Class B Output Stage

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Class B Amplifier Operation

**Class B – Amplifier** BJT conducts for positive-half of \( v_I \) cycle.

Amp conducts for all \( v_I \) s.t.:

\[
V_B = 0 \text{ } V \Rightarrow v_I \geq 0.7 \text{ } V
\]

Transistor cut off \((i_C = 0)\) if:

\[
v_I + V_B < 0.7 \text{ } V
\]

**NOTE:**
1. when \( v_I < 0.7V \), \( i_C = 0 \)
2. a 2\(^{nd}\) class B BJT is needed to conduct for the negative \( v_I \) cycle.
The Class B Output Stage

I. For $v_I > 0.7 \text{ V}$
   - $V_{BEN} = v_I - v_O$
   - $v_O = v_I - 0.7 \text{ V}$

   a. $i_L = i_{EN} \approx i_{CN}$
   b. $Q_N$ saturates if $v_O > V_{CC} - V_{CENSat}$.
   c. $Q_P$ is cut off for $v_I > -0.7 \text{ V}$.

   The output voltage $v_O$ follows the input $v_I$, less the $V_{BEN}$ drop, up to $Q_N$ saturation.

II. For $v_I < -V_{EBP} = -0.7 \text{ V}$, $Q_P = ON$, $Q_N = OFF$.
   - $i_L = -i_{EP} \approx -i_{CP}$
   - $Q_P$ saturates if $v_O < -V_{CC} - V_{ECPsat}$
   - $Q_N$ is cut off for $v_I < 0.7 \text{ V}$.

   The output voltage $v_O$ follows the input $v_I$, plus the $V_{EBP}$ drop, down to $Q_P$ saturation.

0. For $-0.7 \text{ V} \leq v_I \leq 0.7 \text{ V}$, $Q_N$ and $Q_P$ cutoff.
   => $v_O = 0 \text{ V}$
Class B Amplifier VTC Plot

\[ v_o = v_i - 0.7 \, V \]

For:
\[ 0.7 \, V < v_i < (V_{CC} - V_{CENsat}) + 0.7 \, V \]

\[ v_o = 0 \, V \]

For:
\[ -0.7 \, V < v_i < 0.7 \, V \]

\[ v_o = v_i + 0.7 \, V \]

For:
\[ -(V_{CC} - V_{ECPsat}) - 0.7 \, V < v_i < -0.7 \, V \]
Crossover distortion in audio power amps produces unpleasant sounds.
Multisim Simulation Class B VTC
Multisim Simulation Class B VTC - cont.
The “dead band” from $-V_{EBP} = -0.7 \, V < v_i < V_{BEN} = 0.7 \, V$ causes crossover distortion. This distortion is severe, particularly for low voltage signals.
Quick Review

Class B VTC

Class A VTC

Class A Power Efficiency

\[ P_{D_{av}} = 2V_{CC}I \]

\[ P_{L_{av}} = \frac{V_{o-peak}^2}{2R_L} \]

\[ \eta = \frac{1}{4} \frac{V_{o-peak}^2}{IR_L} \frac{V_{o-peak}}{V_{CC}} \]

\[ \eta_{max} = \frac{1}{4} \frac{V_{CC}^2}{V_{CC}} \frac{V_{CC}}{V_{CC}} = 0.25 \]

Note:

\[ P_{Disp}(V_o = 0) = P_{D_{av}} - P_{L_{av}} = 2V_{CC}I \]
Class B Power Analysis

Simplifying Assumptions:
1. Ignore the dead-zone in $VTC$.
2. Let $V_{CEN-sat} = V_{ECP-sat} = 0$ V => maximum $v_o$ swing is $-V_{CC} \leq v_o \leq V_{CC}$

The average power to the load resistor:
$$v_o = V_{o-peak} \sin(\omega t)$$

$$P_{Lav} = V_{o-rms} I_{o-rms} = \frac{V_{o-rms}^2}{R_L} = \frac{1}{2} \frac{V_{o-peak}^2}{R_L}$$

same as Class A

The average power delivered by the positive $+V_{CC}$ power supply over the positive half-cycle $0 \leq t \leq T/2$ ($i_C = 0$ from $T/2 \leq t \leq T$):

$$P_{+V_{CC}av} = \frac{1}{T} \int_0^{T/2} V_{CC} i_{CN} \, dt = \frac{1}{T} \int_0^{T/2} V_{CC} i_L \, dt = \frac{1}{T} \int_0^{T/2} V_{CC} \frac{V_{o-peak}}{R_L} \sin\left(\frac{2\pi}{T} t\right) \, dt$$

$\omega$
From previous slide

\[ P_{+V_{ccav}} = \frac{1}{T} \int_0^{T/2} V_{cc} \frac{V_{o-peak}}{R_L} \sin \left( \frac{2\pi}{T} t \right) dt = \frac{1}{T} V_{cc} \frac{V_{o-peak}}{R_L} \int_0^{T/2} \sin \left( \frac{2\pi}{T} t \right) dt \]

Recalling from calculus \[ \int \sin(\omega t) \, dt = \frac{-1}{\omega} \cos(\omega t) \]

\[ P_{+V_{ccav}} = \frac{1}{T} V_{cc} \frac{V_{o-peak}}{R_L} \left( \frac{-T}{2\pi} \cos \left( \frac{2\pi}{T} \frac{T}{2} t \right) \right) \bigg|_{t=0}^{t=T/2} \]

\[ P_{+V_{ccav}} = -\frac{1}{2\pi} \frac{V_{o-peak}}{R_L} V_{cc} \left\{ \cos \left( \frac{2\pi}{T} \frac{T}{2} \right) - \cos \left( \frac{2\pi}{T} 0 \right) \right\} \]

\[ P_{+V_{ccav}} = -\frac{1}{2\pi} \frac{V_{o-peak}}{R_L} V_{cc} \left\{ \cos(\pi) - \cos(0) \right\} \]

\[ P_{+V_{ccav}} = \frac{1}{\pi} \frac{V_{o-peak}}{R_L} V_{cc} \]
Class B Power Analysis - cont.

Power delivered by the negative $-V_{cc}$ power source is equal to that for $+V_{cc}$:

$$P_{-V_{cc}av} = P_{+V_{cc}av} = \frac{1}{\pi} \frac{V_{o-peak}}{R_L} V_{CC}$$

Hence:

$$P_{Dav} = P_{+V_{cc}av} + P_{-V_{cc}av} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC}$$

The power conversion efficiency of the class B amplifier (accurate for $|V_{o-peak}| > 0.7 \text{ V}$) is:

$$\eta = \frac{P_{Lav}}{P_{Dav}} = \frac{1}{2} \frac{V_{o-peak}^2}{R_L} \frac{\pi}{2} \frac{V_{o-peak}}{R_L} V_{CC} = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}}$$
Class B Power Analysis - cont.

Maximum Class B power conversion efficiency:

Since we assume \(-V_{CC} \leq v_o \leq V_{CC}\)

\[
\eta = \frac{\pi}{4} \frac{V_{o-\text{peak}}}{V_{CC}} \Rightarrow \eta_{\text{max}} = \frac{\pi}{4} = 0.785 \text{ or } 78.5\% 
\]

Recall for Class A: \(\eta_{\text{max}} = 0.25 \text{ or } 25\%\)

Power Dissipation:

Class B power dissipated in the transistors:

\[
P_{\text{Disp}} = P_{\text{Dav}} - P_{Lav} = \frac{2}{\pi} \frac{V_{o-\text{peak}}}{R_L} V_{CC} - \frac{1}{2} \frac{V_{o-\text{peak}}^2}{R_L}
\]

\[
P_{\text{Disp}}(V_{o-\text{peak}} = 0) = 0 \text{ actually } V_{o-\text{peak}} \leq 0.7V
\]
Class B Power Analysis - cont.

\[
P_{Disp} = 0 \quad \text{when } V_{o-peak} = 0 \quad \text{(more precisely } V_{o-peak} \leq 0.7 \, V) \]

\[
P_{Disp} = P_{Dav} - P_{Lav} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} - \frac{1}{2} \frac{V_{o-peak}^2}{R_L}
\]

What value of \( V_{o-peak} \) results in the maximum \( P_{Disp} \) ?

To estimate maximum \( P_{Disp} \): set derivative of \( P_{Disp} \) w.r.t. \( V_{o-peak} \) to zero, i.e.

\[
\frac{d P_{Disp}}{d V_{o-peak}} = \frac{2}{\pi} \frac{V_{CC}}{R_L} - \frac{V_{o-peak}}{R_L} = 0 \quad \Rightarrow \quad V_{o-peak} = \frac{2}{\pi} V_{CC} < V_{CC}
\]

\[
P_{Disp(max)} = \frac{4}{\pi^2} \frac{V_{CC}^2}{R_L} - \frac{1}{2} \frac{4}{\pi^2} \frac{V_{CC}^2}{R_L} = \frac{2}{\pi^2} \frac{V_{CC}^2}{R_L} \quad \text{with } V_{o-peak} = \frac{2}{\pi} V_{CC}
\]

\( \frac{1}{2} P_{Disp(max)} \) is dissipated in \( Q_N \) and \( \frac{1}{2} P_{Disp(max)} \) is dissipated in \( Q_P \).
Class B Power Analysis Summary

Power from sources:

\[
P_{Dav} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC}
\]

\[
P_{Dav(max)} = \frac{2}{\pi} \frac{V_{CC}^2}{R_L}
\]

\[
\eta = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}}
\]

\[
\eta_{max} = \frac{\pi}{4} \approx 0.785
\]

Power output to load:

\[
P_{Lav} = \frac{1}{2} \frac{V_{o-peak}^2}{R_L}
\]

\[
P_{Lav(max)} = \frac{1}{2} \frac{V_{CC}^2}{R_L}
\]

Transistor dissipation \(Q_N + Q_P\):

\[
P_{Disp} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} - \frac{1}{2} \frac{V_{o-peak}^2}{R_L}
\]

\[
P_{Disp(max)} = \frac{2}{\pi^2} \frac{V_{CC}^2}{R_L}
\]

Max dissipation at:

\[
V_{o-peak} = \frac{2}{\pi} V_{CC}
\]

\[
\eta_{max-Disp} = 0.5
\]
Power Dissipation Function Plot

Let $V_{CC} = 12 \text{ V}$ and $R_L = 100 \Omega$

$$P_{Disp(max)} = \frac{2V_{CC}^2}{\pi^2 R_L} = 0.29 \text{ W}$$

$$P_{Disp-B} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} - \frac{1}{2} \frac{V_{o-peak}^2}{R_L}$$

$P_{Disp-B}$

$P_{Disp-A} = 2 V_{CC} I - \frac{1}{2} \frac{V_{o-peak}^2}{R_L}$

$P_{disp-A} = 0.29 \text{ W}$ for $I = 12.08 \text{ mA}$

Not accurate for small $V_{o-peak}$. 

NOTE:
Power Conversion Efficiency vs. Output Voltage Amplitude

Let $V_{CC} = 12$ V

Efficiency ($\eta$)

$\eta_{max} = 0.785$

$\eta = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}}$

$P_{Disp(max)} \quad @ \quad V_{o-peak} = \frac{2}{\pi} V_{CC}$
**Class B Audio Amplifier Example**

It is required to design a Class B output stage to deliver an average power of 20 W to an 8 Ω speaker load.

To avoid saturation of the transistors and non-linear distortion, the power supply $V_{CC}$ is to be 5V greater than peak output voltage.

1. Determine the $V_{CC}$ required.
2. Determine peak current drawn from each power supply.
3. Determine the total power drawn from the power supplies.
4. Determine the power conversion efficiency.
5. Determine the max power each transistor must be able to dissipate safely.
Class B Audio Amplifier Example - cont.

SOLUTION:

1. Determine the $V_{CC}$ required.

$$ P_{Lav} = 20 \, W \text{ and } R_L = 8 \, \Omega $$

$$ P_{Lav} = \frac{1}{2} \frac{V_{o-peak}^2}{R_L} = 20 \, W \Rightarrow V_{o-peak} = \sqrt{2 \cdot P_{L-av} \cdot R_L} = \sqrt{2 \cdot 20 \cdot 8} = 17.9 \, V $$

$$ V_{CC} = V_{o-peak} + 5 \, V = 17.9 \, V + 5 \, V = 23 \, V $$

2. Determine peak current drawn from each power supply.

$$ I_{o-peak} = \frac{V_{o-peak}}{R_L} = \frac{17.9 \, V}{8 \, \Omega} = 2.24 \, A $$
Class B Audio Amplifier Example - cont.

SOLUTION cont.:

3. Determine the total power drawn from the power supplies.

\[
P_{Dav} = \frac{2}{\pi} \frac{V_{o-peak}}{R_L} V_{CC} = \frac{2}{\pi} \frac{17.9 \, V}{8 \, \Omega} 23 \, V = \boxed{32.8 \, W}
\]

4. Determine the power conversion efficiency.

\[
\eta = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}} = \frac{\pi}{4} \frac{17.9 \, V}{23 \, V} = \boxed{0.61 \text{ or } 61 \%}
\]

5. Determine the max power each transistor must dissipate safely.

\[
P_{DispN(max)} = P_{DispP(max)} = \frac{1}{2} P_{Disp(max)} = \frac{1}{\pi^2} \frac{V_{CC}^2}{R_L} = \frac{1}{\pi^2} \frac{(23 \, V)^2}{8 \, \Omega} = \boxed{6.7 \, W}
\]
Multisim Simulation – Max Power Dissipation

\[ V_o = v_I - 0.7V \]

\[ P_{+V_{cc\,av}} = \frac{1}{\pi} \frac{V_{o-\,peak}}{R_L} V_{CC} = 0.265 \, \text{W} \]

\[ V_{i-\,peak} = 7.63 \, V \]

\[ \eta_{\text{sim}} = \frac{P_{L_{av}}}{P_{+V_{cc\,av}} + P_{-V_{cc\,av}}} = \frac{0.2198}{0.2429+0.2449} = 0.45 \]

\[ V_o = v_I \pm 0.7V \]

\[ P_{L_{av}} = \frac{1}{2} \frac{V_{o-\,peak}^2}{R_L} = 0.240 \, \text{W} \]

\[ V_{o-\,peak} = 7.63 \, V \]

\[ P_{-V_{cc\,av}} = \frac{1}{\pi} \frac{V_{o-\,peak}}{R_L} V_{CC} = 0.265 \, \text{W} \]

\[ \eta_{\text{theory}} = \frac{P_{L_{av}}}{P_{V_{cc\,av}} + P_{-V_{cc\,av}}} = \frac{0.240}{0.265+0.265} = 0.45 \]
Multisim Simulation – Max Power
Conversion Efficiency

\[ P_{+V_{ccav}} = 432.103 \text{ mW} \]

\[ P_{-V_{ccav}} = 423.909 \text{ mW} \]

\[ P_{L_{av}} = 677.249 \text{ mW} \]

\[ V_{i-peak} = 12.7 \text{ V} \]

\[ v_O = v_I \pm 0.7V \]

\[ \eta_{sim} = \frac{P_{L_{av}}}{P_{+V_{ccav}} + P_{-V_{ccav}}} = \frac{0.6772}{0.4231 + 0.4239} = 0.78 \]
Anticipating Class AB – Eliminating Crossover Distortion

If we bias the bases of the emitter follower pair, we can set both transistors on the verge of conduction – or have them conduct a small bias current with zero signal input:

\[ \frac{V_{BB}}{2} \approx 0.7 \ V. \]

Class AB is a compromise between Class and Class B
Summary

Class B advantages:
1. Much higher power conversion efficiency than class A for large signal amplitudes.
2. Zero power dissipation with zero input.

Class B disadvantage:
Higher distortion than class A, especially at low input amplitudes.

Class AB operation is a compromise mode:
1. Delivering better linearity than class B, with reduced efficiency.
2. Delivering better efficiency than class A, with reduced linearity.