# Chapter 13 Output Stages and Power Amplifiers

- 13.1 General Considerations
- 13.2 Emitter Follower as Power Amplifier
- 13.3 Push-Pull Stage
- 13.4 Improved Push-Pull Stage
- 13.5 Large-Signal Considerations
- 13.6 Short Circuit Protection
- 13.7 Heat Dissipation
- 13.8 Efficiency
- 13.9 Power Amplifier Classes

# Why Power Amplifiers?

- Drive a load with high power.
- Cellular phones need 1W of power at the antenna.
- Audio systems deliver tens to hundreds of watts of power.
- Ordinary Voltage/Current amplifiers are not suitable for such applications

# Chapter Outline

**Basic Stages**

- Emitter Follower
- Push-Pull Stage and Improved Variants

**Large-Signal Considerations**

- Omission of PNP Transistor
- High-Fidelity Design

**Heat Dissipation**

- Power Ratings
- Thermal Runaway

**Efficiency and PA Classes**

- Efficiency of PAs
- Classes of PAs

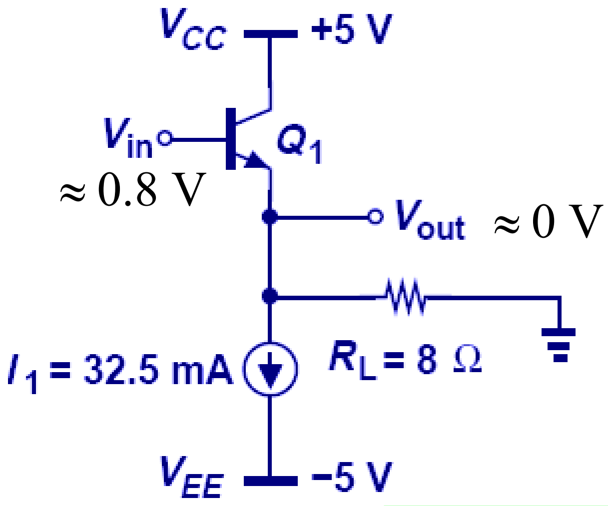
# Power Amplifier Characteristics

- Experiences low load resistance.
- Delivers large current levels.
- Requires large voltage swings.
- Draws a large amount of power from supply.
- Dissipates a large amount of power, therefore gets “hot”.

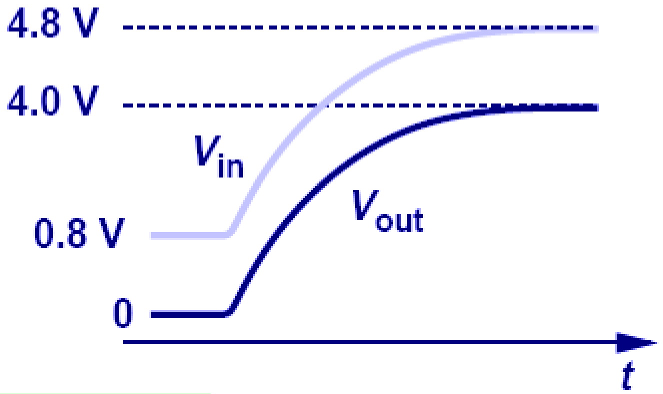
# Power Amplifier Performance Metrics

- **Distortion - Nonlinearity**
- **Power Efficiency** $\eta = \dfrac{\text{Power Delivered to Load}}{\text{Power Drawn from Supply}}$
- **Voltage Rating – Transistor Breakdown voltage**

# Emitter Follower Large-Signal Behavior I



(a)



(b)

$$A_v = R_L/(R_L + 1/g_m)$$

For $R_L = 8\ \Omega$,

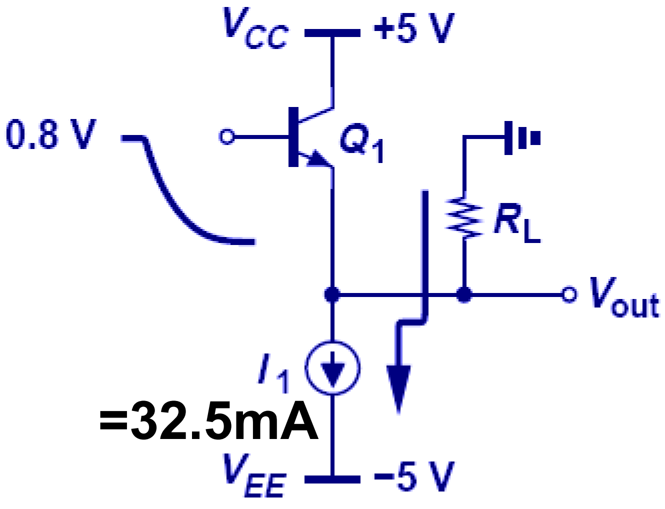
$1/g_m = 0.8\ \Omega$, thus, $I_C = 32.5$ mA

$$\because g_m = \frac{I_C}{V_T}$$

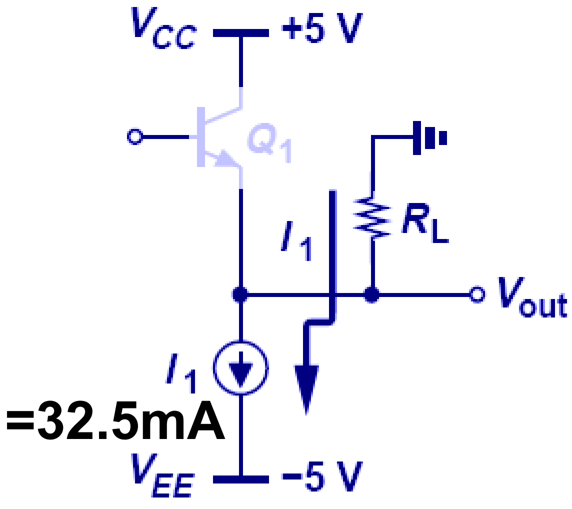
- **As $V_{in}$ increases $V_{out}$ also follows and $Q_1$ provides more current.**

- **If $V_{in}$ rises from 0.8 V to 4.8V, $V_{out}$=4.0V, $I_L$=500mA**

# Emitter Follower Large-Signal Behavior II



(c)



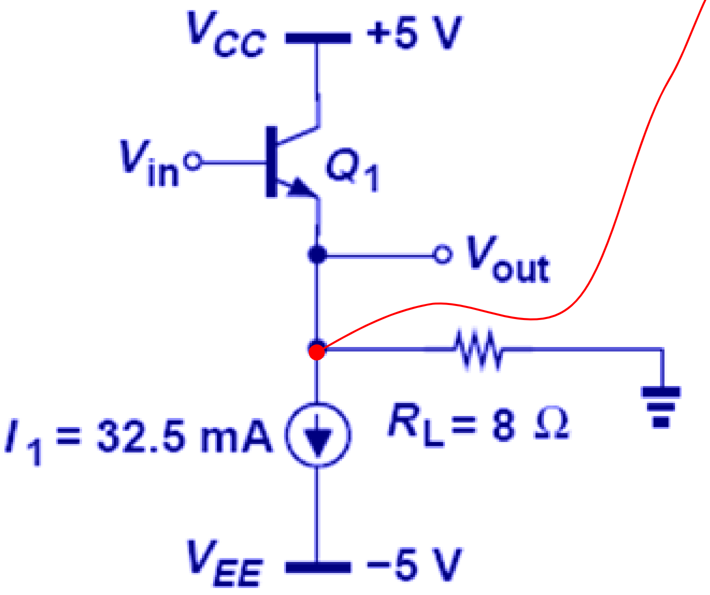
(d)

- **However, as $V_{in}$ decreases, $V_{out}$ also decreases, shutting off $Q_1$ and resulting in a constant $V_{out}$.**

- **For $V_{in}$=0.8V, $V_{out}$=0V, $I_L$=0mA, $I_{E1}$=32.5mA**
- **For $V_{in}$≈0.7V, $V_{out}$≈-0.1V, $I_L$=12.5mA, $I_{C1}$≈$I_{E1}$=20mA**
- **When all current (32.5mA) flows to the load, $V_{out}$=-0.26V**

# Example 13.1: Emitter Follower

- $V_{in}$=0.5V, $V_{out}$=?



By KCL

By KVL

$$V_{in} - V_{BE1} = V_{out}\ , \quad \frac{V_{out}}{R_L} + I_1 = I_{C1}$$

$$V_{BE1} = V_T \ln(I_{C1} / I_S)$$

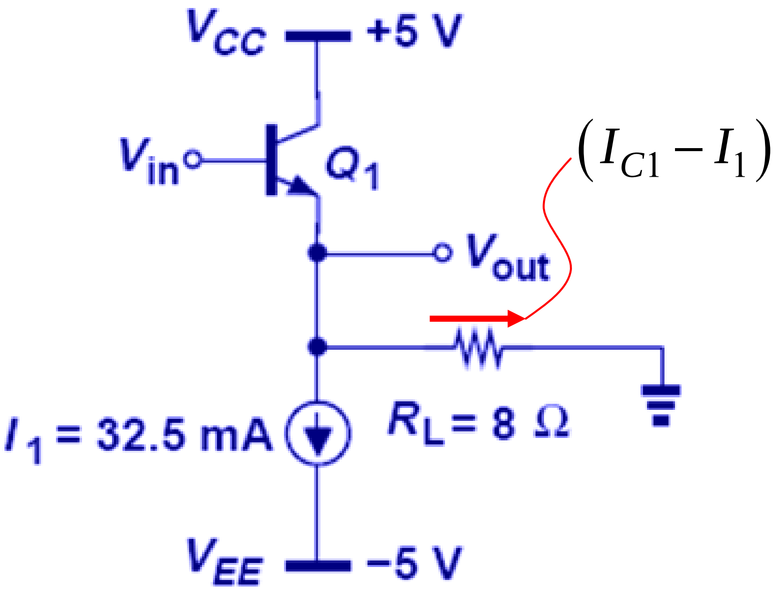
$$V_{in} - V_T \ln\left[\left(\frac{V_{out}}{R_L} + I_1\right)\frac{1}{I_S}\right] = V_{out}$$

For $V_{in} = 0.5\ V$

$\Rightarrow V_{out} \approx -211$ mV by a few iterations

# Example 13.1: Emitter Follower

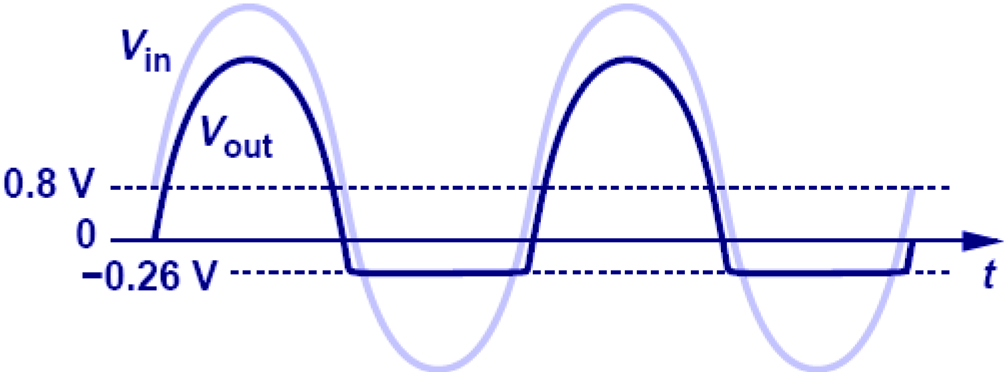
- **For what $V_{in}$, $Q_1$ carries only 1% of $I_1$?**



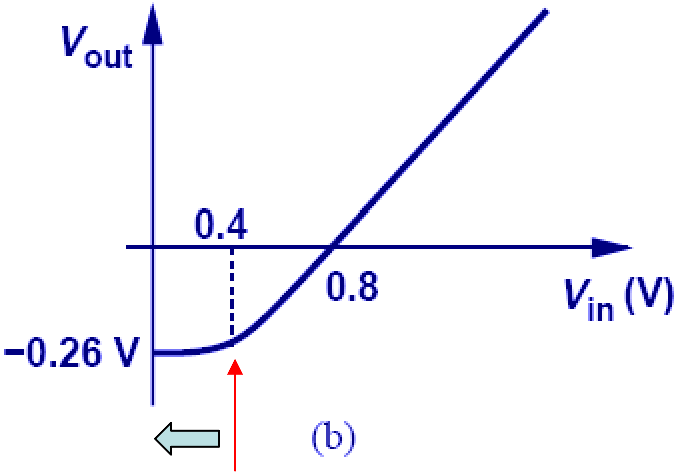
$$V_{in} = V_T \ln\frac{I_{C1}}{I_S} + \left(I_{C1} - I_1\right)R_L$$

$$\boxed{\begin{array}{l}\text{For } I_{C1} \approx 0.01 \cdot I_1 \\ \Rightarrow V_{in} \approx 390\ \text{mV}\end{array}}$$

# Linearity of an Emitter Follower



(a)

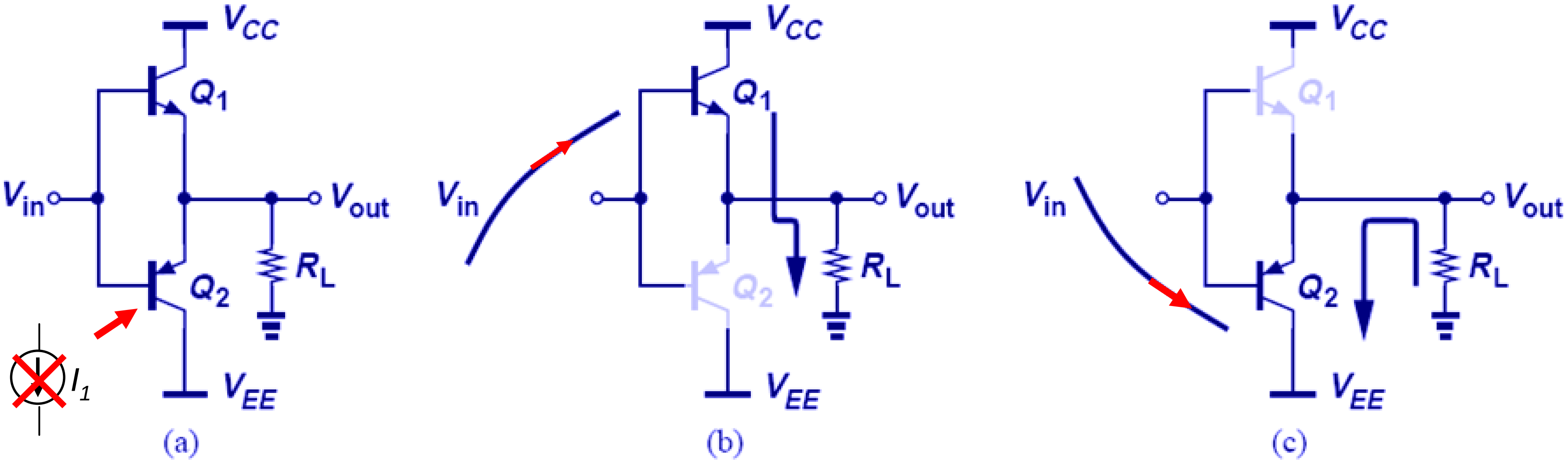


(b)

**Turn-off**

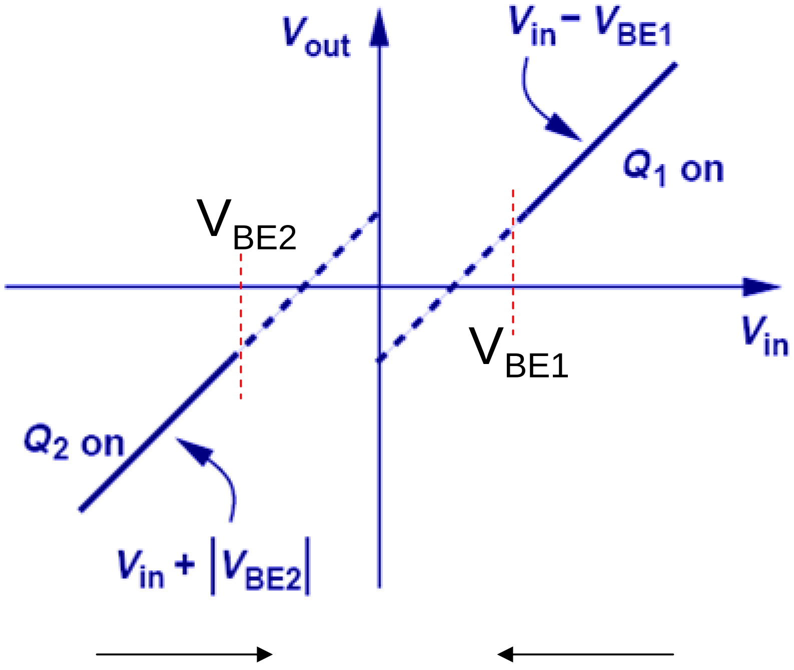
- **As $V_{in}$ decreases the output waveform will be clipped, introducing nonlinearity in I/O characteristics.**

# Push-Pull Stage



- As $V_{in}$ increases, $Q_1$ is on and pushes current into $R_L$.
- As $V_{in}$ decreases, $Q_2$ is on and pulls current out of $R_L$.

# Example 13.2: I/O Characteristics for Large $V_{in}$

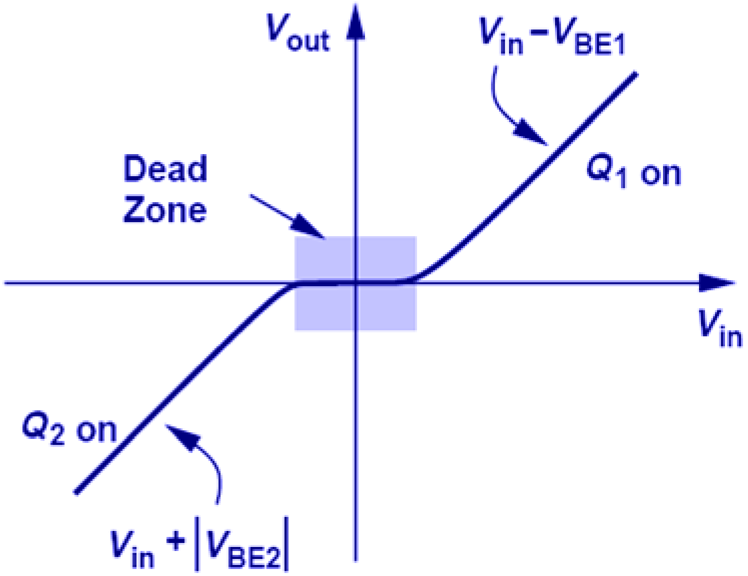


$V_{out} = V_{in} - V_{BE1}$ for large $+V_{in}$

$V_{out} = V_{in} + |V_{BE2}|$ for large $-V_{in}$

- **For positive $V_{in}$, $Q_1$ shifts the output down and for negative $V_{in}$, $Q_2$ shifts the output up.**

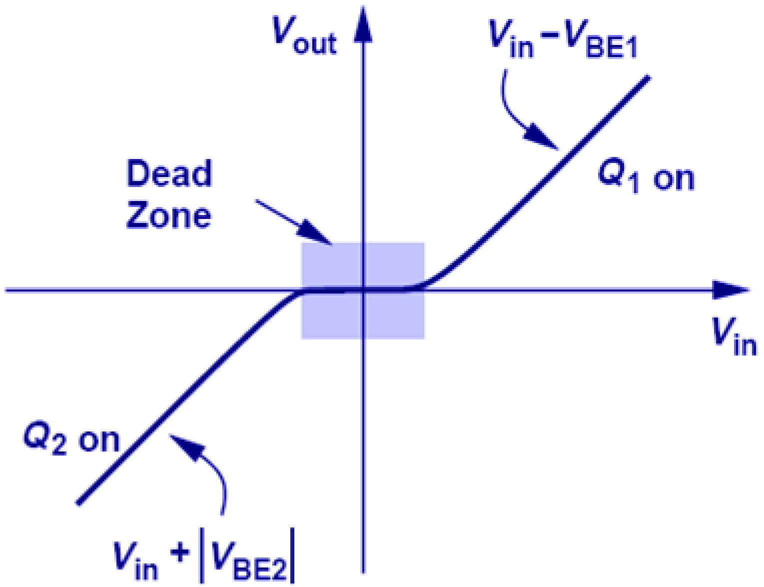
# Overall I/O Characteristics of Push-Pull Stage

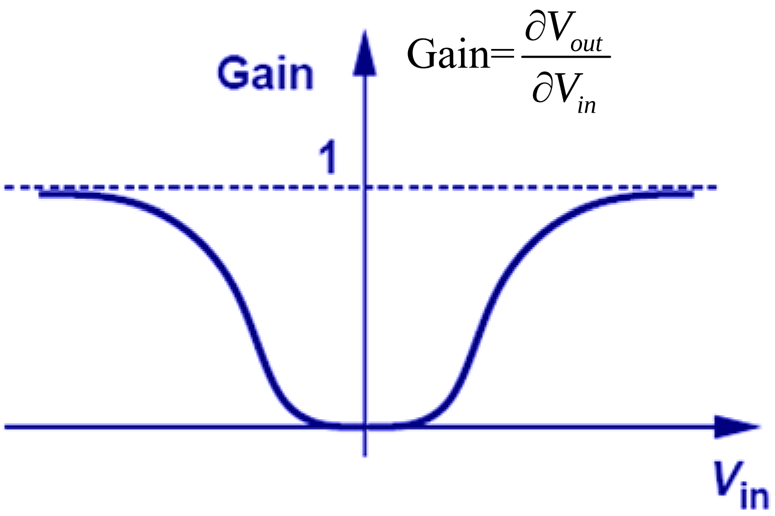


**At least $V_{BE} \approx 600 \sim 700$ mV before BJT turns on**

- **However, for small $V_{in}$, there is a "dead zone" (both $Q_1$ and $Q_2$ are off) in the I/O characteristic, resulting in gross nonlinearity.**

# Example 13.3: Small-Signal Gain of Push-Pull Stage

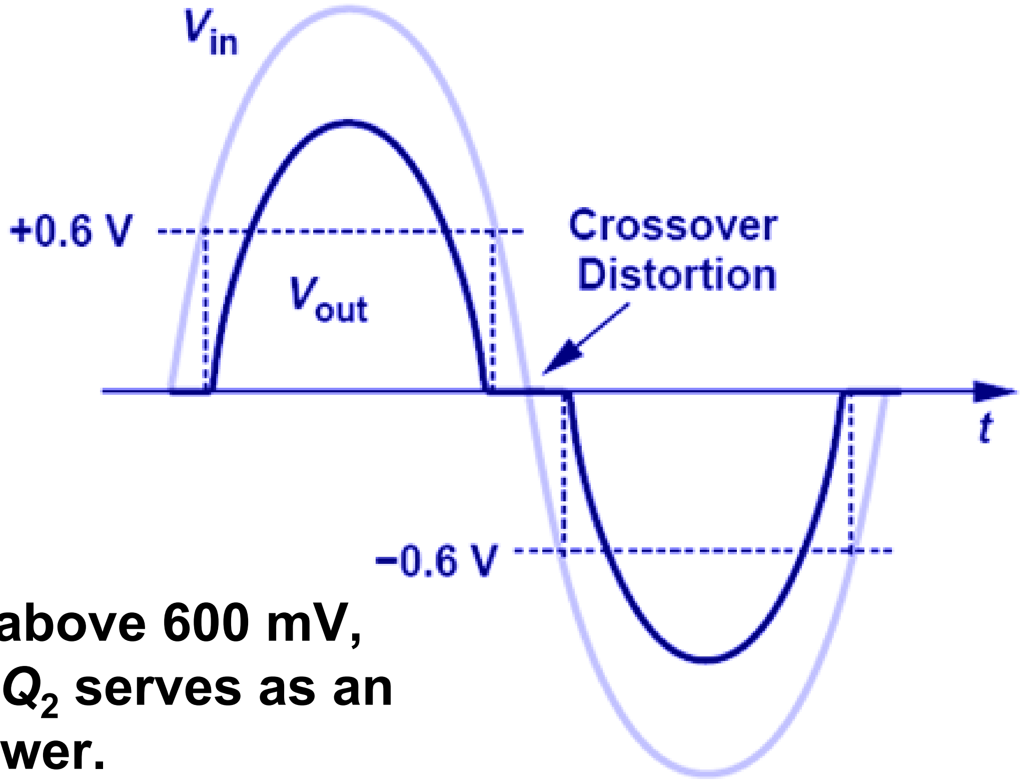




$$\text{Gain} = \frac{\partial V_{out}}{\partial V_{in}}$$

- The push-pull stage exhibits a gain that tends to unity when either $Q_1$ or $Q_2$ is on.
- When $V_{in}$ is very small, the gain drops to zero.

# Example 13.4: Sinusoidal Response of Push-Pull Stage

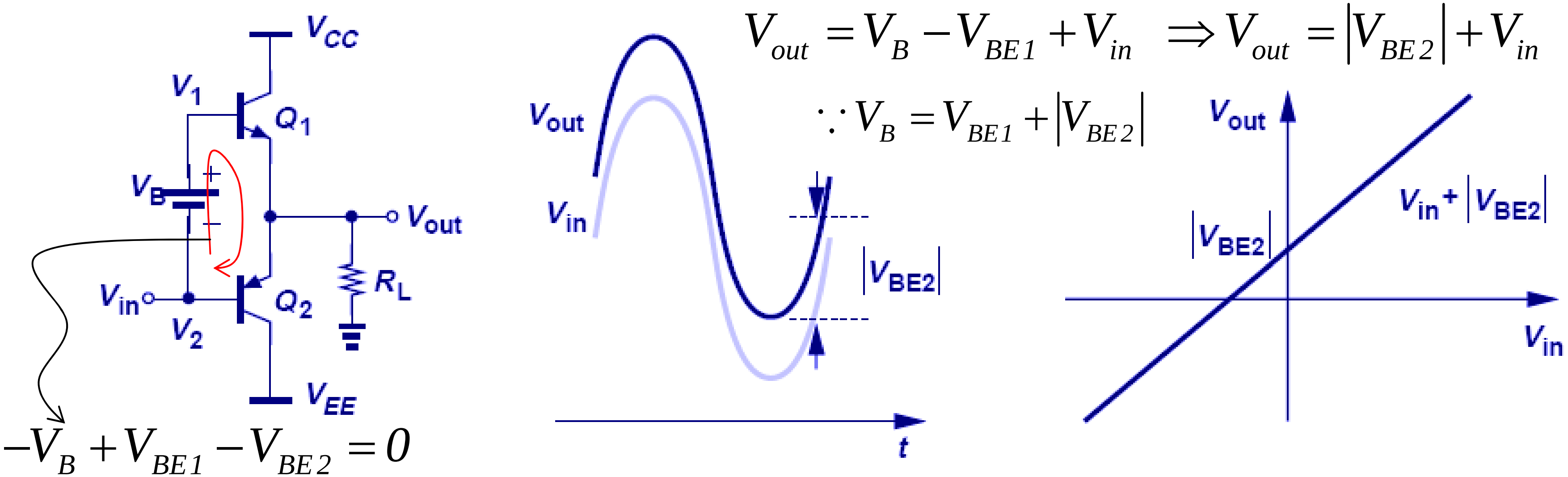


**For $V_{in}$ well above 600 mV, either $Q_1$ or $Q_2$ serves as an emitter follower.**

**Within the dead zone, $V_{out} \approx 0$ V**

- **For large $V_{in}$, the output follows the input with a fixed DC offset, however as $V_{in}$ becomes small the output drops to zero and causes "Crossover Distortion."**

# Improved Push-Pull Stage



$$V_{out} = V_B - V_{BE1} + V_{in} \Rightarrow V_{out} = |V_{BE2}| + V_{in}$$

$$\because V_B = V_{BE1} + |V_{BE2}|$$

$$-V_B + V_{BE1} - V_{BE2} = 0$$

(a) (b) (c)

**If $Q_1$ is to remain on, then $V_1 = V_{out} + V_{BE1}$**

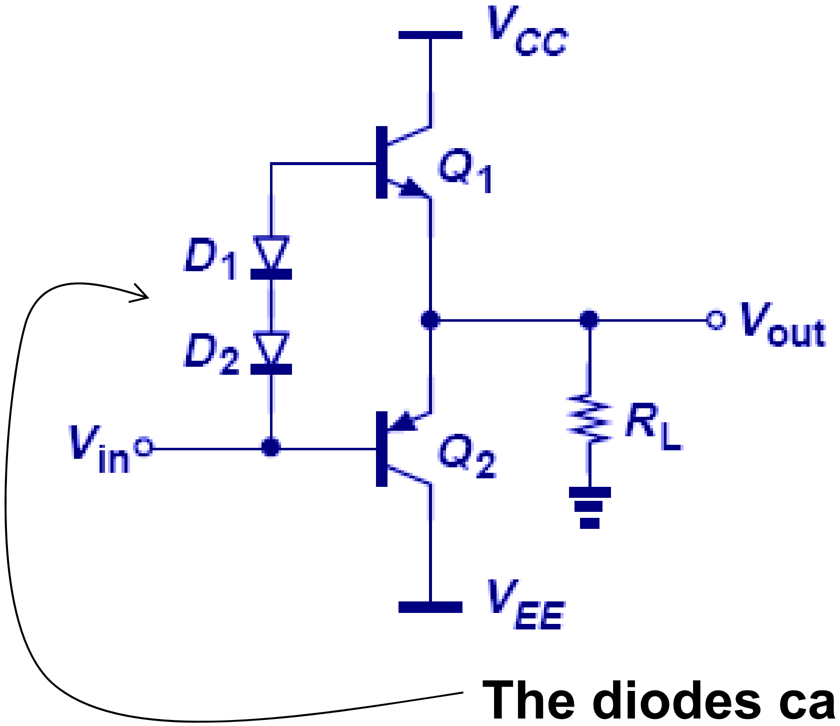
**If $Q_2$ is to remain on, then $V_2 = V_{out} - |V_{BE2}|$**

$$\begin{aligned} V_B &= V_1 - V_2 \\ &= V_{BE1} + |V_{BE2}| \end{aligned}$$

$$\boxed{V_B = V_{BE1} + |V_{BE2}|}$$

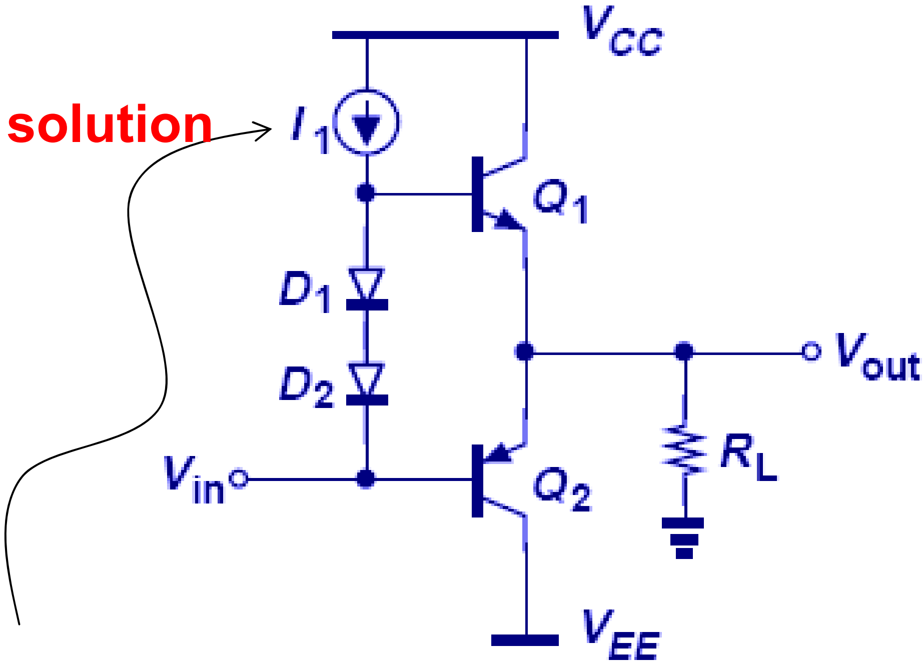
- **With a battery of $V_B$ inserted between the bases of $Q_1$ and $Q_2$, the dead zone is eliminated.**

# Implementation of $V_B$



(a)

The diodes carry no current, exhibiting a zero voltage drop

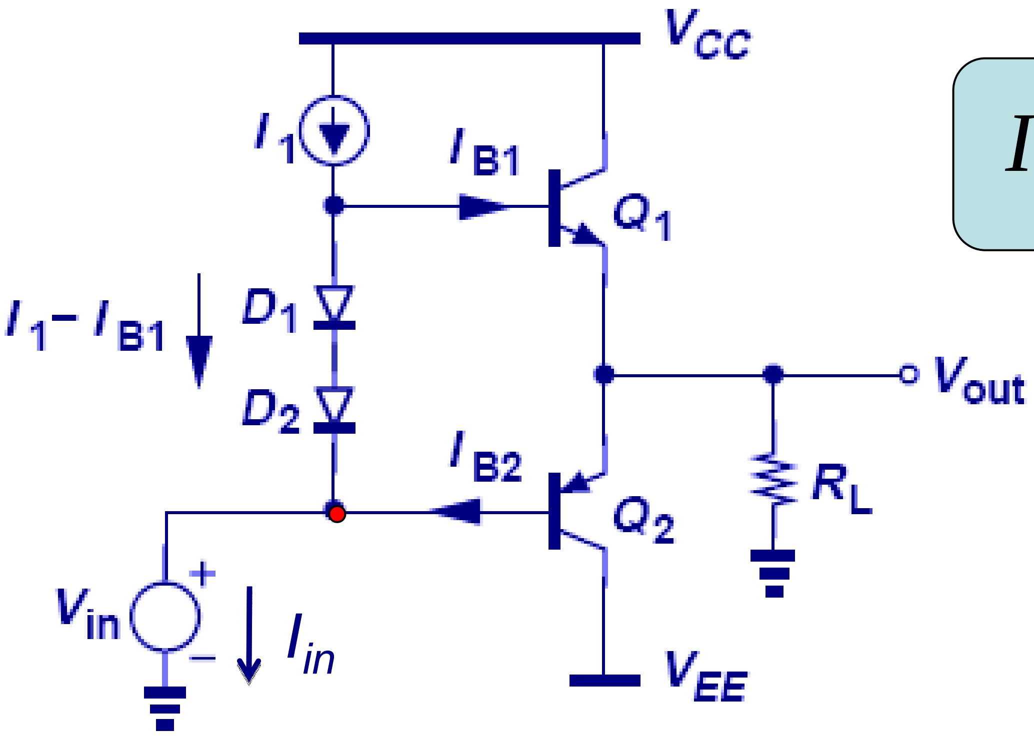


solution

(b)

- Since $V_B = V_{BE1} + |V_{BE2}|$, a natural choice would be two diodes in series.
- $I_1$ in figure (b) is used to bias the diodes and $Q_1$.

# Example 13.6: Current Flow I



$$I_{in} = I_1 - I_{B1} + \left| I_{B2} \right|$$

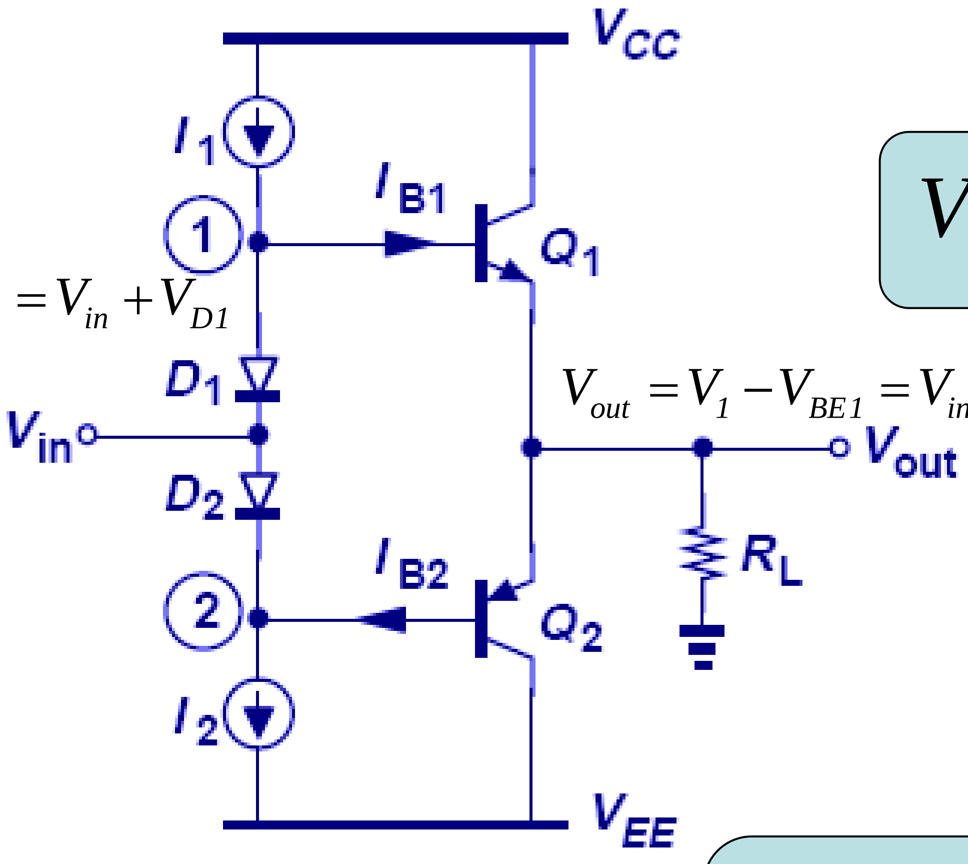
**When $V_{out}$ =0 V, $I_L$ through $R_L$ is 0. Then $I_{C1}$=|$I_{C2}$|**

if $\beta_1 = \beta_2,\ I_{B1} = \left| I_{B2} \right|$

Usually $I_{B1} \neq \left| I_{B2} \right|$ unless $V_{out} = 0$

$I_{in}$ flows even when $V_{out} = 0$.

# Example 13.8: Current Flow II



$$V_1 = V_{in} + V_{D1}$$

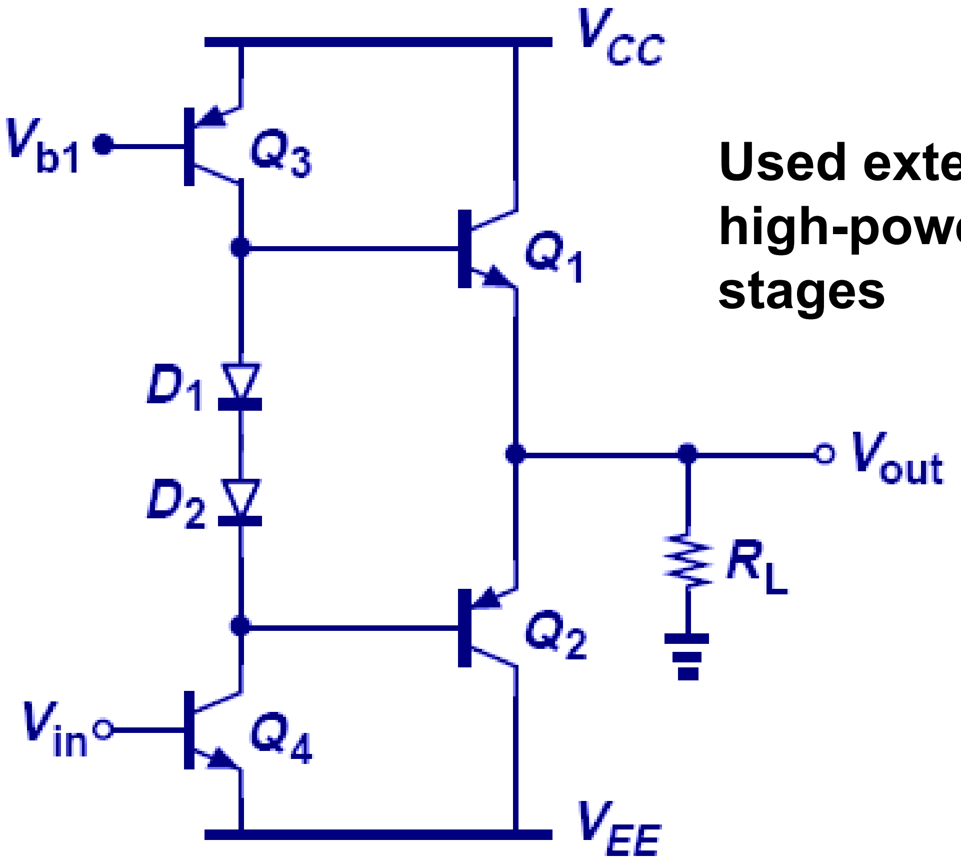
$$V_{out} = V_1 - V_{BE1} = V_{in} + V_{D1} - V_{BE1}$$

$$V_{D1} \approx V_{BE} \rightarrow \ V_{out} \approx V_{in}$$

$$I_{in} = 0 \text{ when } V_{out} = 0 \text{ if } I_1 = I_2$$

$$I_{B1} \approx I_{B2}$$

# Addition of CE Stage

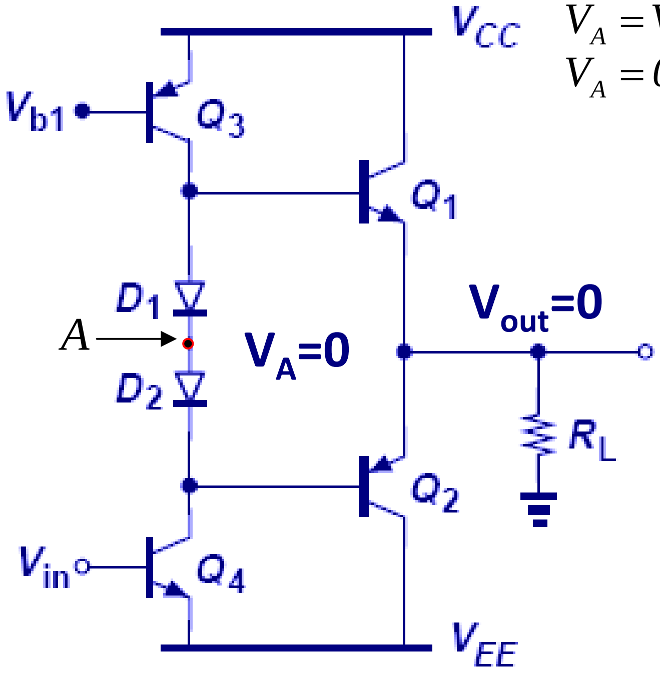


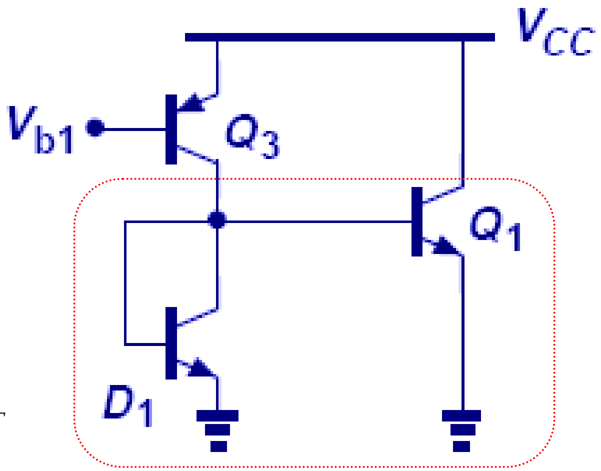
**Used extensively in high-power output stages**

- **A CE stage (predriver) is added to provide voltage gain from the input to the bases of $Q_1$ and $Q_2$.**

# Bias Point Analysis

$$-V_A - V_{D1} + V_{BE1} = 0$$
$$V_A = V_{BE1} - V_{D1}$$
$$V_A = 0 \text{ if } V_{BE1} = V_{D1}$$





Current mirror

$$|I_{C3}| = I_{S,D1} e^{V_{D1}/V_T}$$

$$V_{D1} = V_T \ln \frac{|I_{C3}|}{I_{S,D1}}$$

- For bias point analysis for $V_{out}$=0, the circuit can be simplified to the one on the right, which resembles a current mirror.

$$I_{C1} = \frac{I_{S,Q1}}{I_{S,D1}} \cdot |I_{C3}|$$

**Emitter size difference between *Q*$_1$ and *D*$_1$**

# Summary

- Need to understand large signal behavior of emitter follower.
- As $V_{in}$ decreases the output waveform will be clipped, introducing nonlinearity in I/O characteristics.

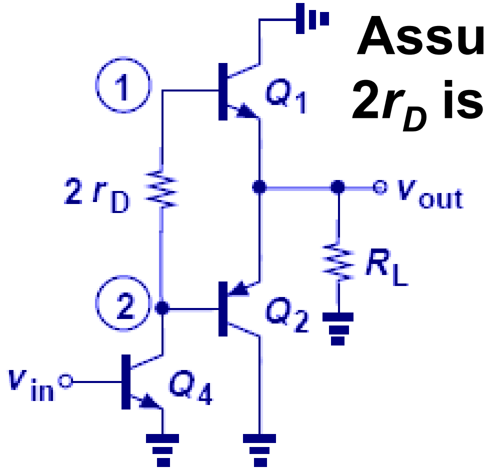
- Push-Pull stage could be a possible solution to solve the nonlinearity in emitter follower, but there is still nonlinearity due to dead zone near small $V_{in}$

- With a battery of $V_B$ inserted between the bases of $Q_1$ and $Q_2$, the dead zone is eliminated.

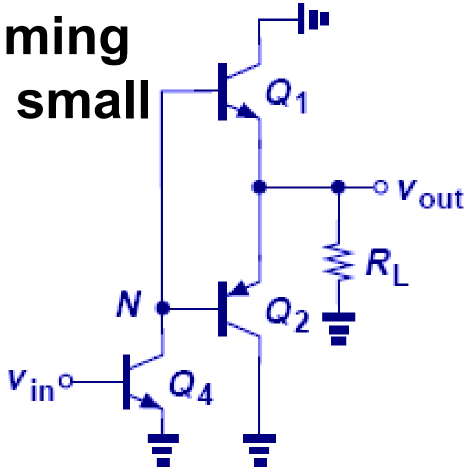
- Two diodes in series are used to implement the battery of $V_B$.

- A CE stage (predriver) is added to provide voltage gain from the input to the bases of $Q_1$ and $Q_2$.

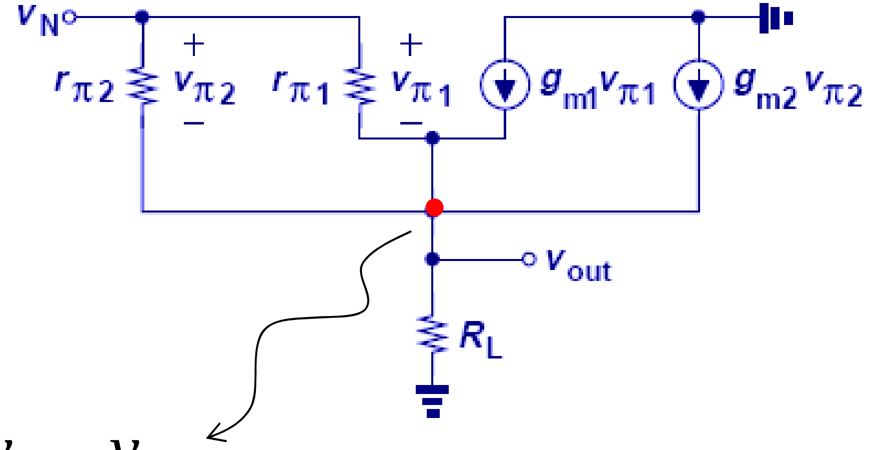
# Small-Signal Analysis



**Assuming $2r_D$ is small**



$$v_N - v_{out} = v_{\pi1} = v_{\pi2}$$



$$\frac{v_{out}}{R_L} = \frac{v_N - v_{out}}{r_{\pi1} \| r_{\pi2}} + \left(g_{m1} + g_{m2}\right)\left(v_N - v_{out}\right)$$

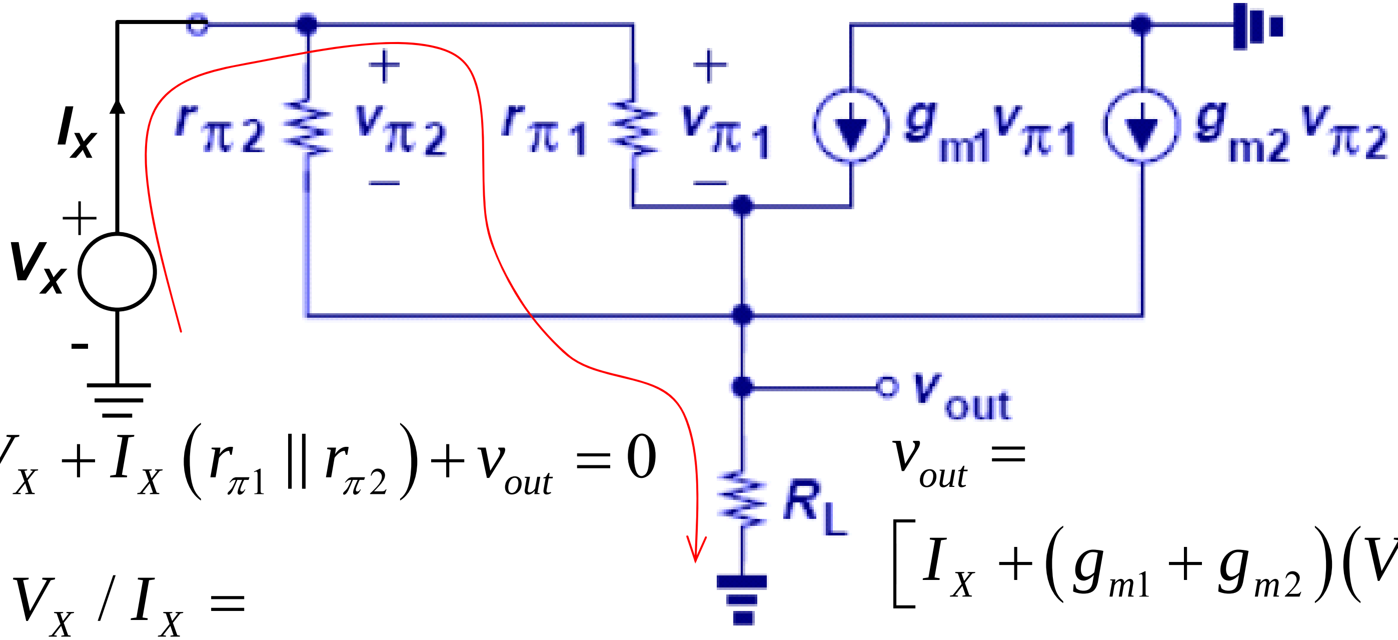
$$A_V = \frac{v_{out}}{v_{in}} = \frac{v_N}{v_{in}} \frac{v_{out}}{v_N}$$

$$\text{if } 1 + (g_{m1} + g_{m2})(r_{\pi1} \| r_{\pi2}) >> 1$$

$$\frac{v_{out}}{v_N} = \frac{R_L}{R_L + \dfrac{1}{g_{m1} + g_{m2}}}$$

**Emitter follower having a transconductance of $g_{m1}$+$g_{m2}$**

# Small-Signal Analysis



$$-V_X + I_X\left(r_{\pi 1} \parallel r_{\pi 2}\right) + v_{out} = 0$$

$$v_{out} = \left[I_X + \left(g_{m1} + g_{m2}\right)\left(V_X - v_{out}\right)\right]R_L$$

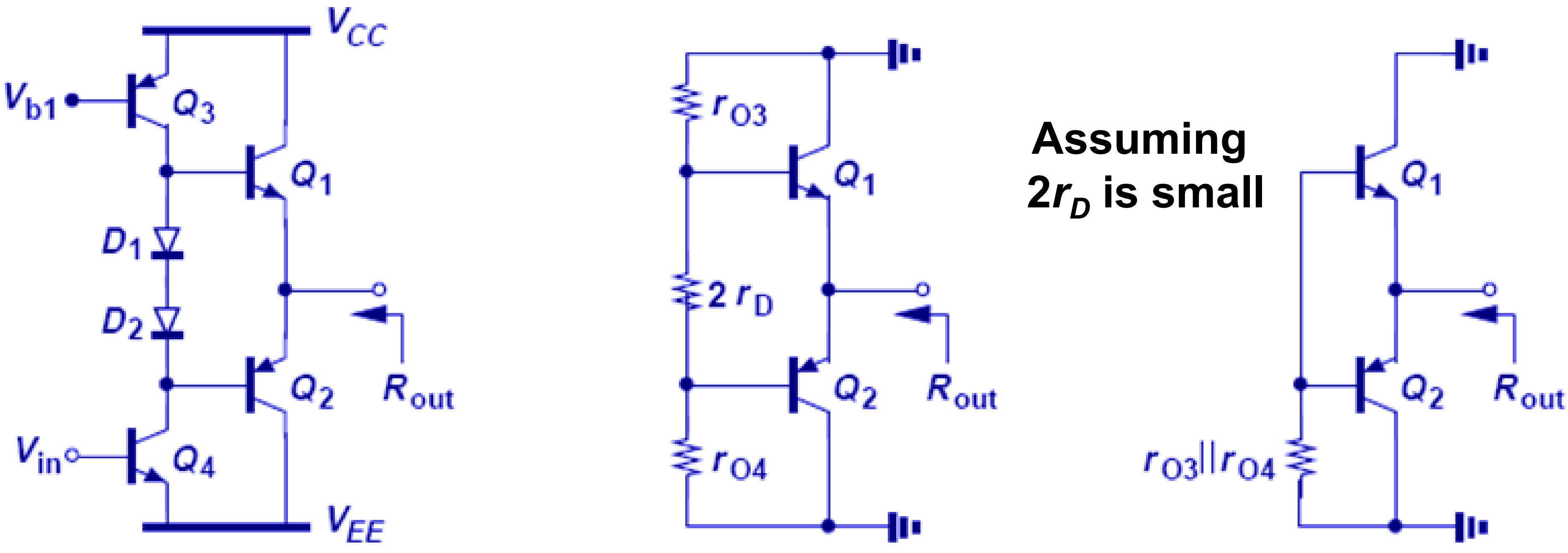
$$V_X / I_X =$$

$$R_N = \left(g_{m1} + g_{m2}\right)\left(r_{\pi 1} \parallel r_{\pi 2}\right)R_L + r_{\pi 1} \parallel r_{\pi 2}$$

$$\frac{v_{out}}{v_{in}} = -g_{m4}\left[\left(g_{m1} + g_{m2}\right)\left(r_{\pi 1} \parallel r_{\pi 2}\right)R_L + r_{\pi 1} \parallel r_{\pi 2}\right]\frac{R_L}{R_L + \dfrac{1}{g_{m1} + g_{m2}}}$$

$$\boxed{A_v = -g_{m4}\left(r_{\pi 1} \parallel r_{\pi 2}\right)\left(g_{m1} + g_{m2}\right)R_L} \quad \text{if } R_L\left(g_{m1} + g_{m2}\right) >> 1$$

# Example 13.9: Output Resistance Analysis

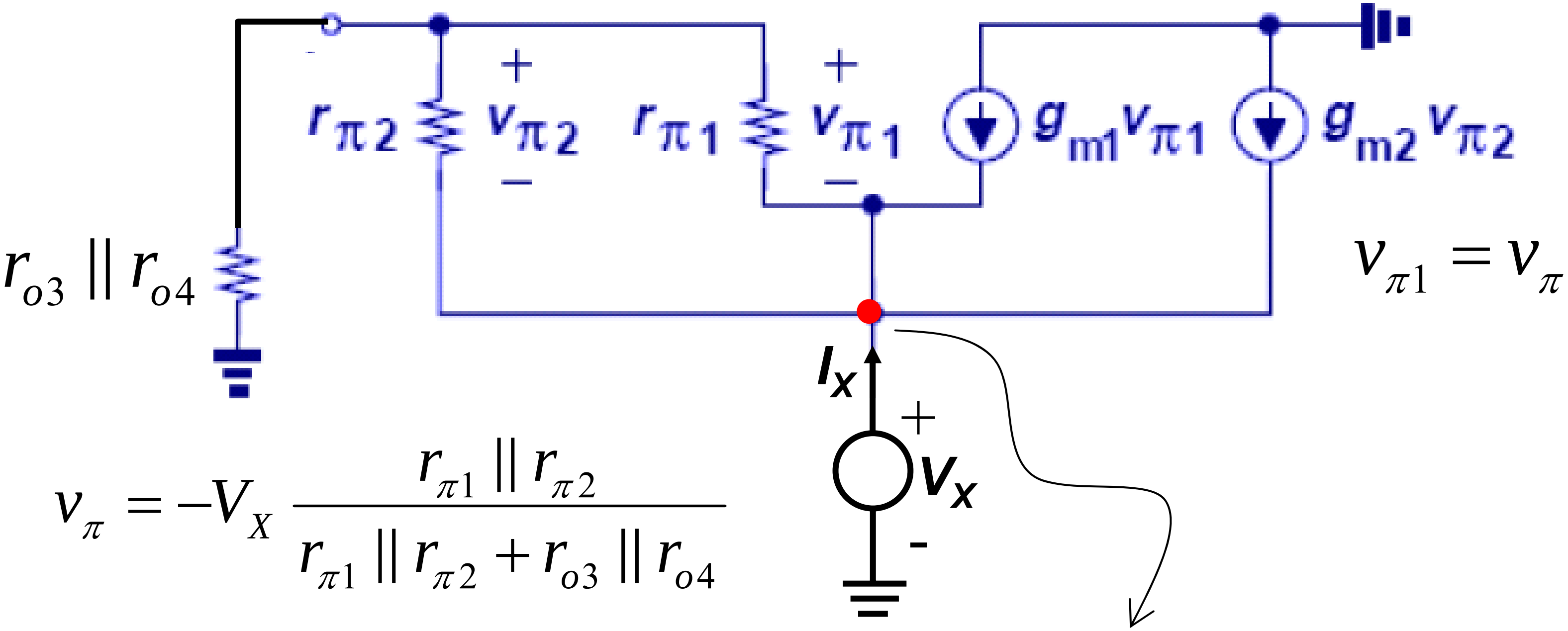


**Assuming $2r_D$ is small**

$$R_{out} \approx \frac{1}{g_{m1}+g_{m2}} + \frac{r_{O3} \,||\, r_{O4}}{(g_{m1}+g_{m2})(r_{\pi 1} \,||\, r_{\pi 2})}$$

- **If β is low, the second term of the output resistance will rise, which will be problematic when driving a small resistance.**

# Example 13.9: Output Resistance Analysis



$$v_{\pi 1} = v_{\pi 2}$$

$$v_\pi = -V_X \frac{r_{\pi 1} \| r_{\pi 2}}{r_{\pi 1} \| r_{\pi 2} + r_{o3} \| r_{o4}}$$

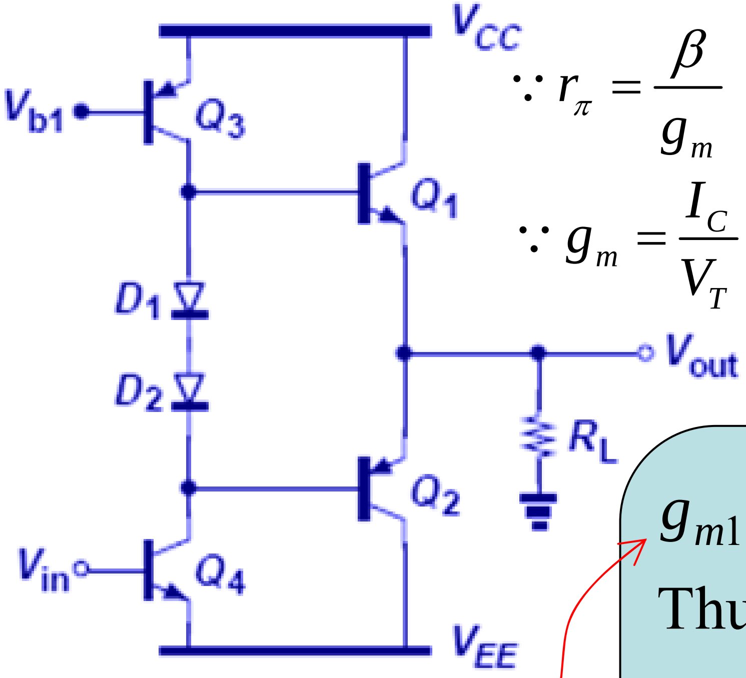
$$I_X = \frac{V_X}{r_{\pi 1} \| r_{\pi 2} + r_{o3} \| r_{o4}} + \left(g_{m1} + g_{m2}\right) V_X \frac{r_{\pi 1} \| r_{\pi 2}}{r_{\pi 1} \| r_{\pi 2} + r_{o3} \| r_{o4}}$$

$$\frac{V_X}{I_X} = \frac{r_{\pi 1} \| r_{\pi 2} + r_{o3} \| r_{o4}}{1 + \left(g_{m1} + g_{m2}\right)\left(r_{\pi 1} \| r_{\pi 2}\right)}$$

if $\left(g_{m1} + g_{m2}\right)\left(r_{\pi 1} \| r_{\pi 2}\right) >> 1$ $\quad R_{out} \approx \frac{1}{g_{m1} + g_{m2}} + \frac{r_{O3} \| r_{O4}}{(g_{m1} + g_{m2})(r_{\pi 1} \| r_{\pi 2})}$

# Example13.10: Biasing

- **Compute the required bias current.**



$$\because r_\pi = \frac{\beta}{g_m}$$

$$\because g_m = \frac{I_C}{V_T}$$

Predriver (CE stage): $A_V = 5$

Output Stage: $A_V = 0.8$ for $R_L = 8\ \Omega$

$\beta_{npn} = 2\beta_{pnp} = 100,\ I_{C1} \approx I_{C2}$

$$0.8 = \frac{8}{8 + \dfrac{1}{g_{m1} + g_{m2}}}$$

$g_{m1} + g_{m2} = (2\ \Omega)^{-1} \Rightarrow g_{m1} \approx g_{m2} \approx (4\ \Omega)^{-1}$

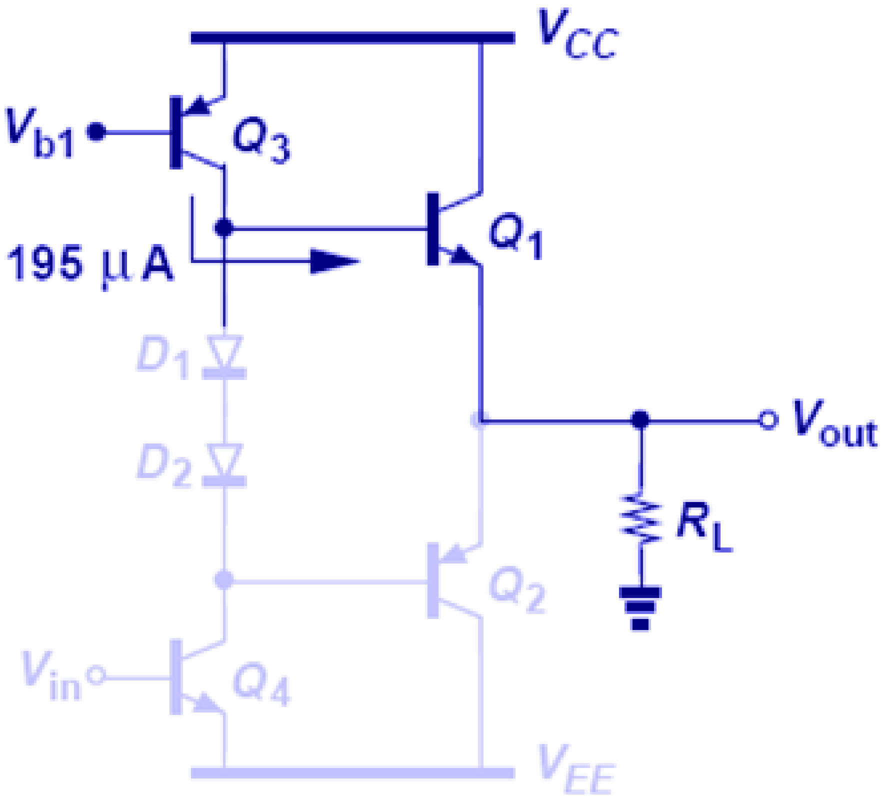
Thus, $I_{C1} \approx I_{C2} \approx 6.5$ mA

$r_{\pi1} \| r_{\pi2} = 400\ \Omega \| 200\ \Omega = 133\ \Omega$

$g_{m4} \cdot (r_{\pi1} \| r_{\pi2}) \cdot \left[1 + (g_{m1} + g_{m2}) \cdot R_L\right] = 4$

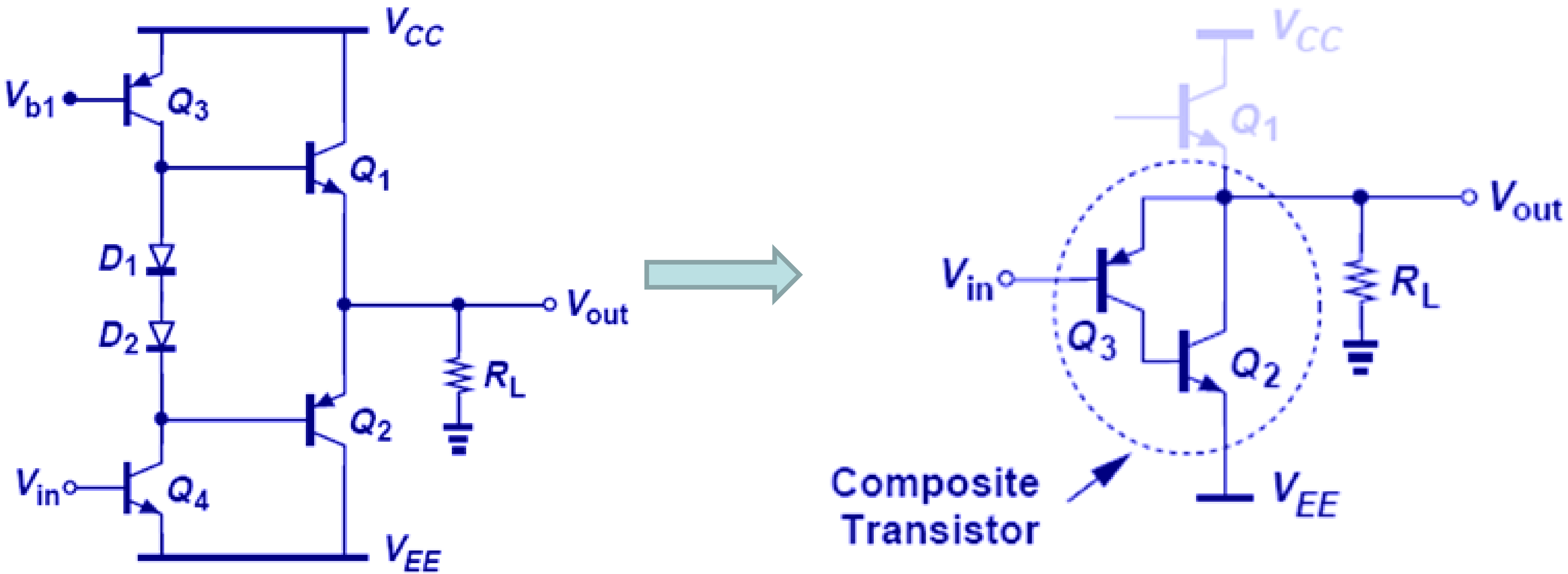
$\Rightarrow g_{m4} = (133\ \Omega)^{-1} \Rightarrow I_{C3} \approx I_{C4} \approx 195\ \mu\text{A}$

# Problem of Base Current



- **195 μA of base current in $Q_1$ can only support 19.5 mA of collector current, insufficient for high current operation (500 mA for 4 V on 8 Ω).**

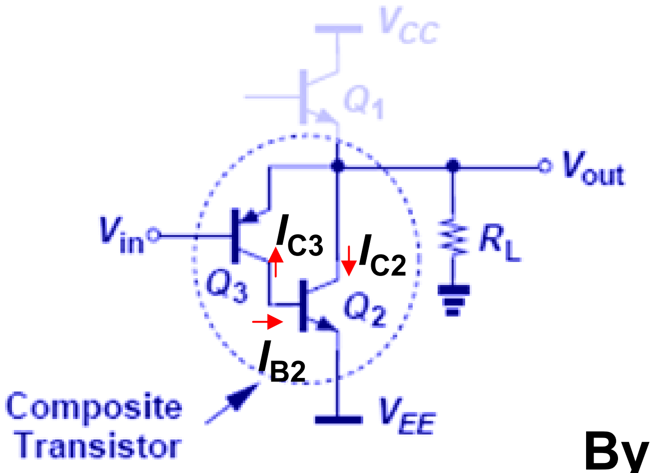
# Modification of the PNP Emitter Follower



$$R_{out} \approx \frac{1}{(\beta_2 + 1) g_{m3}}$$

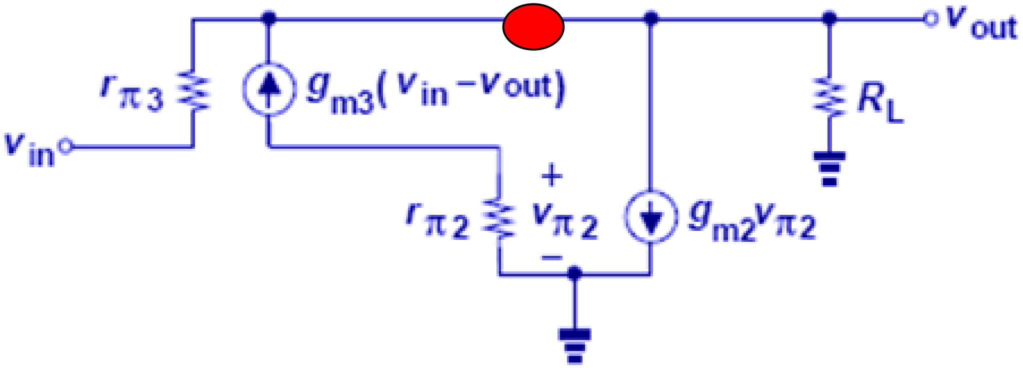
- Instead of having a single PNP as the emitter-follower, it is now combined with an NPN ($Q_2$), providing a lower output resistance.

# Gain



$$I_{C2} = \beta_2 I_{B2} = -\beta_2 I_{C3}$$

$$g_{m2} v_{\pi 2} = -\beta_2 g_{m3} \left( v_{in} - v_{out} \right)$$



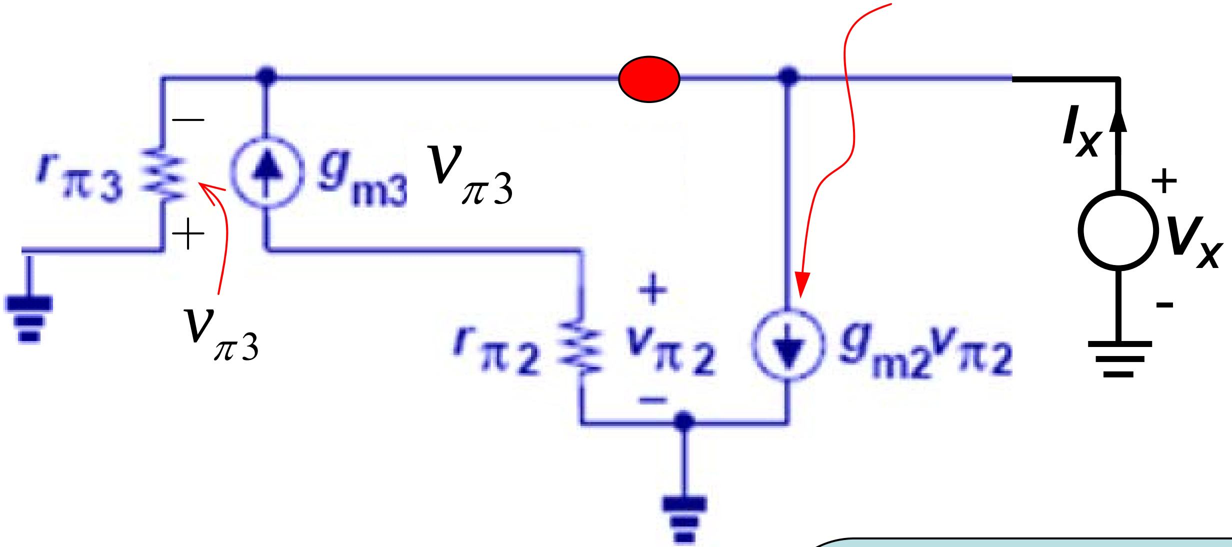
**By KCL**

$$-g_{m3} \left( v_{in} - v_{out} \right) \beta_2 + \frac{v_{out} - v_{in}}{r_{\pi 3}} - g_{m3} \left( v_{in} - v_{out} \right) = -\frac{v_{out}}{R_L}$$

$$\boxed{\frac{v_{out}}{v_{in}} = \frac{R_L}{R_L + \cfrac{1}{\left( \beta_2 + 1 \right) g_{m3} + \cfrac{1}{r_{\pi 3}}}}}$$

# Output Resistance

$$g_{m2}v_{\pi 2} = -\beta_2 g_{m3}\left(v_{in} - v_{out}\right)$$



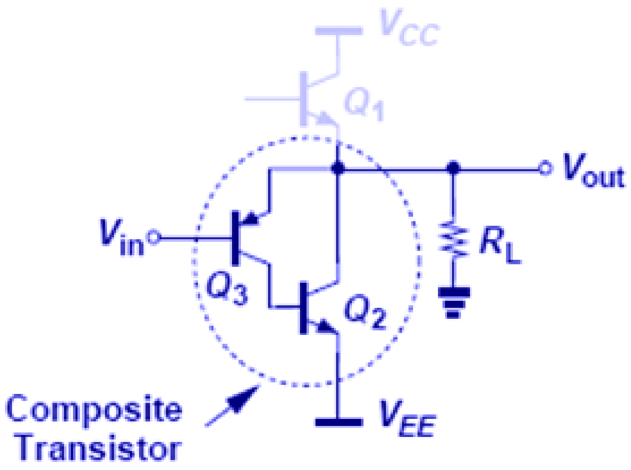
**By KCL**

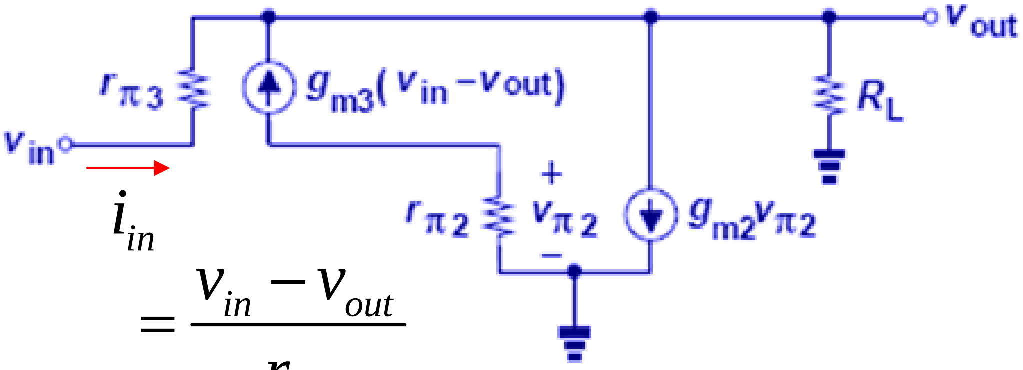
$$-I_X + \frac{V_X}{r_{\pi 3}} + g_{m3}V_X + \beta_2 g_{m3}V_X = 0$$

Comparing with the standard EF,

$$r_{out} = \frac{1}{\left(\beta_2 + 1\right)g_{m3} + \dfrac{1}{r_{\pi 3}}} \approx \frac{1}{\left(\beta_2 + 1\right)g_{m3}}$$

# Example 13.11: Input Resistance



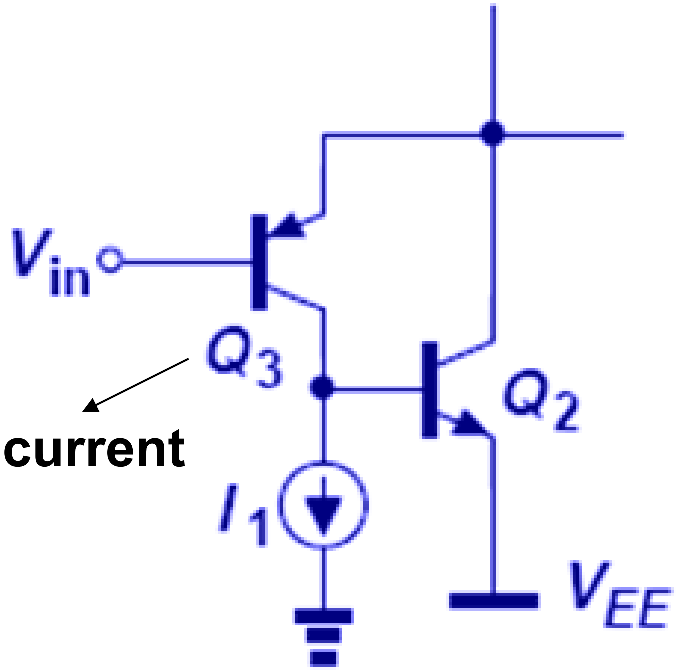


$$i_{in} = \frac{v_{in} - v_{out}}{r_{\pi 3}}$$

$$i_{in} = \frac{1}{r_{\pi 3}}\left( v_{in} - v_{in}\frac{R_L}{R_L + \frac{1}{(\beta_2 + 1) g_{m3}}}\right)$$

$$r_{in} = \beta_3(\beta_2 + 1)R_L + r_{\pi 3}$$

# Additional Bias Current

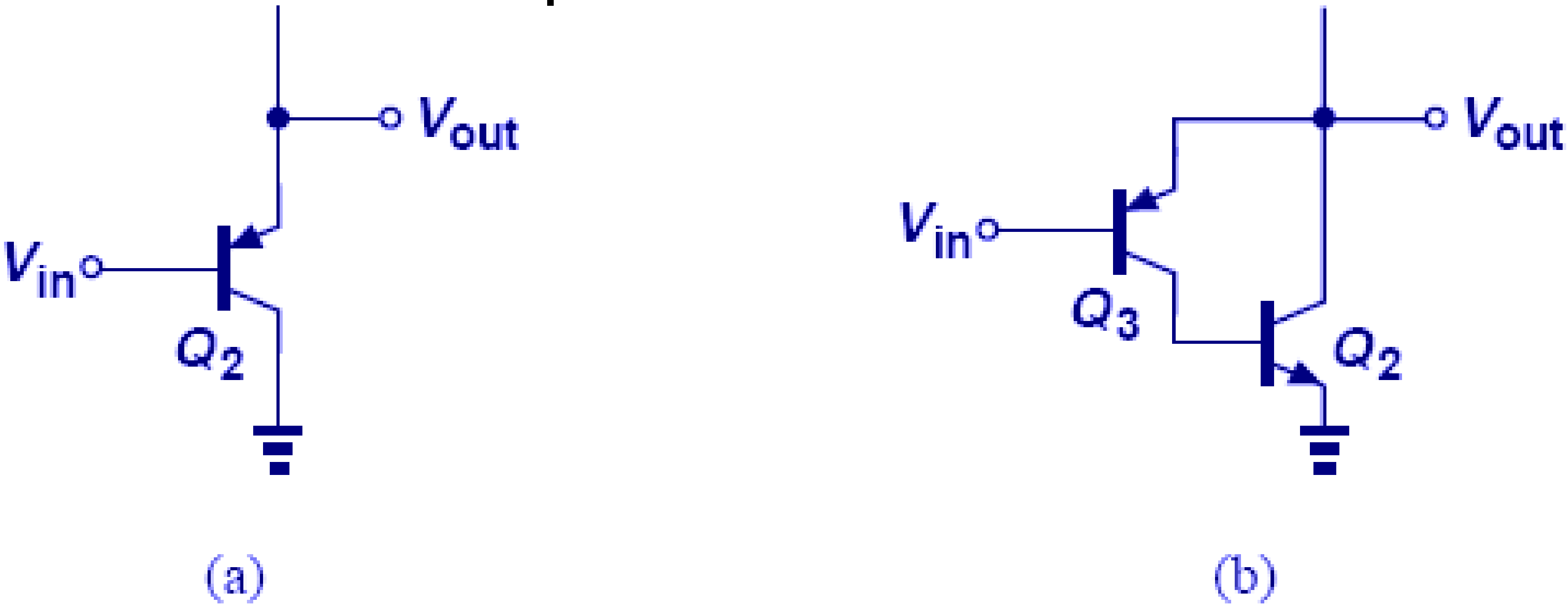


carries a small current

- $I_1$ is added to the base of $Q_2$ to provide an additional bias current to $Q_3$ so the capacitance at the base of $Q_2$ can be charged/discharged quickly. Additional pole at the base of $Q_2$.

# Example 13.12: Minimum $V_{in}$

**Requirement: no saturation**



$$Min\, V_{in} \approx 0$$

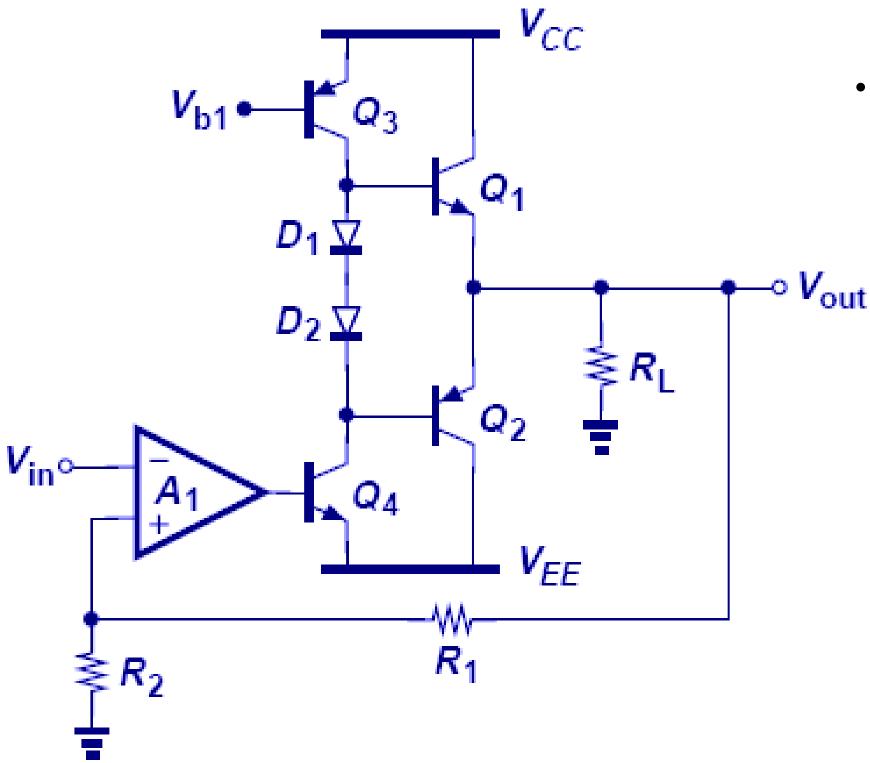
$$V_{out} \approx |V_{EB2}|$$

$$Min\, V_{in} \approx V_{BE2}$$

$$V_{out} \approx |V_{EB3}| + V_{BE2}$$

# HiFi Design

$$\because g_m = \frac{I_C}{V_T}$$

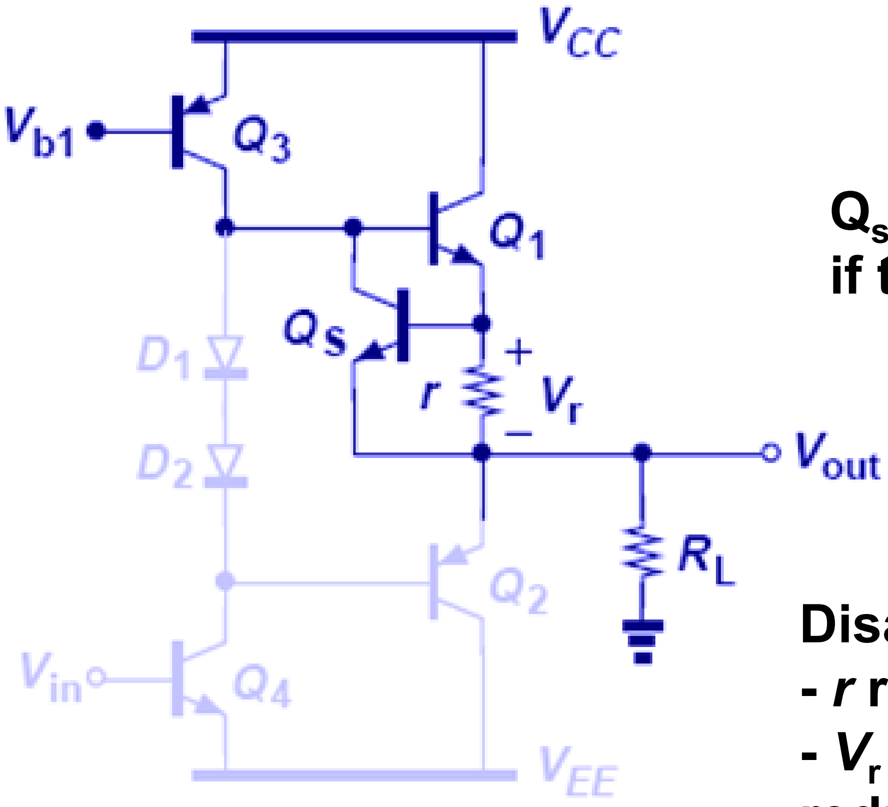


$$\because \frac{v_{out}}{v_N} = \frac{R_L}{R_L + \frac{1}{g_{m1} + g_{m2}}}$$

$$\because \frac{V_{out}}{V_{in}} \approx 1 + \frac{R_1}{R_2}$$

- As $V_{out}$ becomes more positive, $g_m$ rises and $A_v$ comes closer to unity, resulting in nonlinearity.
- Using negative feedback, linearity is improved, providing higher fidelity.

# Short-Circuit Protection



*r*: small resistance

$Q_s$ reduces the base drive of $Q_1$ if the current exceeds a certain level

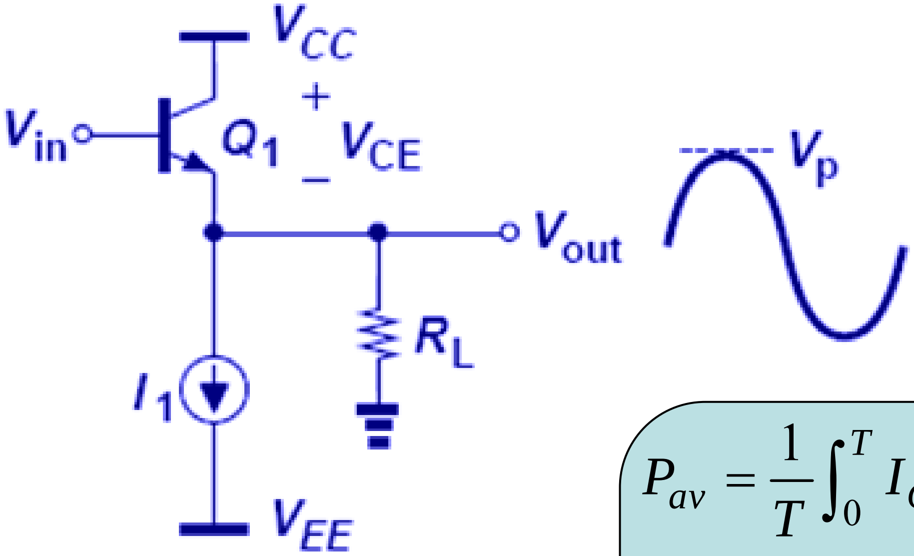
$$V_r \to 0.7\ \text{V}$$

**Disadvantages:**

- *r* raises the output impedance
- $V_r$ under normal operating condition reduces the maximum output swing

➢ $Q_s$ and r are used to "steal" some base current away from $Q_1$ when the output is accidentally shorted to ground, preventing short-circuit damage.

# Emitter Follower Power Rating



$$\sin^2 \omega t = \left(1 - \cos 2\omega t\right)/2$$

$$P_{av} = \frac{1}{T}\int_0^T I_C \cdot V_{CE}\,dt$$

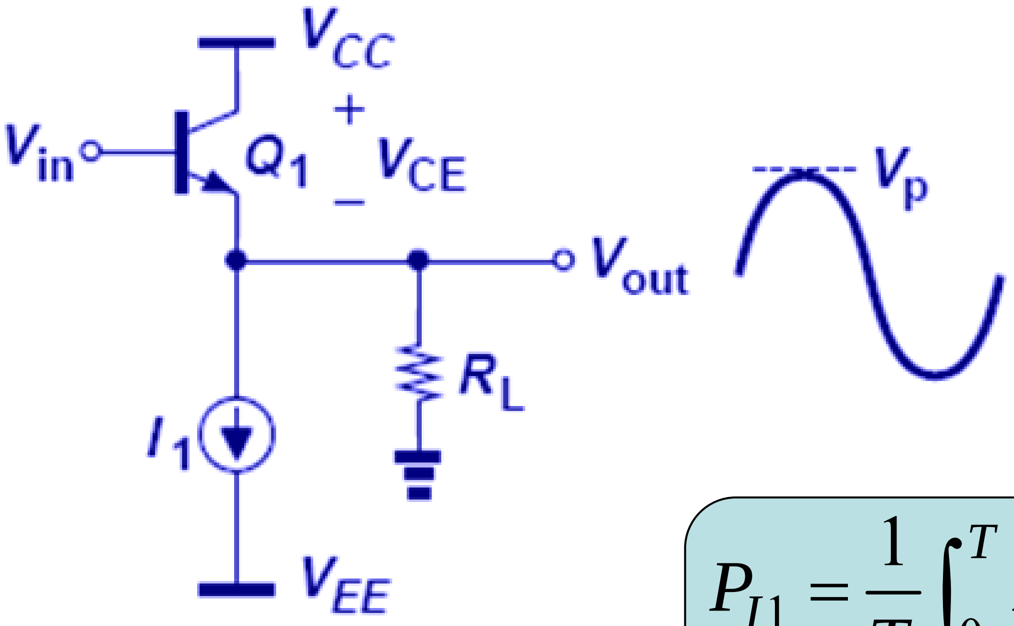
$$= \frac{1}{T}\int_0^T \left(I_1 + \frac{V_P \sin \omega t}{R_L}\right)\cdot\left(V_{CC} - V_P \sin \omega t\right)dt$$

$$= I_1 \cdot V_{CC} - \frac{{V_P}^2}{R_L} = I_1\left(V_{CC} - \frac{V_P}{2}\right) \text{ if } I_1 = \frac{V_P}{R_L}$$

- **Maximum power dissipated across $Q_1$ occurs in the *absence* of a signal, i.e. with $V_p$=0: $P_{av,max}=I_1V_{CC}$**

# Example 13.13: Power Dissipation

- **Avg Power Dissipated in the Current Source $I_1$**



$$P_{I1} = \frac{1}{T}\int_0^T I_1\left(V_p \sin \omega t - V_{EE}\right)dt$$
$$= -I_1 \cdot V_{EE}$$

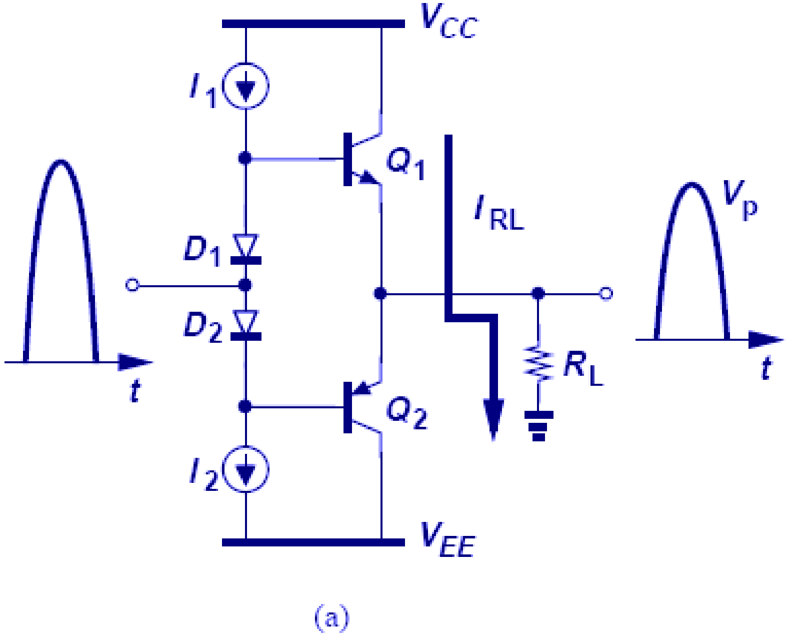
# Push-Pull Stage Power Rating

$$\cos 2\omega t = \sin^2 \omega t - \cos^2 \omega t$$

$$\cos^2 \omega t = 1 - \sin^2 \omega t$$

$$\sin^2 \omega t = \left(1 - \cos 2\omega t\right)/2$$

$$\int_0^{T/2} \cos 2\omega t dt = 0$$



$$P_{av,NPN} = \frac{1}{T}\int_0^{T/2} I_C \cdot V_{CE} dt$$

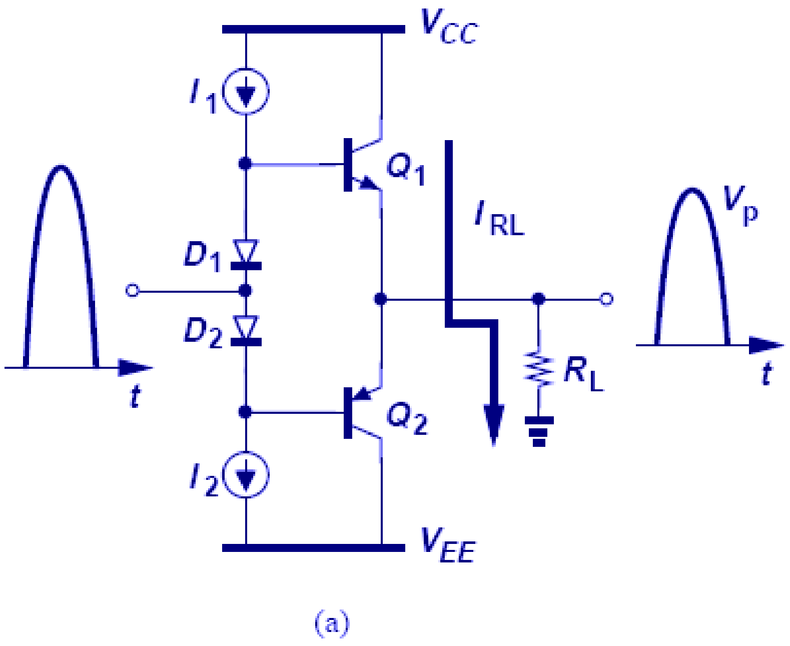
$$= \frac{1}{T}\int_0^{T/2} \left(V_{CC} - V_P \sin \omega t\right) \cdot \frac{V_P \sin \omega t}{R_L} dt$$

$$= \frac{V_{CC} \cdot V_P}{\pi R_L} - \frac{V_P{}^2}{4R_L} = \frac{V_P}{R_L}\left(\frac{V_{CC}}{\pi} - \frac{V_P}{4}\right)$$

**For $V_p \approx 0$ or $V_p \approx 4V_{CC}/\pi$, the power dissipated in $Q_1$ approaches zero**

- **No power for half of the period.**

# Push-Pull Stage Power Rating



(a)

$$P_{av,NPN}=\frac{1}{T}\int_0^{T/2} I_C\cdot V_{CE}\,dt$$

$$=\frac{1}{T}\int_0^{T/2}\left(V_{CC}-V_P\sin\omega t\right)\cdot\frac{V_P\sin\omega t}{R_L}dt$$

$$=\frac{V_{CC}\cdot V_P}{\pi R_L}-\frac{V_P{}^2}{4R_L}=\frac{V_P}{R_L}\left(\frac{V_{CC}}{\pi}-\frac{V_P}{4}\right)$$

- No power for half of the period.
- Maximum power occurs between $V_p$=0 and $4V_{cc}/\pi$.

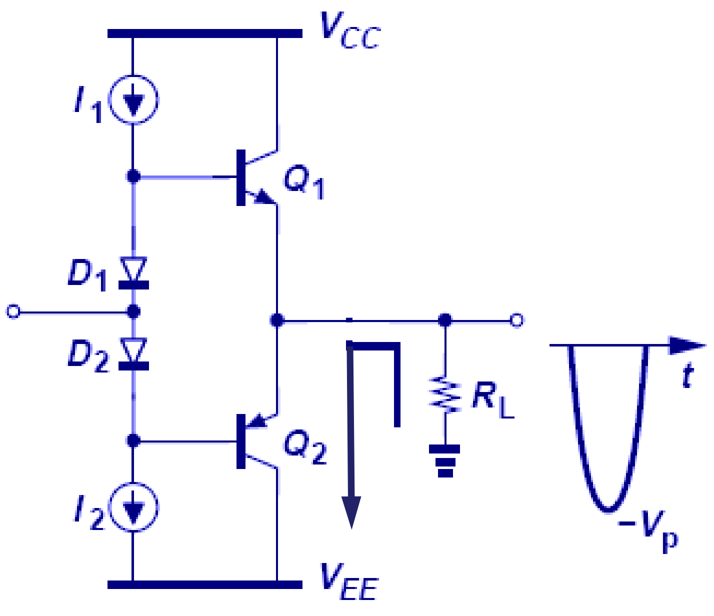
$$P_{av,\max}=\frac{V_{CC}{}^2\cdot V_P}{\pi^2 R_L}\ \text{when}\ V_P=2\cdot\frac{V_{CC}}{\pi}$$

# Push-Pull Stage Power Rating

$$P_{av,PNP} = \frac{1}{T}\int_{T/2}^{T} |I_C|\cdot|V_{CE}|\,dt$$

$$= \frac{1}{T}\int_{T/2}^{T}(V_P\sin\omega t - V_{EE})\cdot\left(-\frac{V_P\sin\omega t}{R_L}\right)dt$$

$$= \frac{-V_{EE}\cdot V_P}{\pi R_L} - \frac{{V_P}^2}{4R_L} = \frac{V_P}{R_L}\left(\frac{-V_{EE}}{\pi} - \frac{V_P}{4}\right)$$

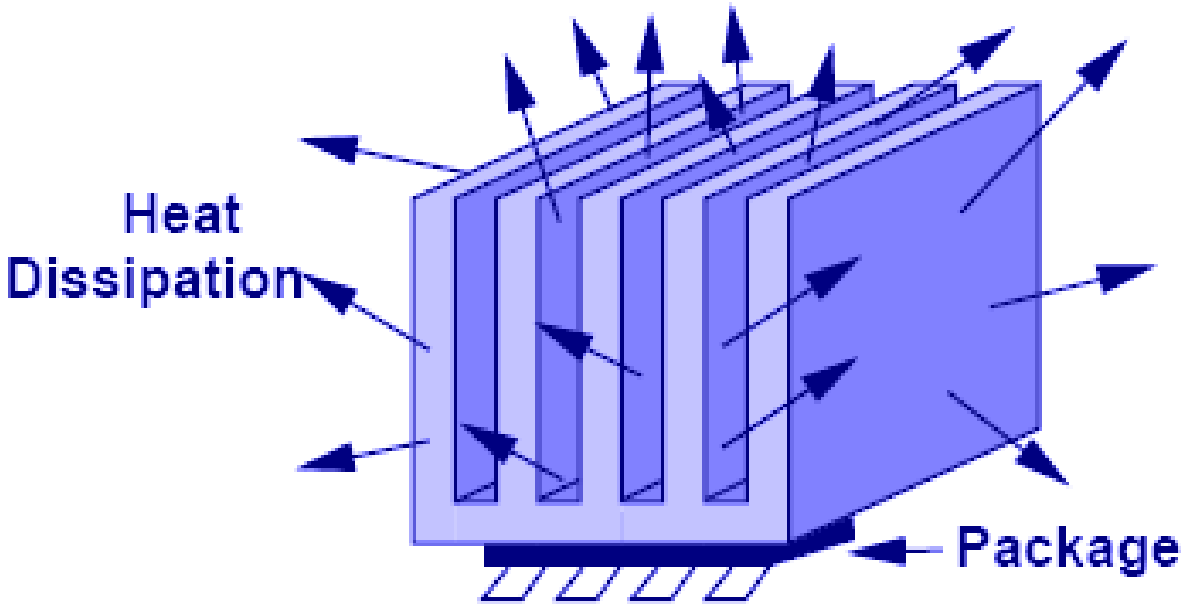


(b)

- **Maximum power occurs between $V_p$=0 and $4V_{CC}/\pi$.**

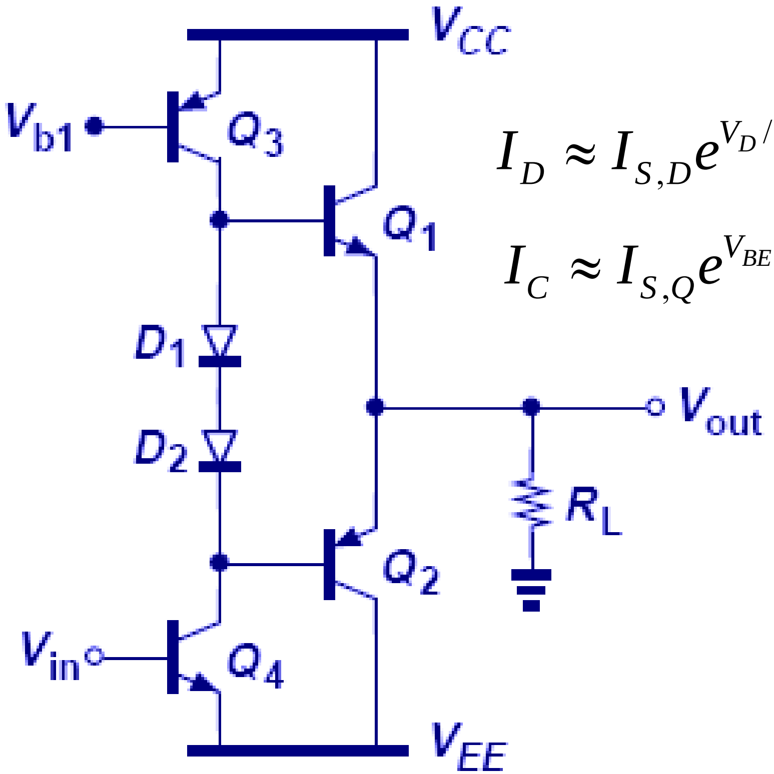
$$P_{av,\max} = \frac{{V_{CC}}^2\cdot V_P}{\pi^2 R_L} \quad \text{when } V_P = 2\cdot\frac{V_{CC}}{\pi}$$

# Heat Sink



- **Heat sink, provides large surface area to dissipate heat from the chip.**

# Thermal Runaway Mitigation



$$I_D \approx I_{S,D} e^{V_D/V_T}$$

$$I_C \approx I_{S,Q} e^{V_{BE}/V_T}$$

$$V_{D1} + V_{D2} = V_T \ln \frac{I_{D1}}{I_{S,D1}} + V_T \ln \frac{I_{D2}}{I_{S,D2}}$$

$$= V_T \ln \frac{I_{D1} I_{D2}}{I_{S,D1} I_{S,D2}}$$

$$V_{BE1} + V_{BE2} = V_T \ln \frac{I_{C1}}{I_{S,Q1}} + V_T \ln \frac{I_{C2}}{I_{S,Q2}}$$

$$= V_T \ln \frac{I_{C1} I_{C2}}{I_{S,Q1} I_{S,Q2}}$$

With the same $V_T$,

$$\frac{I_{D1} I_{D2}}{I_{S,D1} I_{S,D2}} = \frac{I_{C1} I_{C2}}{I_{S,Q1} I_{S,Q2}}$$

- **Using diode biasing prevents thermal runaway since the currents in $Q_1$ and $Q_2$ will track those of $D_1$ and $D_2$ as long as their $I_s$'s track with temperature.**

# Efficiency

- Efficiency is defined as the average power delivered to the load divided by the power drawn from the supply

$$\eta = \frac{\text{Power Delivered to Load}}{\text{Power Drawn From Supply Voltage}} = \frac{P_{out}}{P_{out} + P_{ckt}}$$

*Emitter Follower*

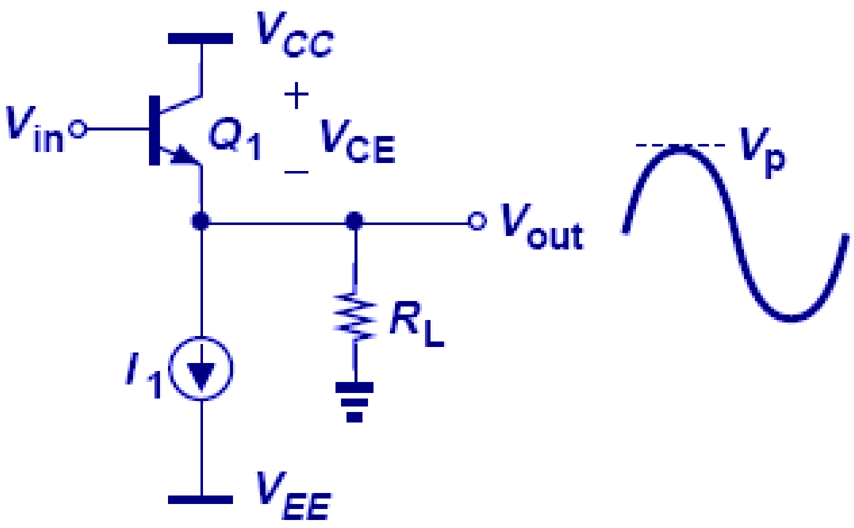
$$\eta_{EF} = \frac{V_P^2 / 2R_L}{\underbrace{V_P^2 / 2R_L}_{\text{Load}} + \underbrace{I_1 \left( V_{CC} - V_P / 2 \right)}_{\text{Tr.}} \underbrace{- I_1 \cdot V_{EE}}_{\text{Current source}}}$$

$$= \frac{V_P}{4V_{CC}} \quad \text{if } I_1 = \frac{V_P}{R_L} \text{ and } -V_{EE} = V_{CC}$$

- Maximum efficiency for EF is 25% if $V_P$ approaches $V_{CC}$.

# Example 13.15: Efficiency of EF

- EF designed for full swing operates with half swing.



$$\text{With } I_1 = \frac{V_P}{R_L} = \frac{V_{CC}}{R_L} \text{ and } -V_{EE} = V_{CC}$$

$$\eta_{EF} = \frac{V_P^2 / 2R_L}{V_P^2/2R_L + I_1\left(V_{CC} - V_P/2\right) - I_1 \cdot V_{EE}}$$

$$= \frac{V_P^2/2R_L}{V_P^2/2R_L + \frac{V_{CC}}{R_L}\left(V_{CC} - V_P/2\right) + \frac{V_{CC}}{R_L} \cdot V_{CC}}$$

Thus,

$$\eta_{EF}\Big|_{V_P = V_{CC}/2} = \frac{1}{15}$$

# Efficiency

*Push-Pull Stage*

$$\eta_{PP} = \frac{\dfrac{V_P^2}{2R_L}}{\dfrac{V_P^2}{2R_L} + \dfrac{2V_P}{R_L}\left(\dfrac{V_{CC}}{\pi} - \dfrac{V_P}{4}\right)}$$

$$= \frac{\pi}{4}\frac{V_P}{V_{CC}}$$

- **Maximum efficiency for PP is 78.5% for $V_P \approx V_{CC}$.**

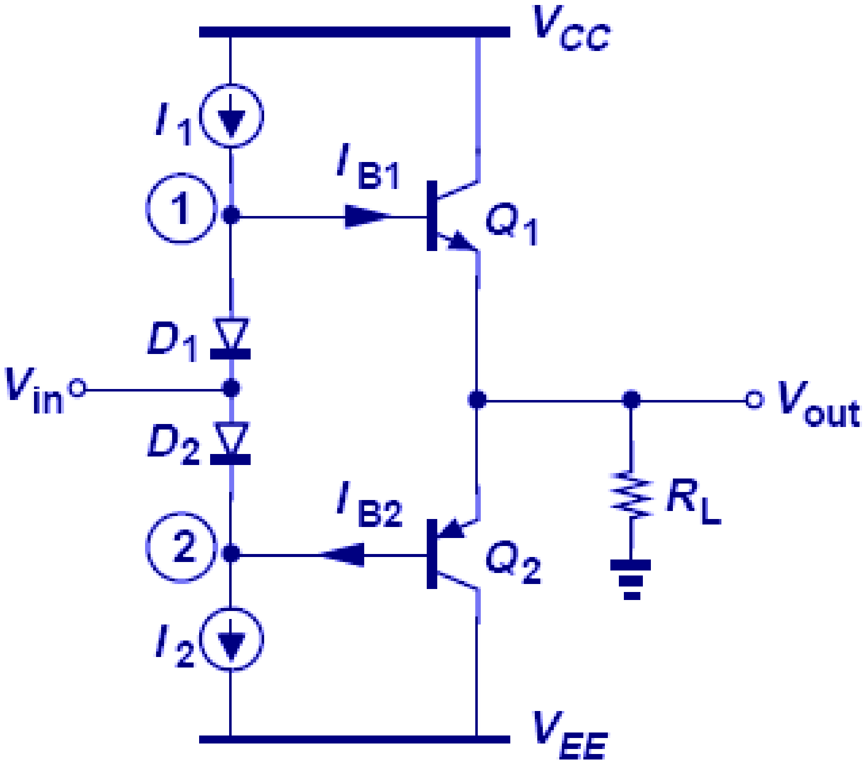
# Example 13.16: Efficiency incl. Predriver

$$I_1 = (V_P/R_L)/\beta$$

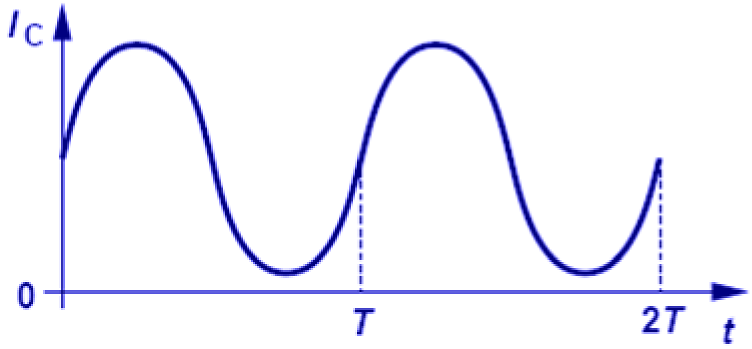
$$\eta = \frac{\dfrac{V_P^2}{2R_L}}{\dfrac{2V_P V_{CC}}{\pi R_L} + (V_{CC} - V_{EE})\dfrac{V_P}{\beta R_L}}$$

$$= \frac{1}{4}\frac{V_P}{V_{CC}/\pi + V_{CC}/\beta}$$

$$= \frac{1}{4}\frac{1}{\dfrac{1}{\pi} + \dfrac{1}{\beta}}\frac{V_P}{V_{CC}}$$

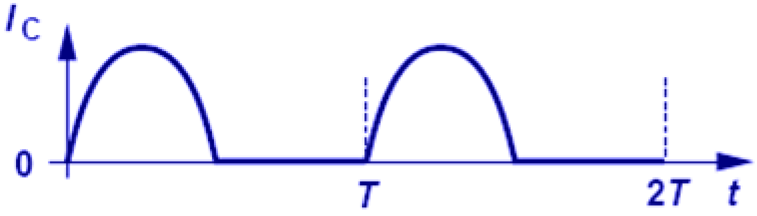


# Power Amplifier Classes



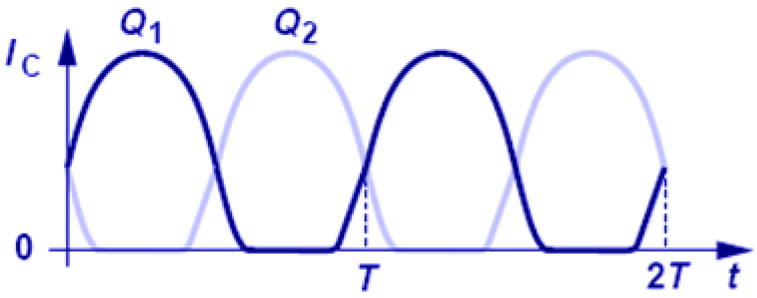
(a)

**Class A: High linearity, low efficiency**



(b)

**Class B: High efficiency, low linearity**



(c)

**Class AB: Compromise between Class A and B**

# Summary

- Small signal analysis push-pull stage: gain, $R_{in}$, and $R_{out}$.
- Composite transistor: lower $R_{out}$ and higher $R_{in}$

- Using negative feedback, linearity is improved, providing higher fidelity

- Power rating of devices.

- Efficiency is defined as the average power delivered to the load divided by the power drawn from the supply:

Emitter Follower (25%), Push-Pull (78.5%)

- Amplifier classes: Class A, Class B, and Class AB