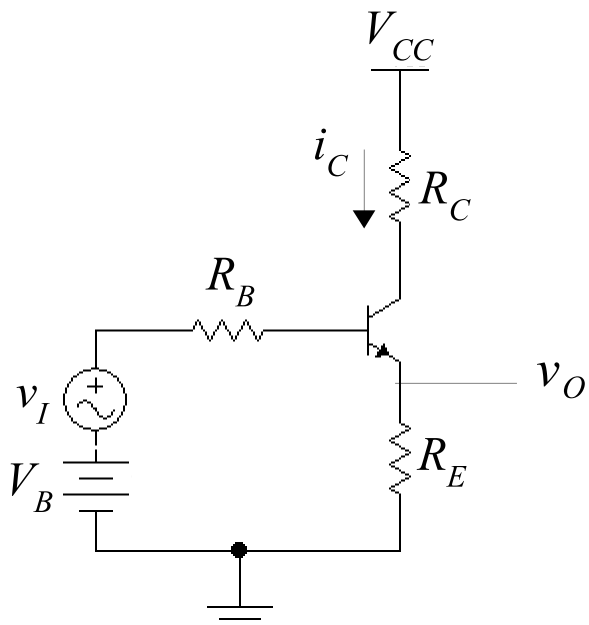
Output Stages

- Power amplifier classification
- Class A amplifier circuits
- Class A Power conversion efficiency
- Class B amplifier circuits
- Class B Power conversion efficiency
- Class AB amplifier circuits
- Class AB Power conversion efficiency

Output Stage Functions

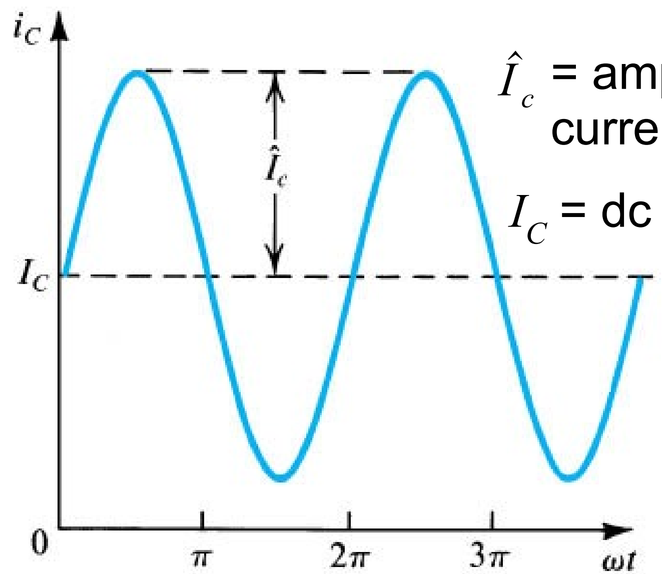
- Provide amplifier with low output resistance
- Handle large signals with low THD
- Deliver power to the load efficiently
- Output stages are classified according to the i_C waveform due to input v_I waveform

Amplifier Classifications



Class A amplifier – amplifier BJT conducts for entire v_I cycle. For all v_I s.t.

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



$\hat{I}_c$ = amplitude of the signal current due to v_i.

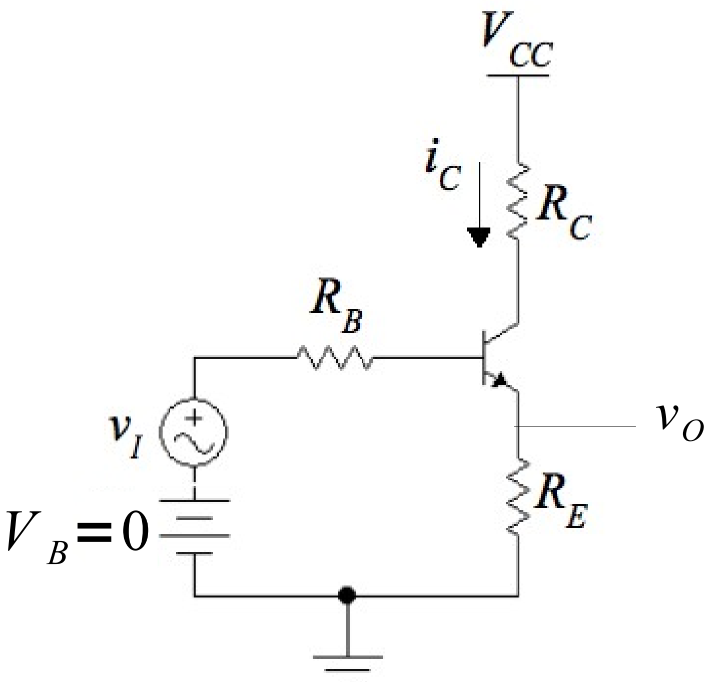
I_C = dc current

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

$$v_I + V_B < 0.7\,V$$

NOTE: when $v_I = 0$, $i_C = I_C$

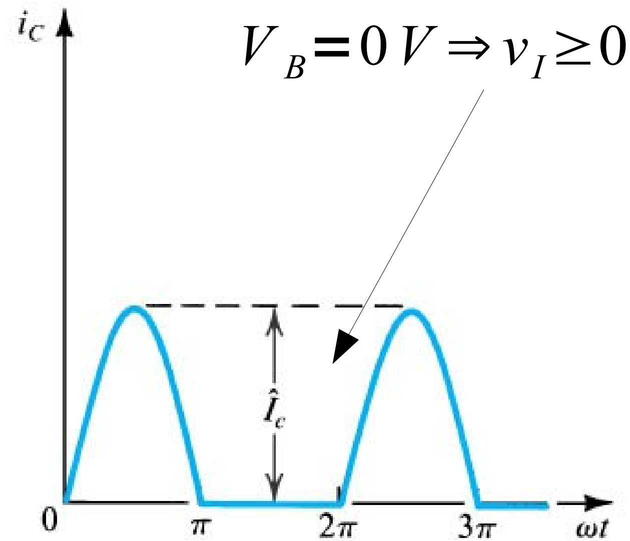
Amplifier Classifications - cont.



Class B – Amplifier BJT conducts positive-half of v_I cycle.

Amp BJT conducts for all v_I s.t.:

$$V_B = 0\,V \Rightarrow v_I \geq 0.7\,V$$



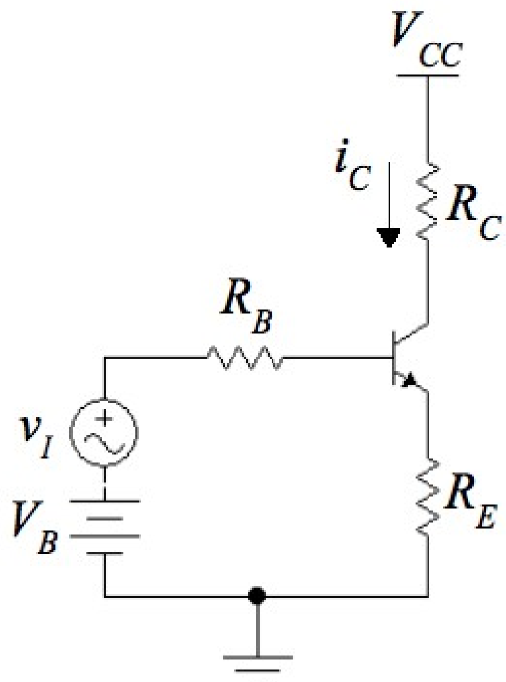
Transistor cut off ($i_C = 0$) if:

$$v_I + V_B < 0.7\,V$$

NOTE: 1. when $v_I < 0.7V$, $i_C = 0$

2. A 2nd class B BJT (PNP) is needed to conduct for the negative v_I cycle.

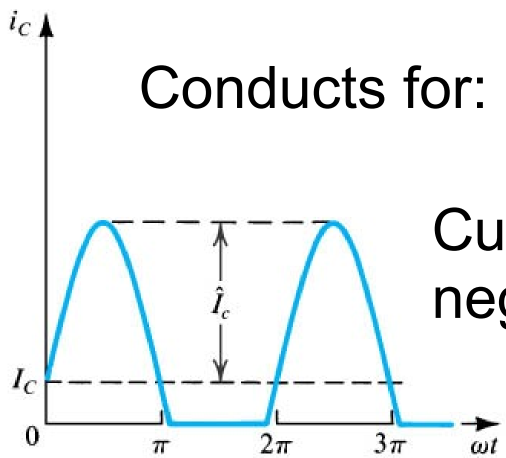
Amplifier Classifications - cont.



Class AB – Amplifier BJT conducts for positive v_I swing + part of negative v_I swing s.t.:

$$v_I + V_B \geq 0.7\,V \quad \text{where} \quad 0 < V_B < max(v_I) + 0.7\,V$$

Conducts for: $v_I \geq 0.7 - V_B$



Cut-off for rest of negative v_I swing:

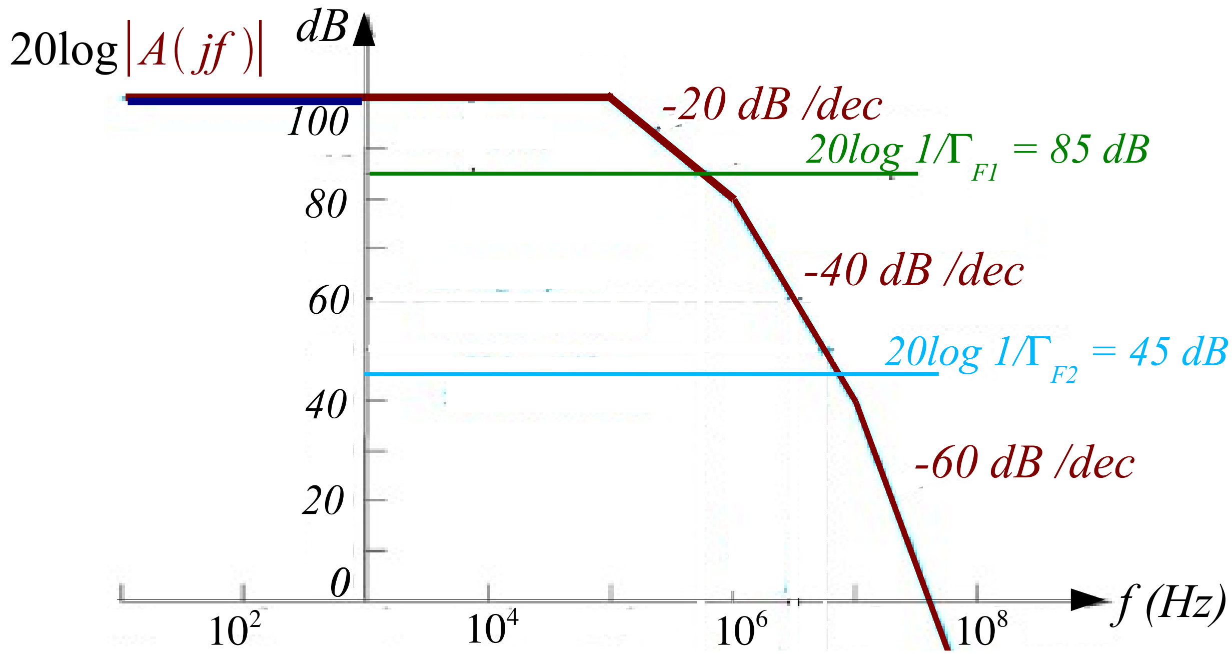
Transistor cut-off ($i_C = 0$) if:

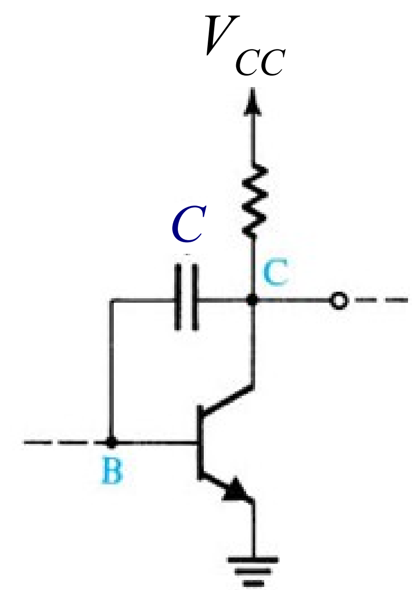
$$v_I + V_B < 0.7\,V$$

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

2. A 2nd class AB BJT (PNP) is needed to conduct for interval slightly larger than the negative v_I cycle.

Quick Review

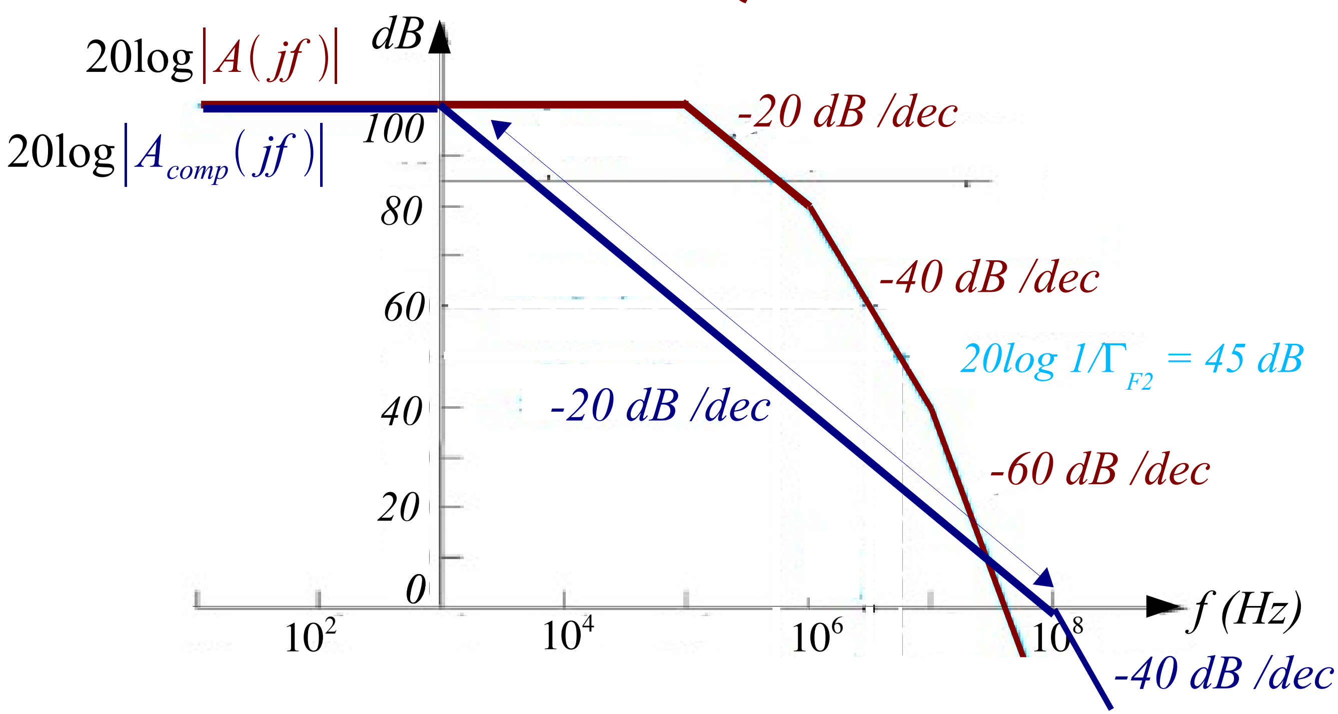


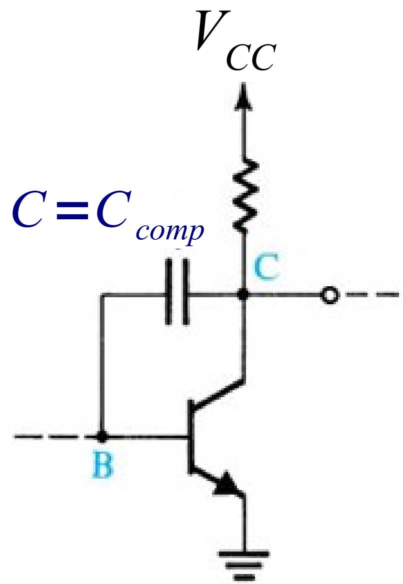


$$A(jf) = \frac{10^5}{(1 + jf/10^5)(1 + jf/10^6)(1 + jf/10^7)}$$

What is the purpose of capacitor "C"?
What does it do the pole locations and its impact on stability?

Quick Review





$$A(jf)=\frac{10^5}{(1+jf/10^5)(1+jf/10^6)(1+jf/10^7)}$$

$$A_{comp}(jf)\approx\frac{10^5}{(1+jf/10^3)(1+jf/10^8)(1+jf/10^7)}$$

Quick Review

1. What is the BJT basic output stage circuit?

2. **Class A amplifier:**
   What is its characteristic performance?
   Advantage?
   Disadvantage?

3. **Class B amplifier:**
   What is its characteristic performance?
   Advantage?
   Disadvantage?

4. **Class AB amplifier:**
   What is its characteristic performance?
   Advantage?
   Disadvantage?

Quick Review

1. What is the BJT basic output stage circuit? Emitter follower.

2. **Class A amplifier:**

   What is its characteristic performance? Conducts over entire v_i cycle.

   Advantage? Low THD except when signal amplitude is large.
   Disadvantage? Conducts current and dissipates power when $v_i = 0$.

3. **Class B amplifier:**

   What is its characteristic performance? Conducts over $1/2\ v_i$ cycle.

   Advantage? High THD even when signal amplitude is small.
   Disadvantage? No power dissipated when $v_i = 0$.

4. **Class AB amplifier:**

   What is its characteristic performance? Conducts over $>1/2\ v_i$ cycle.

   Advantage? Reduced THD over Class B.
   Disadvantage? Increased power dissipation over Class A.

Class A Power Amplifier Design

Used as op amp output stage and some audio output power amps.

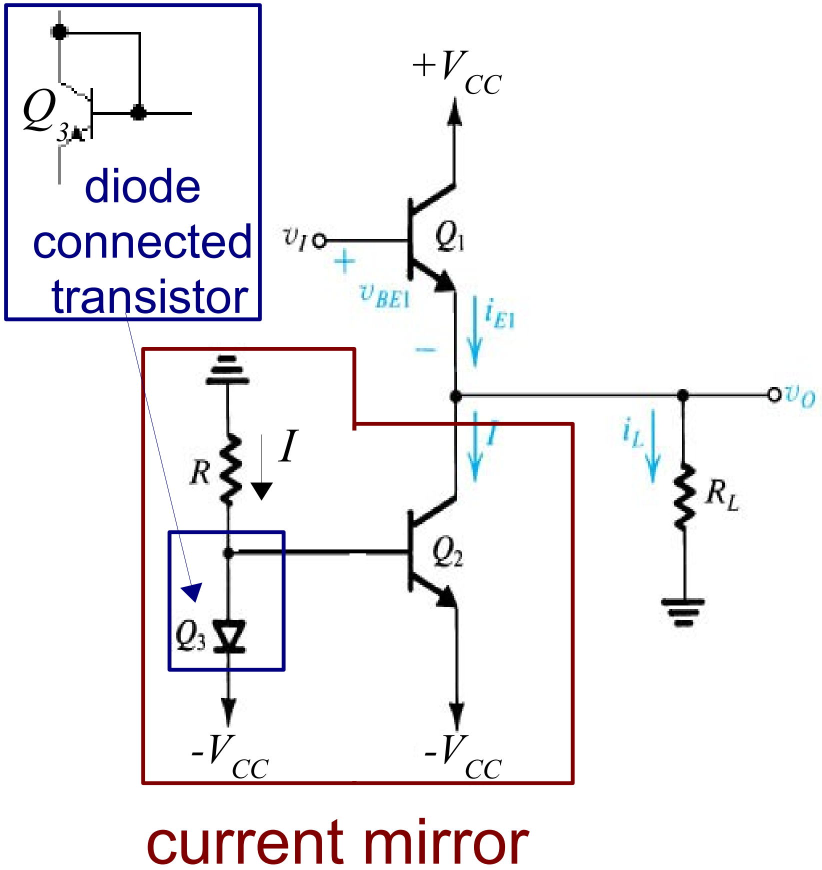
Basic considerations for low (audio) frequency operation.

1. Power usually delivered to a low impedance load.
2. Signal usually has little, preferably no dc content.
3. May have low frequency content, as low as $20\ Hz$.

Emitter follower circuit has best power transfer efficiency, since its output impedance is low. As a bonus, its input impedance is relatively high.

Principal advantage – lower distortion than Class B & AB.
Principal disadvantage – lower power efficiency than Class B & AB.

Current Biased Class A Emitter Follower



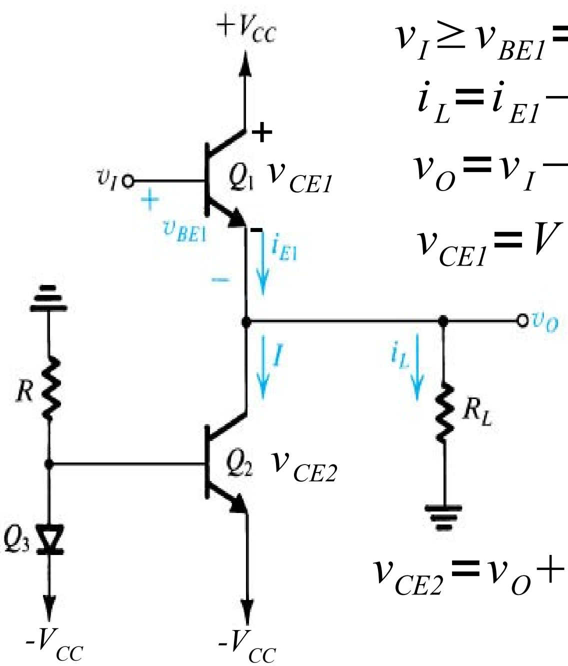
A current mirror establishes the bias current "I".

$$i_L = i_{E1} - I$$

To operate reliably,

1. Q_1 and Q_2 must be forward active.
2. Current Mirror Q_3 and Q_2 need to be matched as well as possible and be at the same ambient temperature.

Class A Amplifier Analysis



$$v_I \geq v_{BE1} = 0.7\,V$$

$$i_L = i_{E1} - I$$

$$v_O = v_I - 0.7\,V = i_L R_L$$

$$v_{CE1} = V_{CC} - v_O$$

$$v_{CE2} = v_O + V_{CC}$$

To operate reliably,

1. Q_1 and Q_2 must be forward active, i.e.

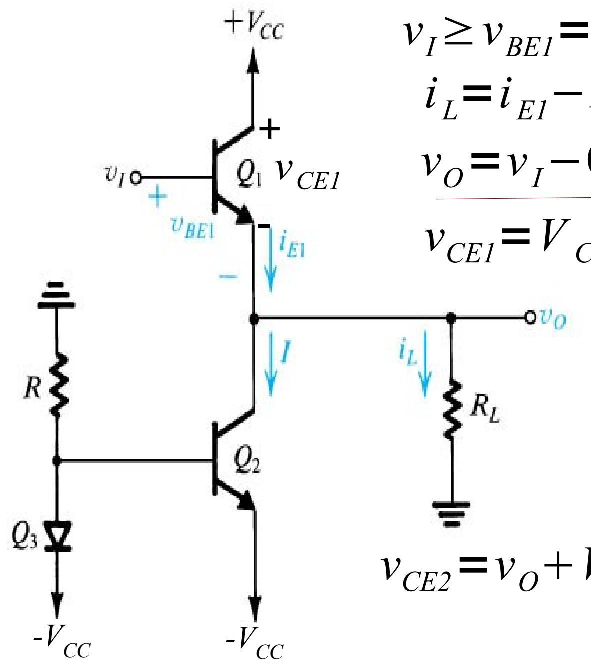
$Q_1 \neq$ sat. => $v_{CE1} > V_{CE1sat}$

$Q_2 \neq$ sat. => $v_{CE2} > V_{CE2sat}$

$Q_1 \neq$ cut-off => $i_{E1} > 0$

Class A Amplifier Analysis

Consider the case when $v_I \geq v_{BE1} = 0.7\,V$ (pos. swing of v_I):



$$v_I \geq v_{BE1} = 0.7\,V$$
$$i_L = i_{E1} - I$$
$$v_O = v_I - 0.7\,V = i_L R_L$$
$$v_{CE1} = V_{CC} - v_O$$

$$v_{CE2} = v_O + V_{CC}$$

if $v_{CE1} < V_{CE1\text{-}sat}$ => Q_1 sat.

For $Q1 \neq$ sat: $v_{CE1} > V_{CE1-sat}$

$$v_{CE1} = V_{CC} - v_O > V_{CE1-sat}$$
$$-v_O > -V_{CC} + V_{CE1-sat}$$
$$v_O < V_{CC} - V_{CE1-sat} \Rightarrow v_{O-max} = V_{CC} - V_{CE1-sat}$$

Max values: $Q_1 \neq$ sat.

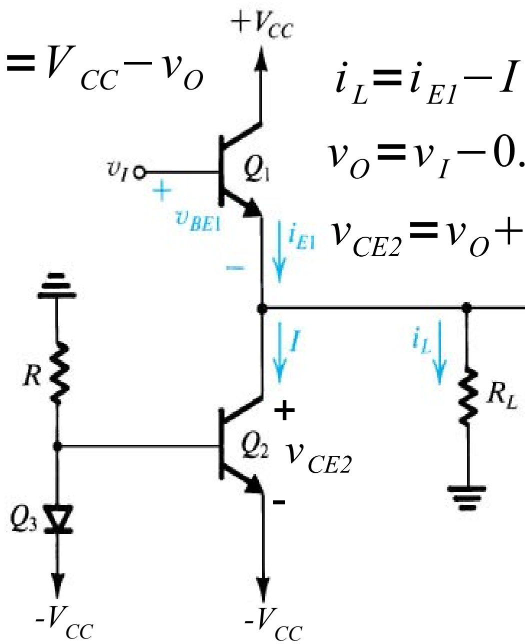
$$v_O < v_{O-max} = V_{CC} - V_{CE1-sat}$$
$$v_I < v_{I-max} = V_{CC} - V_{CE1-sat} + 0.7\,V$$

Class A Amplifier Analysis - cont.

Consider the case where $v_I < 0.7\ V$ (*neg.* swing of v_I):

if $v_{CE2} < V_{CE2\text{-}sat}$ => Q_2 sat. and/or if $i_{E1} = 0$ => Q_1 off

$v_{CE1} = V_{CC} - v_O$



$i_L = i_{E1} - I$

$v_O = v_I - 0.7\ V = i_L R_L$

$v_{CE2} = v_O + V_{CC}$

$$v_{CE2} > V_{CE2-sat}$$

$$v_{CE2} = v_O + V_{CC} > V_{CE2-sat}$$

$$\Rightarrow v_O > -V_{CC} + V_{CE2-sat}$$

$$v_I > -V_{CC} + V_{CE2-sat} + 0.7$$

Min values: Q_2 forward-active

$$v_O > v_{O-min} = -V_{CC} + V_{CE2-sat}$$

$$v_I > v_{I-min} = -V_{CC} + V_{CE2-sat} + 0.7\ V$$

$v_I < 0.7\ V$

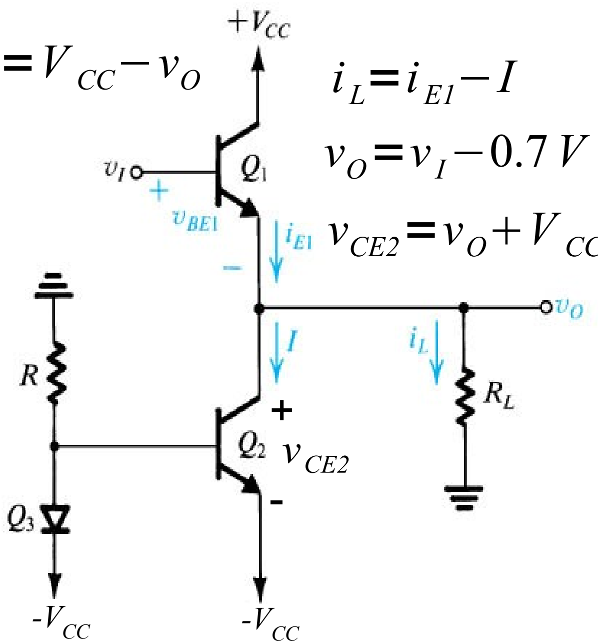
$v_O = v_I - 0.7$ & $v_O = i_L R_L$

$v_{CE2} = v_O + V_{CC} = v_I - 0.7 + V_{CC}$

Class A Amplifier Analysis - cont.

Consider the case where $v_I < 0.7\ V$ (*neg.* swing of v_I):

$v_{CE1} = V_{CC} - v_O$



$i_L = i_{E1} - I$

$v_O = v_I - 0.7\ V = i_L R_L$

$v_{CE2} = v_O + V_{CC}$

From previous slide

$v_O > -V_{CC} + V_{CE2-sat}$

$v_I > -V_{CC} + V_{CE2-sat} + 0.7$

if $i_{E1} = 0$ => Q_1 off

$i_{E1} = i_L + I > 0$

$i_L = \frac{v_O}{R_L} > -I$

$v_O > -I\ R_L$

$v_I > -I\ R_L + 0.7\ V$

Min values: Q_1 and Q_2 forward-active

$v_I < 0.7\ V$

$v_O = v_I - 0.7$ & $v_O = i_L R_L$

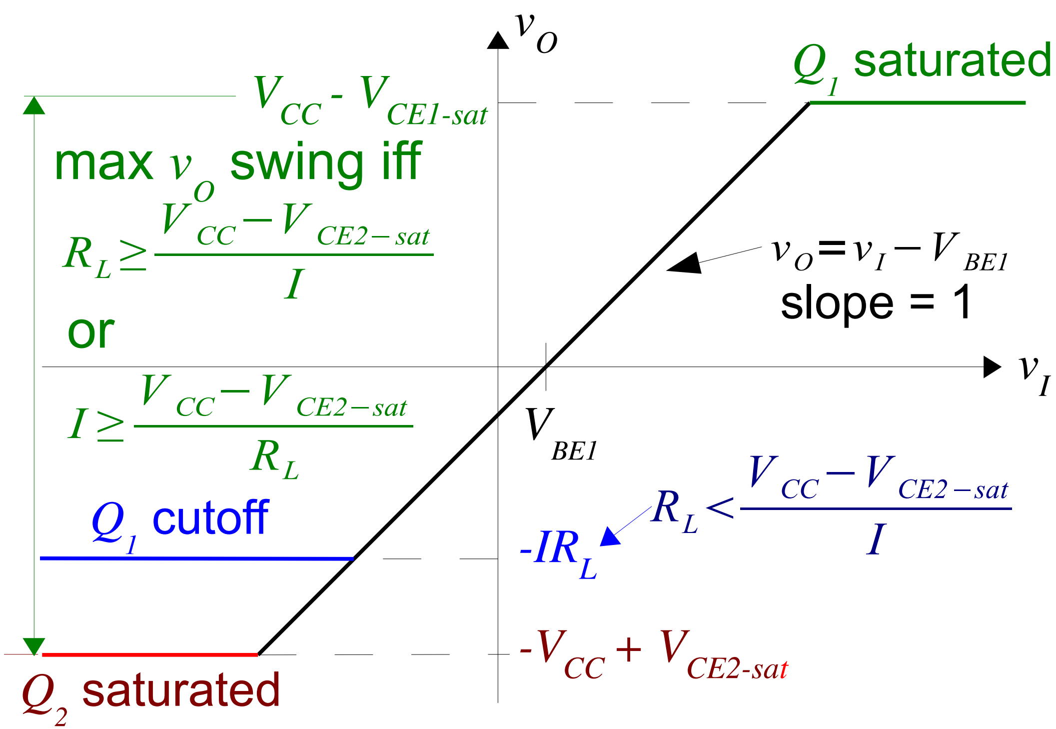
$v_{CE2} = v_O + V_{CC} = v_I - 0.7 + V_{CC}$

$$v_O > v_{O-min} = max\{-IR_L, -V_{CC} + V_{CE2-sat}\}$$

$$v_I > v_{I-min} = max\{-IR_L + 0.7\ V, -V_{CC} + V_{CE2-sat} + 0.7\ V\}$$

NOTE: *max* means least negative

Class A Amplifier VTC – Plot



Bias current I & R_L set limits on negative $v_O = v_{O\text{-}min}$ swing

Iff $-IR_L > -(V_{CC} - V_{CE2-sat})$

$$v_O > v_{O-min} = -IR_L \Rightarrow$$

$$R_L < \frac{V_{CC} - V_{CE2-sat}}{I}$$

If $-IR_L < -(V_{CC} - V_{CE2-sat})$

$$v_O > v_{O-min} = -V_{CC} + V_{CE2-sat} \Rightarrow$$

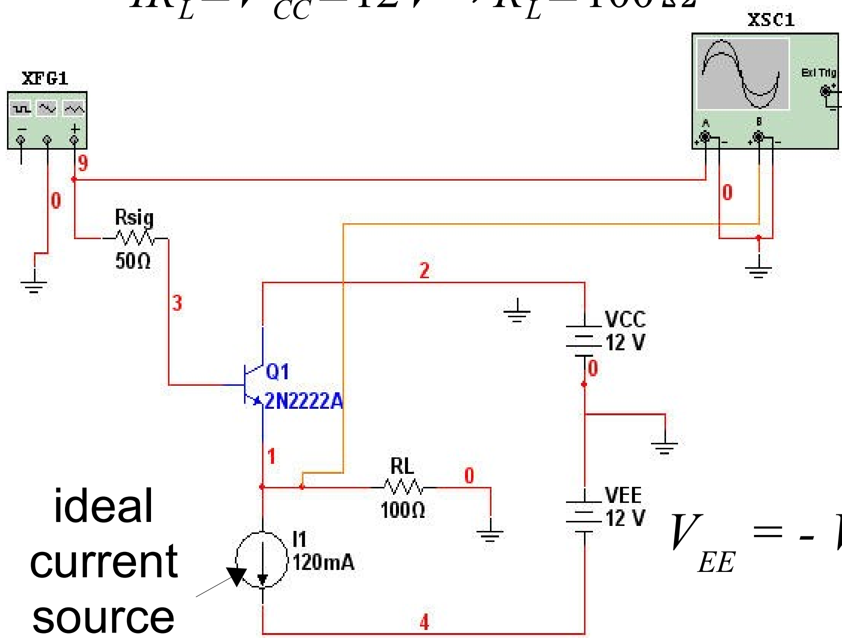
$$R_L > \frac{V_{CC} - V_{CE2-sat}}{I} ¿$$

$v_O = v_I - 0.7$ where $max\{-IR_L, -(V_{CC} - V_{CE2-sat})\} < v_O < V_{CC} - V_{CE1-sat}$

Class A Stage VTC Simulation

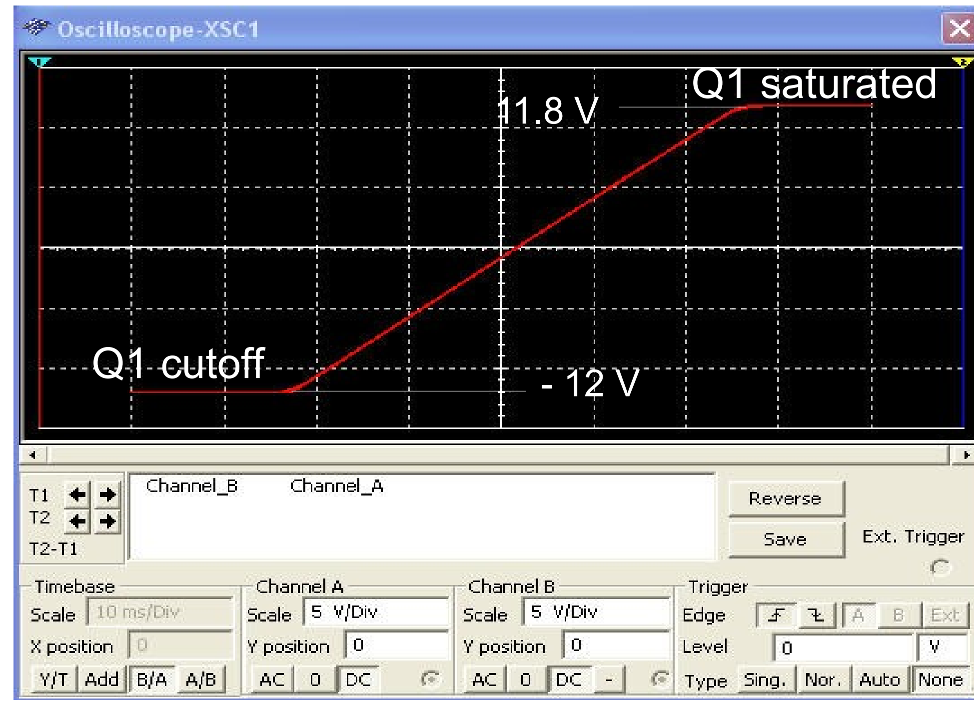
$I = 120\,mA$

$IR_L = V_{CC} = 12\,V \Rightarrow R_L = 100\,\Omega$



$V_{EE} = -V_{CC}$

ideal current source i.e. no Q_2



Q1 forward active => no clipping

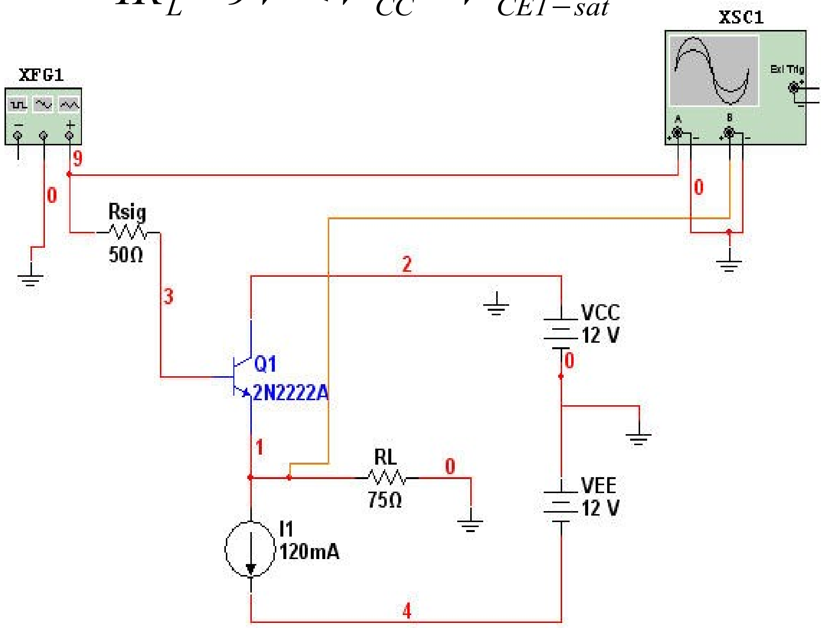
$v_O < v_{O-max} = V_{CC} - V_{CE1-sat} = 11.8\,V$ Q1 not Sat

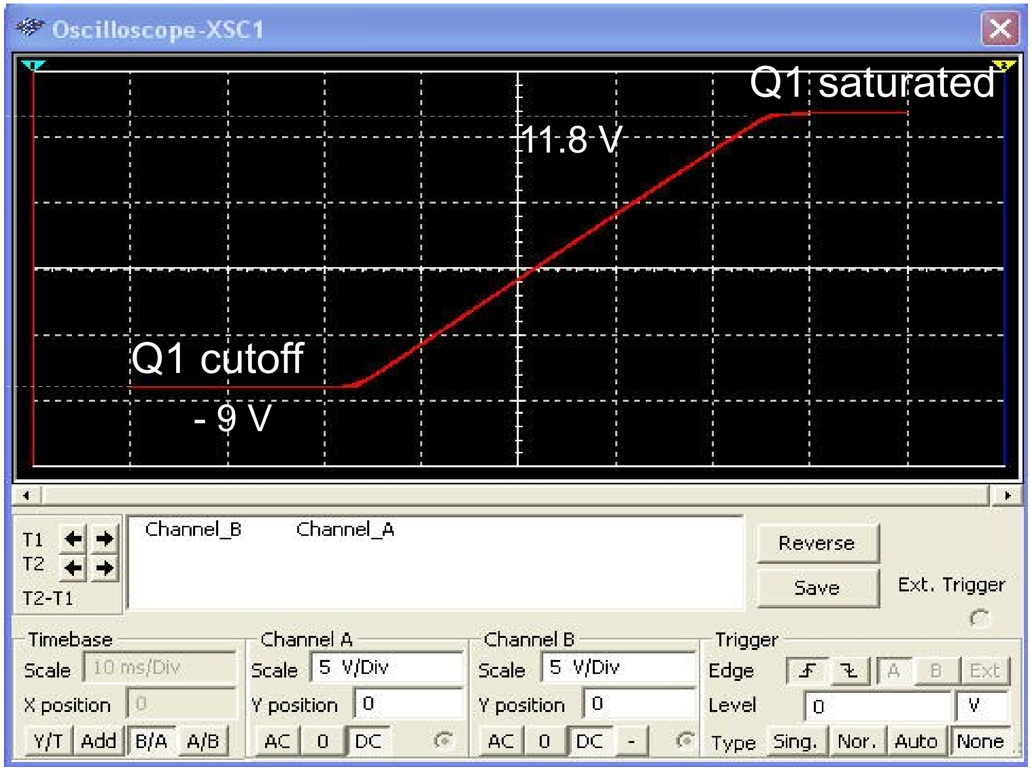
$v_O > v_{O-min} = -IR_L = -12\,V$ Q1 not Cut-off (there is no Q2)

Class A Stage VTC Simulation - cont.

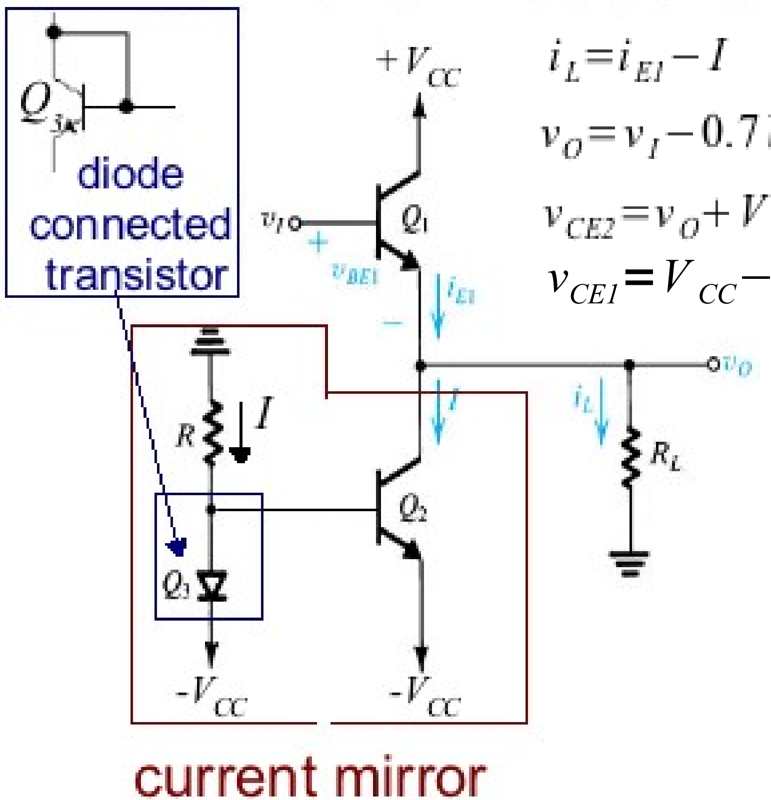
$I = 120\,mA \qquad R_L = 75\,\Omega$

$IR_L = 9\,V < V_{CC} - V_{CE1-sat}$





Quick Review



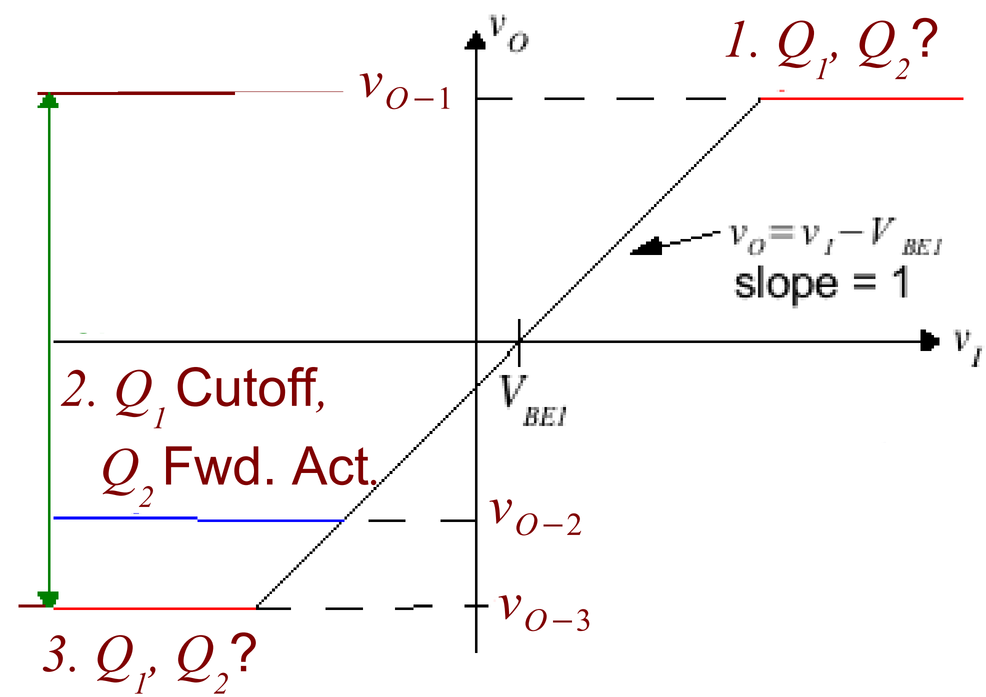
$i_L = i_{E1} - I$

$v_O = v_I - 0.7V = i_L R_L$

$v_{CE2} = v_O + V_{CC}$

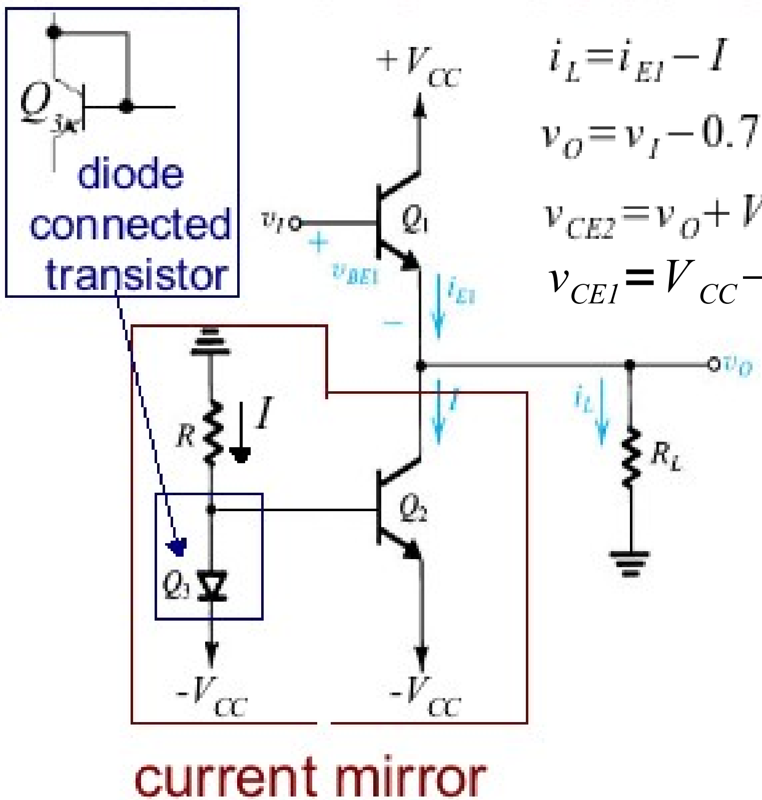
$v_{CE1} = V_{CC} - v_O$

Class A Amp VTC



4. Max swing v_O occurs iff

Quick Review



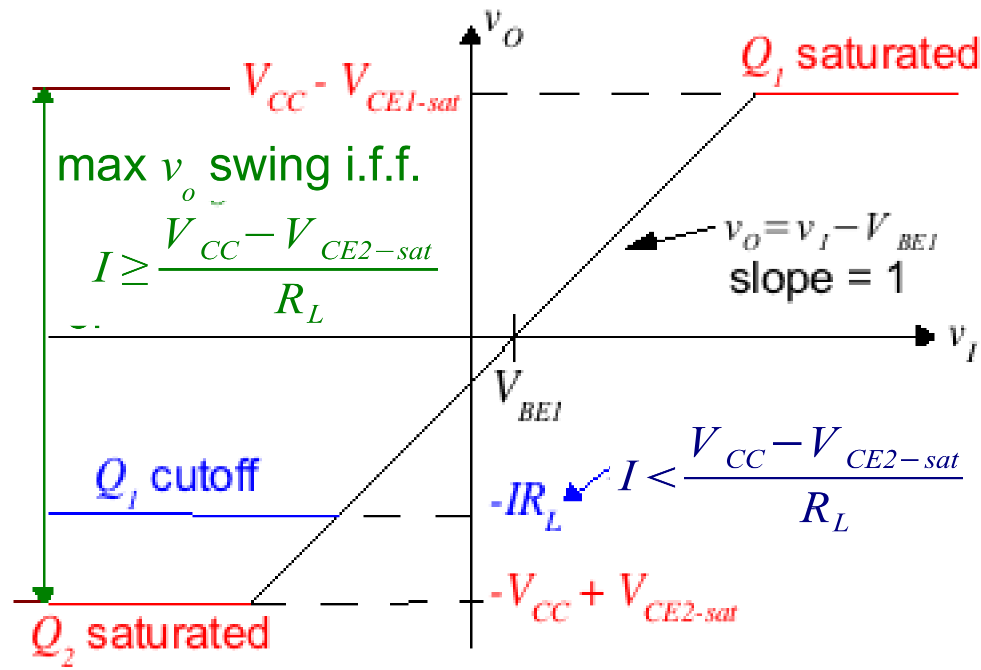
$$i_L = i_{E1} - I$$

$$v_O = v_I - 0.7V = i_L R_L$$

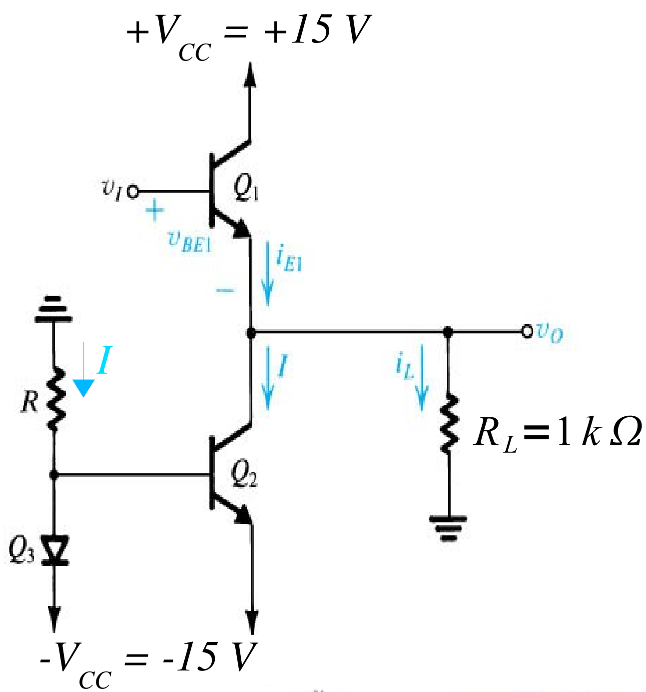
$$v_{CE2} = v_O + V_{CC}$$

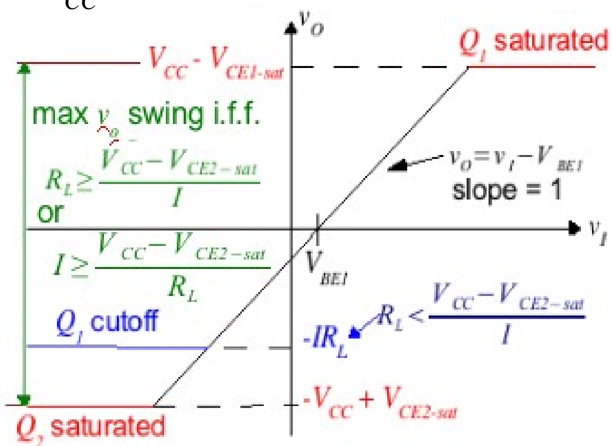
$$v_{CE1} = V_{CC} - v_O$$

Class A Amp VTC



$$v_O = v_I - 0.7 \quad \text{where} \quad max\{-IR_L, -(V_{CC} - V_{CE2-sat})\} < v_O < V_{CC} - V_{CE1-sat}$$





Example

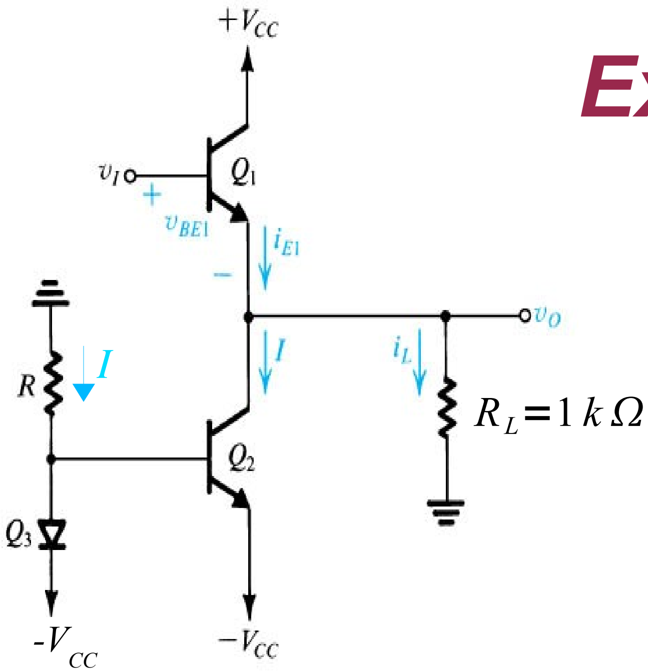
Let $V_{CE1\text{-}sat} = V_{CE2\text{-}sat} = 0.2\ V$, $V_{BE1} = V_{BE2} = 0.7\ V$ and

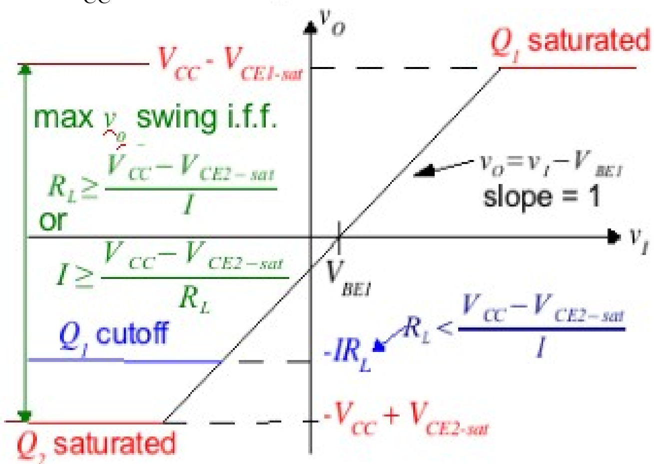
$$\beta_1 = \beta_2 = large$$

1. Determine the value for resistor R that will set the bias current I sufficiently large to allow the largest possible output voltage v_O swing.

2. Determine the resulting output voltage swing and the maximum and minimum Q_1 emitter currents.

Example cont.





SOLUTION:

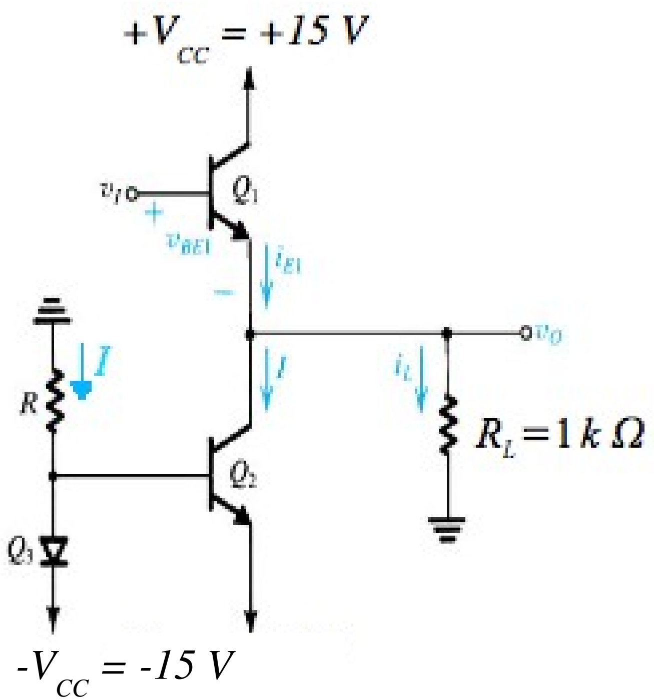
1. For maximum output voltage swing:

$$IR_L = V_{CC} - V_{CE2-sat} \quad \text{where } R_L = 1\ k\Omega$$

$$I = \frac{V_{CC} - V_{CEsat}}{R_L} = \frac{15\,V - 0.2\,V}{1\,k\,\Omega} = 14.8\,mA$$

$$R = \frac{0 - (V_{BE} - V_{CC})}{I} = \frac{15\,V - 0.7\,V}{14.8\,mA} = 0.97\,k\,\Omega$$

Example - cont.



$$I = \frac{0-(V_{BE2}-V_{CC})}{R}$$

From Part 1:

$$I = 14.8\,mA$$

SOLUTION:

2. Output voltage swing:

$$V_{o-peak} = I\,R_L = 14.8\,V \Rightarrow \boxed{-14.8\,V < v_O < 14.8\,V}$$

$$-14.8\,V < v_O < 14.8\,V \Rightarrow -I < i_L < I$$

Max and min Q_1 emitter currents:

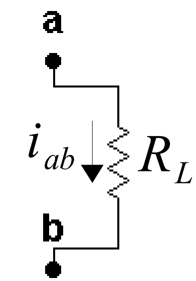
$$\boxed{i_{E1} = I + i_L \Rightarrow 0\,mA < i_{E1} < 2I = 29.6\,mA}$$

Instantaneous and Average Power

The source of power to the amplifier load, R_L, comes from the supplies, V_{CC} & $-V_{CC}$. The supplies deliver power, & the load and the transistors absorb it.

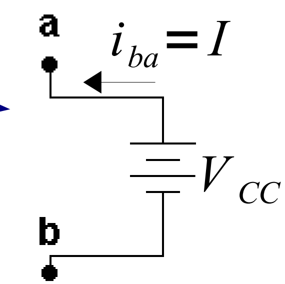
Instantaneous power absorbed by resistor R_L:

$$p_L(t)=v_{ab}(t)i_{ab}(t)=i_{ab}^2(t)R_L=v_{ab}^2(t)/R_L$$



Instantaneous power delivered by battery V_{CC}:

$$p_D(t)=v_{ab}(t)i_{ba}(t)=V_{CC}I$$



Average power: $i_{ab}=I_{ab-peak}\sin(\omega t)$ for period T

$$P_{Lav}=\frac{1}{T}\int_0^T i_{ab}^2(t)R_L\,dt=I_{ab-rms}^2R_L=\frac{I_{ab-peak}^2}{2}R_L=\frac{V_{ab-peak}^2}{2R_L}$$

$$P_{Dav}=V_{CC}I$$

Power dissipation: $P_{Disp}(V_{ab-peak})=P_{Dav}-P_{Lav}$

Emitter Follower Power Relationships

I. Average power delivered by the batteries:

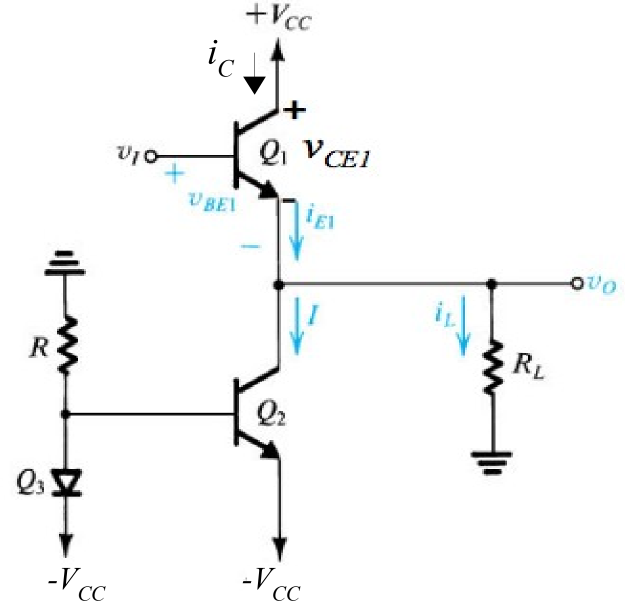
For the current mirror transistor side:

$$P_{-VCC}=V_{CC}I$$

For the amplifier transistor side:

$$P_{+VCC}=\frac{1}{T}\int_0^T V_{CC}i_{C1}dt \quad \text{where} \quad i_{C1}=I+\hat{I}_c\sin(\omega t)$$

$$P_{+VCC}=V_{CC}I\frac{1}{T}\int_0^T (1+\frac{\hat{I}_c}{I}\sin(\omega t))dt=V_{CC}I$$



Total delivered power: $P_{D\,av}=p_D(t)=P_{-VCC}+P_{+VCC}=2V_{CC}I$

II. Average power to the load:

$$v_O=V_{o-peak}\sin(\omega t)$$

$$P_{L\,av}=\frac{V_{o-rms}^2}{R_L}=\frac{(V_{o-peak}/\sqrt{2})^2}{R_L}=\frac{V_{o-peak}^2}{2R_L}$$

Class A Power Conversion Efficiency

Using the power delivered to transistors from the batteries P_{Dav} and the power delivered to the load P_{Lav}:

$$P_{D\,av}=2\,V_{CC}\,I \qquad \text{and} \qquad P_{L\,av}=\frac{V_{o-peak}^2}{2\,R_L}$$

Note:
1. Average currents and $P_{D\,av}$ from the power supply do not change with the signal level $V_{o\text{-}peak}$.
2. $P_{L\,av}$ increases with the square of the signal level $V_{o\text{-}peak}$.

power conversion efficiency

$$\eta=\frac{P_{L\,av}}{P_{D\,av}}=\frac{V_{o-peak}^2/2\,R_L}{2\,V_{CC}\,I}=\frac{1}{4}\frac{V_{o-peak}^2}{V_{CC}\,I\,R_L}=\frac{1}{4}\frac{V_{o-peak}}{I\,R_L}\frac{V_{o-peak}}{V_{CC}}$$

Power Conversion Efficiency

$$\eta=\frac{1}{4}\frac{V_{o-peak}^2}{I R_L V_{CC}}=\frac{1}{4}\frac{V_{o-peak}}{I R_L}\frac{V_{o-peak}}{V_{CC}}$$

Since $V_{o-peak}<V_{CC}$ and $V_{o-peak}<I R_L$:

Maximum power conversion efficiency is realized when

$$V_{o-peak}=V_{CC}=I R_L$$ ignoring the $V_{CE1\text{-}sat}$ and $V_{CE2\text{-}sat}$

Hence:

$$\eta_{max}=\frac{1}{4}\frac{V_{CC}}{V_{CC}}\frac{V_{CC}}{V_{CC}}=\frac{1}{4} \text{ or } 25\,\%$$

and

$$P_{Disp}(V_{o-peak}=0)=P_{D\,av}-P_{L\,av}=2 V_{CC} I$$

Class A Power Analysis Summary

Power from sources: $P_{D\,av} = 2V_{CC}I$ $P_{D\,av(max)} = 2V_{CC}I$

max $V_{0\text{-}peak} = V_{CC}$

Power output to load: $P_{L\,av} = \frac{1}{2}\frac{V_{o-peak}^2}{R_L}$ $P_{L\,av(max)} = \frac{1}{2}\frac{V_{CC}^2}{R_L} = \frac{1}{2}V_{CC}I$

max $V_{0\text{-}peak} = V_{CC}$

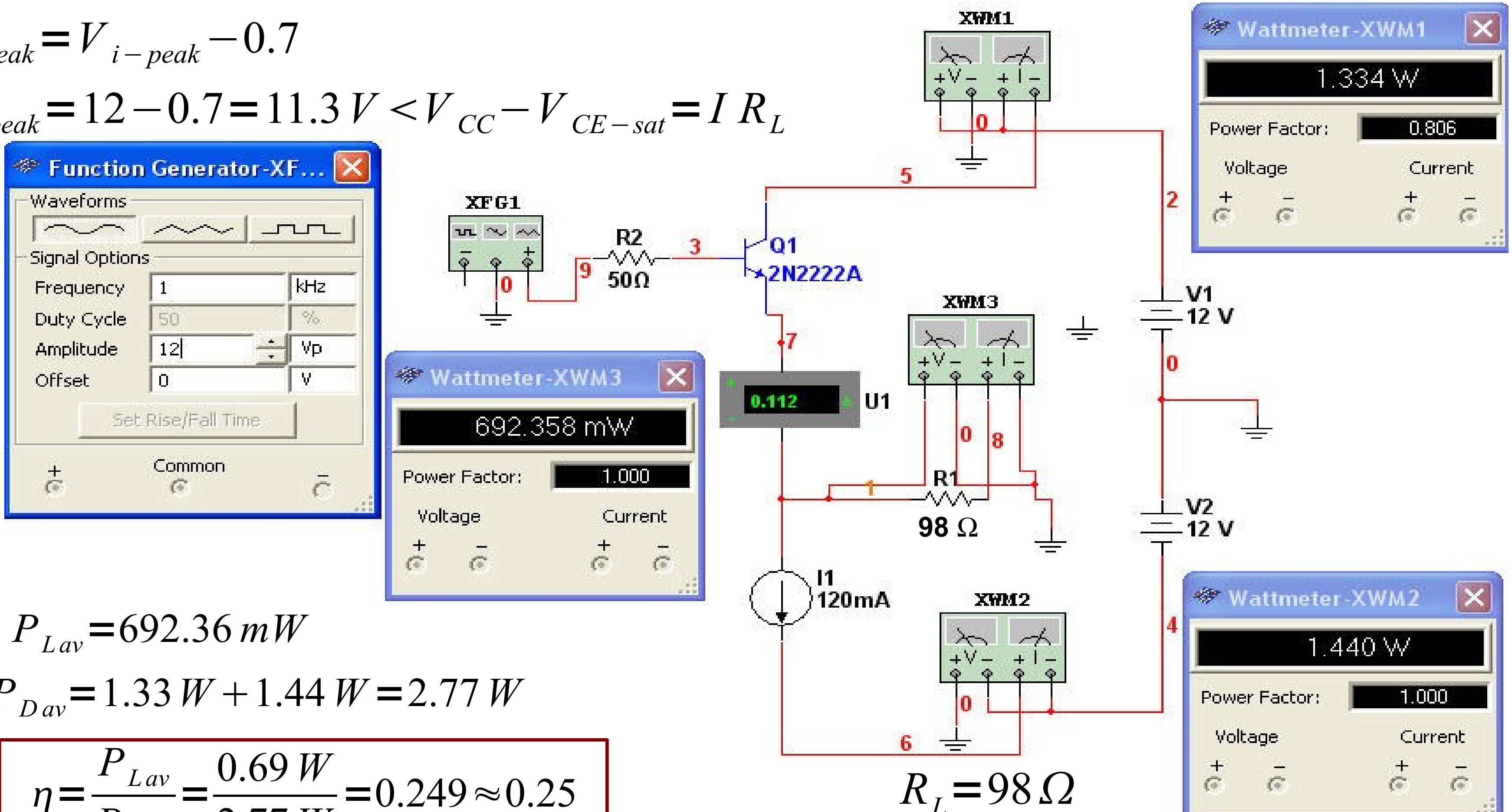
Power Conversion Efficiency: $\eta = \frac{1}{4}\frac{V_{o-peak}^2}{I R_L V_{CC}}$ $\eta_{max} = \frac{1}{4} = 0.25$

Power dissipation $P_{Disp} = 2V_{CC}I - \frac{1}{2}\frac{V_{o-peak}^2}{R_L}$ $P_{Disp(max)} = 2V_{CC}I$

Class A Power Efficiency Simulation

$$V_{o-peak} = V_{i-peak} - 0.7$$

$$V_{o-peak} = 12 - 0.7 = 11.3\,V < V_{CC} - V_{CE-sat} = I\,R_L$$



$$P_{L\,av} = 692.36\,mW$$

$$P_{D\,av} = 1.33\,W + 1.44\,W = 2.77\,W$$

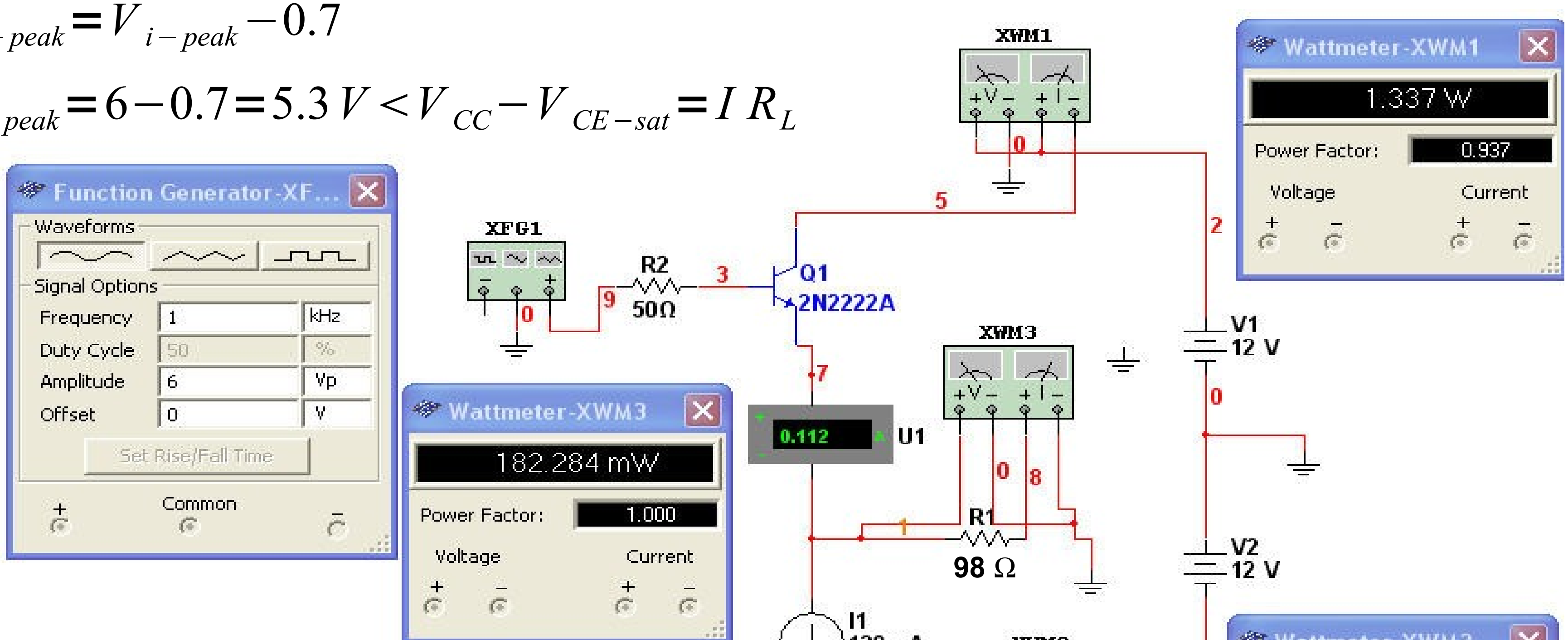
$$\eta = \frac{P_{L\,av}}{P_{D\,av}} = \frac{0.69\,W}{2.77\,W} = 0.249 \approx 0.25$$

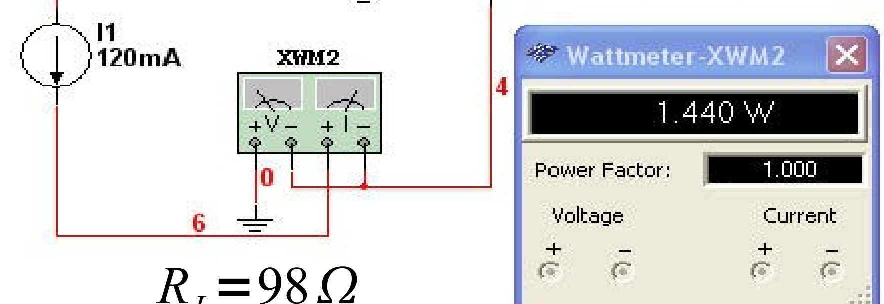
$$R_L = 98\,\Omega$$

Class A Power Simulation - cont.

$$V_{o-peak}=V_{i-peak}-0.7$$

$$V_{o-peak}=6-0.7=5.3\,V<V_{CC}-V_{CE-sat}=I\,R_L$$





$$P_{L\,av}=182.28\,mW$$

$$P_{D\,av}=1.33\,W+1.44\,W=2.77\,W$$

$$\eta=\frac{P_{L\,av}}{P_{D\,av}}=\frac{0.18\,W}{2.77\,W}=0.065<0.25$$

$$R_L=98\,\Omega$$

Conclusions

1. The class A amplifier provides the most "nearly linear" amplification of its input, but this comes at a price: The best power conversion efficiency that can be obtained is 25%.

2. That is 75% of the power supplied by the sources is dissipated in the transistors. This is a waste of power, and it leads to a potentially serious heating problems with the transistors. All of this constant battery power is dissipated in the transistors even when no signal is applied – zero percent efficiency!

Next we will consider a much more efficient amplifier configuration – the class B amplifier.