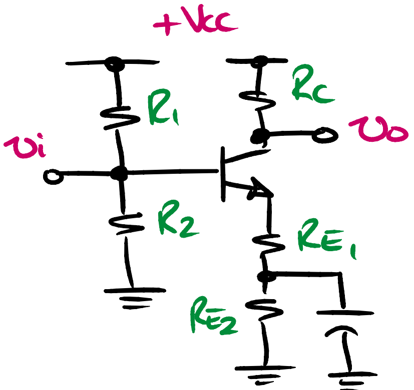
BJT Amplifier Example

Design an Amp w/: $R_{in} \geq 10K\Omega$
$R_o \simeq 10K\Omega$
$|A_{vo}| \simeq 50\ V/V$
$V_{CC} = 10V$.

Assume $V_{BE,ON} = 0.7V$
$V_{CE,sat} = 0.3V$
$\beta = 100$.

Given the requirements, let's use a CE:

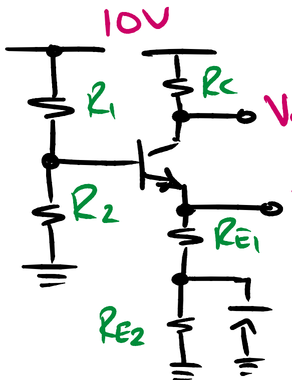


→ for bias current stability (i.e. insensitivity to β & temperature variations), the voltage across the emitter degen. should be $> 3V_{BE}$

→ for a good swing set $V_C \simeq \frac{1}{2}(V_{CC} + V_E)$

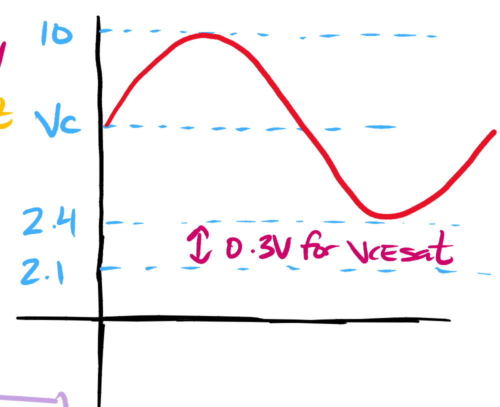
not to scale

so:



$V_C = \frac{1}{2}(10 + 2.1 \underbrace{+0.3}_{\text{accounting for } V_{CEsat}}) = 6.2V$

$V_E = 3 \cdot 0.7 = 2.1V$

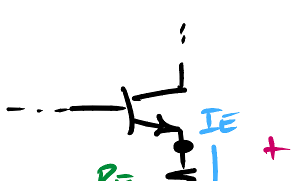


→ In a CE, $R_o = R_C$ → set $\boxed{R_C = 10K\Omega}$

→ Therefore $\boxed{I_C = \frac{10 - 6.2}{10} = 0.38mA}$

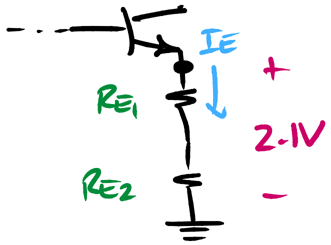
$I_C = \alpha I_E \rightarrow \beta = 100 \rightarrow \alpha = 0.99$

$\boxed{I_E = 0.384\,mA}$



→ $2.1 = 0.384(R_{E1} + R_{E2})$

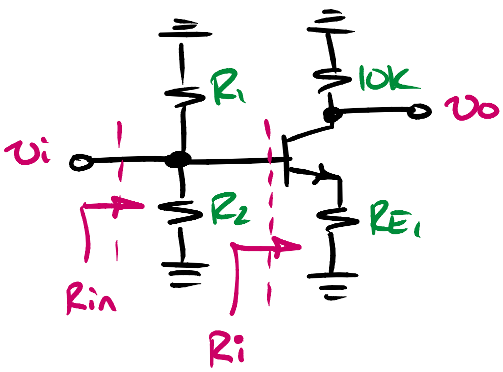
$\boxed{R_{E1} + R_{E2} = 5.47}$



$\rightarrow 2.1 = 0.384(R_{E1}+R_{E2})$

$\boxed{R_{E1}+R_{E2}=5.47}$ (1)

AC Analysis:



$\rightarrow R_i = r_\pi + (\beta+1)R_{E1}$

$\hookrightarrow g_m = 40I_C = 40(0.38)$

$\boxed{g_m = 15.2\,mS}$

$$\rightarrow A_{vo} = \frac{-g_m R_C}{1+g_m R_{E1}} \Rightarrow 50 = \frac{(15.2)(10)}{1+(15.2)(R_{E1})}$$

$\hookrightarrow \boxed{R_{E1} = 0.134\,k\Omega}$

FROM (1); $R_{E2} = 5.47-0.134 \Rightarrow \boxed{R_{E2}=5.34\,k\Omega}$

Since Rin should be $\geq 10k\Omega$;

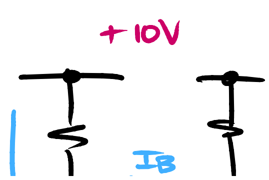
$R_{in} = R_1 // R_2 // R_i$

$\rightarrow R_i = \frac{\beta}{g_m} + (\beta+1)R_{E1} = \frac{100}{15.2} + 101(0.134)$

$\boxed{R_i = 20.1\,k\Omega}$

$$\frac{1}{10} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{20} \rightarrow R_1 // R_2 \geq \left(\frac{1}{10} - \frac{1}{20}\right)^{-1}$$

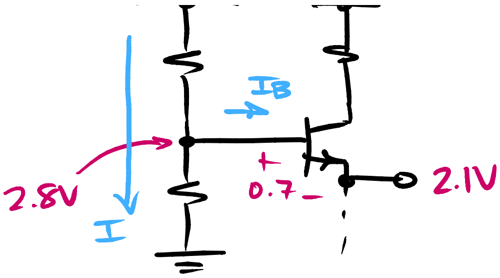
Let $R_1 // R_2 = 20k$;



$\rightarrow I_C = \beta I_B \rightarrow I_B = 0.0038\,mA.$

$\hookrightarrow$ assume $I_B \ll I$:

Since $R_1//R_2 = 20 \rightarrow \boxed{\frac{R_1 R_2}{\quad} = 20}$ (2)



note: I is the current flowing in the divider, ignoring IB.

Since $R_1 // R_2 = 20 \rightarrow$ $\boxed{\dfrac{R_1 R_2}{R_1 + R_2} = 20}$ (2)

Ignoring I_B: $2.8 \simeq 10 \cdot \dfrac{R_2}{R_1 + R_2}$

$\boxed{\dfrac{R_1 + R_2}{R_2} = 3.57}$ (3)

Solve (2) and (3);

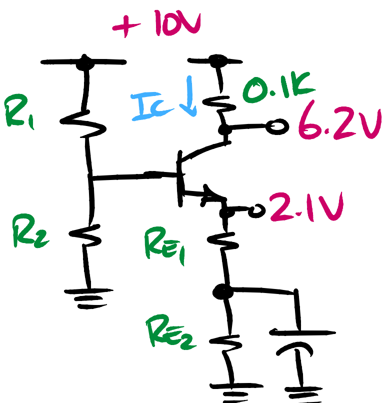
$$\boxed{\begin{aligned} R_1 &= 71.4 k\Omega \\ R_2 &= 27.8 k\Omega \end{aligned}}$$

Check I: $I \simeq \dfrac{10}{71.4 + 27.8} = 0.1 mA = 100 \mu A$

↳ $I \gg I_B$, so our approximation is valid.

What if we want a lower output resistance, which most practical amps have?

Suppose $R_o = 0.1 k\Omega$



$\rightarrow I_C = \dfrac{10 - 6.2}{0.1} = 38 mA.$

↳ stupid big.

$\rightarrow R_{E1} + R_{E2} = \dfrac{2.1}{\underbrace{38 \cdot \frac{101}{100}}_{I_E}} = 0.0547 k\Omega$

$\rightarrow g_m = 40 \cdot 38 = 1520 mS$

$\rightarrow A_{vo} = \dfrac{-g_m R_C}{1 + g_m R_{E1}} \rightarrow R_{E1} = 0.00134 k\Omega$

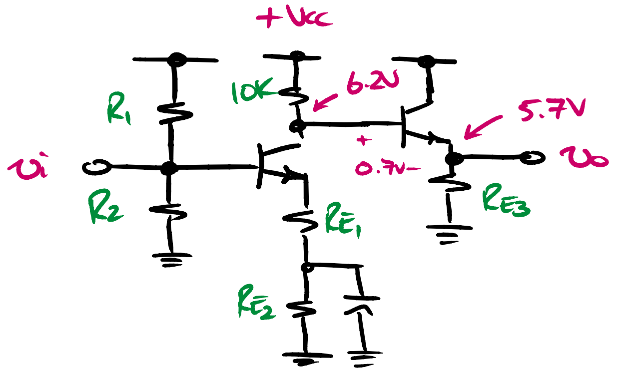
$\rightarrow R_{in} = R_1 // R_2 // \underbrace{[r_\pi + (\beta + 1) R_{E1}]}_{R_i = \frac{100}{} + 101(0.00134) = 0.2k}$

$\rightarrow$ $R_{in} = R_1 // R_2 // [r_\pi + (\beta+1)R_{E1}]$

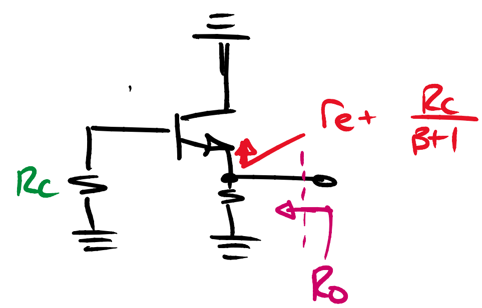
$$\underbrace{[r_\pi + (\beta+1)R_{E1}]}_{R_i = \frac{100}{1520} + 101(0.00134) = 0.2k}$$

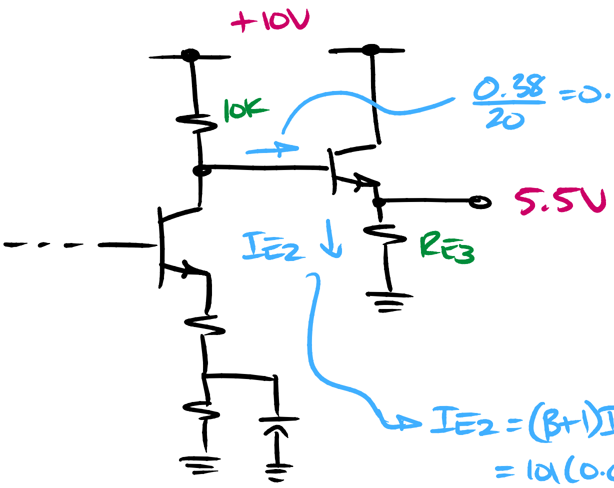
$\hookrightarrow$ This means R_{in} cannot exceed $0.2k\Omega$, meaning we can't achieve our goal.

$\rightarrow$ We can solve the problem by adding a CC stage:



OUTPUT Resistance:





$\frac{0.38}{20} = 0.019 = I_{B2}$

to make sure that I_{B2} is 20 times smaller than I_{C1}. Could have made it 10 times too, just want significantly lower. Alternatively, you could use a DC-blocking cap & bias the second stage separately w/ another voltage divider.

$R_o = R_{E3} // [r_e + \frac{R_C}{\beta+1}]$

$I_{E2} = (\beta+1)I_{B2}$
$= 101(0.019)$
$I_{E2} = 1.92mA$

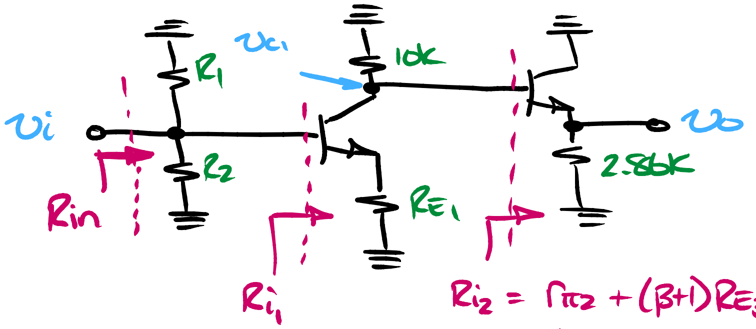
$\rightarrow$ $R_{E3} = \frac{5.5}{1.92} = 2.86k\Omega$

$\rightarrow$ $I_{C2} = \beta I_{B2} = 1.9mA \rightarrow g_{m2} = 76mS$

$\rightarrow$ $r_{e2} \simeq \frac{1}{g_{m2}} = 0.013k\Omega$

$\rightarrow$ $R_o = 2.86k\Omega // \underbrace{[0.013 + \frac{10K}{101}]}_{0.112k\Omega} = 0.108k\Omega$

AMPLIFIER GAIN: - AC ANALYSIS



$R_{i2} = r_{\pi 2} + (\beta+1)R_{E3}$

$= \frac{100}{76} + 101 \cdot 2.86$

$R_{i2} = 290.2k$ if $R_L = \infty$

$\rightarrow \frac{v_{c1}}{v_i} = \frac{-g_{m1}(R_C // R_{i2})}{1 + g_{m1}R_{E1}} = \frac{-15.2(10//290)}{1 + 15.2 \cdot 0.134} = -48.4 \, V/V$

$\rightarrow \frac{v_o}{v_{c1}} = \frac{g_{m2}R_{E2}}{1 + g_{m2}R_{E3}} = \frac{76 \cdot 2.86}{1 + 76 \cdot 2.86} = 0.995 \, V/V$

$\rightarrow A_{vo} = \frac{v_o}{v_{c1}} \cdot \frac{v_{c1}}{v_i} = (48.4 \cdot 0.995) = -48.2 \, V/V$

→ But we wanted a gain of 50, so let's increase it by adjusting R_{E1}:

Since we lost some gain to the CC: $\frac{v_{c1}}{v_i} = \frac{-50}{0.995} = -50.3 \, V/V$

↳ -50.3 is what we need @ the CE to have a gain of 50 overall.

$\rightarrow -50.3 = \frac{-15.2(10//290)}{1 + 15.2R_{E1}} \rightarrow \boxed{R_{E1} = 0.126 k\Omega}$

Meaning R_{E2} becomes: $R_{E2} = 5.47 - 0.126 \rightarrow \boxed{R_{E2} = 5.34 k\Omega}$

The change in R_{E1} also changes the input resistance of the whole amp:

The change in R_{E1} also changes the input resistance of the whole amp:

$$R_{i1} = r_{\pi 1} + (\beta+1)R_{E1} = \frac{100}{15.2} + 101 \cdot 0.126 \rightarrow \boxed{R_{i1} = 19.3k\Omega}$$

To achieve $R_{in} = 10k\Omega$;

$$R_1 // R_2 // 19.3 = 10 \rightarrow R_1 // R_2 = 20.8k\Omega$$

Since; $V_B = 2.8V \rightarrow 2.8 = 10 \cdot \frac{R_2}{R_1 + R_2}$

Which results in $\boxed{R_1 = 74.3k\Omega \;\;\&\;\; R_2 = 28.9k\Omega}$

The current in the divider is: $I = \dfrac{10}{74.3 + 28.9}$

$$\boxed{I = 0.099\,mA = 99\mu A}$$

↳ which is $\ll 3.8\mu A$, so our assumption is valid.

Final Amplifier Design: