Now let's analyze the emitter follower as an output stage.

- Need to consider large signal operation.
- Q1 is biased with current I_E through use of Q2 as a current source.
- \( i_E = I_E + I_L \)

1. When \( I_E \) increases above \( I_E \), extra current flows into load.
2. When \( I_E \) decreases below \( I_E \), difference in current flows out of load.

From (1), we need to choose more negative load current \( < I_E \) to avoid shutting off Q1.

Output voltage can be expressed as \( V_{out} = V_{in} - V_{BE1} \).

Plot this:

- Upper limit when \( Q1 \) is forced into saturation.
- Lower limit when \( Q2 \) is forced into saturation. (As long as \( I_E \) is greater than neg. load current at this point).

Examine signal waveform:
- From above, max. swing for \( V_{out} \) is \( V_{cc} + V_{CE1} \) (since \( V_{CE1} \) is \( \approx 0.4 \))
- \( V_{out} = V_{cc} \cdot \sin(wt) \)
- \( V_{CE1} = V_{cc} - V_{out} = V_{cc} (1 - \sin(wt)) \)
As we showed before, \( I_{E_1} \) swings for \( 2I_B \) to 0.

\[
I_{E_1} = I_B(1 + \sin wt)
\]

Power dissipated in \( Q_1 \) is \( I_{E_1} \cdot V_{CE_1} = I_B \cdot V_{CC} (1 + \sin wt)(1 - \sin wt) = I_B \cdot V_{CC} (1 - \sin^2 wt) = \frac{I_B \cdot V_{CC}}{2}(1 - \frac{1}{2}(1 - \cos 2wt)) = \frac{I_B \cdot V_{CC}}{2}(1 + \cos 2wt)
\]

Efficiency

Efficiency for an output stage is defined as: \( \eta = \frac{\text{Power delivered to Load}}{\text{Power drawn from Supply}} \)

- Assume \( I_B \), \( R_L \) are chosen so that \( V_{Adc} = V_{CC} = I_B \cdot R_L \) (this corresponds with maximum efficiency for class A).

1. Power to Load: \( P_L = \left( \frac{V_{Adc} \cdot \sin \omega t}{R_L} \right)^2 = \frac{(V_{Adc} \cdot \sin \omega t)^2}{2 \cdot R_L} = \frac{V_{CC}^2}{2 \cdot R_L} \)

2. Power from supply:
   - Current to negative supply is \( I_B \), power is \( I_B \cdot V_{CC} \).
   - Average current from positive supply is \( I_B \), power is \( I_B \cdot V_{CC} \).

\[
P_S = 2 \cdot I_B \cdot V_{CC}
\]

\[
\eta = \frac{V_{CC}^2}{2 \cdot R_L \cdot 2 \cdot I_B \cdot V_{CC}} = \frac{V_{CC}}{4 \cdot I_B \cdot R_L} = \frac{1}{4} = 25\%
\]

- Recall that \( V_{CC} = I_B \cdot R_L \)

Maximum possible efficiency from a class A stage is 25%.

- Practically attainable efficiencies are in the 10-20% range due to need to avoid transistor saturation.

Example: Consider the circuit below, where \( I_S = 10^{-15} \text{ A and } V_{cc} = 3 \cdot \sin wt \text{ V} \).

\[
\begin{align*}
V_{in} & \quad K_0 & \quad K_0 & \quad V_{out} \\
V_b & \quad K_0 & \quad 2k_0 & \quad R_L = 2k_0
\end{align*}
\]

(a) If \( V_b \) is chosen so that \( I_b = 1 \text{ mA} \), will this be class A?

- Assume \( V_{BE} = 0.7 \) (will check this later)

\[
V_{out} = 3 \cdot \sin(\omega t) - 0.7 \rightarrow V_{out, min} = -3.7 \text{ V}
\]
The required current \( I_L = \frac{V_{out}}{R_L} = \frac{-3.7}{2k} = 1.85 \text{ mA} \).

- Q1 will be forced into cutoff, this will not be Class A operation.
- Adjust \( V_C \) to get \( I_B = 2 \text{ mA} \) for Class A operation.

(b) Draw signal waveforms.

\[
V_{out} = V_C - V_{BE} = V_C - 0.7
\]

\[
I_L = \frac{V_{out}}{R_L} \rightarrow I_{out, \text{max}} = 2.3 = 1.15 \text{ mA} \quad \rightarrow \quad I_{out, \text{min}} = -3.7 = -1.85 \text{ mA}.
\]

\[
I_{C1} = I_L + I_B = 2 \text{ mA} + I_L
\]

\[
\rightarrow I_{C1, \text{max}} = 3.15 \text{ mA} \quad \rightarrow \quad I_{C1, \text{min}} = 0.15 \text{ mA}
\]

(6) Check \( V_{BE} = 0.7 \) V assumption

\[
I_C = I_S \cdot e^{V_{BE}/V_T} \rightarrow V_{BE} = V_T \cdot \ln \left( \frac{I_C}{I_S} \right)
\]

\[
I_{C_{\text{min}}} = 0.15 \text{ mA} \rightarrow V_{BE} \approx 0.67 \text{ V}
\]

\[
I_{C_{\text{max}}} = 3.15 \text{ mA} \rightarrow V_{BE} \approx 0.75 \text{ V} \quad \text{(not bad)}
\]

(1) Calculate efficiency

\[
P_L = \frac{V_{out, \text{rms}}^2}{R_L}\]

\[
V_{out, \text{rms}} = \sqrt{\frac{W}{2\pi} \int_0^{2\pi} (3 \sin \omega t - 0.7)^2 dt}
\]

\[
\text{after some number crunching, } V_{out, \text{rms}} = 5.99
\]

\[
P_L = 5.99 \approx 3 \text{ mW}
\]

\[
R_S = 5 \cdot (1.65 \text{ mA}) + 5 \cdot (2 \text{ mA}) = 18.25 \text{ mW}
\]

\[
\eta = \frac{3 \text{ mW}}{18.25 \text{ mW}} = 16.4 \%
\]