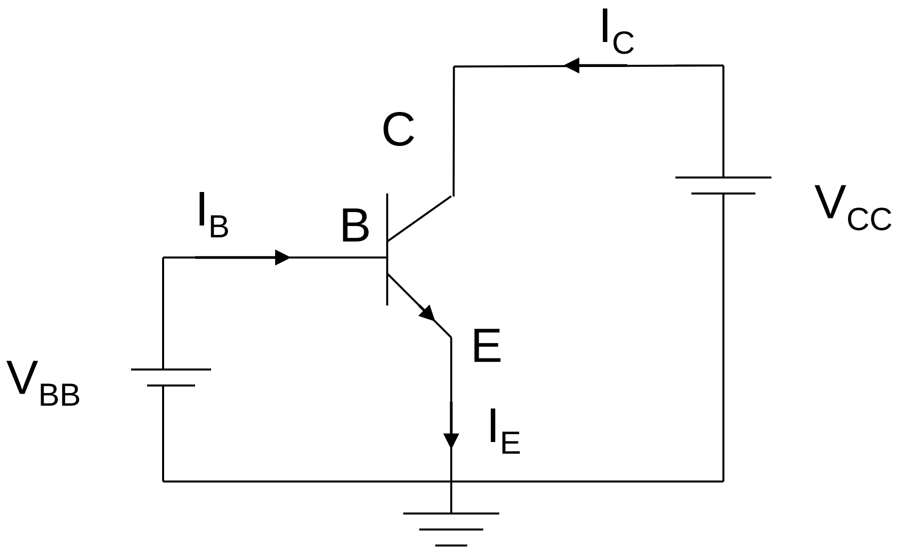
Bipolar Junction Transistors - II
(BJT-II)

Transistor Biasing



Common Emitter (CE) Transistor

β = Common emitter current amplification factor

$= I_C/I_B$

Current Gain of the Transistor

$$I_C = \beta I_B + (\beta+1) I_{CO}$$

$$\beta = \alpha/(1-\alpha)$$

Example -

For $\alpha = 0.98$,

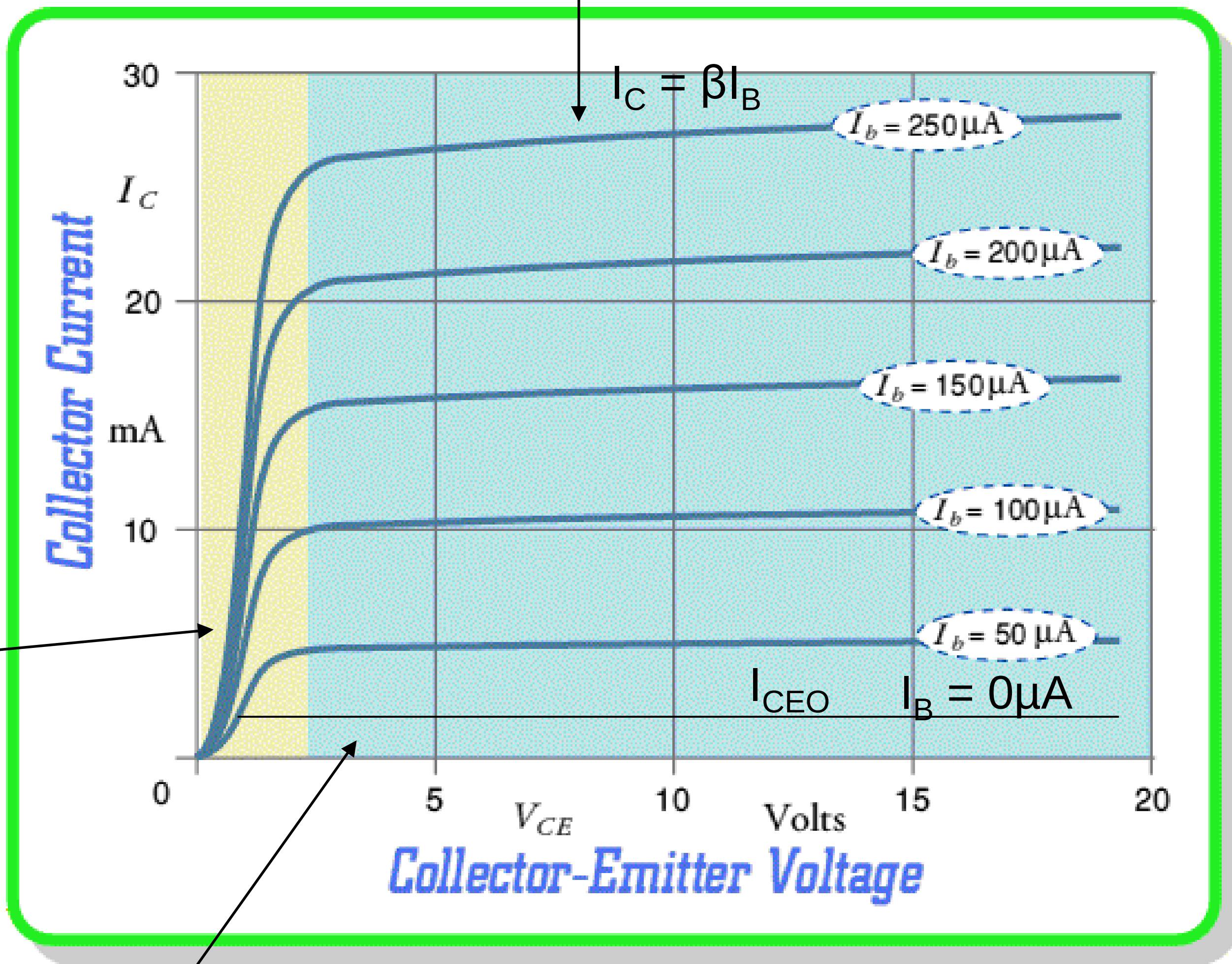
$\beta = 49$

β increases rapidly as $\alpha \rightarrow 1$

Output Characteristic of CE Transistor

Active Region

I_C has a slope due to “Early Effect ”



$I_C < \beta I_B$

Saturation region

Cutoff Region

Transistor in Cutoff Region

Both the BC and the BE junctions are reverse biased

$I_E=0$ $I_C=I_{CO}\approx 0$ $I_B=-I_C=-I_{CO}\approx 0$

Transistor in Saturation Region

Both the BC and BE junctions are forward biased and $I_C<\beta I_B$

$V_{BE}\approx 0.7$ V $V_{BC}\approx 0.6$ V $V_{CE}\approx 0.1$

When transistor is used as a switch, it will be forced to operate either in the CUTOFF region or in the SATURATION region.

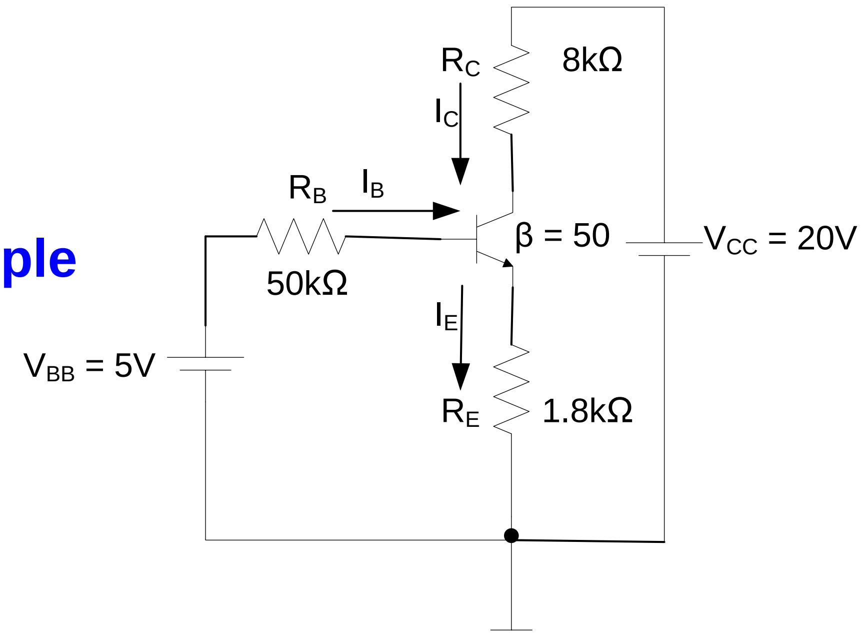
Transistor in Active Region

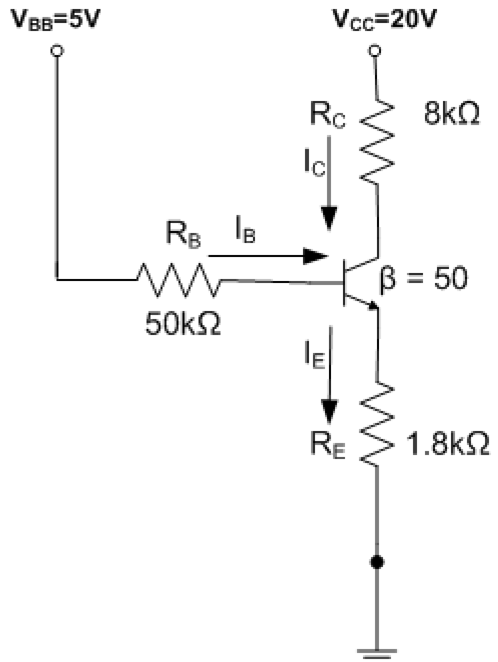
The BE junction is forward biased but the BC junction is reverse biased and $I_C \approx \beta I_B$

V_{BE}=0.7 V

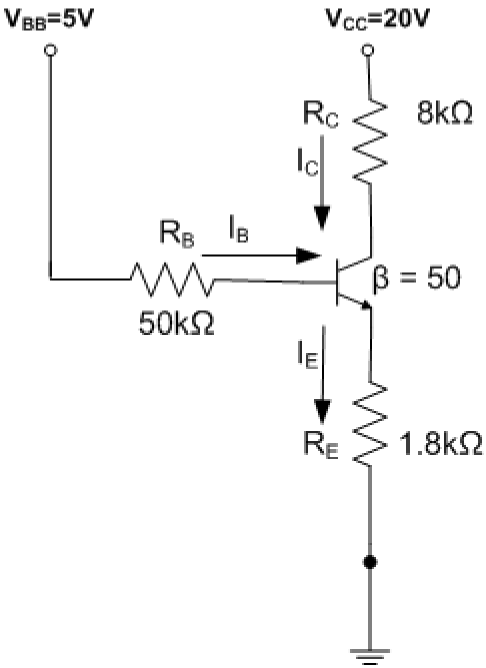
Transistor is operated in this region when we want to use it as an amplifier!

Example





Example: Calculate all the relevant voltages and currents



$$I_c = \beta I_B = 50 I_B \qquad I_E = I_c + I_B = 51 I_B$$

$$\boxed{\begin{gathered} I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta + 1) R_E} = \frac{5 - 0.7}{50 + 51 * 1.8} = 0.0303\, mA \\ I_C = 50 * 0.0303 = 1.52\, mA \qquad I_E = 1.55\, mA \end{gathered}}$$

$$V_E = I_E R_E = 1.55 * 1.8 = 2.79\, V$$

$$V_B = V_E + V_{BE} = 2.79 + 0.7 = 3.49\, V$$

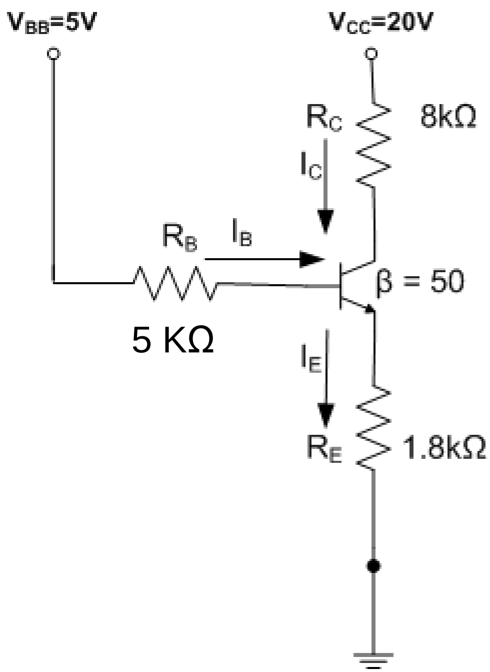
$$V_C = V_{CC} - I_C R_C = 20 - 1.52 * 8 = 7.84$$

$$\boxed{V_{CE} = V_C - V_E = 7.84 - 2.79 = 5.05\, V}$$

Note that V_{BC} = 3.49 -7.84 = -4.35 V, i.e. the B-C junction is reverse biased, implying that the transistor is working in the Active Mode

The Bias Point is specified by (V_{CE}, I_C, I_B)

What would happen if we reduced the base resistance to 5KΩ?



Let's assume that the transistor is still in the active region so $I_C=\beta I_B$ and $I_E=(\beta+1)I_B$. Then -

$$5-0.7=5I_B+51I_B(1.8) \quad \Rightarrow \quad I_B=\frac{4.3}{5+51\times 1.8}=0.0444\ \text{mA}$$

$I_C=50I_B$ = 2.22 mA

$I_E=51I_B$ = 2.2644 mA

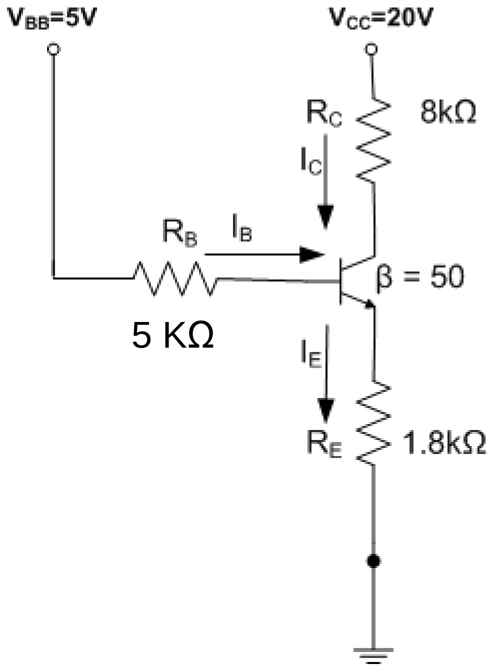
$V_E=I_E R_E$ = 4.076V

$V_B=V_E+0.7$= 4.776V

$V_C=V_{CC}-I_C R_C$ = 20 – 8IC = 2.24V

Note that B-C junction is then forward-biased which violates our earlier assumption that the transistor is in the active region. Therefore, our earlier assumption is WRONG – the transistor will not be in the active region

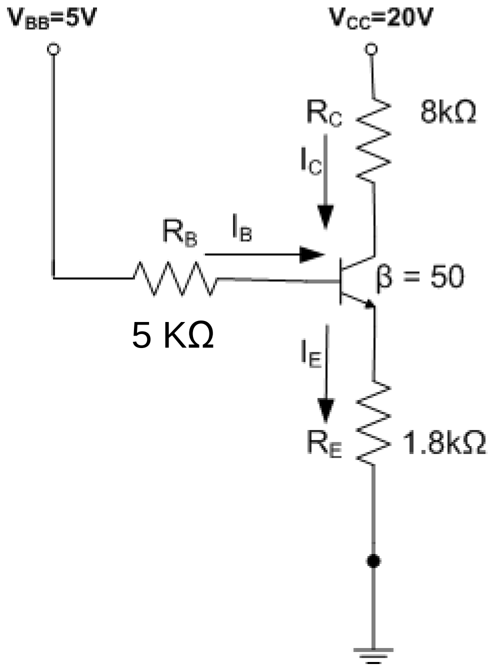
What would happen if we reduced the base resistance to 5KΩ?



Can the transistor be in CUTOFF?

If the transistor is in CUTOFF then $I_B=I_C=I_E=0$. Therefore V_B=5V and V_E=0V but that will forward bias B-E which violates the condition for transistor to be in CUTOFF. Therefore, the transistor cannot be in CUTOFF.

What would happen if we reduced the base resistance to 5KΩ?



Can the transistor be in Saturation?

In saturation, $V_{CE(sat)}$ =0.1V and V_{BE}=0.7V

Note that $I_C=\beta I_B$ will not hold in saturation, but we will still have $I_E=I_B+I_C$

$$+5 = 5I_B + 0.7 + 1.8(I_B + I_C) \quad \Rightarrow \quad 6.8I_B + 1.8I_C = 4.3$$

$$+20 = 8I_C + 0.1 + 1.8(I_B + I_C) \quad \Rightarrow \quad 1.8I_B + 9I_C = 19.1$$

Solving - I_B=0.0745 mA, I_C=2.107 mA & I_E=2.182 mA

Note that

(a) $I_C > \beta I_B$

(b) V_E=3.93 V V_B=4.63 V V_C=4.03 V

So B-C is reverse biased

The transistor is indeed in saturation

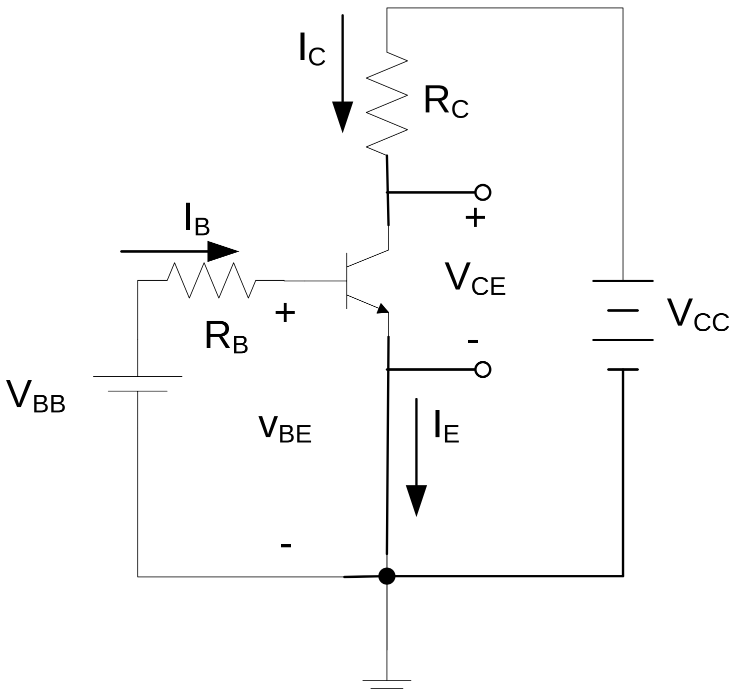
Biasing the Transistor

To operate as an amplifier a transistor must be biased in the active region. In that case, the transistor can amplify a *small ac signal* faithfully.

Bias Point (or Quiescent Operating Point, i.e. Q-Point) is decided by the DC voltages applied and the values of the resistances used. (See earlier example.)

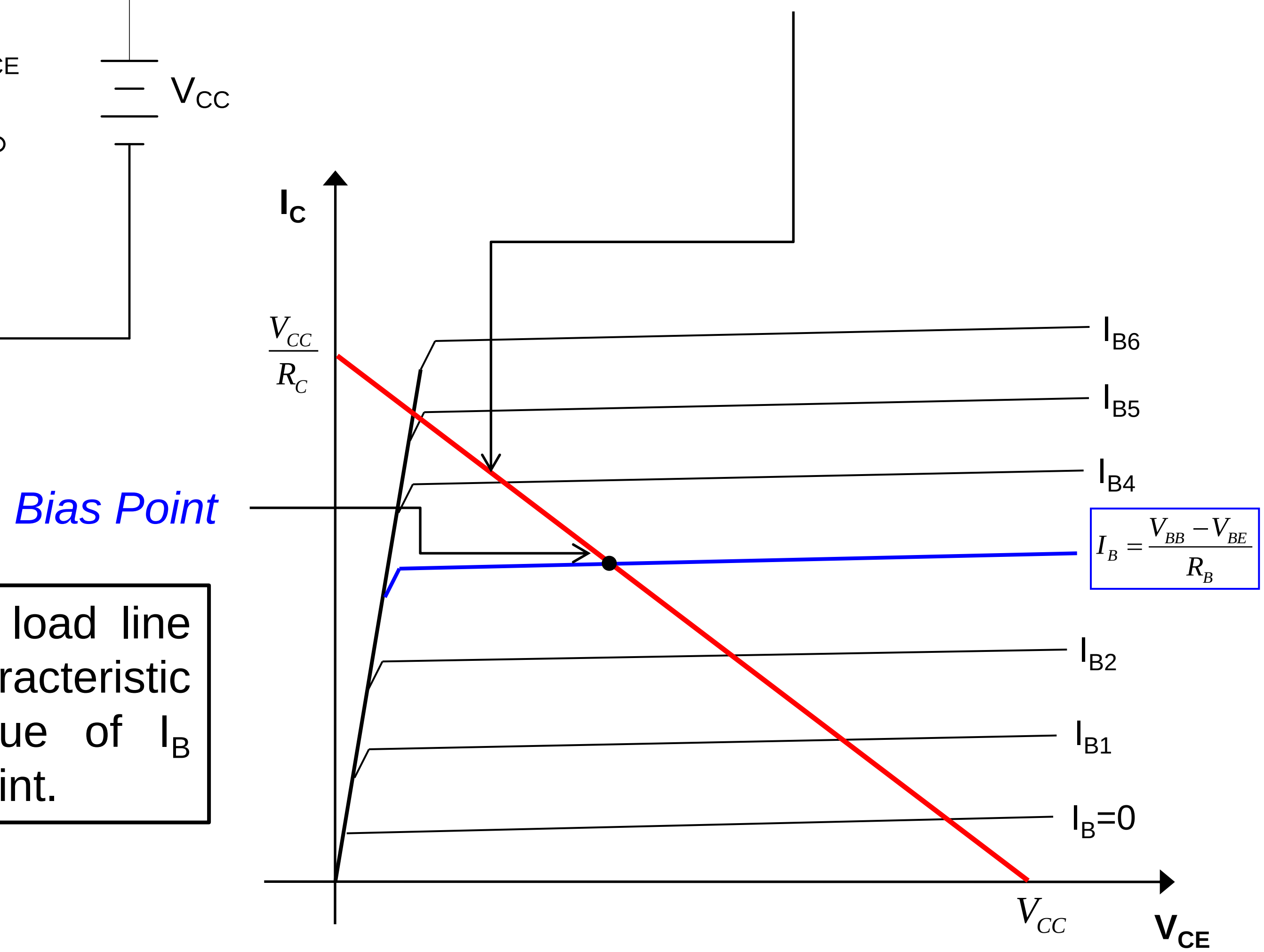
The Bias Point is specified by the three quantities **V_{CE}, I_C and I_B**. *This point must be in the active region of the transistor if we want to use the transistor (with that bias point) as an amplifier.*

Biasing the Transistor



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

Plot of I_C vs. V_{CE} is called the 'Load Line"



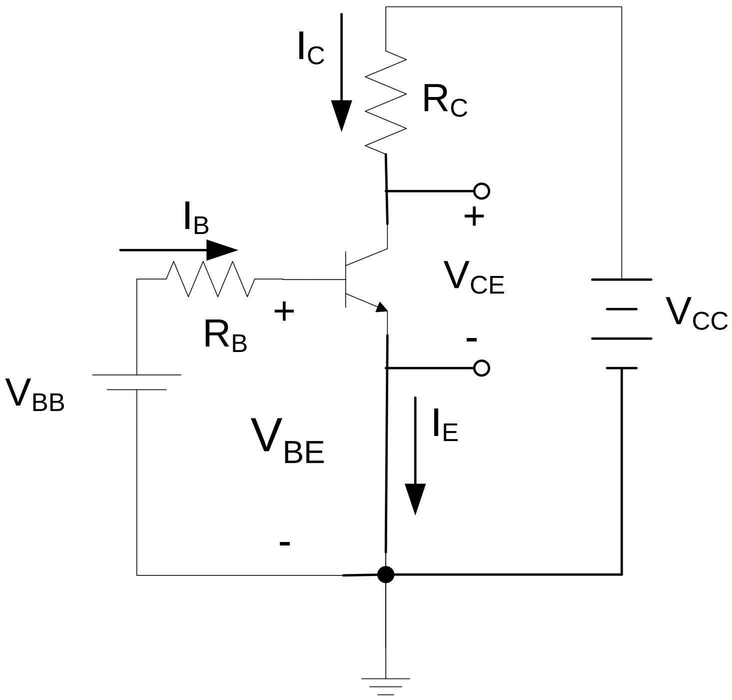
Intersection of the load line with the I_C-V_{CE} characteristic for the given value of I_B decides the bias point.

Notation

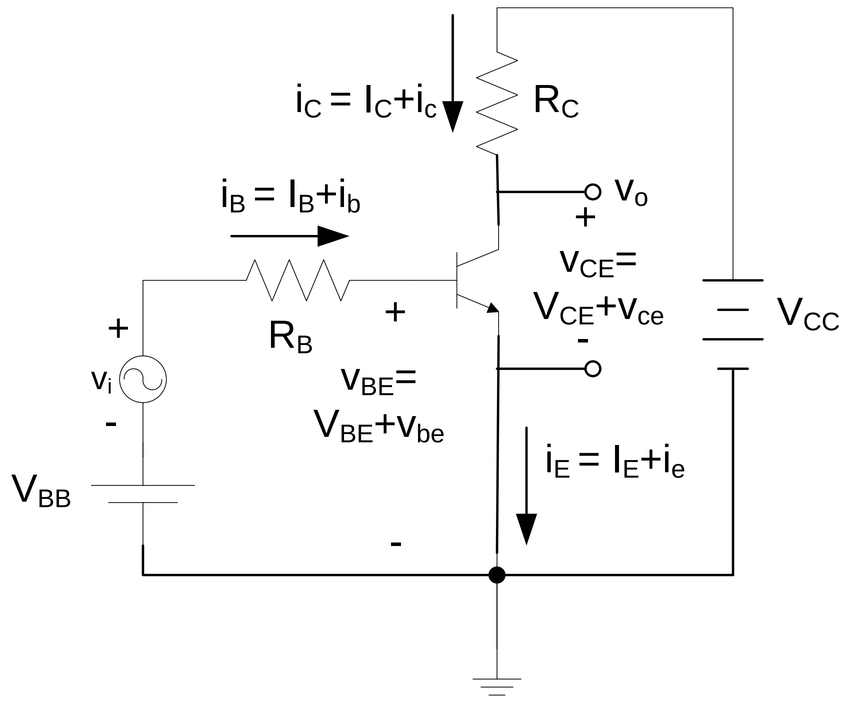
V_{MN} or V_D	DC voltage between M-N or at D
v_{mn} or v_d	AC voltage between M-N or at D
v_{MN} or v_D	(DC+AC) voltage between M-N or at D

Note the different ways in which small and capital letters are used to denote DC, AC or DC+AC values

Similar notation used to represent current values

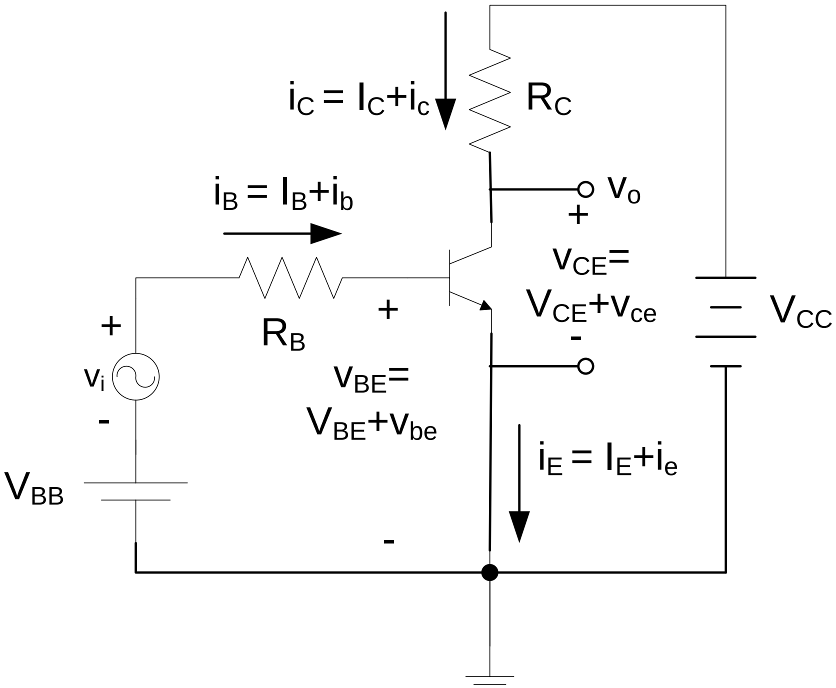


Transcristor Circuit
under DC Condition



Transistor Circuit with
AC Signal applied over
the DC bias

Transistor Circuit with AC Signal

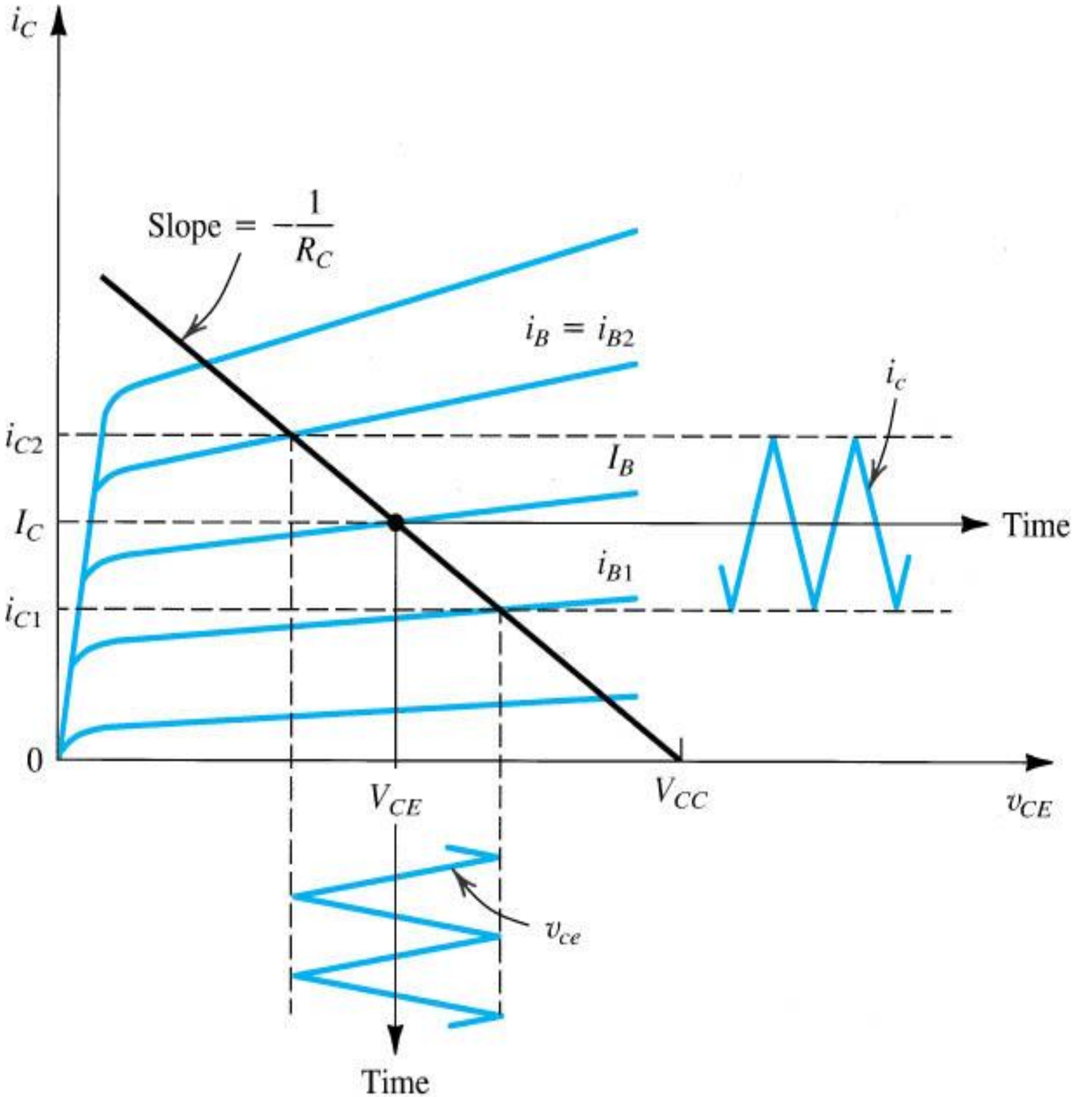


$i_B = I_B + I_b$
$i_E = I_E + i_e$
$i_C = I_C + i_c$

I_B, I_C, I_E – DC currents
i_b, i_c, i_e – AC currents
i_B, i_C, i_E – DC + AC currents

Similarly,
V_{BE}, V_{CE} – DC Voltages
v_{be}, v_{ce} – AC Voltages
v_{BE}, v_{CE} – DC+ AC Voltages

Interpreting "Transistor Gain" (between i_b and i_c) from the characteristics of the transistor



$i_C = \beta i_B$

so $(I_C + i_c) = \beta(I_B + i_b)$

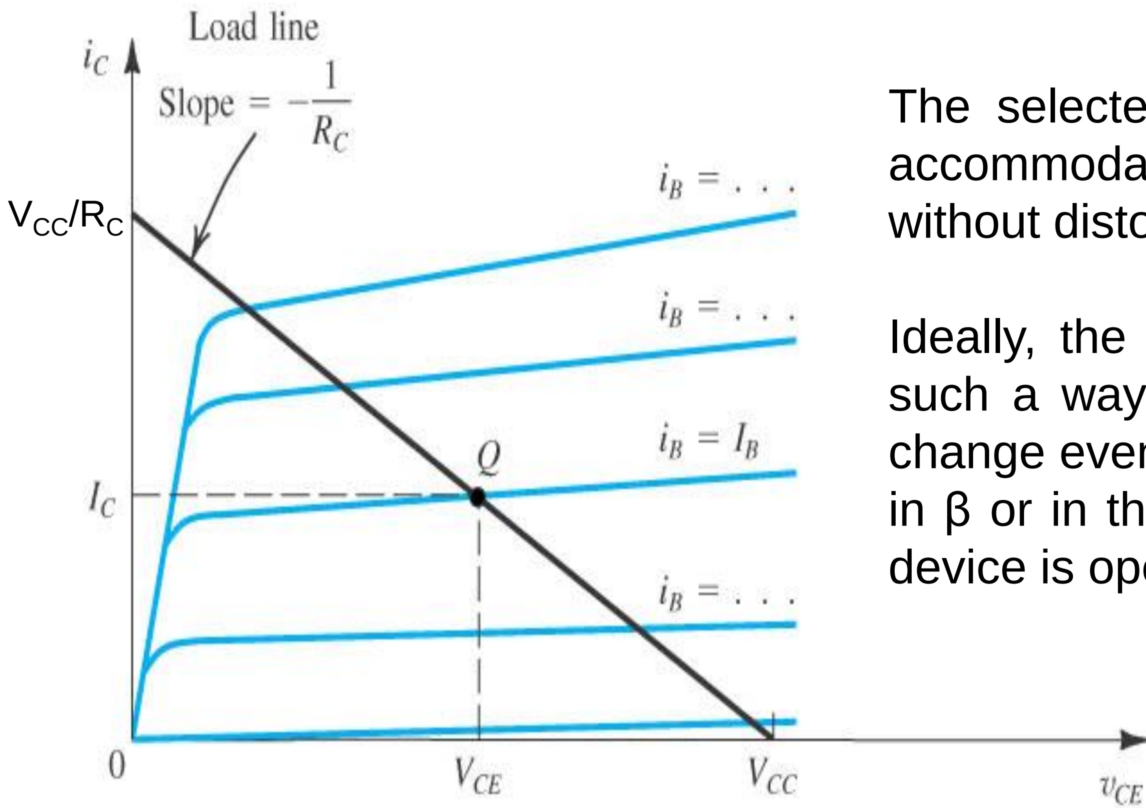
But $I_C = \beta I_B$

so $i_c = \beta i_b$

AC Current Gain

Operating Point or Quiescent Point

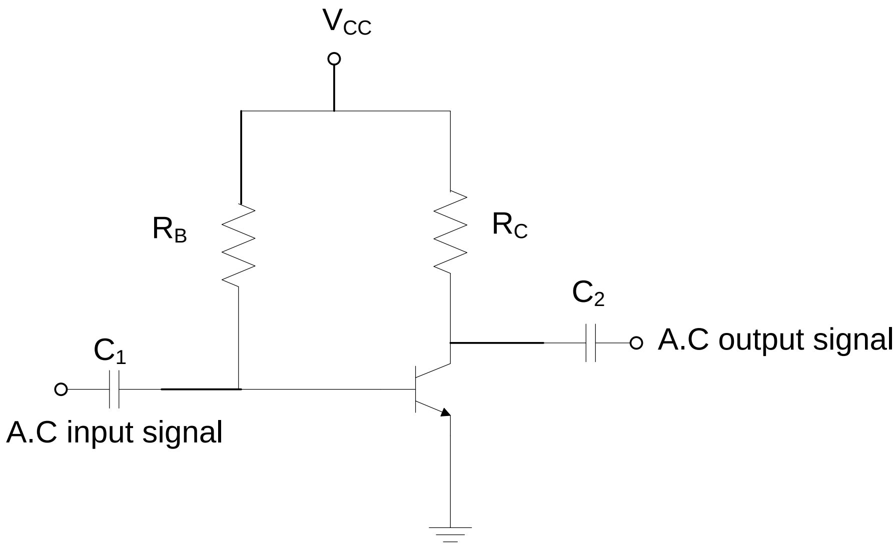
A good selection of the operating point Q is essential in order that an amplifier circuit amplifies an A.C signal without any distortion.

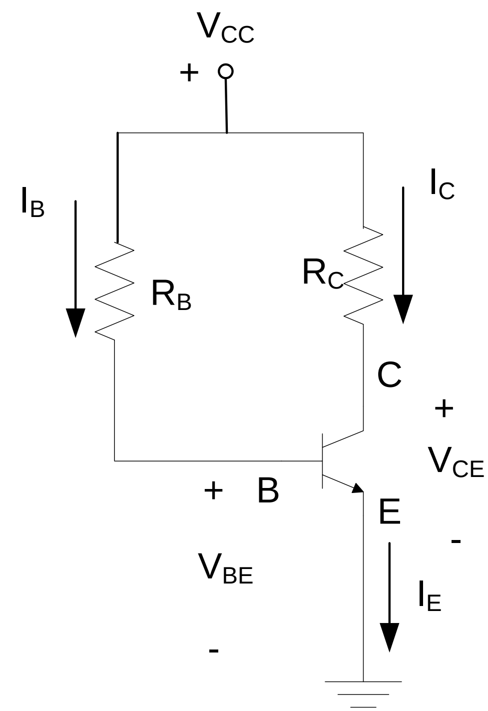


The selected point should be able to accommodate the "output signal swing" without distortion.

Ideally, the biasing should be done in such a way that the Q-point does not change even if there are some changes in β or in the temperature at which the device is operating

Transistor Biasing - Fixed Bias





$$I_B = \frac{V_{CC} - 0.7}{R_B}$$

Assuming transistor in active region

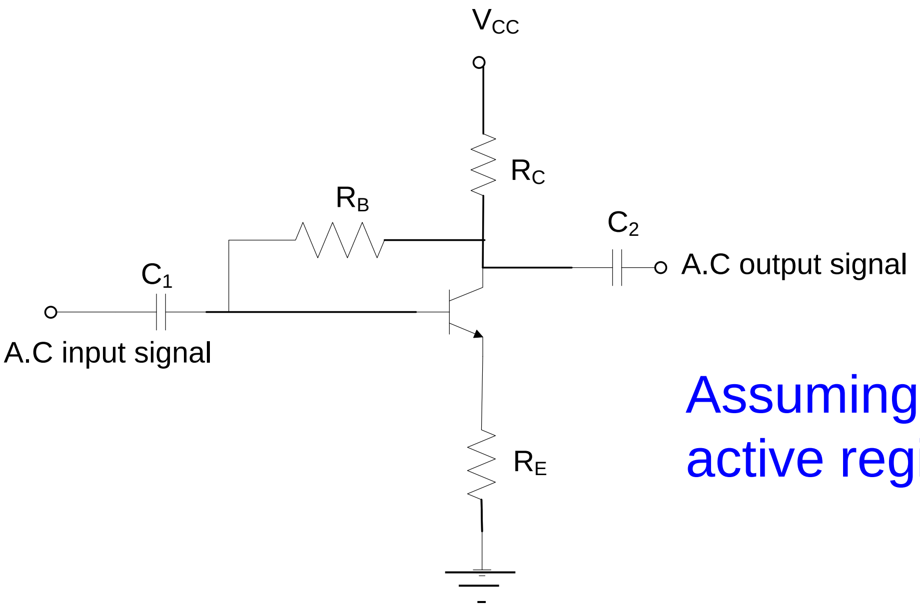
$$I_C = \beta I_B = \frac{\beta\left(V_{CC} - 0.7\right)}{R_B}$$

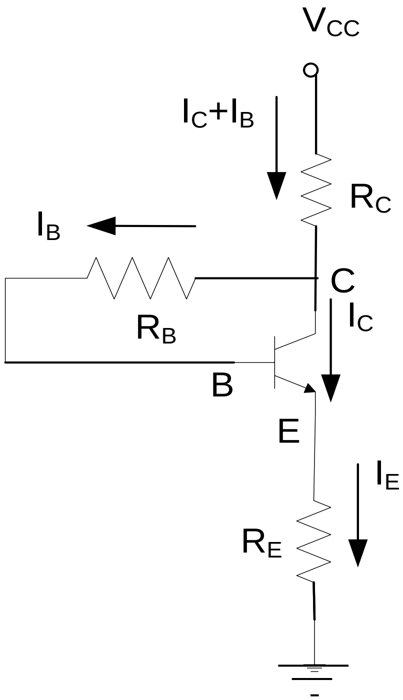
$$V_{CE} = V_{CC} - I_C R_C = V_{CC} - \beta \frac{R_C}{R_B}\left(V_{CC} - 0.7\right)$$

DC Equivalent

C_1 and C_2 will be open circuit under DC

Emitter and Collector Feedback Bias





Assuming transistor in active region

DC Equivalent

$$V_{CC} = (I_C+I_B)R_C + I_BR_B + V_{BE} + (\beta+1)I_BR_E$$

Using $I_C = \beta I_B$, we get

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

and

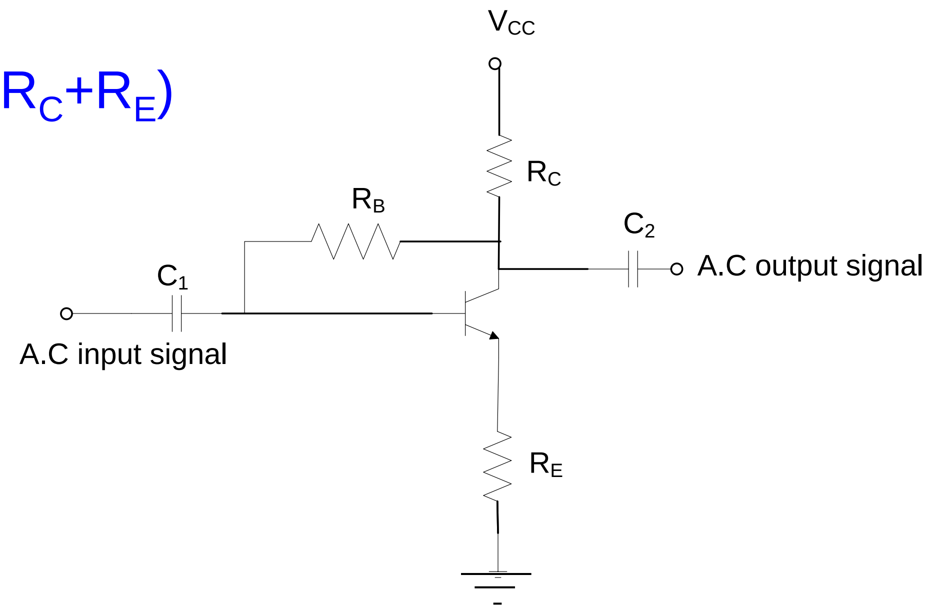
$$V_{CE} = V_{CC} - (I_C+I_B)(R_C+R_E)$$

Q-Point

Emitter and Collector Feedback Bias

Typically, β is large so $R_B \ll (\beta+1)(R_C+R_E)$

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

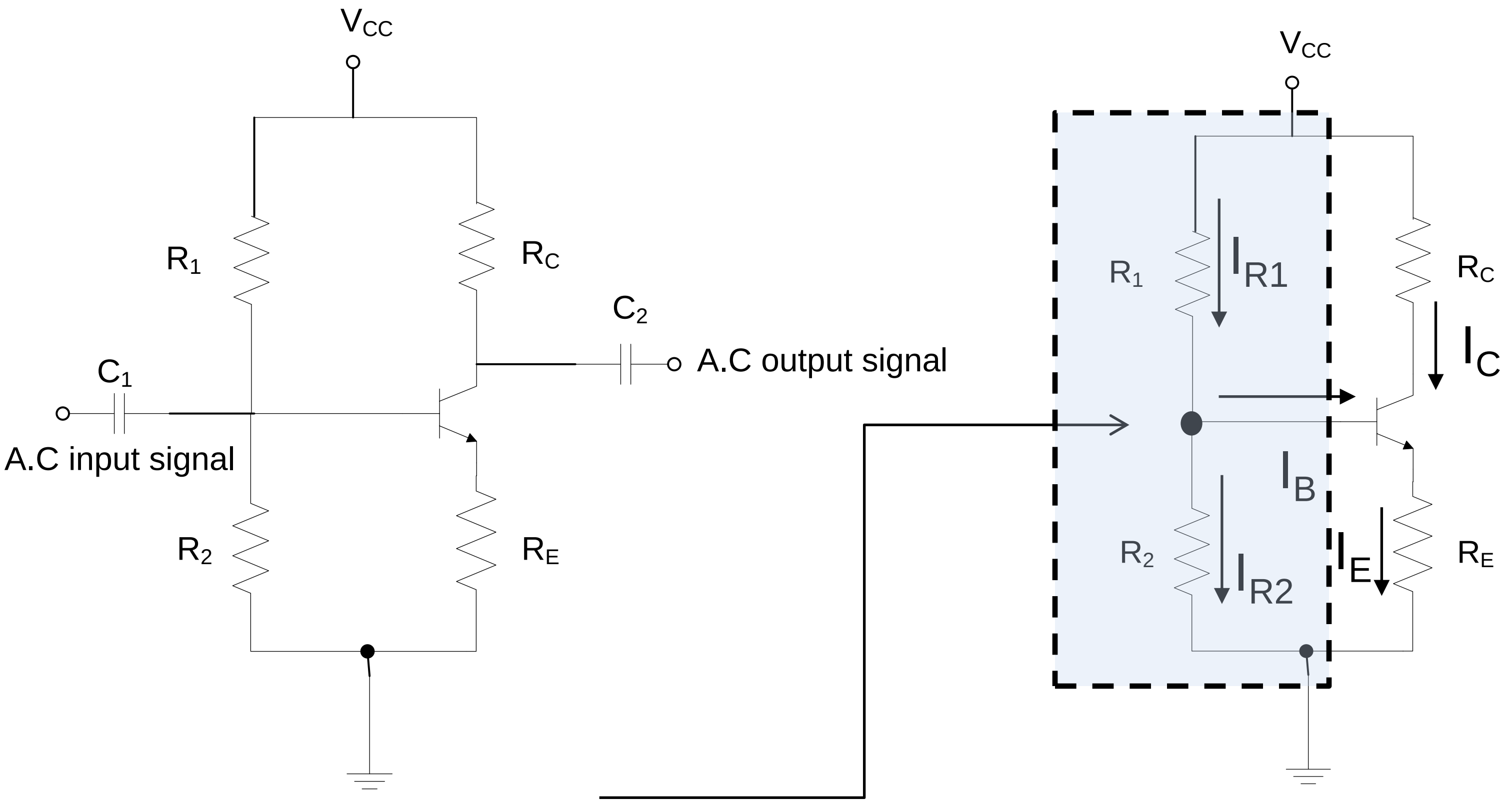


and $$I_C = \beta I_B \cong \left(\frac{V_{CC} - V_{BE}}{R_C + R_E}\right)$$

Note the desirable feature that I_C is independent of β as long as we choose a transistor which has a large β. This is an example of *Bias Stabilization* – making the bias point insensitive to β.

Can you give a qualitative argument as to why I_C tends to get stabilized?

Voltage Divider Bias



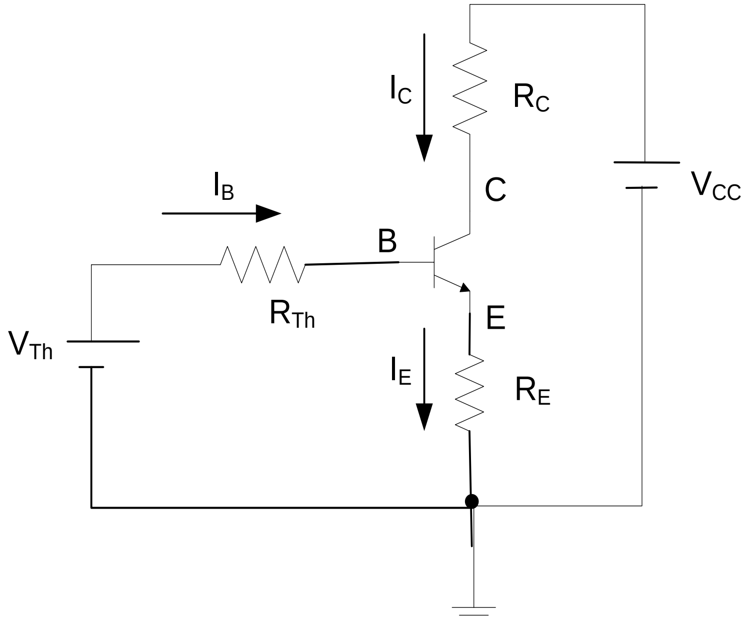
DC Equivalent

It is convenient to replace the biasing circuit at the base by its Thevenin's Equivalent using -

$$V_{\text{Th}} = V_{CC}\frac{R_2}{R_1 + R_2} = V_{BB} \qquad R_{\text{Th}} = R_B = \frac{R_1 R_2}{R_1 + R_2}$$

Voltage Divider Bias

Assuming transistor in active region



$$V_{\mathrm{Th}} = V_{CC}\frac{R_2}{R_1+R_2} \qquad R_{\mathrm{Th}} = \frac{R_1R_2}{R_1+R_2}$$

$$V_{\mathrm{Th}} = I_B R_{\mathrm{Th}} + V_{BE} + (\beta+1)I_B R_E$$

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

with $I_C=\beta I_B$ and $I_E=(\beta+1)I_B$

Solve the above to get the Q-point where the transistor has been biased, i.e. I_C, I_B *and* V_{CE}

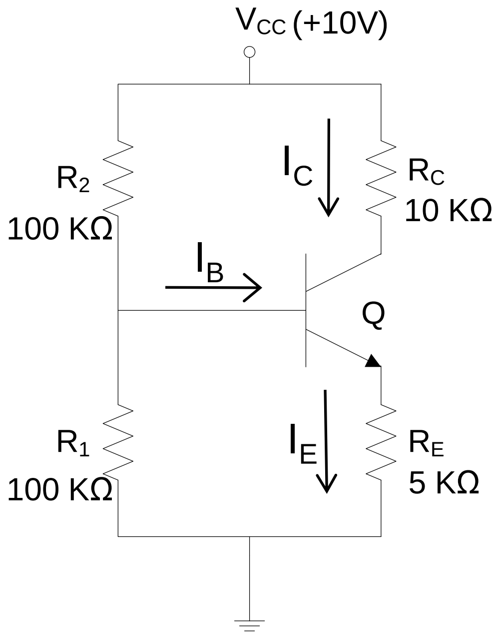
For large β, I_C independent of β

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

$$I_C = \frac{V_{\mathrm{Th}} - V_{\mathrm{BE}}}{R_E}$$

This biasing also provides bias stabilization against changes in β. It also provides stabilization against changes in temperature (not shown here).

Problem – Verifying if a transistor is in saturation



If V_{CC}=+10 V, R_1=R_2=100 KΩ, R_C=10 K Ω, R_E=5 K Ω, can the transistor Q be in saturation? Assume $V_{CE,\,Sat}$=0.1 V, β=50

V_{BB}=5 V $\qquad$ R_B=50 KΩ

$5 = 50I_B+0.7+5(I_B+I_C)$ $\qquad$ $55I_B+5I_C=4.3$

$10=10I_C+0.1+5(I_C+I_B)$ $\qquad$ $5I_B+15I_C=9.9$

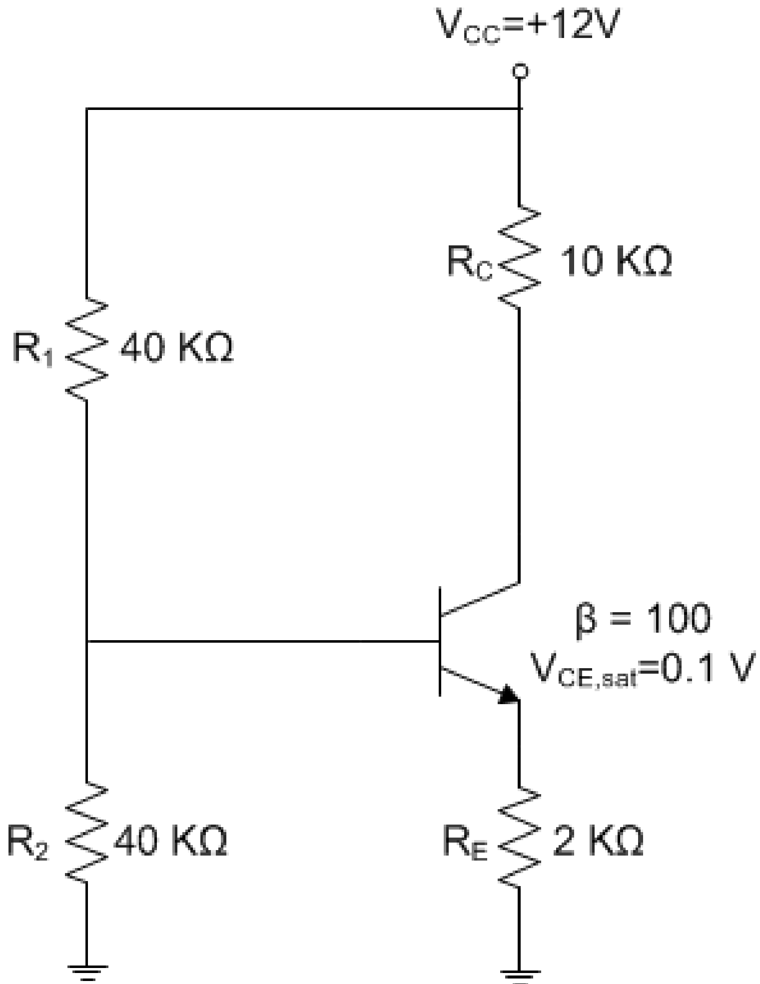
Solving these, we get –

I_C=0.66 mA $\qquad$ I_B= 0.019 mA

I_C=0.66< βI_B=0.95, therefore transistor is indeed in saturation

If we assume transistor in active region, then we get I_B=0.0143 mA, I_C=0.717 mA, I_E=0.731 mA. This gives V_E=3.66 V, V_B=4.36 V and V_C=2.83 V. Since B-C junction is forward biased, transistor CANNOT BE IN ACTIVE REGION.

Find the Bias-Point (Q-Point) of the Transistor



Assume transistor is in saturation, i.e.$V_{CE,sat}$=0.1 V

$$20I_B + 2(I_B + I_C) = 5.3$$

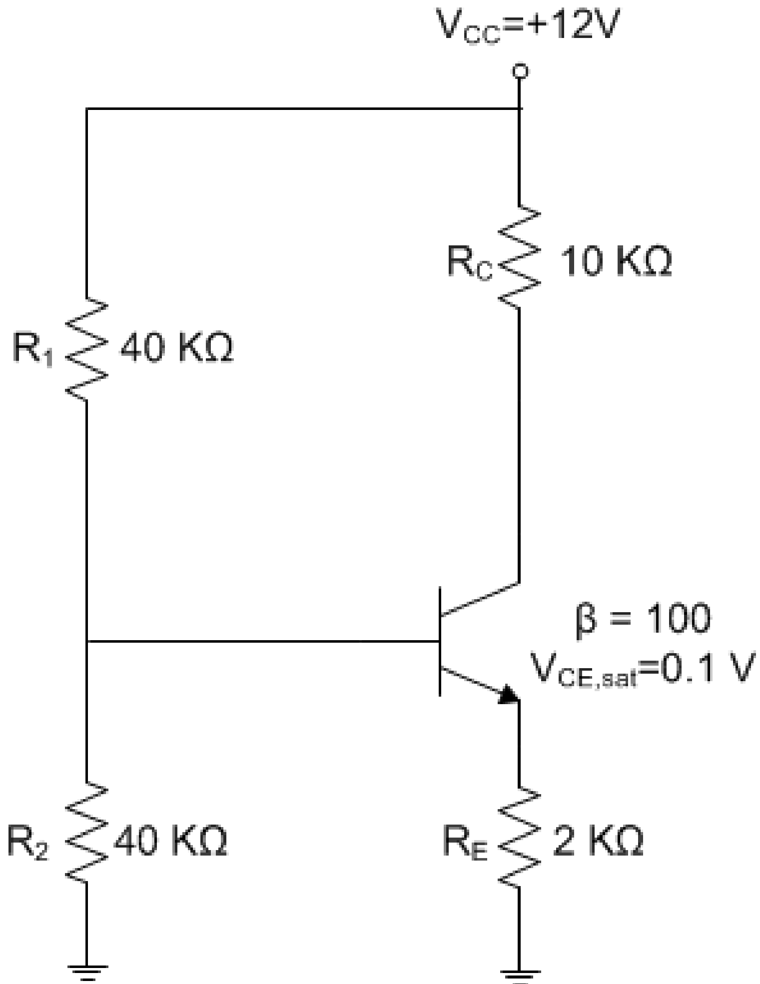
$$10I_C + 2(I_B + I_C) = 11.9$$

Solving, we get I_B=0.153 mA
I_C=0.967 mA

Confirm that transistor is indeed in saturation as $I_C=0.967<\beta I_B=15.3$ mA

Bias Point: V_{CE}=0.1 V, I_C=0.967 mA
I_B=0.967 mA

Find the Bias-Point (Q-Point) of the Transistor



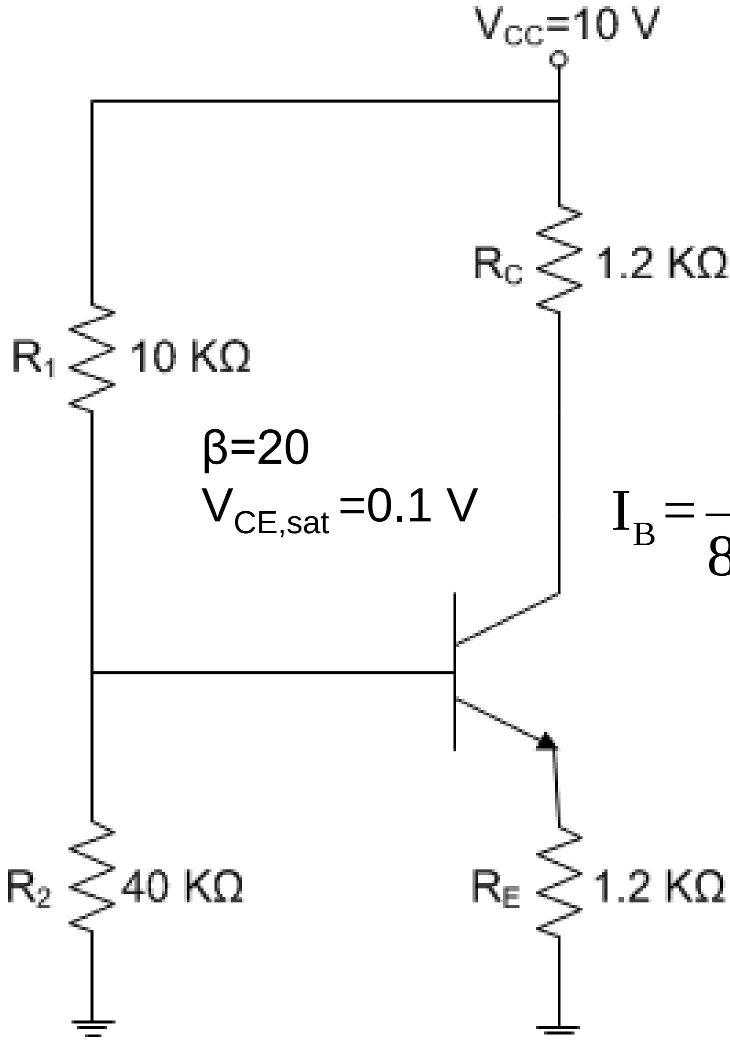
If we had assumed the transistor to be in the active region –

$$I_B = \frac{6-0.7}{20+101(2)} = 0.024mA$$

I_C= 2.4 mA, I_E= 2.424 mA
V_E= 4.85 V, V_B= 5.55 V
V_C=12 - 2.4x10= -12 V

This is clearly impossible so transistor cannot be in the active region

Find the Bias-Point (Q-Point) of the Transistor



$$V_{BB}=\frac{10}{40+10}\times 40=8V \qquad R_B=\frac{10\times 40}{50}=8K\Omega$$

Let us assume that the transistor is in the active region

$$I_B=\frac{8-0.7}{8+21\times 1.2}=0.22mA \qquad I_C=4.4mA \qquad I_E=4.62mA$$

$$V_C=10-1.2\times 4.4=4.72V$$

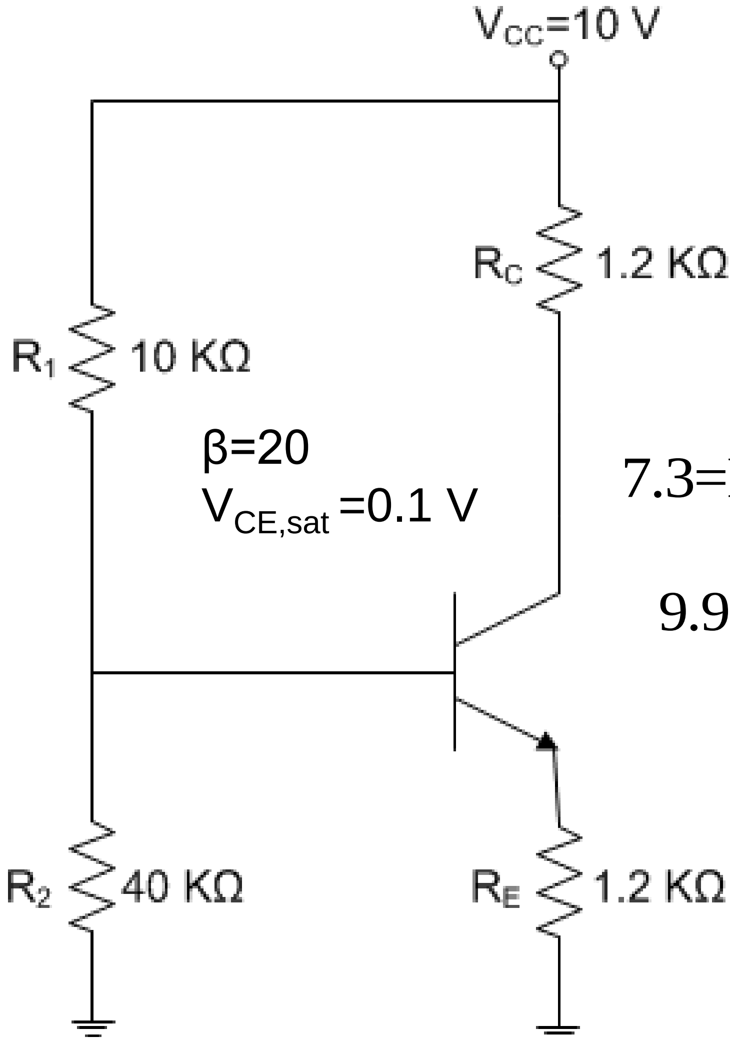
$$V_E=1.2\times 4.62=5.54V$$

$$V_B=5.54+0.7=6.24V$$

V_{BC}= 1.52 V implying that the B-C junction will then be forward biased

Our assumption of the transistor being in the active region MUST be wrong!

Find the Bias-Point (Q-Point) of the Transistor



$$V_{BB} = \frac{10}{40+10} \times 40 = 8V \quad R_B = \frac{10 \times 40}{50} = 8K\Omega$$

Let us now assume that the transistor is in the saturation region

$$7.3 = I_B R_B + (I_B + I_C) R_E \qquad 9.2 I_B + 1.2 I_C = 7.3$$

$$9.9 = 1.2 I_C + (I_C + I_B) 1.2 \qquad 1.2 I_B + 2.4 I_C = 9.9$$

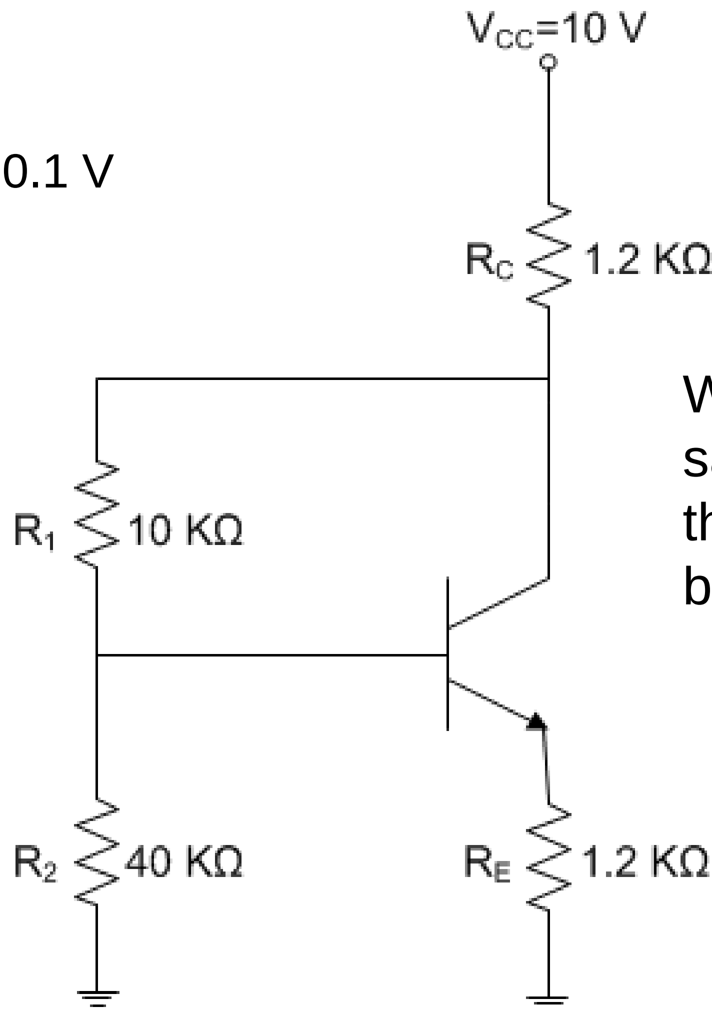
Solving these equations, we get –

I_B=0.273 mA $\quad$ I_C=3.99 mA

Note that I_C=3.99 <βI_B=5.46, therefore the transistor is indeed in saturation as assumed in the beginning

Find the Bias-Point (Q-Point) of the Transistor

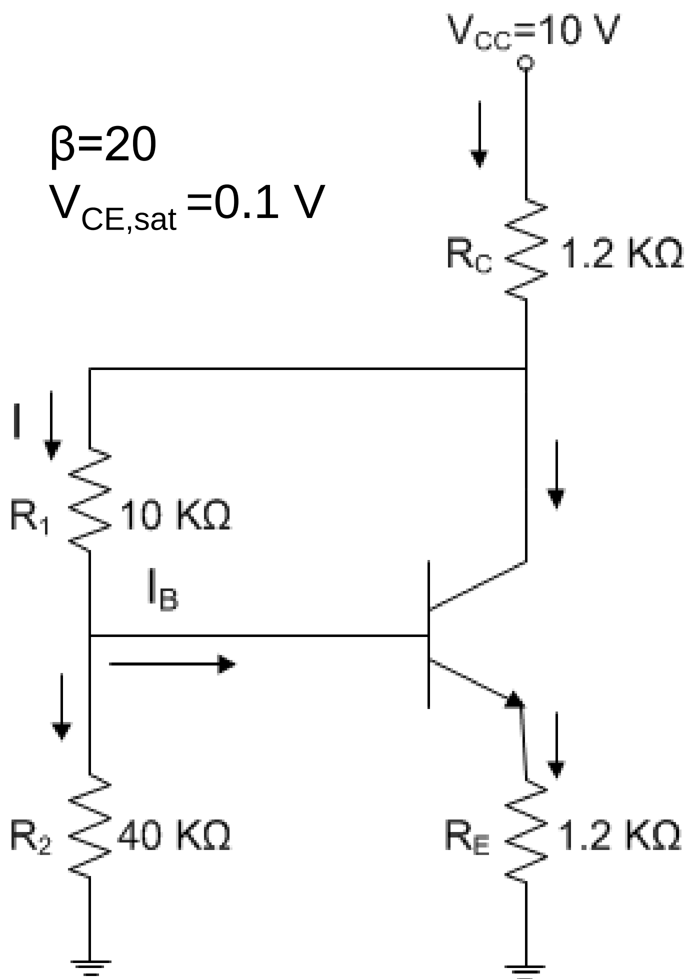
β=20
$V_{CE,sat}$ =0.1 V



We only need to consider the saturation and active regions as the transistor obviously cannot be in cutoff

Find the Bias-Point (Q-Point) of the Transistor

β=20
$V_{CE,sat}$ =0.1 V



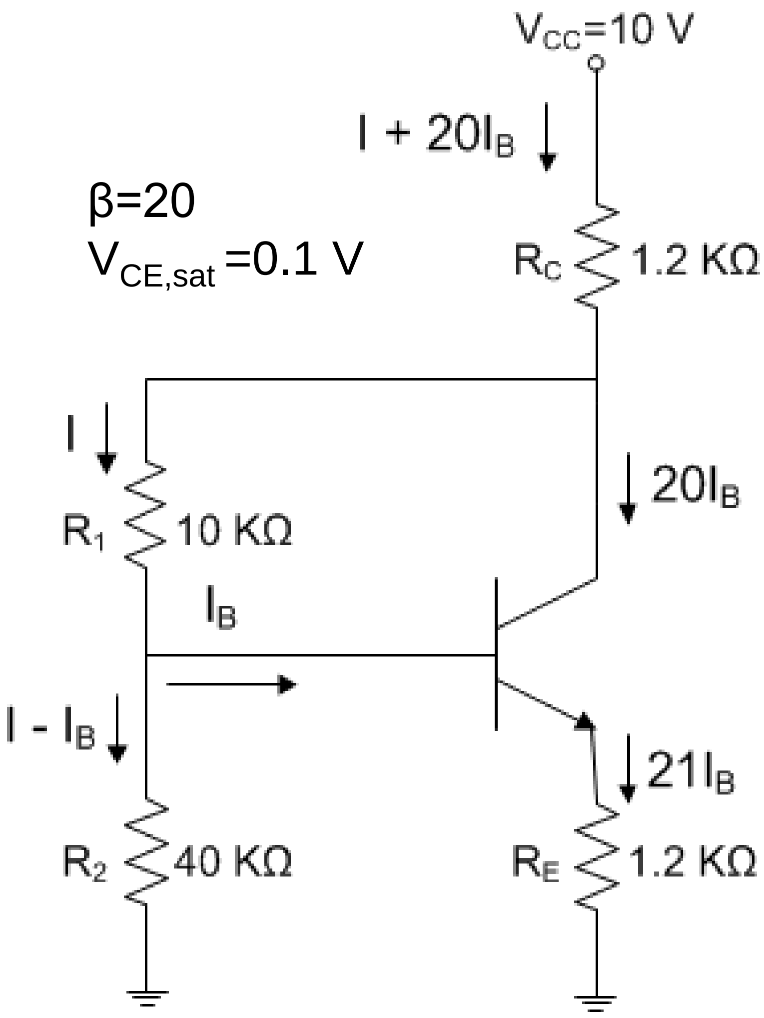
Can the transistor be in saturation?

If it was in saturation, the B-C junction would be forward-biased. In that case, the current I as shown will be negative and therefore I_B will also be negative.

If I_B is negative, then the BE junction cannot be driven into forward-bias and therefore the transistor cannot be in saturation!

Therefore, the transistor must be in the active region and we can then assume that $I_C=\beta I_B$

Find the Bias-Point (Q-Point) of the Transistor



Transistor is in the active region

$$\frac{0.7+1.2\times 21I_B}{40} = I - I_B \qquad I = 1.63I_B + 0.0175$$

$V_E=25.2I_B$ $\qquad$ $V_B=0.7+25.2I_B$

$V_C=10-1.2(I+20I_B) = 9.98-26I_B$

$$I=\frac{V_{CB}}{10}=\frac{V_C-V_B}{10}=0.928-5.12I_B$$

Equating the two expressions for I, we can solve for I_B to get –

$I_B=0.135$ mA, $I_C=2.7$ mA, $I_E=2.835$ mA

$V_E=3.4V$, $V_B=4.1V$ and $V_C=6.47V$

Note that the B-C junction is reverse biased so the transistor is indeed in the active region.