Chapter 9

Output Stages And Power Amplifiers

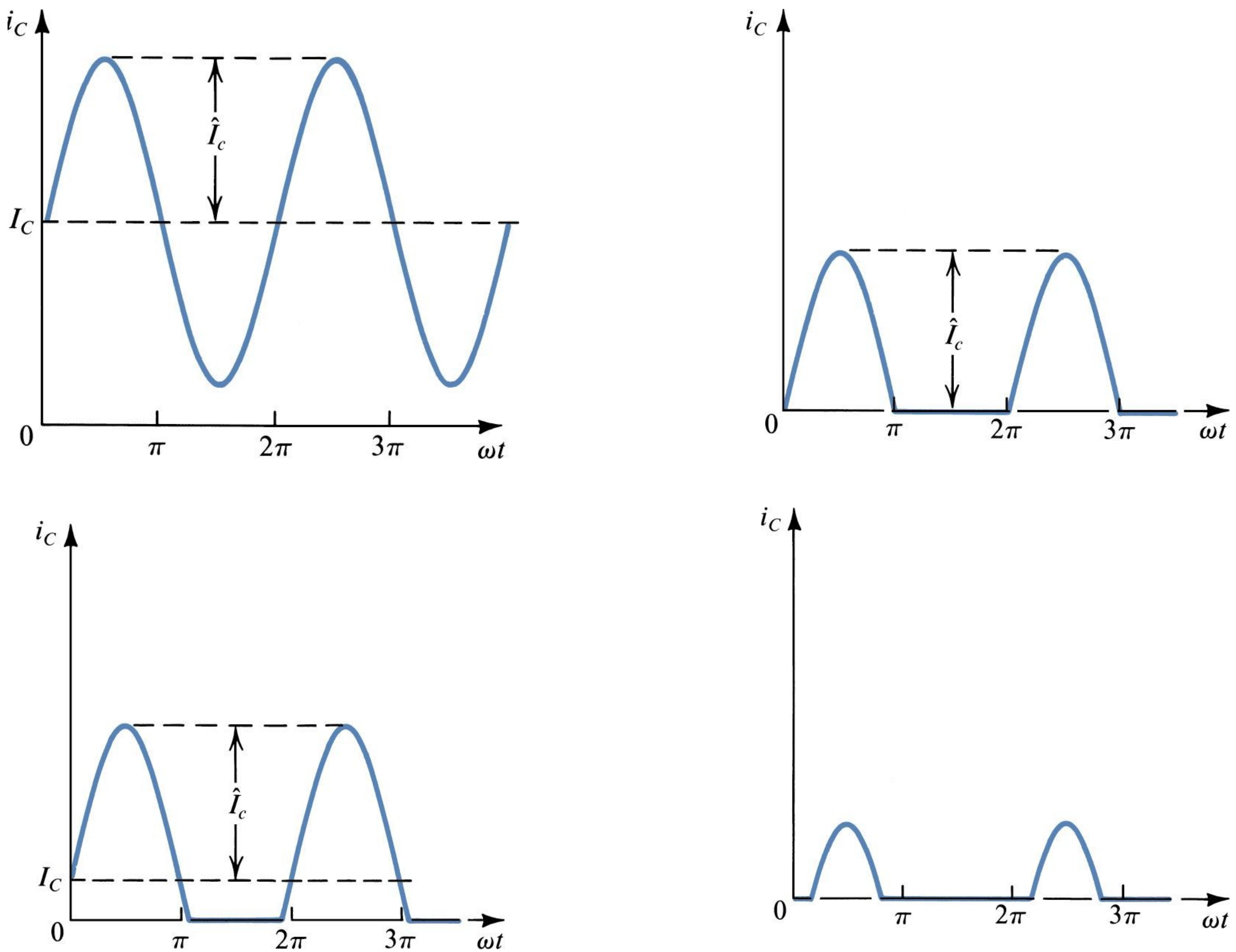
Low Output Resistance – no loss of gain

Small-Signal Not applicable

Total-Harmonic Distortion (fraction of %)

Efficiency

Temperature Requirements

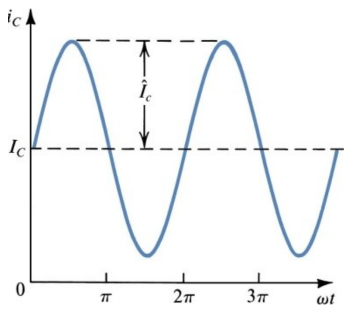


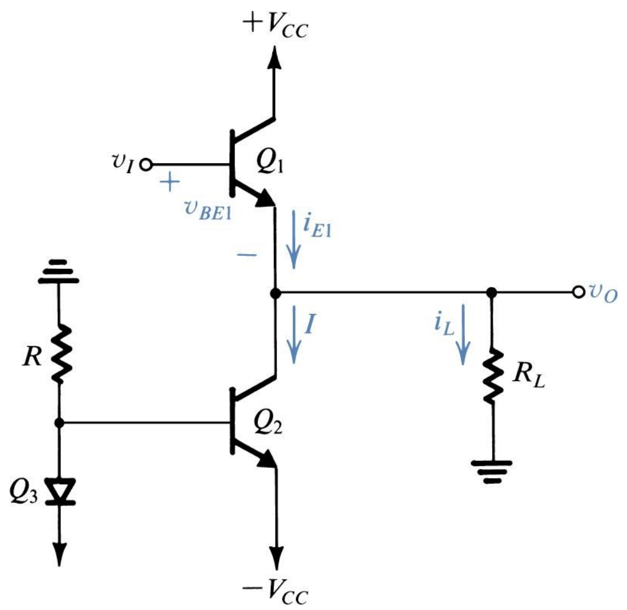
Collector current waveforms for transistors operating in (a) class A, (b) class B, (c) class AB, and (d) class C amplifier stages.

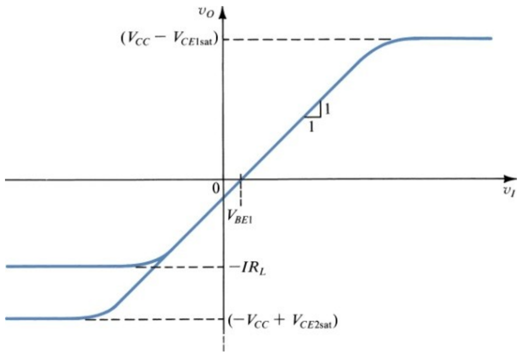
Class A

An emitter follower (Q_1) biased with a constant current I supplied by transistor Q_2.

Transfer Characteristics





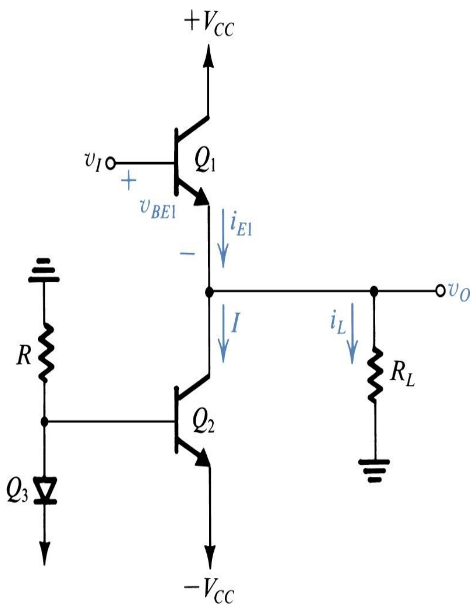


Transfer characteristic of the emitter follower. This linear characteristic is obtained by neglecting the change in v_{BE1} with i_L. The maximum positive output is determined by the saturation of Q_1. In the negative direction, the limit of the linear region is determined either by Q_1 turning off or by Q_2 saturating, depending on the values of I and R_L.

Class A

Transfer Characteristics

Crossover distortion can be eliminated by biasing the transistors at a small, non-zero current.
A bias Voltage VBB is applied between Qn and Qp.
For vi = 0, vo = 0, and a voltage VBB/2 appears across the base-emitter junction of each transistor.



$$i_N = i_P = I_Q = I_S \cdot e^{\frac{V_{BB}}{2 \cdot V_T}}$$

VBB is selected to result the required quiscent current IQ

$$v_o = v_i + \frac{V_{BB}}{2} - v_{BEN}$$

$$i_N = i_P + i_L$$

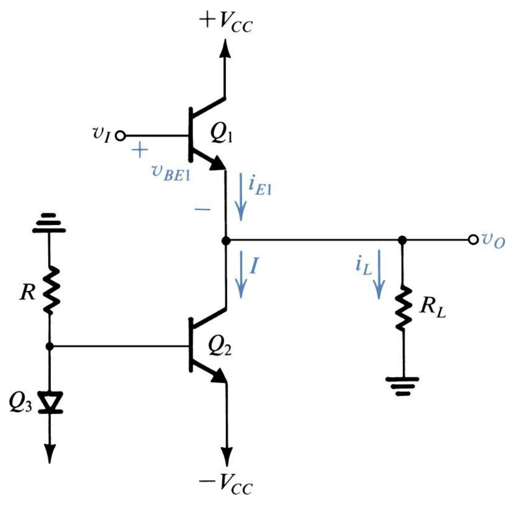
$$v_{BEN} + v_{EBP} = V_{BB} \qquad V_T \cdot \ln\left(\frac{i_N}{I_S}\right) + V_T \cdot \ln\left(\frac{i_P}{I_S}\right) = 2 \cdot V_T \cdot \ln\left(\frac{i_Q}{I_S}\right)$$

$$i_N^{\ 2} = I_Q^{\ 2}$$

$$i_N^{\ 2} - i_L \cdot i_N - I_Q^{\ 2} = 0$$

Class A

Transfer Characteristics



From figure 9.3 we can see that

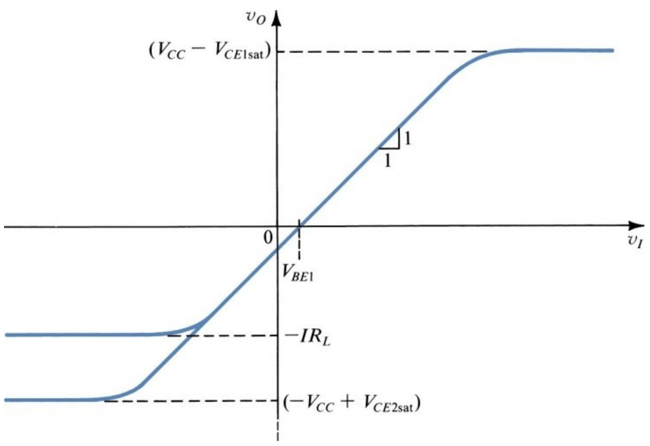
$$v_{omax} = V_{CC} - V_{CE1sat}$$

In the negative direction, the limite of the linear region is determined either by Q1 turning off

$$v_{Omin} = -I \cdot R_L$$

or by Q2 saturating

$$v_{Omin} = -V_{CC} + V_{CE2sat}$$



Depending on the values of I and RL. The absolutely lowest output voltage is that given by the previous equation and is achieved provided that the bias current I is greater than the magnitude of the corresponding load current

$$I \geq \frac{\left|-V_{CC} + V_{CE2sat}\right|}{R_L}$$

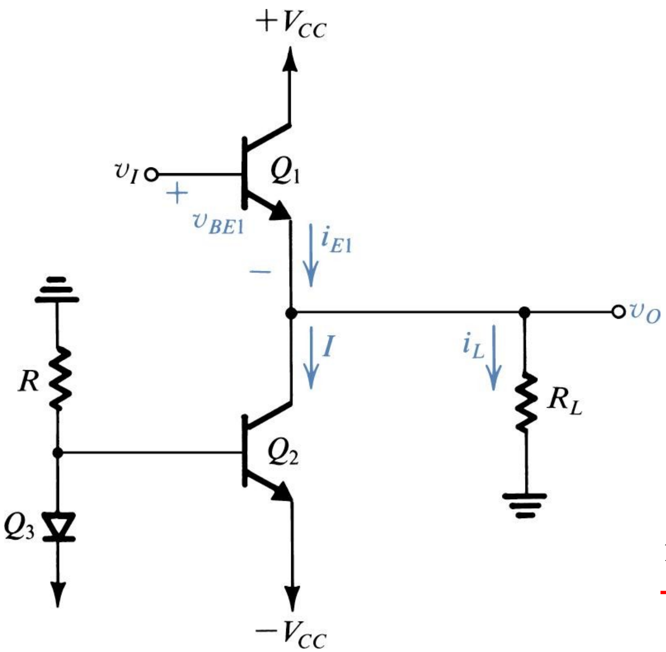
Class A

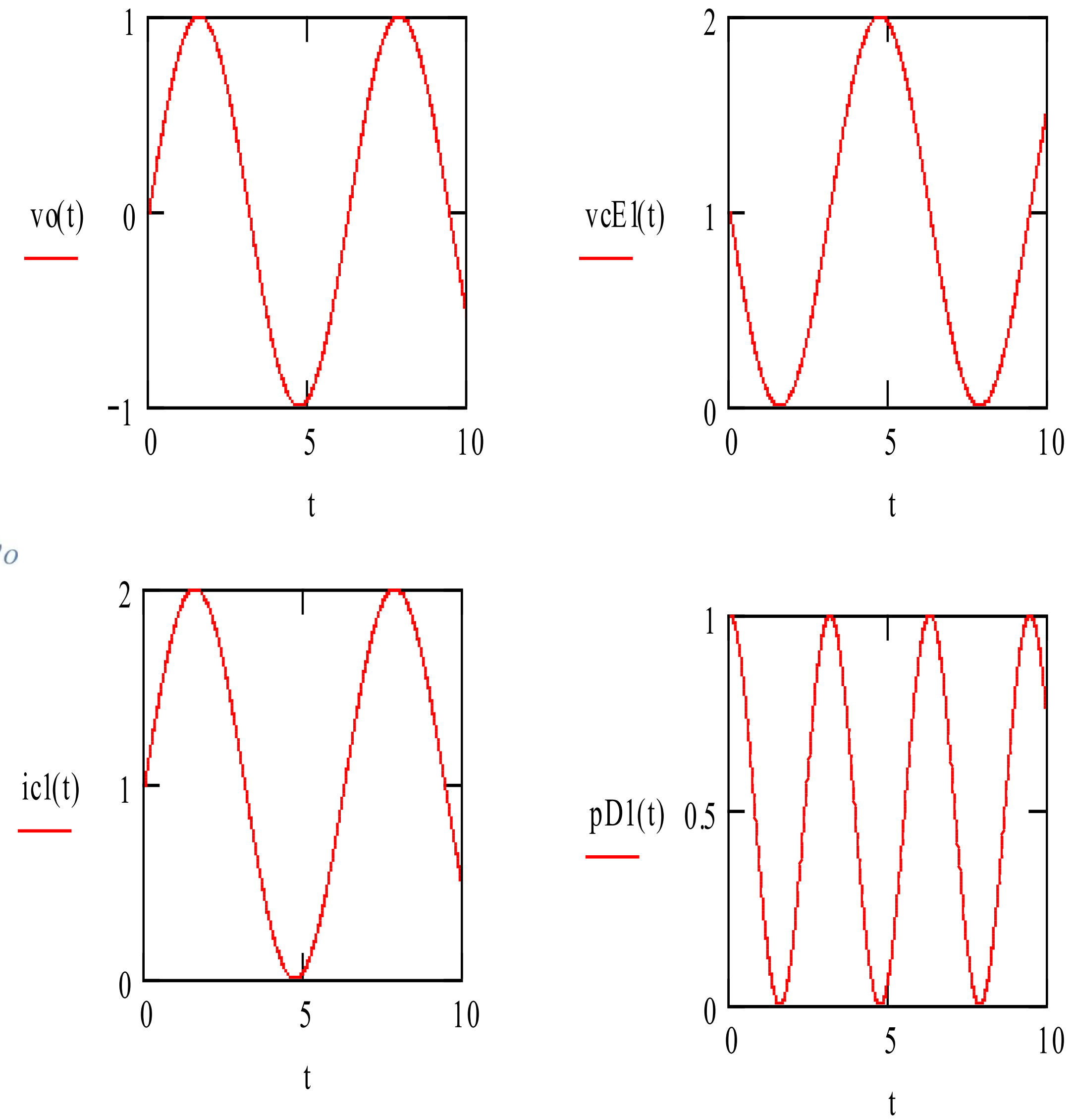
Transfer Characteristics

Exercises D9.1 and D9.2

Class A

Signal Waveforms





Class A

Power Dissipation

$$P = V_{CC} \cdot I$$

Largest Power Dissipation When vo = 0
Q1 must be able to withsatnd a continuous dissipation of VCC*I

The power dissipation of Q1 depends on the value of RL.
If RL is infinite, iC1 = I and the dissipation in Q1 depends on vo.
Maximum power dissipation will occur when vo = -VCC since vCE1 will be 2VCC
pD1 = 2VCC*I. This condition would not normally persist for a prolonged interva
the design need not be that conservative. The average pD1 = VCC*I

When RL is zero a positive voltage would result in a theoretically infinite current
practical value) would flow through Q1. Short-circuit protection is necessary.

Class A

Power Conversion Efficiency

$$\eta = \frac{\text{load\_power}(P_L)}{\text{supply\_power}(P_S)}$$

$$P_L = \frac{1}{2} \cdot \frac{{V_o}^2}{R_L}$$

V_o average voltag

$$P_S = 2 \cdot V_{CC} \cdot I$$

$$\eta = \frac{1}{4} \cdot \frac{{V_o}^2}{I \cdot R_L \cdot V_{CC}} = \frac{1}{4} \cdot \left(\frac{V_o}{I \cdot R_L}\right) \cdot \left(\frac{V_o}{V_{CC}}\right)$$

$V_o \leq V_{CC}$ $\qquad$ $V_o \leq I \cdot R_L$

maximum efficiency is obtained when

$$V_o = V_{CC} = I \cdot R_L$$

Class A

Exercise 9.4

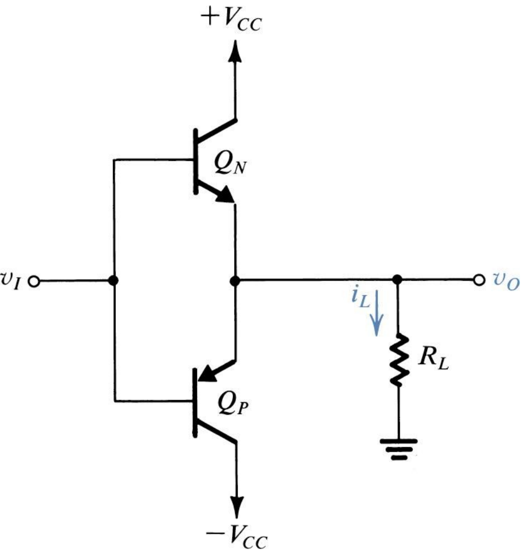
$Vopeak := 8$ $\quad I := 100 \cdot 10^{-3}$ $\quad R_L := 100$ $\quad V_{CC} := 10$

$$P_L := \frac{\left(\frac{Vopeak}{\sqrt{2}}\right)^2}{100} \qquad P_L = 0.32$$

$$Pplus := V_{CC} \cdot I \qquad Pplus = 1$$

$$Pminus := V_{CC} \cdot I \qquad Pminus = 1 \qquad P_S := Pplus + Pminu$$

$$\eta := \frac{P_L}{P_S} \qquad \eta = 0.16$$



Biasing the Class B Output

- No DC current is used to bias this configuration.
- Activated when the input voltage is greater than the Vbe for the transistors.
- npn Transistor operates when positive, pnp when negative.
- At a zero input voltage, we get no output voltage.

Class A

Power Conversion Efficiency

CLASS A

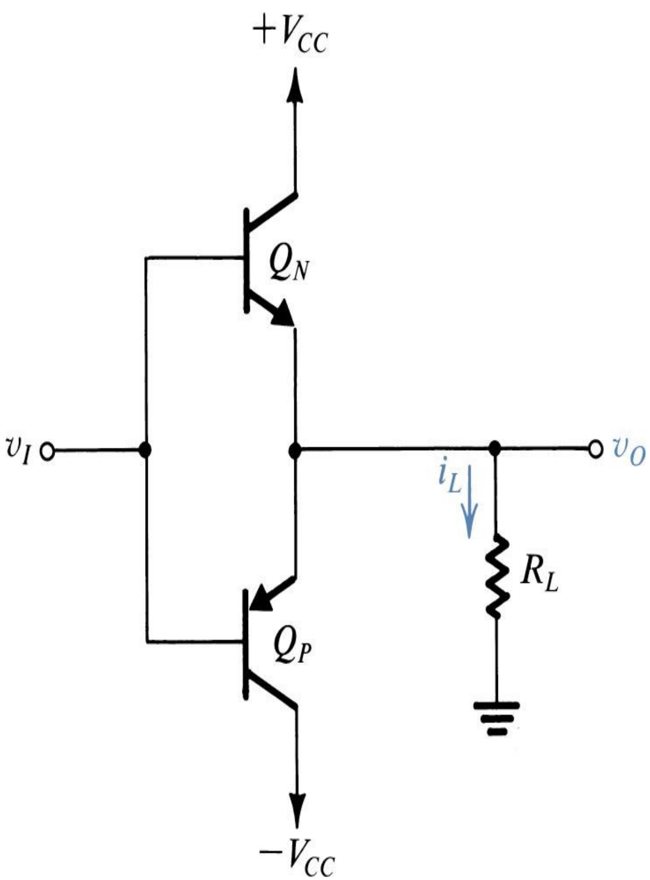
Many class A amplifiers use the same transistor(s) for both halves of the audio waveform. In this configuration, the output transistor(s) always has current flowing through it, even if it has no audio signal (the output transistors never 'turn off'). The current flowing through it is D.C.

A pure class 'A' amplifier is very inefficient and generally runs very hot even when there is no audio output. The current flowing through the output transistor(s) (with no audio signal) may be as much as the current which will be driven through the speaker load at FULL audio output power. Many people believe class 'A' amps to sound better than other configurations (and this may have been true at some point in time) but a well designed amplifier won't have any 'sound' and even the most critical 'ear' would be hard-pressed to tell one design from another.

NOTE: Some class A amplifiers use complimentary (separate transistors for positive and negative halves of the waveform) transistors for their output stage.

Class B

Circuit Operation



Class B output stage.

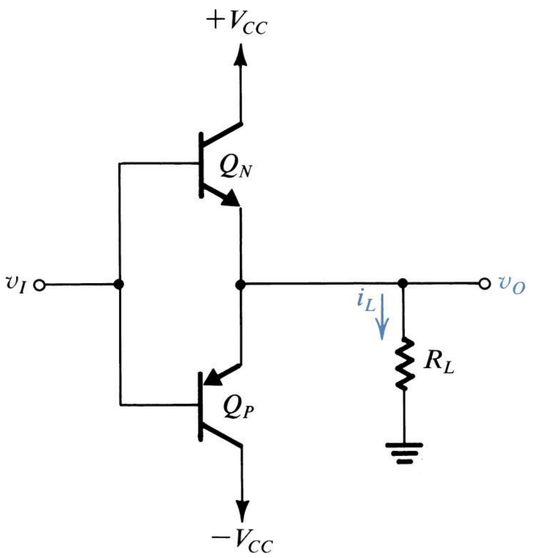
CLASS 'B'

A class 'B' amplifier uses complimentary transistors for each half of the waveform.

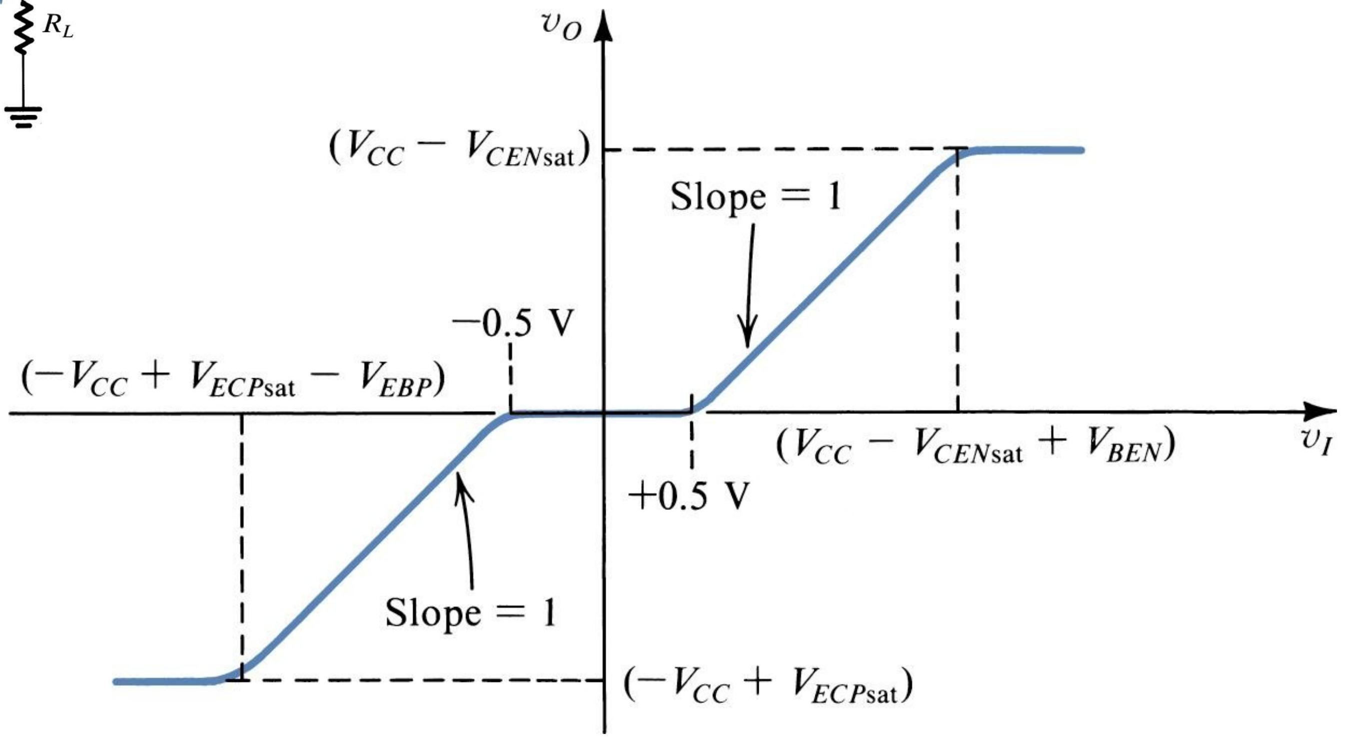
A true class 'B' amplifier is NOT generally used for audio. In a class 'B' amplifier, there is a small part of the waveform which will be distorted. You should remember that it takes approximately .6 volts (measured from base to emitter) to get a bipolar transistor to start conducting. In a pure class 'B' amplifier, the output transistors are not "biased" to an 'on' state of operation. This means that the the part of the waveform which falls within this .6 volt window will not be reproduced accurately.

The output transistors for each half of the waveform (positive and negative) will each have a .6 volt area in which they will not be conducting. The distorted part of the waveform is called 'crossover' or 'notch' distortion. Remember that distortion is any unwanted variation in a signal (compared to the original signal). The diagram below shows what crossover distortion looks like.

Class B

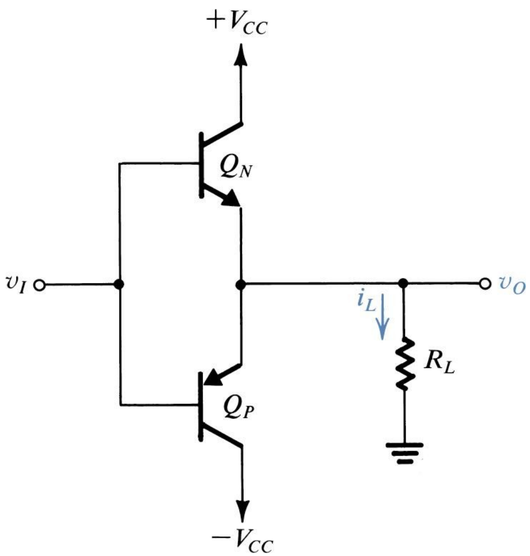


Circuit Operation



Transfer characteristic for the class B output stage in Fig. 9.5.

Operation



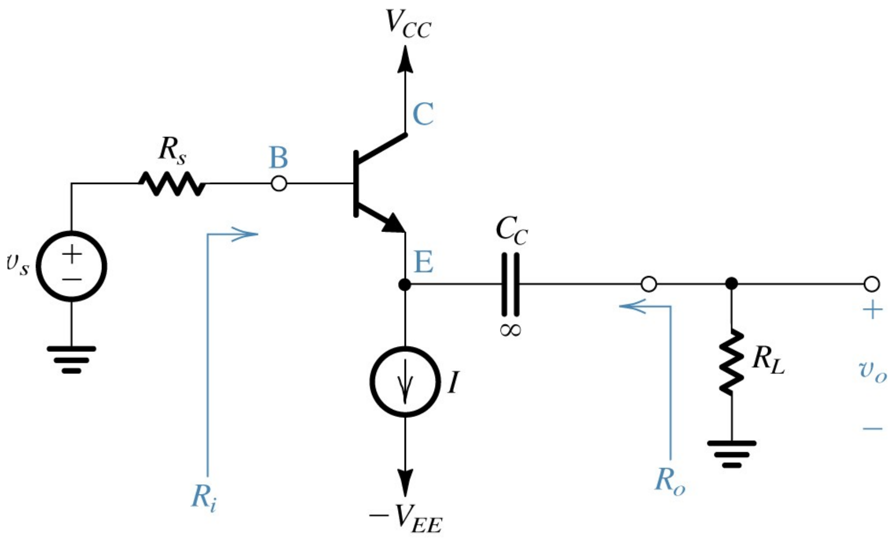
When the input voltage rises to be large enough to overcome the Vbe, it will begin to cause an output voltage to appear. This occurs because Qn begins to act like an emitter follower and Qp shuts off. The input will be followed on the emitter until the transistor reaches saturation. The maximum input voltage is equal to the following:

$$v_{imax} = V_{CC} - V_{CENsat}$$

The same thing will begin to happen if the input voltage is negative by more than the Veb of the transistor. This causes the Qp to act like an emitter follower and Qn turns off. This will continue to behave this way until saturation occurs at a minimum input voltage of:

$$v_{imin} = -V_{cc} + V_{ECPsat}$$

Emitter Follower Configuration (Chapter 4)



(a)

$$\frac{v_b}{v_s} = \frac{(\beta + 1)\left(r_e + \mathrm{par}(R_L, r_o)\right)}{R_S + (\beta + 1)\left(r_e + \mathrm{par}(R_L, r_o)\right)}$$

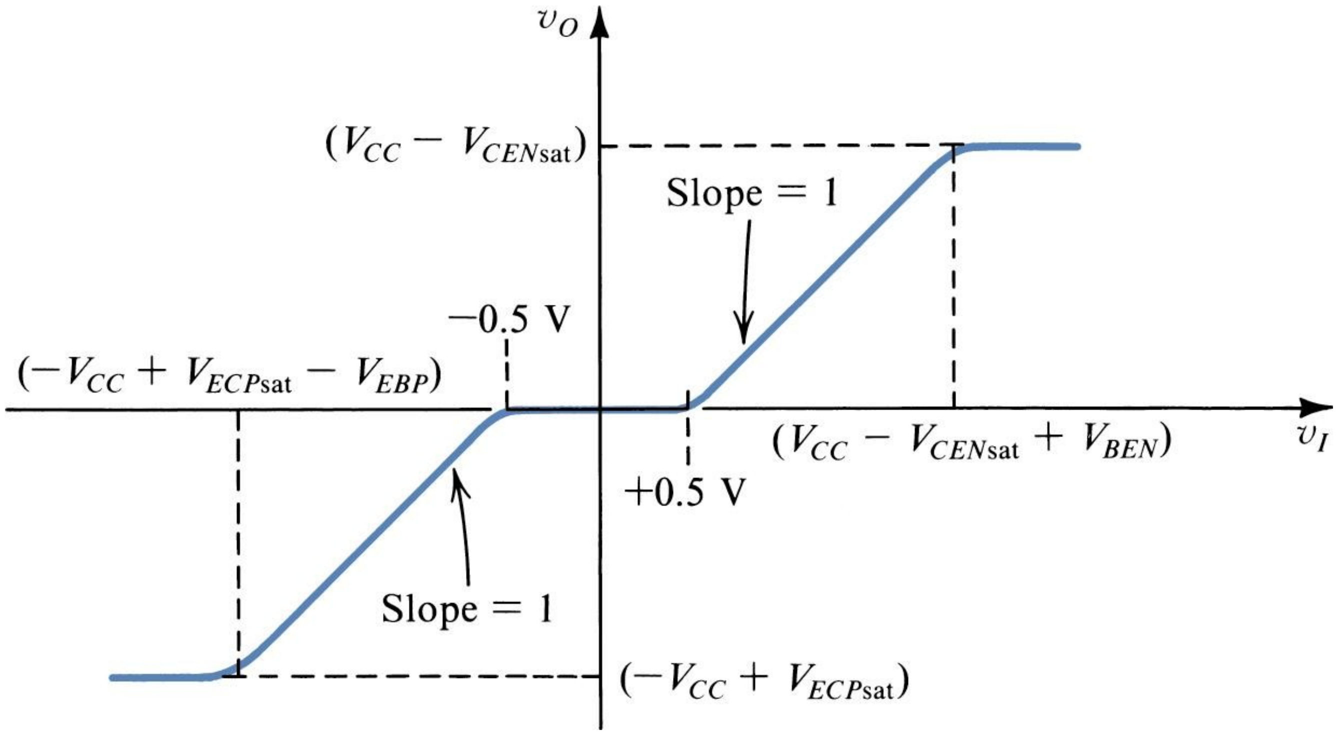
$$\frac{v_o}{v_b} = \frac{\mathrm{par}(r_o, R_L)}{r_e + \mathrm{par}(r_o, R_L)}$$

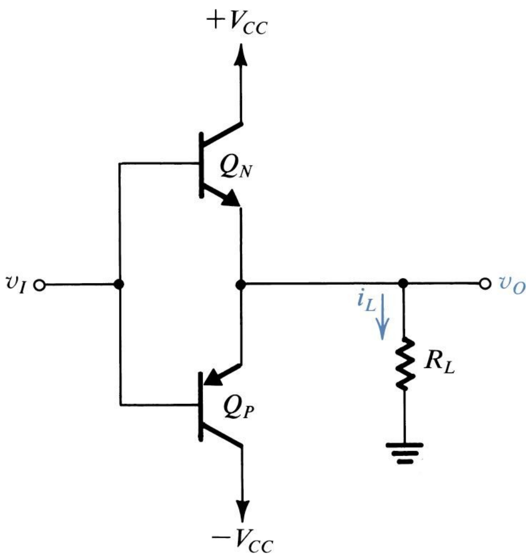
Rs will be small for most configurations, so the vb/vs will be a little less than unity. The same is true for re, so vo/vb will be a little less than unity making our vo/vs a little less than unity.

Characteristics of the Emitter Follower:

- High Input Resistance
- Low Output Resistance
- Near Unity Gain

Transfer Characteristic





Push-Pull Nature of Class B

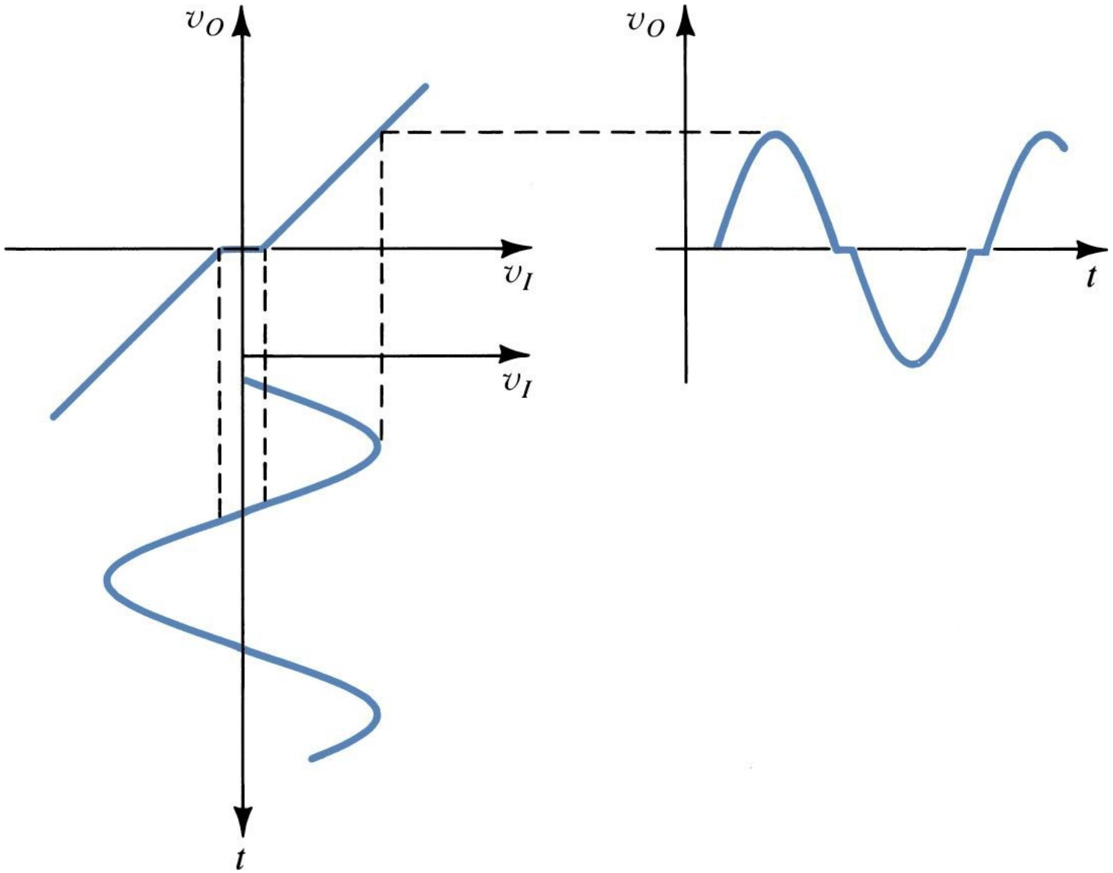
- Push: The npn transistor will push the current to ground when the input is positive.

- Pull: The pnp transistor will pull the current from the ground when the input is negative.

Crossover Distortion

The Crossover Distortion is due to the dead band of input voltages from -.5V to .5V. This causes the Class B output stage to be a bad audio amplifier. For large input signals, the crossover distortion is limited, but at small input signals, it is most pronounced.

Graph of Crossover Distortion



Illustrating how the dead band in the class B transfer characteristic results in crossover distortion.

Power Efficiency

Load Power:

$$P_L = \frac{1}{2} \cdot \frac{{V_{op}}^2}{R_L}$$

Since each transistor is only conducting for one-half of the time, the power drawn from each source will be the same.

$$P_s = \frac{1}{\pi} \cdot \frac{V_{op}}{R_L} \cdot V_{CC}$$

$$\eta = \frac{P_L}{2 \cdot P_s} = \frac{\frac{1}{2} \cdot \frac{{V_{op}}^2}{R_L}}{2 \frac{1}{\pi} \cdot \frac{V_{op}}{R_L} \cdot V_{CC}}$$

This efficiency will be at a max when Vop is at a max. Since Vop cannot exceed Vcc, the maximum efficiency will occur at pi/4.

$$\eta = \frac{\pi}{4} \cdot \frac{V_{op}}{V_{CC}}$$

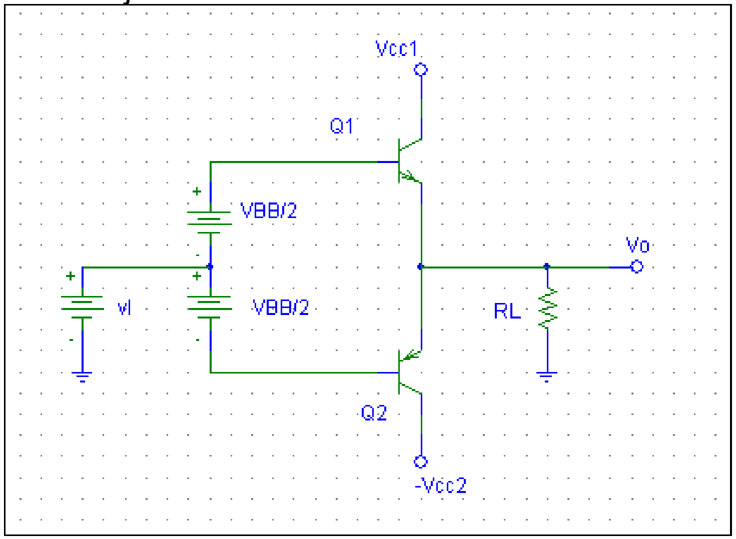
$$\boxed{\eta_{max} = \frac{\pi}{4}}$$

This will be approximately 78.5%, much greater than the 25% for Class A.

Class AB

Circuit Operation

Crossover distortion can be eliminated by biasing the transistors at a small, non-zero current.
A bias Voltage VBB is applied between Qn and Qp.
For vi = 0, vo = 0, and a voltage VBB/2 appears across the base-emitter junction of each transistor.



$$i_N = i_P = I_Q = I_S \cdot e^{\frac{V_{BB}}{2 \cdot V_T}}$$

VBB is selected to result the required quiscent current IQ

$$v_o = v_i + \frac{V_{BB}}{2} - v_{BEN}$$

$$i_N = i_P + i_L$$

$$v_{BEN} + v_{EBP} = V_{BB} \qquad V_T \cdot \ln\left(\frac{i_N}{I_S}\right) + V_T \cdot \ln\left(\frac{i_P}{I_S}\right) = 2 \cdot V_T \cdot \ln\left(\frac{i_Q}{I_S}\right)$$

$$i_N^{\ 2} = I_Q^{\ 2}$$

$$i_N^{\ 2} - i_L \cdot i_N - I_Q^{\ 2} = 0$$

Class AB

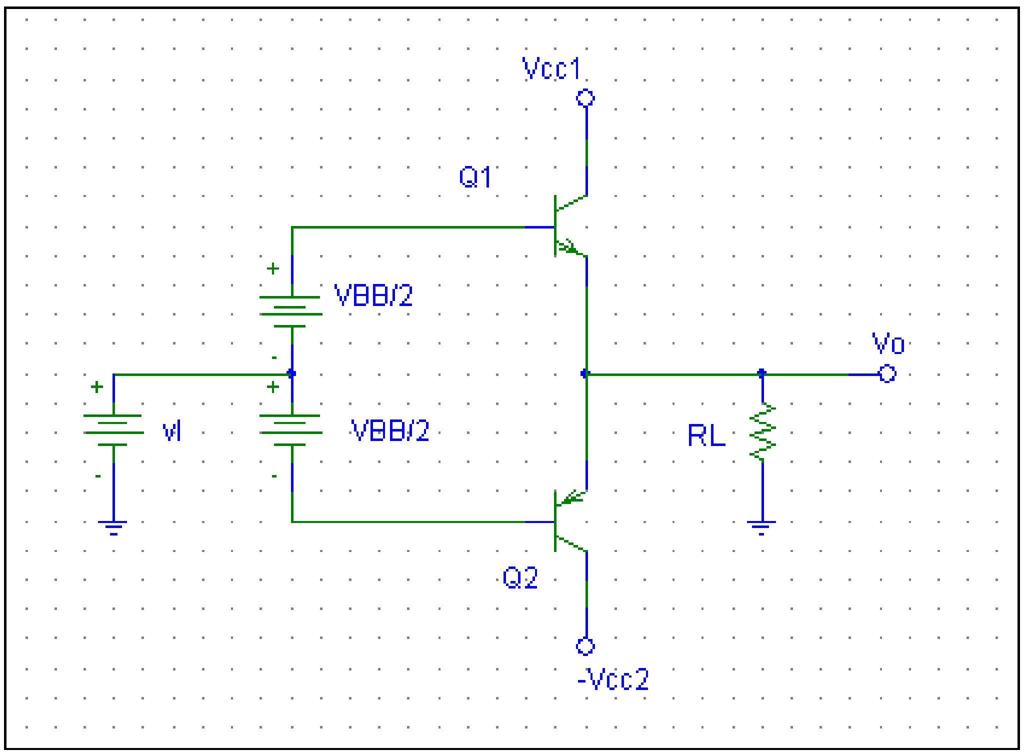
Output Resistance

Class AB

Exercise 9.6

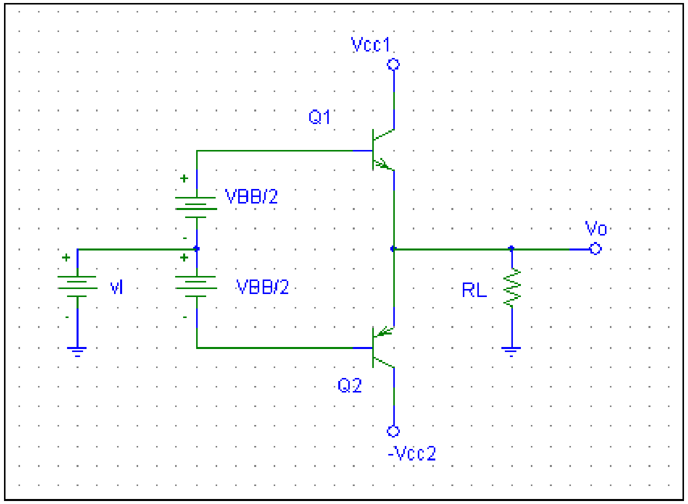
Calvin College - ENGR 332
Class AB Output Stage Amplifier

Consider the class AB circuit (illustrated below) with Vcc=15 V, IQ=2 mA, RL=100 ohms.
Determine VBB. Determine the values of iL, iN, iP, vBEN, vEBP, vI, vO/vI, Rout, and vo/vi v
vO for vO varying from -10 to 10V.
Note that vO/vI is the large signal voltage gain and vo/vi is the incremental gain obtained a
RL/(RL+Rout). The incremental gain is equal to the slope of the transfer curve.
Assume QN and QP to be matched, with IS=10E-13.



Class AB

Exercise 9.6



under quiescent conditions iN=iP=IQ vO=vI=0

Solving for VBB

$VBB := 1$ $IS := 10^{-13}$ $VT := 0.025$ $IQ := 2\cdot 10^{-3}$ $RL := 10($

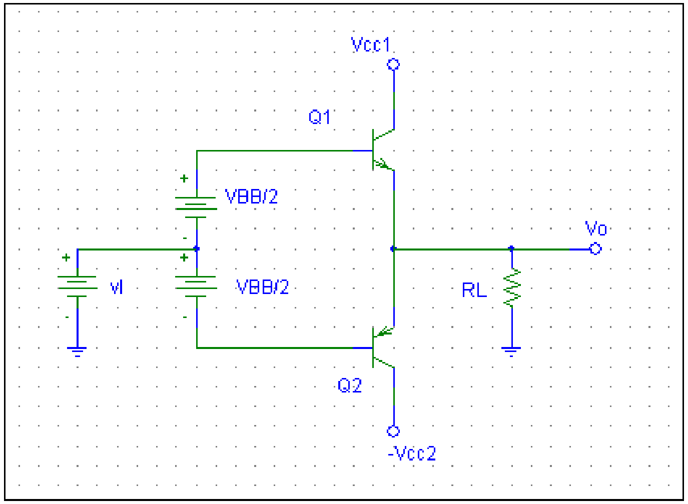
Given

$$IQ = IS\cdot e^{\frac{\frac{|VBB|}{2}}{VT}}$$

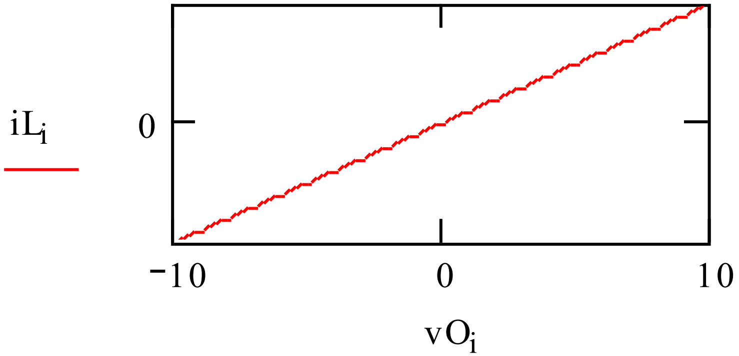
$VBB := Find(VBB)$ $i := 0..100$ $VBB = 1.186$

Class AB

Exercise 9.6

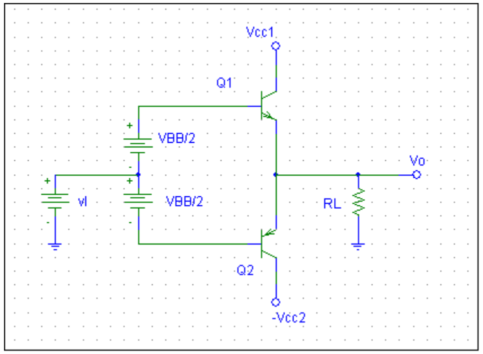


$$vO_i := -10 + \frac{i}{5} \qquad iL_i := \frac{vO_i}{RL}$$



Class AB

Exercise 9.6



Solving for iN

initial guesses $iN := 0.02$ $iLD := 0.02$ $IQ := 0.002$

Given

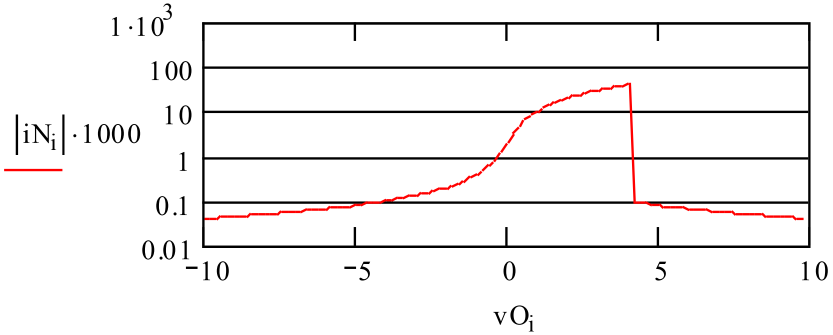
$$iN^2 - iLD \cdot iN - IQ^2 = 0$$

$$iNN(IQ, iLD) := Find(iN)$$

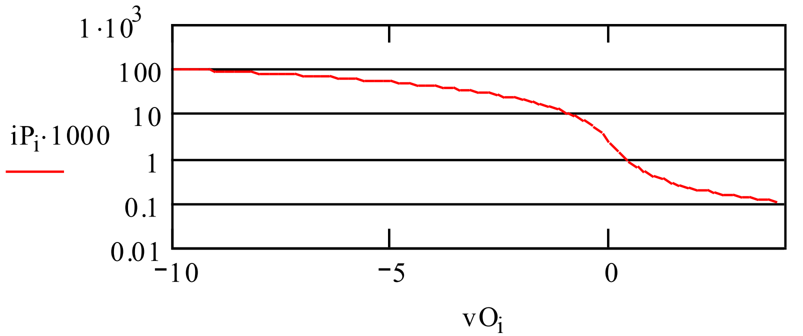
$i := 0..100$ $IQ_i := 0.002$ $iLD_i := iL_i$

$$iN_i := iNN(IQ_i, iL_i)$$

$$iN_{10} = 4.997 \times 10^{-5}$$



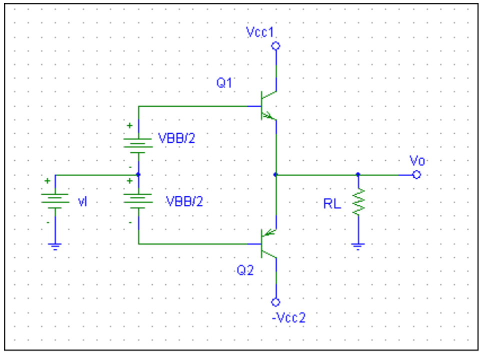
$$iP_i := iN_i - iLD_i$$



$$\left(iN_i \right)$$

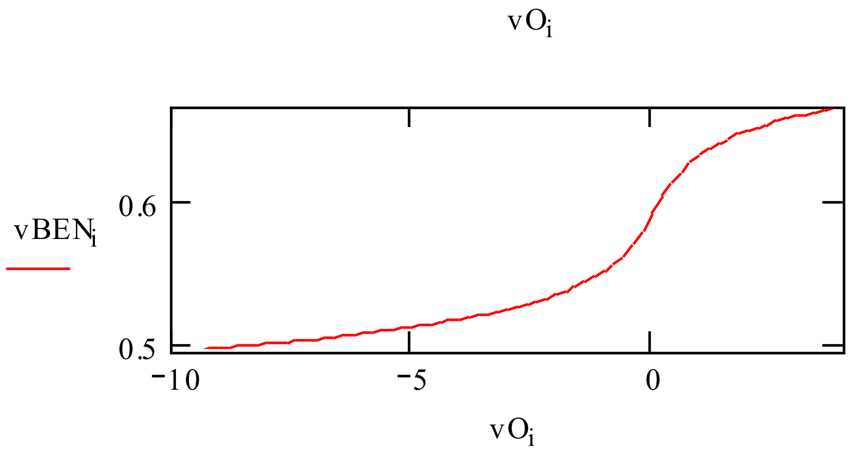
Class AB

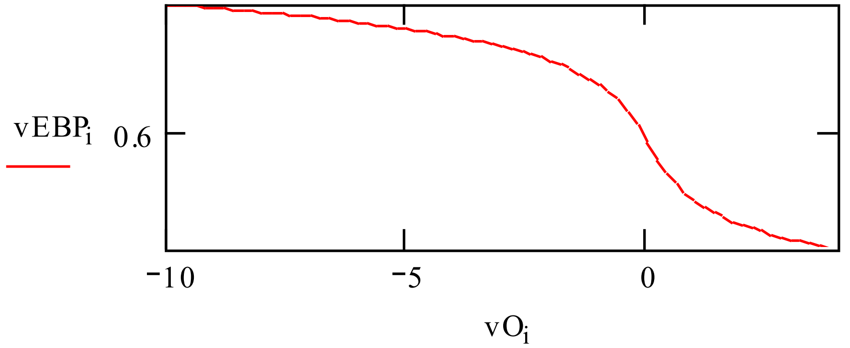
Exercise 9.6



$$vBEN_i := VT \cdot \ln\left(\frac{iN_i}{IS}\right)$$

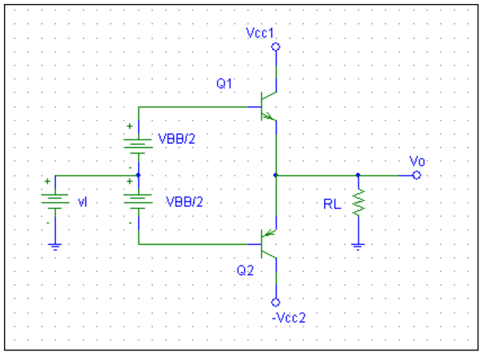
$$vEBP_i := VT \cdot \ln\left(\frac{iP_i}{IS}\right)$$





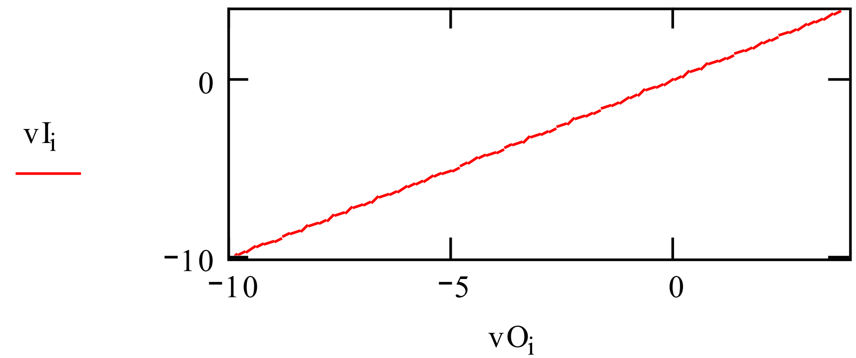
Class AB

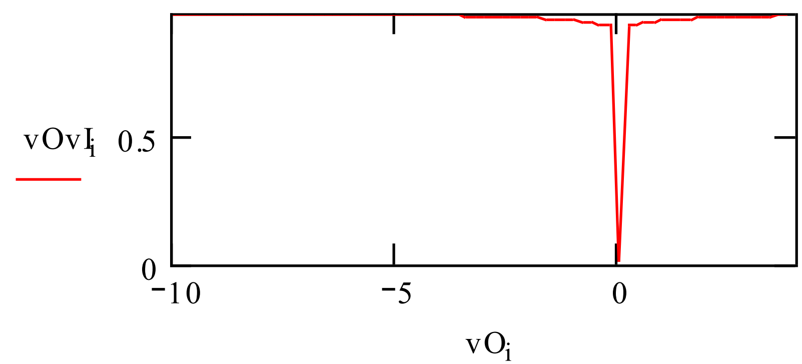
Exercise 9.6



$$vI_i := vO_i + vBEN_i - \frac{VBB}{2}$$

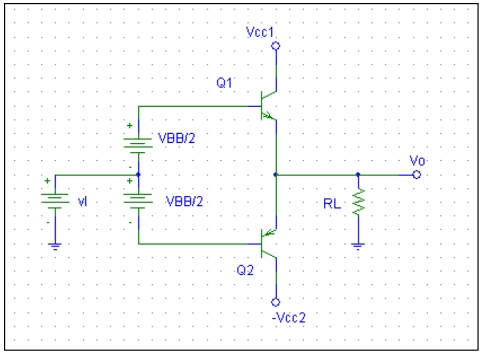
$$vOvI_i := \frac{vO_i}{vI_i}$$



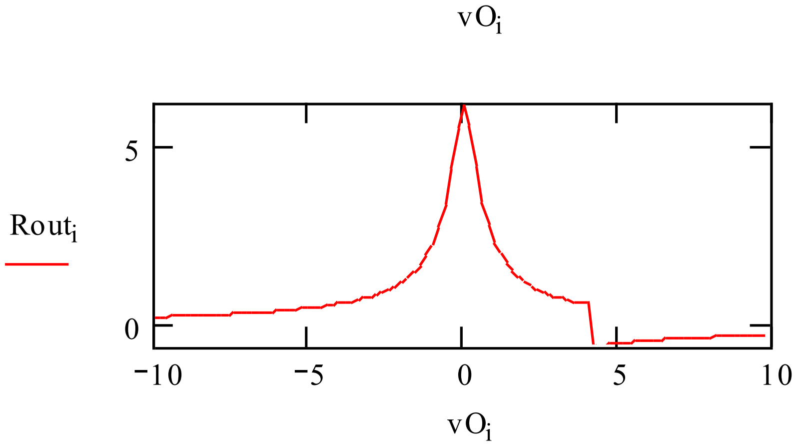


Class AB

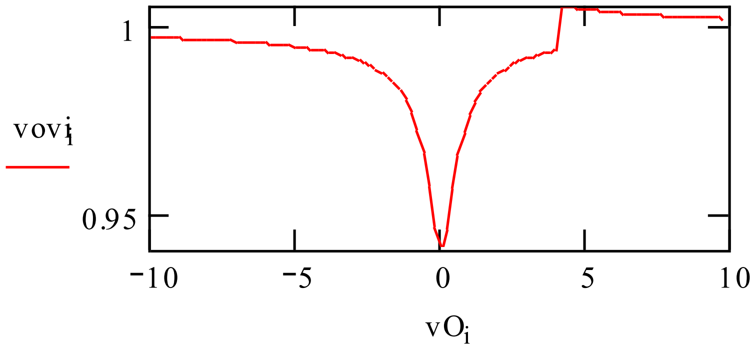
Exercise 9.6

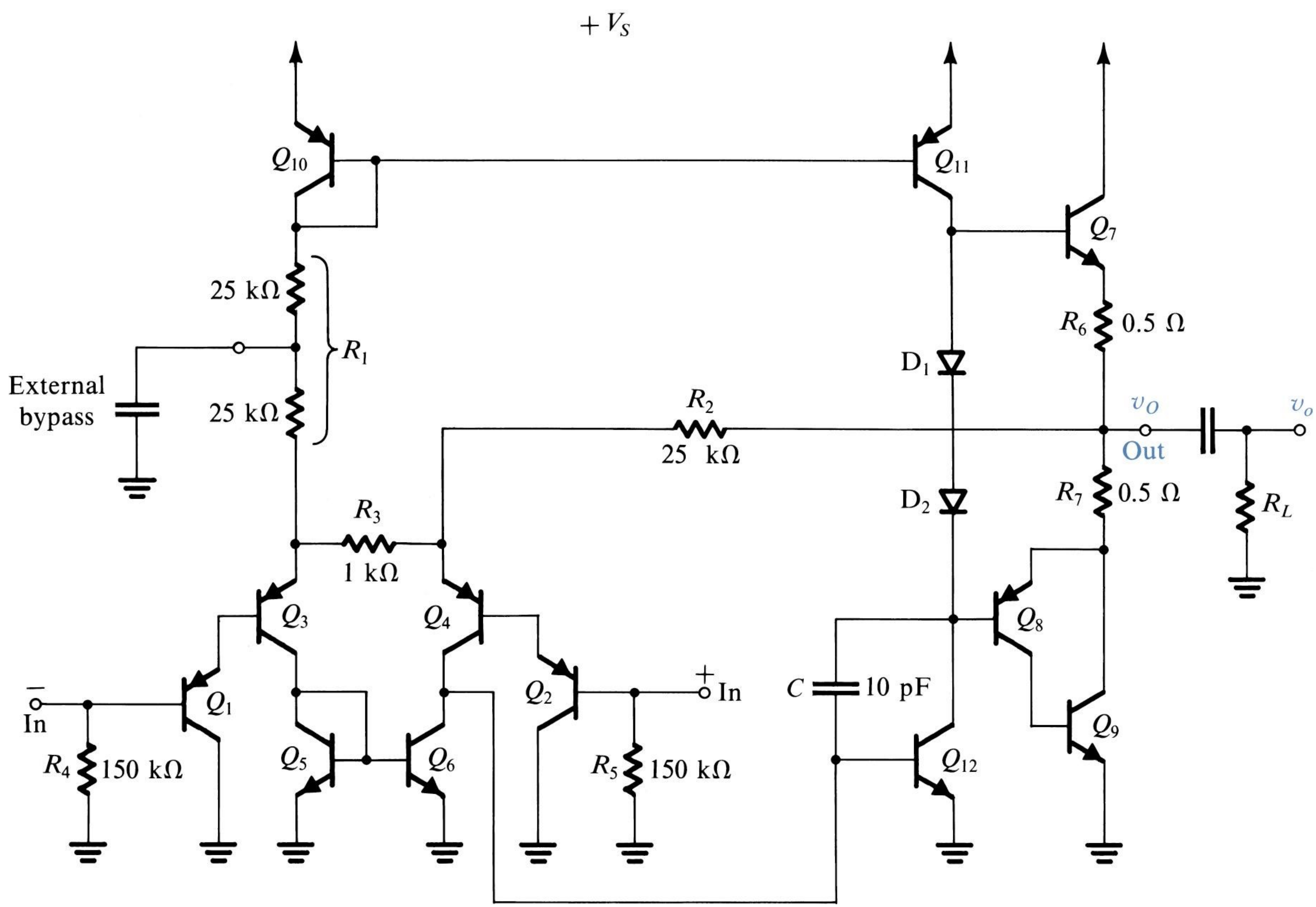


$$Rout_i := \frac{VT}{iP_i + iN_i}$$

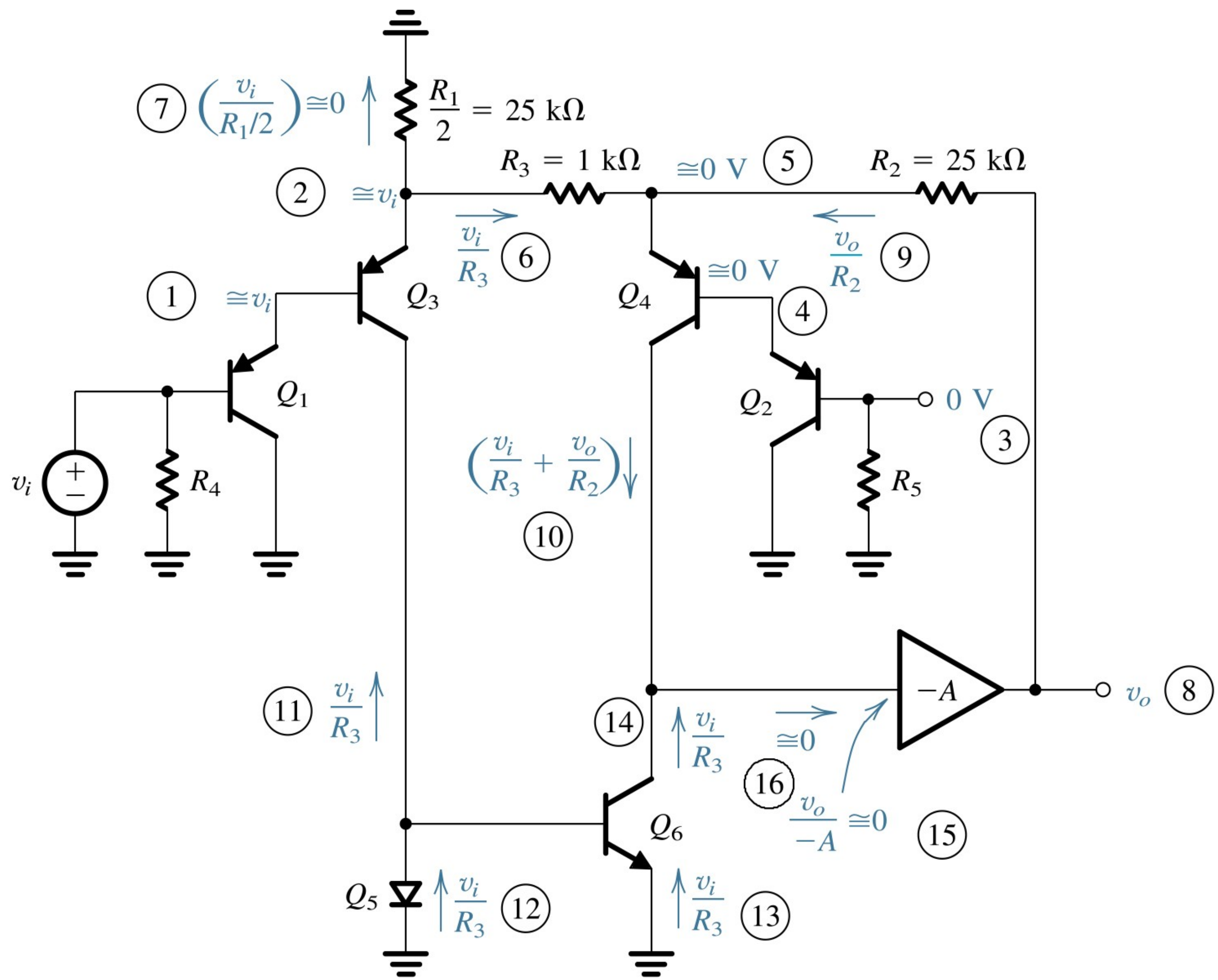


$$vovi_i := \frac{RL}{RL + Rout_i}$$

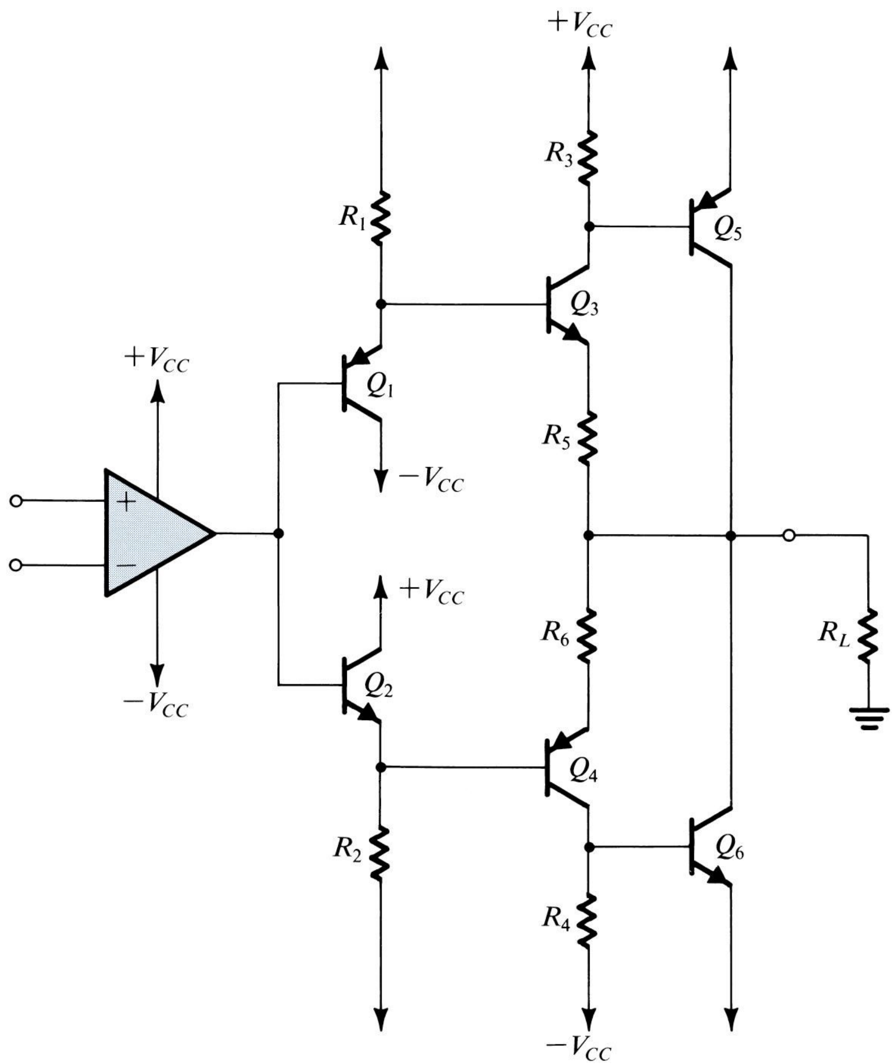




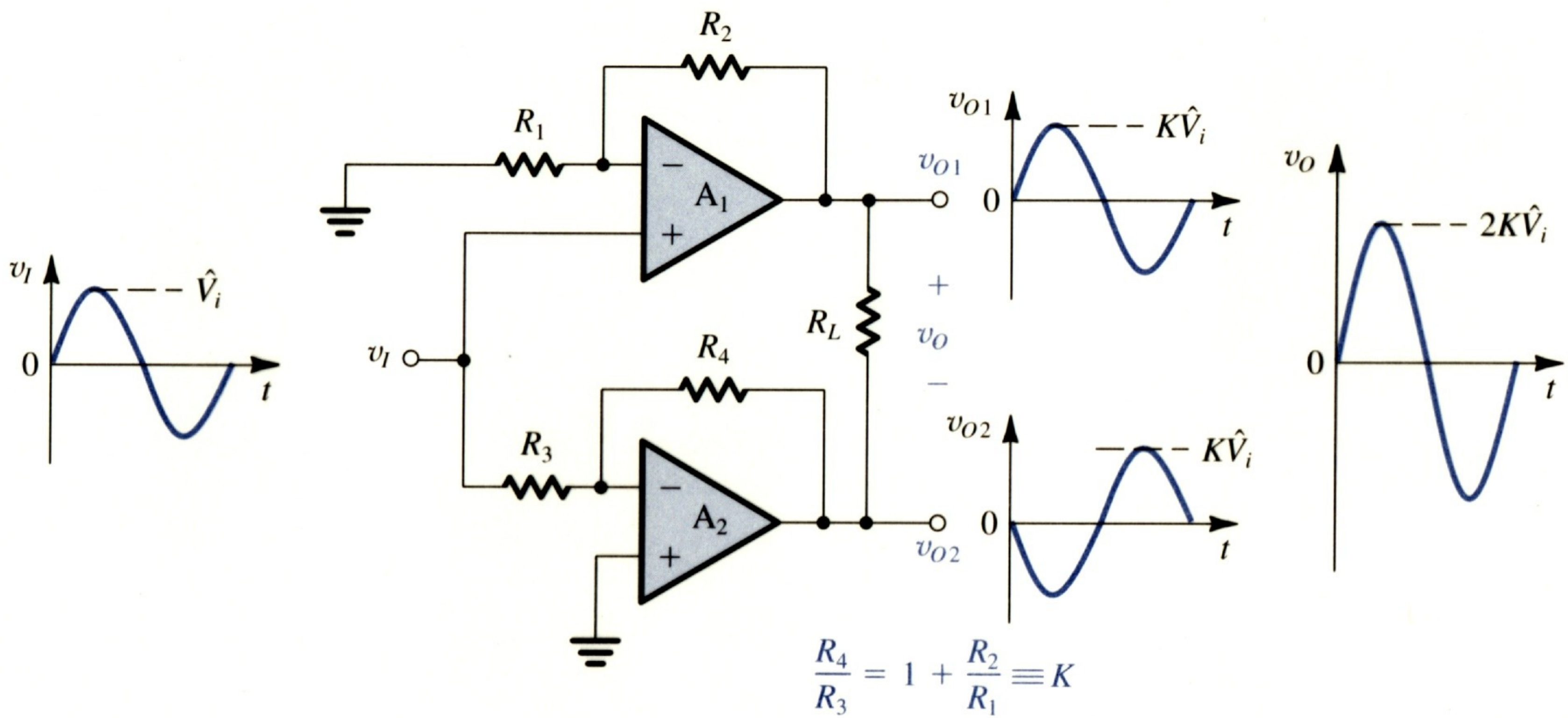
Simplified internal circuit of the LM380 IC power amplifier (Courtesy National Semiconductor Corporation.)



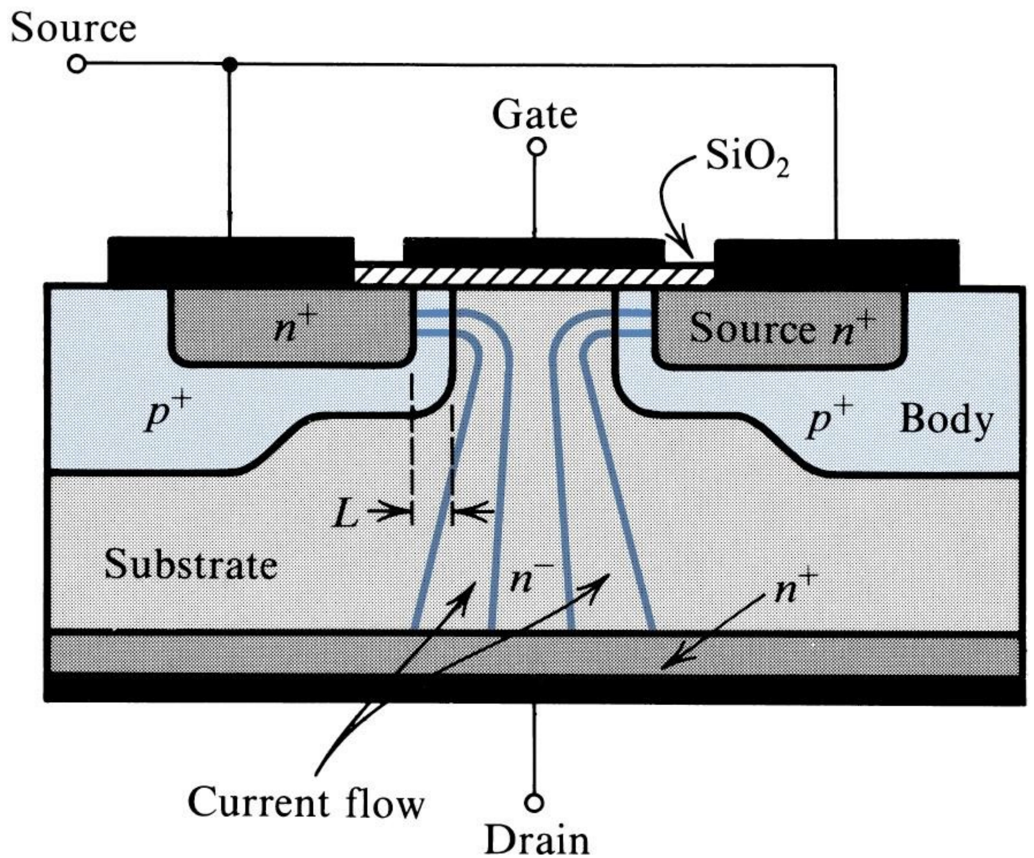
Small-signal analysis of the circuit in Fig. 9.30. The circled numbers indicate the order of the analysis steps.



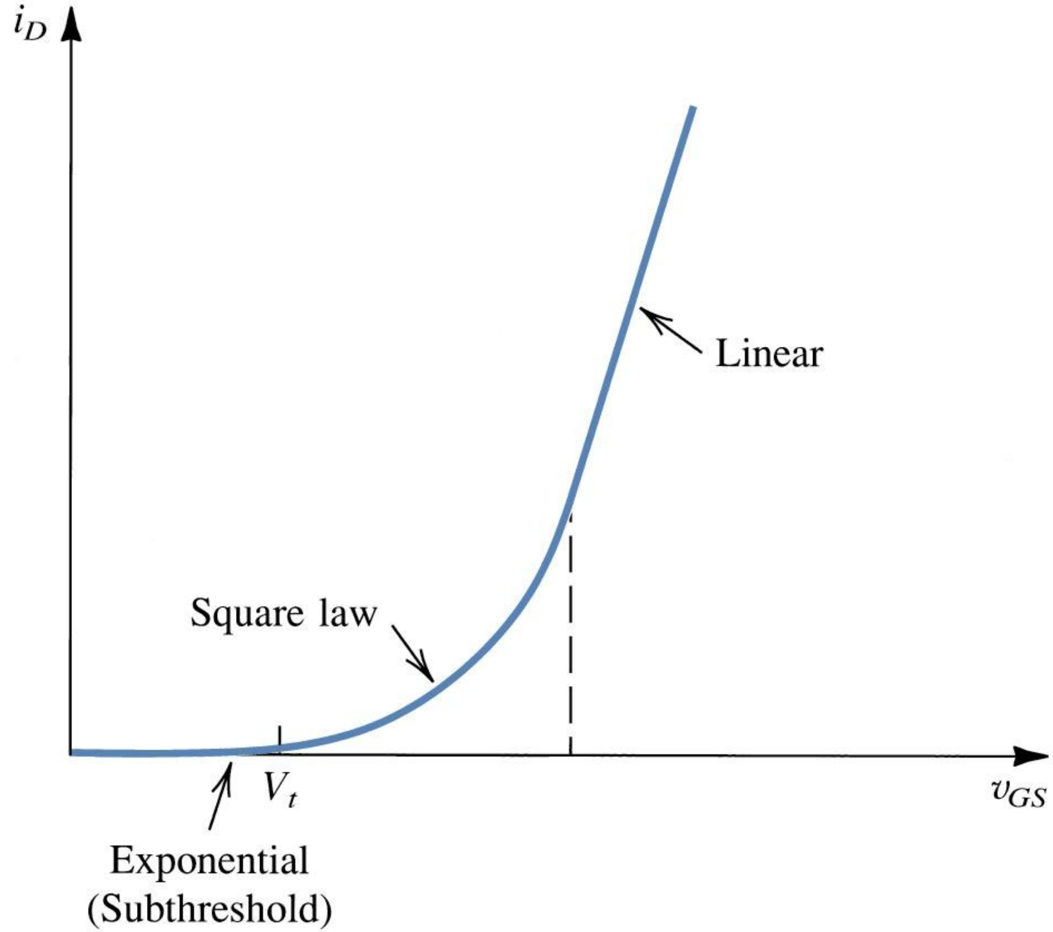
Structure of a power op amp. The circuit consists of an op amp followed by a class AB buffer similar to that discussed in Section 9.7. The output current capability of the buffer, consisting of Q_1, Q_2, Q_3, and Q_4, is further boosted by Q_5 and Q_6.



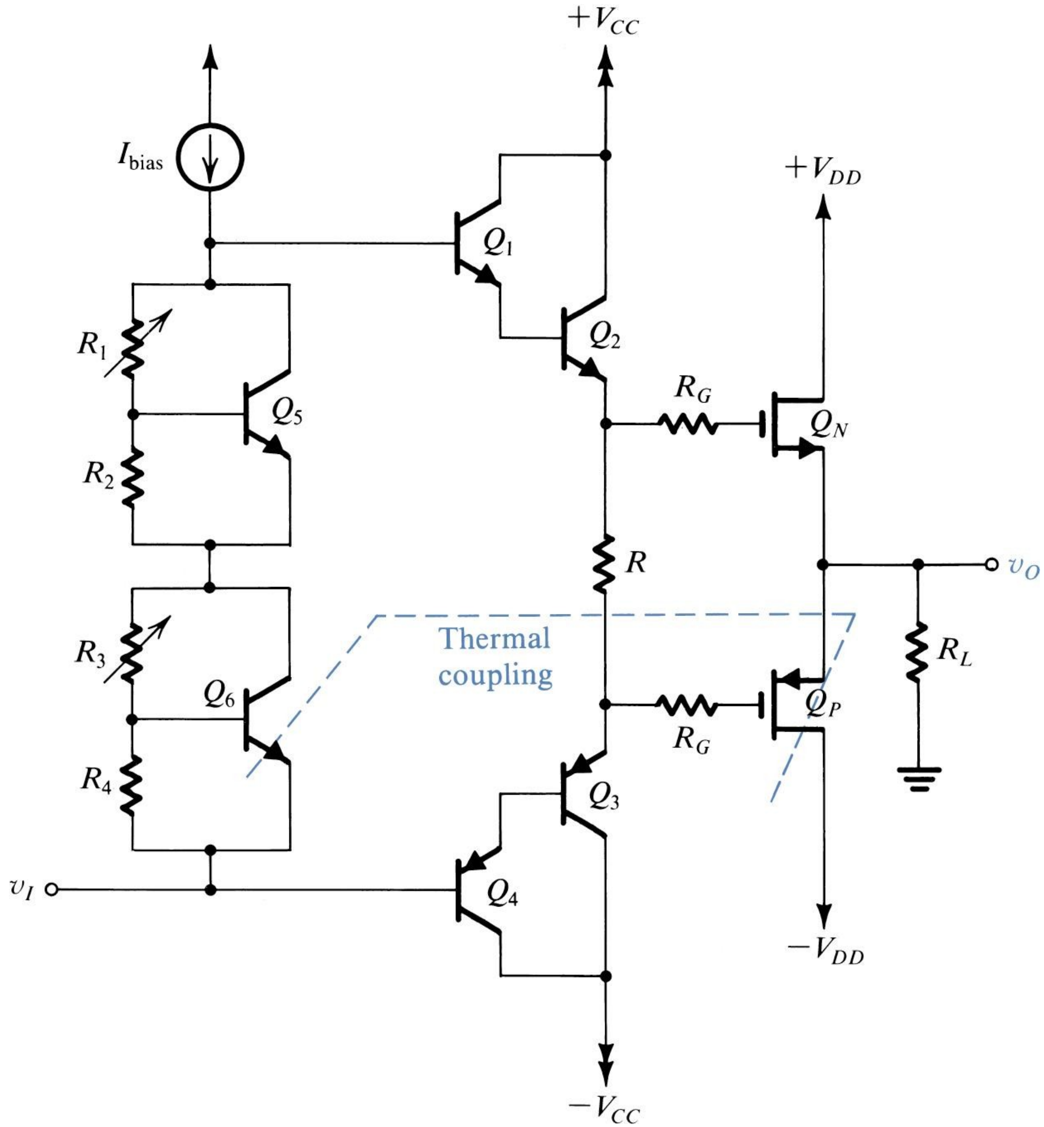
The bridge amplifier configuration.



Double-diffused vertical MOS transistor (DMOS).



Typical i_D-v_{GS} characteristic for a power MOSFET.



A class AB amplifier with MOS output transistors and BJT drivers. Resistor R_3 is adjusted to provide temperature compensation while R_1 is adjusted to yield to the desired value of quiescent current in the output transistors.