Quick Review

Class A Power

\[ P_{Dav} = 2V_{CC}I \]
\[ P_{Lav} = \frac{V_{o-peak}^2}{2R_L} \]
\[ \eta = \frac{1}{4} \frac{V_{o-peak}}{I R_L} \frac{V_{o-peak}}{V_{CC}} \]
\[ \eta_{\text{max}} = \frac{1}{4} \frac{V_{CC}}{V_{CC}} \frac{V_{CC}}{V_{CC}} = 0.25 \]
\[ P_{Disp} = P_{Dav} - P_{Lav} \]
\[ P_{Disp(\text{max})} = 2V_{CC}I \]

when \[ V_{o-peak} = 0 \]

Class B Power

\[ P_{Dav} = \frac{2}{\pi} \frac{V_{o-peak}^2}{R_L} \]
\[ P_{Lav} = \frac{V_{o-peak}^2}{2R_L} \]
\[ \eta = \frac{\pi}{4} \frac{V_{o-peak}}{V_{CC}} \]
\[ \eta_{\text{max}} = \frac{\pi}{4} \approx 0.785 \]

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

when \[ P_{Disp(\text{max})} = \frac{2}{\pi^2} \frac{V_{CC}^2}{R_L} \]
Class AB Output Stage

- Class AB amplifier Operation
- Multisim Simulations - Operation
- Class AB amplifier biasing
- Multisim Simulations - Biasing
Class AB Operation

Class AB – Amplifier transistor conducts for positive $v_I$ swing + part of negative $v_I$ swing

s.t.:

$$v_I + V_B \geq 0.7V \quad \text{where} \quad V_B < \max(v_I)$$

Conducts for:

$$v_I \geq 0.7 - V_B$$

Cut-off for rest of negative $v_I$ swing:

Transistor cut-off ($i_C = 0$) if:

$$v_I + V_B < 0.7V$$

NOTE:

1. when $v_I = 0$, $i_C = I_C$

2. a 2$^{nd}$ class AB BJT is needed to conduct for interval slightly larger than the negative $v_I$ cycle.
Basic Class AB Amplifier Circuit

Bias \( Q_N \) and \( Q_P \) into slight conduction when \( v_I = 0 \).

Ideally \( Q_N \) and \( Q_P \) are:

1. Matched (unlikely with discrete transistors and challenging in IC).
2. Operate at same ambient temperature.

\[ i_L = i_N - i_P \]

NOTE. This is base-voltage biasing with all its stability problems!

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Class AB Circuit Operation - VTC

Output voltage for $v_i \neq 0$:

- For $v_i > 0$: $v_o = v_i + \frac{V_{BB}}{2} - v_{BEN} \Rightarrow v_o \approx v_i$
- For $v_i < 0$: $v_o = v_i - \frac{V_{BB}}{2} + v_{EBP} \Rightarrow v_o \approx v_i$

Base-to-base voltage is constant!

There is a corresponding conservation relation between $i_N$ & $i_P$, i.e.

Using: $i_N = I_S e^{\frac{v_{BEN}}{V_T}}$, $i_P = I_S e^{\frac{v_{EBP}}{V_T}}$, $I_Q = I_S e^{\frac{V_{BB}}{2V_T}}$

$$V_T \ln \left( \frac{i_N}{I_S} \right) + V_T \ln \left( \frac{i_P}{I_S} \right) = 2V_T \ln \left( \frac{I_Q}{I_S} \right)$$
Class AB Circuit Operation - VTC

For \( v_i > 0 \) \( v_o = v_i + \frac{V_{BB}}{2} - v_{BEN} \Rightarrow v_{BEN} = v_i - v_o + \frac{V_{BB}}{2} \) ADD

For \( v_i < 0 \) \( v_o = v_i - \frac{V_{BB}}{2} + v_{EBP} \Rightarrow v_{EBP} = v_o - v_i + \frac{V_{BB}}{2} \)

\( v_{BEN} + v_{EBP} = V_{BB} \) for all \( v_i \)

Using the currents

\( i_N = I_S e^{\frac{v_{BEN}}{V_T}} \Rightarrow v_{BEN} = V_T \ln \left( \frac{i_N}{I_S} \right) \)

\( i_P = I_S e^{\frac{v_{EBP}}{V_T}} \Rightarrow v_{EBP} = V_T \ln \left( \frac{i_P}{I_S} \right) \)

\( I_N = I_P = I_Q = I_S e^{2V_T} \Rightarrow V_{BB} = 2V_T \ln \left( \frac{I_Q}{I_S} \right) \)

\( V_T \ln \left( \frac{i_N}{I_S} \right) + V_T \ln \left( \frac{i_P}{I_S} \right) = 2V_T \ln \left( \frac{I_Q}{I_S} \right) \) for all \( v_i \)

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Class AB Circuit Operation - VTC cont.

from the previous slide

\[ V_T \ln \left( \frac{i_N}{I_S} \right) + V_T \ln \left( \frac{i_P}{I_S} \right) = 2 V_T \ln \left( \frac{I_Q}{I_S} \right) \]

\[ V_T \ln \left( \frac{i_N i_P}{I_S^2} \right) = 2 V_T \ln \left( \frac{I_Q}{I_S} \right) \]

\[ V_T \ln (i_N i_P) - V_T \ln (I_S^2) = 2 V_T \ln (I_Q) - 2 V_T \ln (I_S) \]

\[ \ln (i_N i_P) = \ln (I_Q^2) \quad \text{or} \quad i_N i_P = I_Q^2 \]

Constant base voltage condition:

\[ v_{BEN} + v_{EBP} = V_{BB} \Rightarrow i_N i_P = I_Q^2 \]
Constant base voltage condition:

\[ i_N i_P = I_Q^2 \]

Kirchhoff’s Current Law condition:

\[ i_N = i_P + i_L \implies i_P = i_N - i_L \]

Combining equations:

\[ i_N(i_N - i_L) = I_Q^2 \quad \text{or} \quad i_P(i_P + i_L) = I_Q^2 \]

for \( v_I > 0 \) V \quad \text{or} \quad \text{for } v_I < 0 \) V

Hence:

\[ i_N^2 - i_N i_L - I_Q^2 = 0 \quad \text{or} \quad i_P^2 + i_P i_L - I_Q^2 = 0 \]

for \( v_I > 0 \) V \quad \text{or} \quad \text{for } v_I < 0 \) V
Class AB Circuit Operation – VTC cont.

\[
i_L = i_N - i_P
\]
\[
i_N i_P = I_Q^2
\]

Observations:
1. Since with constant base voltage \( V_{BB} \): \( i_N i_P = I_Q^2 \), if \( i_P \) increases by \( i_P = i_P (1 + \Delta i) \) then \( i_N \) decreases by \( i_N = i_N / (1 + \Delta i) \), and vice-versa.

2. For \( v_O > 0 \), the load current \( i_L \) is supplied by the complementary emitter followers \( Q_N \) and \( Q_P \). As \( v_O \) increases, \( i_P \) decreases and for large, positive \( v_O \) i.e. \( i_P = i_N - i_L = i_N - \frac{v_O}{R_L} \) hence \( v_O \rightarrow V_{CC} - V_{CENsat} \Rightarrow i_P \rightarrow 0 \)

3. For \( v_O < 0 \), the load current \( i_L \) supplied by the complementary emitter followers \( Q_N \) and \( Q_P \). As \( v_O \) decreases, \( i_N \) decreases and for large, negative \( v_O \) i.e. \( i_N = i_P + i_L = i_P + \frac{v_O}{R_L} \) hence \( -v_O \rightarrow -V_{CC} + V_{ECPsat} \Rightarrow i_N \rightarrow 0 \)
Class AB Circuit Operation – VTC cont.

The constant base voltage condition \( i_P i_N = I_Q^2 \) where \( I_Q \) is typically small.

For example let \( I_Q = 1 \text{ mA} \) and \( i_N = 10 \text{ mA} \).

\[
i_P = \frac{I_Q^2}{i_N} = \frac{1 \cdot 10^{-6}}{10 \cdot 10^{-3}} = 0.1 \text{ mA} = \frac{1}{100} i_N
\]

The Class AB circuit, over most of its input signal range, operates as if either the \( Q_N \) or \( Q_P \) transistor is conducting and the \( Q_P \) or \( Q_N \) transistor is cut off.

For small values of \( v_I \) both \( Q_N \) and \( Q_P \) conduct, and as \( v_I \) is increased or decreased, the conduction of \( Q_N \) or \( Q_P \) dominates, respectively.

Using this approximation we see that a class AB amplifier acts much like a class B amplifier; but without the dead zone.
Class AB VTC Plot

Requires the two DC base voltage sources to be matched and $V_{BB}/2 = 0.7 \, V$. 
Amplitude: 20 V<sub>p</sub>
Frequency: 1 kHz

Class AB VTC Simulation

- **Waveforms**: Amplitude: 20 V<sub>p</sub>, Frequency: 1 kHz
- **Function Generator**: Amplitude: 20 V<sub>p</sub>, Frequency: 1 kHz, Duty Cycle: 50%, Offset: 0 V
- **Oscilloscope**: XSC1
- **Circuit Components**:
  - Q1, Q2: Transistors
  - R<sub>L</sub>: 100Ω
  - R<sub>Sig</sub>: 50Ω
  - V<sub>BB</sub>/2: 0.7 V
  - V<sub>CC</sub>: 12 V
  - V<sub>CC</sub>: 12 V
  - V<sub>CC</sub>: 12 V
Class AB VTC Simulation - cont.

Amplitude: 2 V
Frequency: 1 kHz

\[
\frac{V_{BB}}{2} = 0.5 V
\]

\[
\frac{V_{BB}}{2} = 0.1 V
\]

\[
\frac{V_{BB}}{2} = 0.7 V
\]
Class AB Small-Signal Output Resistance

Instantaneous resistance for the $Q_N$ transistor - assume $\alpha = 1$:

$$i_N = I_S e^{v_T/v_{BEN}}$$

$$\frac{di_N}{dv_{BEN}} = I_S \frac{v_{BEN}}{V_T} = \frac{i_N}{V_T}$$

For the $Q_P$ transistor:

$$\frac{di_P}{dv_{EBP}} = \frac{i_P}{V_T}$$

Hence:

$$r_{eN} = \frac{V_T}{i_N}$$

and

$$r_{eP} = \frac{V_T}{i_P}$$

for $v_I > 0$ V: $R_{out} \approx r_{eN}$

for $v_I < 0$ V: $R_{out} \approx r_{eP}$
Small-Signal Output Resistance - cont.

The two emitter resistors are in parallel:

\[ R_{out} = r_{eN} \parallel r_{eP} = \frac{V^2_T}{i_N i_P} = \frac{V_T}{\frac{V_T}{i_N} + \frac{V_T}{i_P}} = \frac{V_T}{i_N + i_P} \]

and

\[ i_L = \frac{v_O}{R_L} = i_N - i_P \]

At \( i_N = i_P \) (the no-signal condition i.e. \( v_O = 0 \Rightarrow i_L = 0 \)):

\[ i_N = i_P = I_Q \]

\[ R_{out} = \frac{V_T}{2I_Q} \]

So, for small signals, a small load current \( I_Q \) flows => no dead-zone!
A straightforward biasing approach: $D1$ and $D2$ are diode-connected transistors identical to $QN$ and $QP$, respectively. They form mirrors with the quiescent currents $I_Q$ set by matched $R$'s:

$$I_Q = \frac{2V_{CC} - 1.4}{2R} = \frac{V_{CC} - 0.7}{R}$$

or:

$$R = \frac{V_{CC} - 0.7}{I_Q}$$

Recall: With mirrors, the ambient temperature for all transistors needs to be matched!
### Widlar Current Source

$I_N = \text{bias current for Class AB amplifier NPN}$

\[ I_{Q} = I_N \]

Q2 = QN

\[ V_{BE1} = V_T \ln \left( \frac{I_{REF}}{I_S} \right) \]

\[ V_{BE2} = V_T \ln \left( \frac{I_Q}{I_S} \right) \]

\[ V_{BE1} - V_{BE2} = V_T \ln \left( \frac{I_{REF}}{I_S} \right) \cdot \frac{I_S}{I_Q} = V_T \ln \left( \frac{I_{REF}}{I_Q} \right) \]

\[ V_{BE1} = V_{BE2} + I_Q R_e \]

\[ I_Q R_e = V_T \ln \left( \frac{I_{REF}}{I_Q} \right) \]

Note: Pages 543-546 in Sedra & Smith Text.

Note $R_e > 0$ iff $I_Q < I_{REF}$
Widlar Current Source - cont.

If $I_Q$ specified and $I_{REF}$ chosen by designer:

$$R_e = \frac{V_T}{I_Q} \ln \left( \frac{I_{REF}}{I_Q} \right)$$

Example Let $I_Q = 10 \mu A$ & choose $I_{REF} = 10 mA$, determine $R$ and $R_e$:

$$R = \frac{V_{CC} - V_{BE1}}{I_{REF}} = \frac{12 V - 0.7 V}{10 mA} = 1.13 k\Omega$$

$$R_e = \frac{V_T}{I_Q} \ln \left( \frac{I_{REF}}{I_Q} \right) = \frac{0.025 V}{10 \mu A} \ln \left( \frac{10 m A}{10 \mu A} \right) = 2500 \ln (1000) = 17.27 k\Omega$$

Solve for $I_Q$ graphically.

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Widlar Current Mirror Small-Signal Analysis

\[ i_x = g_m v_\pi + i_{ro} = g_m v_\pi + \frac{v_x - (-v_\pi)}{r_o} \]

\[ v_\pi = -r_\pi \| R_e i_x \]

\[ i_x = -g_m r_\pi \| R_e i_x + \frac{v_x}{r_o} - \frac{r_\pi \| R_e i_x}{r_o} \]

\[ \approx -g_m r_\pi \| R_e i_x + \frac{v_x}{r_o} \]

\[ R_{out} \] is greatly enhanced by adding emitter degeneration.

\[ R_{out} = \frac{v_x}{i_x} = (R_e \| r_\pi)(1 + g_m r_o) \]

\[ g_m r_o \gg 1 \]
Quick Review

$$i_L = i_N - i_P$$

$$v_{BEN} + v_{EBP} = V_{BB} \Rightarrow i_N i_P = I_Q^2$$

Widlar Current Mirror

$$R_e = \frac{V_T}{I_Q} \ln \left( \frac{I_{REF}}{I_Q} \right)$$
Class AB Current Biasing Simulation

Bias currents set at $I_{REF}$ and $I_Q$ by $R$ and emitter resistor(s) $R_e$.

$I_{REF} \approx 4 \text{ mA}$

$I_Q = I_{QN} = I_{QP} \approx 2 \text{ mA}$

$R_e = 10 \Omega$

$R_L = 100 \Omega$

$V_{CC} = 12 \text{ V}$

$V_{BE1} = V_{EB3} = 0.7 \text{ V}$

$V_T = 25 \text{ mV/}^\circ \text{C}$

$T = 300 \text{ K}$

$g_m = 100 \text{ mS}$

$A_{v1} = 100$

$A_{v2} = 10$

$A_{v3} = 1$

$A_{v4} = 0.1$

$V_{in} = 1 \text{ mV}$

$V_{out} = 1 \text{ V}$

$R = V_{CC} - V_{BE1} = \frac{V_{CC} - V_{EB3}}{I_{REF}} \approx 2.8 \text{ k} \Omega$

$R_e = \frac{V_T}{I_{QN}} \ln \left( \frac{I_{REF}}{I_{QN}} \right) \approx 10 \Omega$

$i_L = i_N - i_P$
Class AB $I_{REF} = 4 \ mA$ Current Bias Simulation

Amplitude: $0 \ V$
Frequency: $1 \ kHz$

Quiescent Power Dissipation $v_i = 0 \ V$:

$$P_{Disp} = P_{D-av} = 76.31 \ mW + 75.53 \ mW = 151.84 \ mW$$
For linear operation: $-9 \, V < v_o < +9 \, V$

VTC has no dead-zone.
Conclusions

ADVANTAGE:
Class AB operation improves on Class B linearity.

DISADVANTAGES:
1. Emitter resistors absorb output power.
2. Power Conversion Efficiency is less than Class B.
3. Temperature matching will be needed – more so. if emitter resistors are not used.

TRADEOFFS:
Tradeoffs - involving bias current - between power efficiency, power dissipation and output signal swing need to be addressed.