be}}{V_T}\right)}\right]$$

$V_{BEQ} \rightarrow$ refers base-emitter turn-on voltage, $V_{BE(on)}$

$\frac{I_S}{\beta} \times \left[e^{\left(\frac{V_{BEQ}}{V_T}\right)}\right] \rightarrow$ quiescent base current.

Therefore, we can write, $i_B = I_{BQ} \times e^{\left(\frac{v_{be}}{V_T}\right)}$



Base-current vs base-emitter voltage characteristics

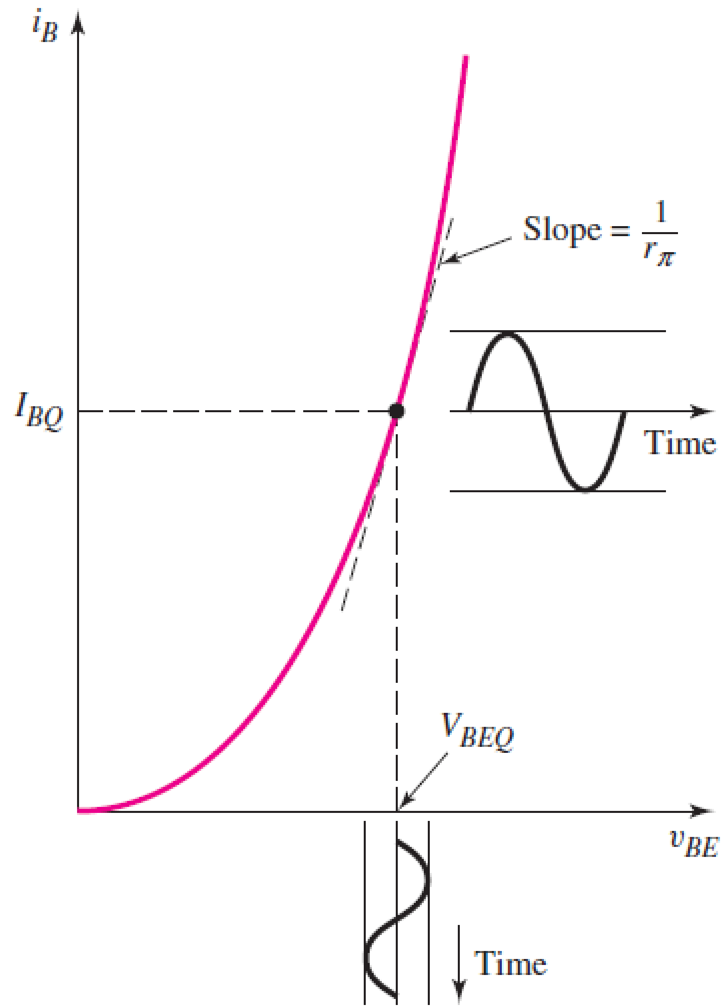
*Bipolar Linear Amplifier – **Small Signal***

The i_B is not linear and cannot be written as ac current superimposed on dc quiescent value. However, if $v_{be} \ll V_T$, we can use *Taylor series*, keeping only linear term – *this approximation is what refers to the term small signal*.

$$i_B \cong I_{BQ}\left(1 + \frac{v_{be}}{V_T}\right) = I_{BQ} + \frac{I_{BQ}}{V_T} v_{be} = I_{BQ} + i_b$$

where, $i_b = \left(\frac{I_{BQ}}{V_T}\right) v_{be} \rightarrow$ is linearly related to sinusoidal base-emitter voltage, v_{be}.

The term *small-signal* refers to the condition in which v_{be} is sufficiently small for the linear relationships between i_b and v_{be} to be valid.



Base-current vs base-emitter voltage characteristics

AC Equivalent Circuit – ***Small Signal***

- ✓ Note that the *ac equivalent parameters* can be obtained by setting all *dc currents and voltages equal to zero*, so the dc voltage sources become short circuits and any dc current sources would become open circuits.

Small-signal equivalent circuit

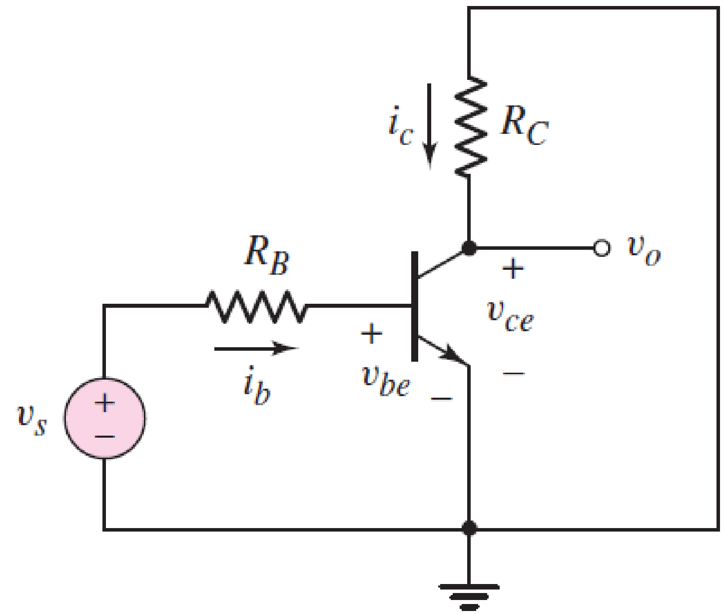
Input Base-Emitter Port: Recall base current versus base-emitter voltage characteristics,

$$v_{be} = i_b \, r_\pi$$

where $1/r_\pi$ is equal to the slope of $i_B - v_{BE}$ curve.

We can write, $\frac{v_{be}}{i_b} = r_\pi = \frac{V_T}{I_{BQ}} = \frac{\beta V_T}{I_{CQ}} = \frac{\beta}{g_m}$

r_π – diffusion resistance or base-emitter input resistance. *Note that r_π is a function of Q-point parameters*.



AC equivalent circuit of CE circuit

AC Equivalent Circuit – ***Small Signal***

Output Collector-Emitter Port: We can note the following,

$$v_{CE} = V_{CEQ} + v_{ce}; \quad v_{BE} = V_{BEQ} + v_{be}\,; \quad i_B = I_{BQ} + i_b; \quad i_C = I_{CQ} + i_c$$

Recall, $i_C = I_S\, e^{v_{BE}/V_T} = I_S\, e^{\left(V_{BEQ}+v_{be}\right)/V_T} = I_S\, e^{V_{BE}/V_T} e^{v_{be}/V_T}$

Since, $I_{CQ} = I_S \times e^{\left(\frac{V_{BE}}{V_T}\right)} \rightarrow i_C = I_{CQ} e^{v_{be}/V_T} \cong I_{CQ}\left(1 + \frac{v_{be}}{V_T}\right)$, if $v_{be} \ll V_T$

Thus, the collector current, $i_C = I_{CQ} + i_c \cong I_{CQ} + I_{CQ}\frac{v_{be}}{V_T}$

Therefore, we can write, $i_c = \frac{I_{CQ}}{V_T} v_{be}$

The term $\frac{I_{CQ}}{V_T}$ is a conductance. Since this conductance relates a current in the collector to voltage in the B-E circuit – called *transconductance* $\left(g_m = \frac{I_{CQ}}{V_T}\right)$.

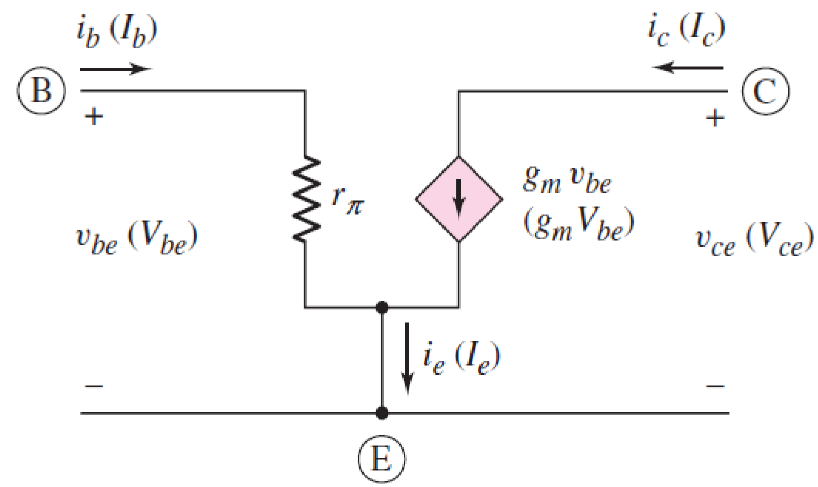
We can then write the small-signal collector current as, $i_c = g_m v_{be}$.

Hybrid–π Equivalent Circuit

We can now *develop an equivalent circuit model* of BJT – voltage controlled current source and explicitly includes input resistance looking into base (r_π).

At emitter node, we have

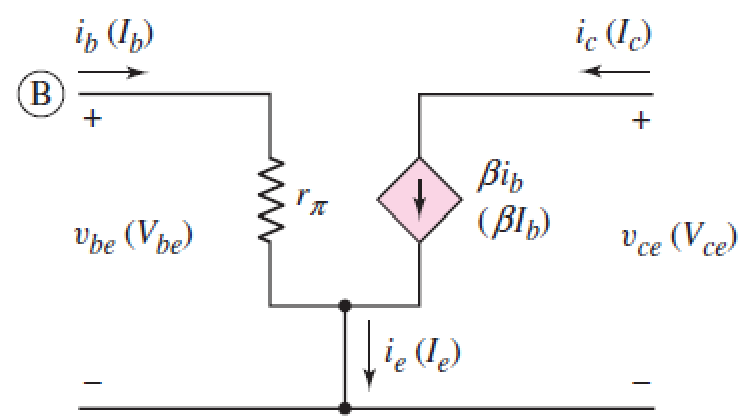
$$i_e = \frac{v_{be}}{r_\pi} + g_m v_{be} = \frac{v_{be}}{r_\pi}(1 + g_m r_\pi) = \frac{v_{be}}{r_\pi}(1+\beta)$$



We can relate small-signal collector current to the small-signal base current as,

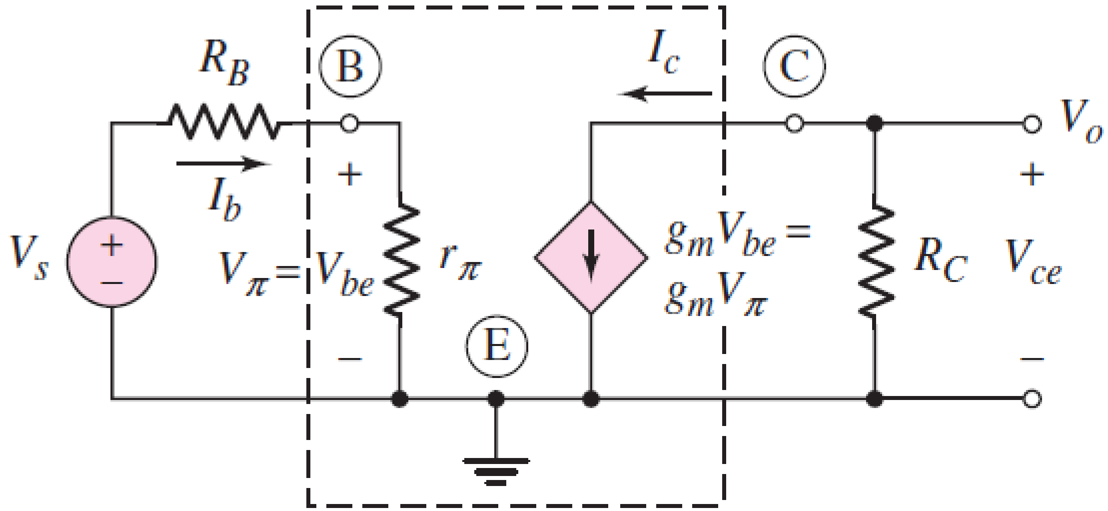
$$i_c = g_m v_{be} = g_m(i_b\, r_\pi) = (g_m r_\pi) i_b = \beta i_b$$

Consider, $g_m r_\pi = \frac{I_{CQ}}{V_T} \times \frac{\beta V_T}{I_{CQ}} = \beta$



Small-Signal Voltage Gain

We can now *incorporate the small-signal hybrid–π* model into the ac equivalent circuit – replace the equivalent model of the transistor.



Small-signal voltage gain

$$A_v = \frac{V_o}{V_s} = \frac{V_{ce}}{V_s} = \frac{-(g_m V_\pi) R_C}{V_\pi / \left(\frac{r_\pi}{r_\pi + R_B}\right)} = -(g_m R_C)\left(\frac{r_\pi}{r_\pi + R_B}\right)$$

Note that, $V_\pi = \left(\frac{r_\pi}{r_\pi + R_B}\right) V_s$

Voltage divider rule

Problem-Solving Technique

Since we are dealing with linear amplifier circuits, superposition applies, which means that we can perform the *dc* and *ac* analyses separately. The procedure is as follows:

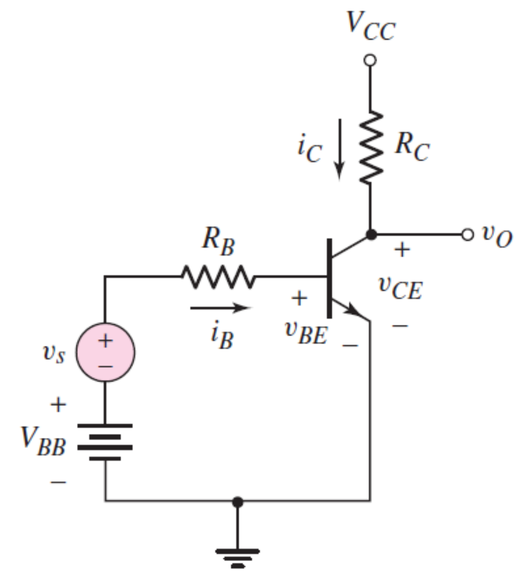
1. Analyze the circuit with *only the dc sources present*. This solution is the dc or quiescent solution, which uses the dc signal models. The transistor must be biased in the forward-active region in order to produce linear amplifier.

2. Replace each element in the circuit with its *small-signal model*. The small-signal model *hybrid*$-\pi$ applies to the transistor.

3. Analyze the small-signal equivalent circuit, *setting the dc source components equal to zero*, to produce the response of the circuit to the time-varying input signals only.

Calculate Small-Signal Voltage Gain

<u>Exercise–5</u>: Consider the circuit parameters: $V_{CC} = 12\ V, \beta = 100, V_{BE} = 0.7\ V, R_C = 6\ k\boldsymbol{\Omega}, R_B = 50\ k\boldsymbol{\Omega}$, and $V_{BB} = 1.2\ V$. Determine the small-signal voltage gain.



Solution

Do it by yourself

DC solution: First do the dc analysis to find Q-point values. $I_{CQ} = 1\ mA$ and $V_{CEQ} = 6\ V$.

AC Solution: The small-signal hybrid$-\pi$ parameters are

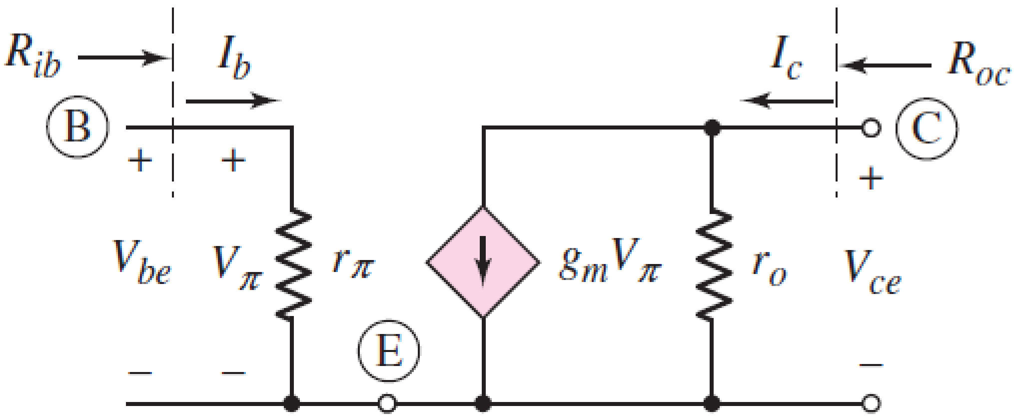
$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{100 \times 0.026}{1\ mA} = 2.6\ k\boldsymbol{\Omega}\ \&\ g_m = \frac{I_{CQ}}{V_T} = \frac{1\ mA}{0.026} = 38.5\ mA/V$$

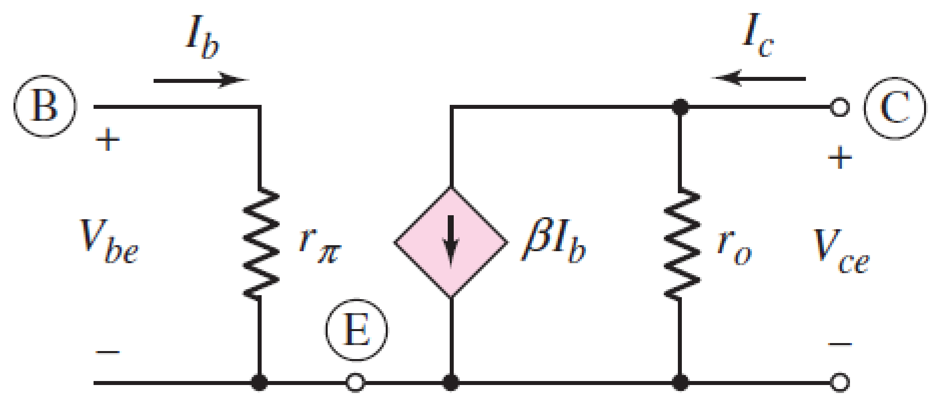
The small-signal voltage gain, $A_v = \frac{V_o}{V_s} = -g_m(R_C)\left(\frac{r_\pi}{r_\pi + R_B}\right)$

$$= -(38.5)(6)\left(\frac{2.6}{2.6+50}\right) = -11.4$$

Hybrid–π Equivalent Circuit with Early Effect

So far we have assumed that the collector current is independent of the collector-emitter voltage in the small-signal equivalent circuit. Recall Early Effect, where the collector current varies with collector-emitter voltage.





$i_C = I_S\, e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$ & $r_o \cong \frac{V_A}{I_C}$ is *small-signal transistor output resistance*.

This resistance is an equivalent *Norton resistance*, which means that r_o is in parallel with the dependent current sources.

Input resistance, r_π (ohms); current gain, β (dimensionless)
output resistance, r_o (ohms); transconductance, g_m (mhos);

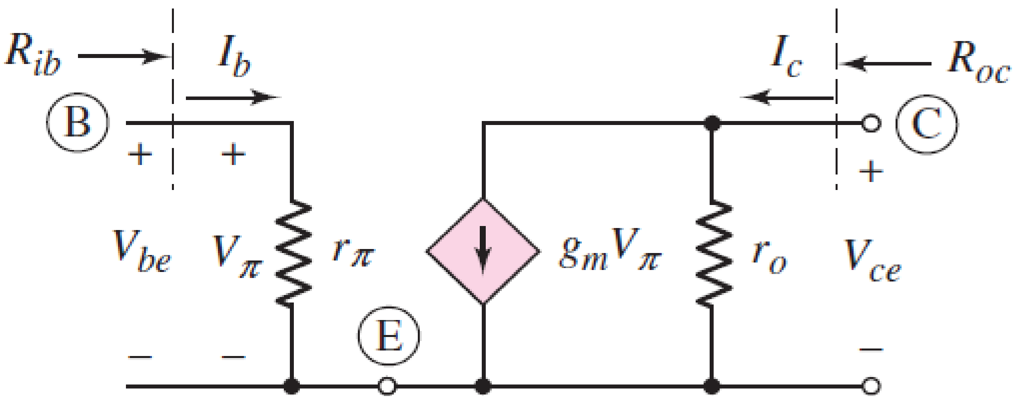
Hybrid–π Equivalent Circuit with Early Effect

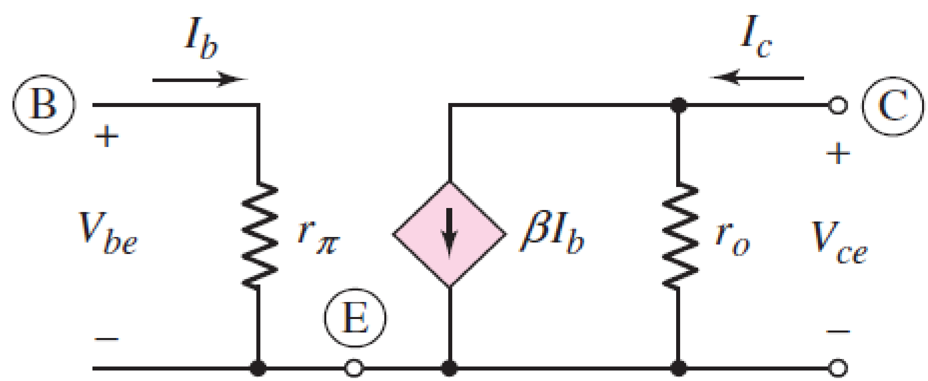
Input and Output Resistance

Two other parameters (input and output resistances) also affect the performance of an amplifier.

1. Small-signal input resistance looking into the base terminal, $R_{ib} = r_\pi$.

2. In order to find small-signal output resistance (R_{oc}), set all independent sources to zero, i.e., we set $V_\pi = 0 \rightarrow g_m V_\pi = 0$. Zero-valued current source means an open-circuit. Output resistance looking back into the collector terminal, $R_{oc} = r_o$.





Calculate Small-Signal Voltage Gain

Exercise–6: Consider the circuit parameters: $V_{CC} = 12\ V, V_{BE} = 0.7\ V, R_C = 6\ k\boldsymbol{\Omega}, R_B = 50\ k\boldsymbol{\Omega}$, and $V_{BB} = 1.2\ V$. Determine the small-signal voltage gain including the effect of transistor output resistance, r_o. Assume $V_A = 50\ V$.

Solution

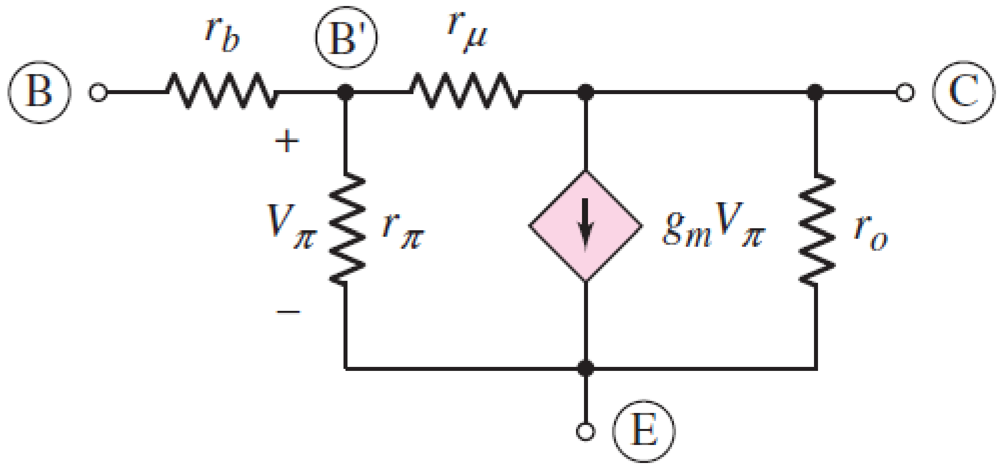
The small-signal output resistance, $r_o = \frac{V_A}{I_{CQ}} = \frac{50}{1\ mA} = 50\ k\boldsymbol{\Omega}$

The small-signal voltage gain, $A_v = \frac{V_o}{V_s} = -g_m(R_C||r_o)\left(\frac{r_\pi}{r_\pi + R_B}\right)$

$$= -(38.5)(6||50)\left(\frac{2.6}{2.6+50}\right) = -10.2$$

Expanded Hybrid−π Equivalent Circuit

The parameter (r_b) is the *series resistance* between the external base terminal B and an idealized internal base region B'. It is typically of few tens of ohms and is *usually much smaller than r_π*. Note that r_b is normally *negligible (a short circuit) at low frequencies*.



The parameter (r_μ) is the reverse-biased diffusion resistance of the base-collector junction. It is typically of megohms and can normally be negligible (an open-circuit). Thus, note that the resistances $(r_b \,\&\, r_\mu)$ *will be neglected* when using hybrid−π model, unless they are specifically mentioned.

Summary:–

- ✓ Current in the transistor is due to the flow of both electrons & holes, hence named *bipolar* – 2 pn junctions, so has 4 possible modes of operation.
- ✓ The collector current is plotted against the collector–emitter voltage, for various constant values of the base current – slope is due to *Early effect*.
- ✓ One of the basic transistor circuit configuration is *common-emitter (CE) circuit* – the *emitter terminal* is obviously at *ground potential*.
- ✓ The *quiescent point* or *Q-point*, of the transistor is given by the dc collector currents & C-E voltage.
- ✓ Small-signal equivalent parameters: $g_m = \frac{I_{CQ}}{V_T}$; $\quad g_m r_\pi = \frac{I_{CQ}}{V_T} \times \frac{\beta V_T}{I_{CQ}} = \beta$
- ✓ Small-signal voltage gain: $A_v = \frac{V_o}{V_s} = -(g_m R_C)\left(\frac{r_\pi}{r_\pi + R_B}\right)$
- ✓ Note that r_b is normally *negligible (a short circuit) at low frequencies*.

See you in the next class

The End