

EE3122: Analogue Circuit Fundamentals

Output Stages

Department of Electrical Engineering

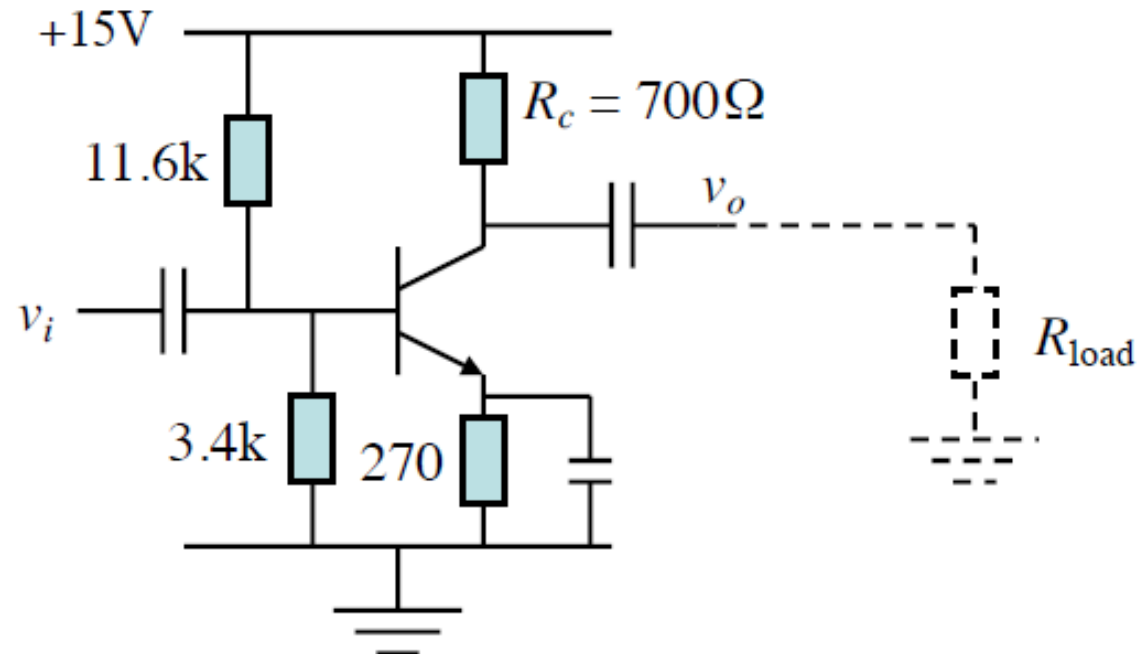
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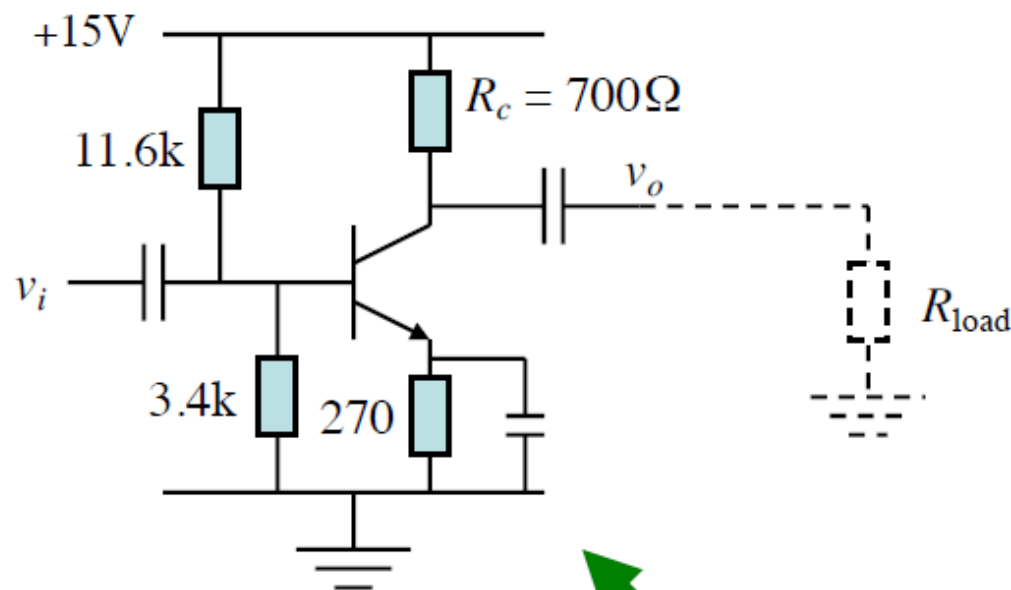
Motivation

- **Limitation of CE amplifier:** It provides a good gain, but it fails to drive a low-resistance (high-power) load.

Find the gain



Motivation



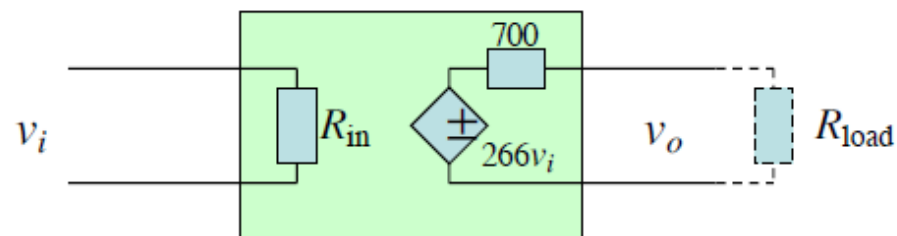
Quick calculation:

Biasing: $V_B = 3.4 \text{ V}$, $V_E \approx 2.7 \text{ V}$
 $I_C \approx I_E = 2.7/270 = 10 \text{ mA}$
 $V_C = 15 - 0.01R_c = 8 \text{ V}$

Small-signal:

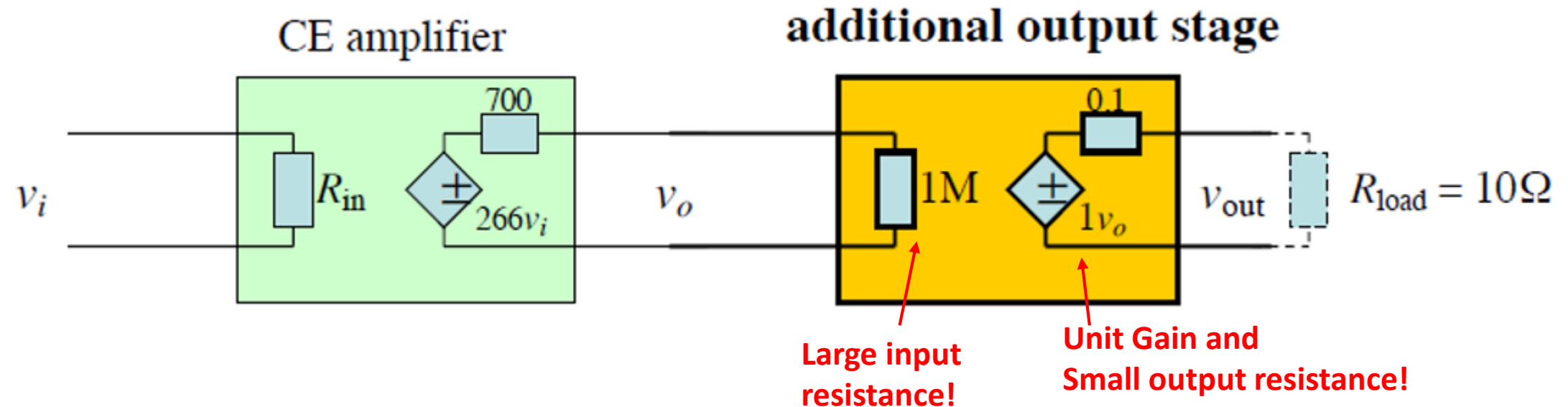
$g_m = I_C/26\text{mV} = 0.38 \text{ A/V}$
 $\text{gain} = g_m R_c = 266 \text{ or } 48\text{dB}$
 $R_{\text{out}} = R_c = 700 \Omega$
 $R_{\text{in}} = r_\pi \parallel 3.4\text{k} \parallel 11.6\text{k}$

Equivalent circuit:

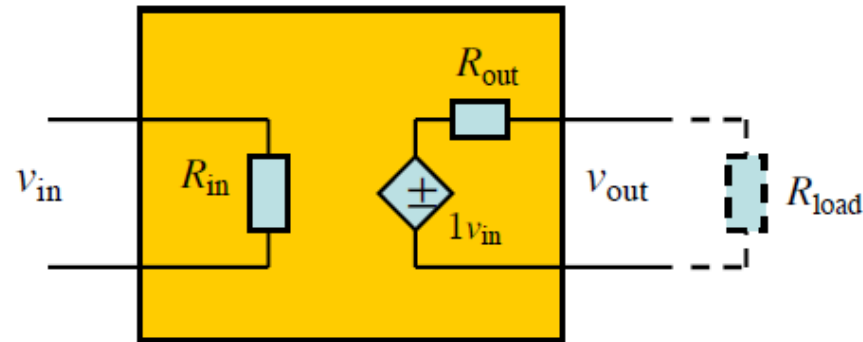


Solution

- **Never load the CE amplifier directly!** Use an output stage or buffer.



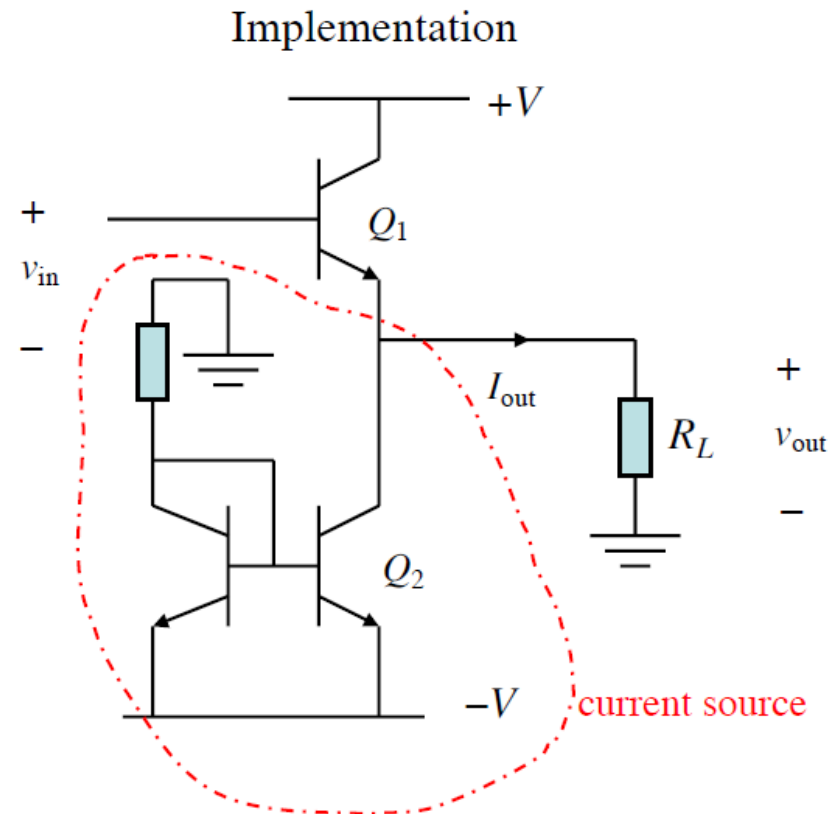
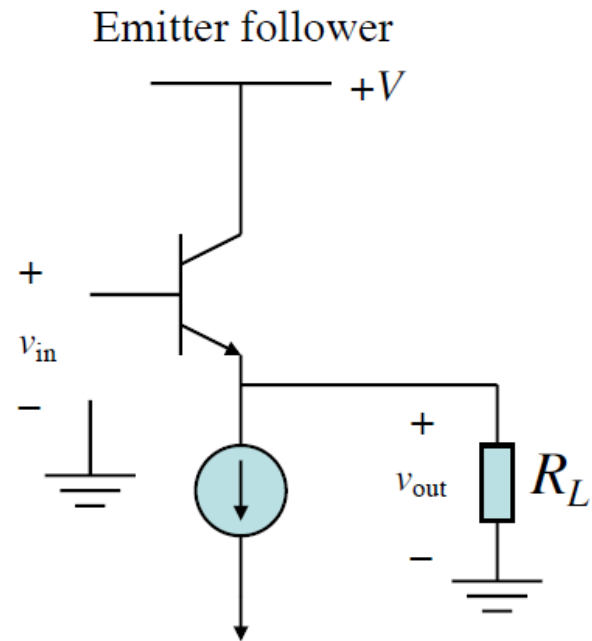
Output Stage



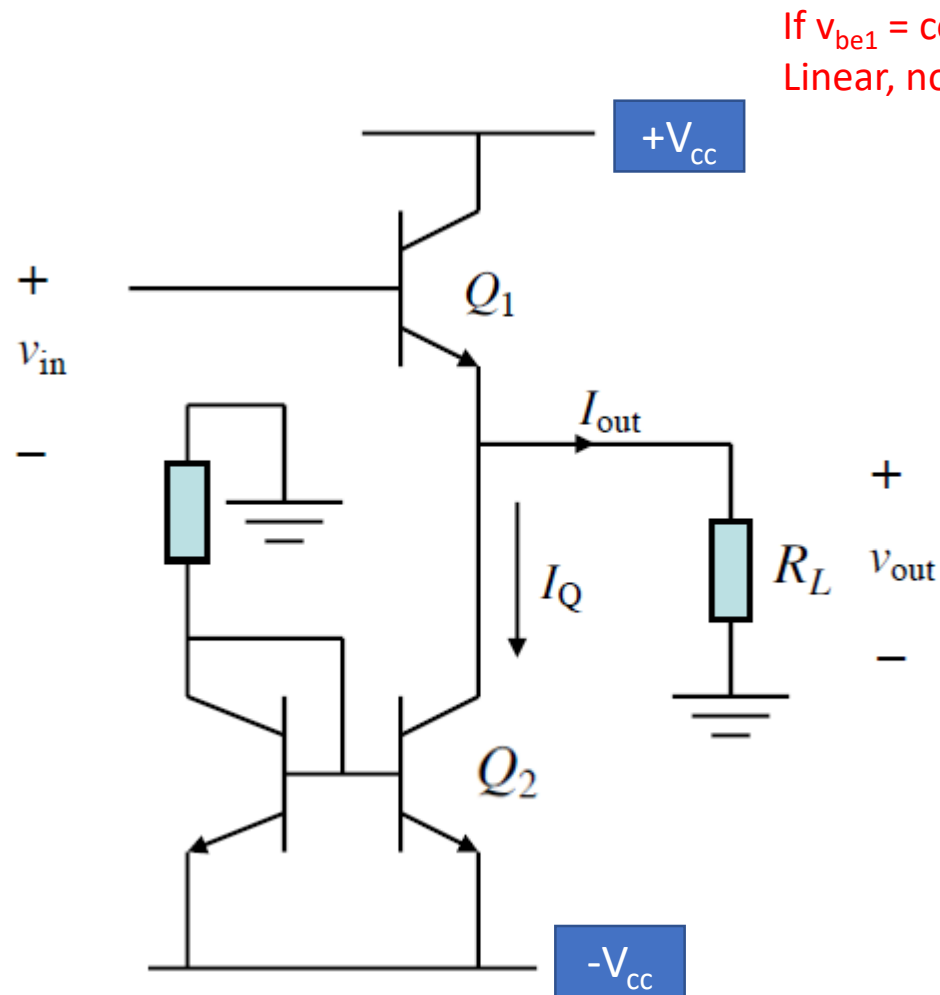
An output stage is designed to

- deliver current to a load ($R_{out} \ll R_{load}$)
- reproduce the voltage as faithfully as possible (low distortion)
- seamlessly load the previous amplifier stage ($R_{in} \gg R_{out,CE}$ of previous stage)

Emitter Follower (Class A)



Emitter Follower: Large Signal Analysis



If $v_{be1} = \text{constant}$,
Linear, no distortion!

$$\text{For } Q_1 : \begin{cases} v_{in} = v_{be1} + v_{out} \\ v_{be1} = \frac{kT}{q} \ln \frac{I_{c1}}{I_{s1}} \end{cases} \quad \text{if } Q_1 \text{ is active.}$$

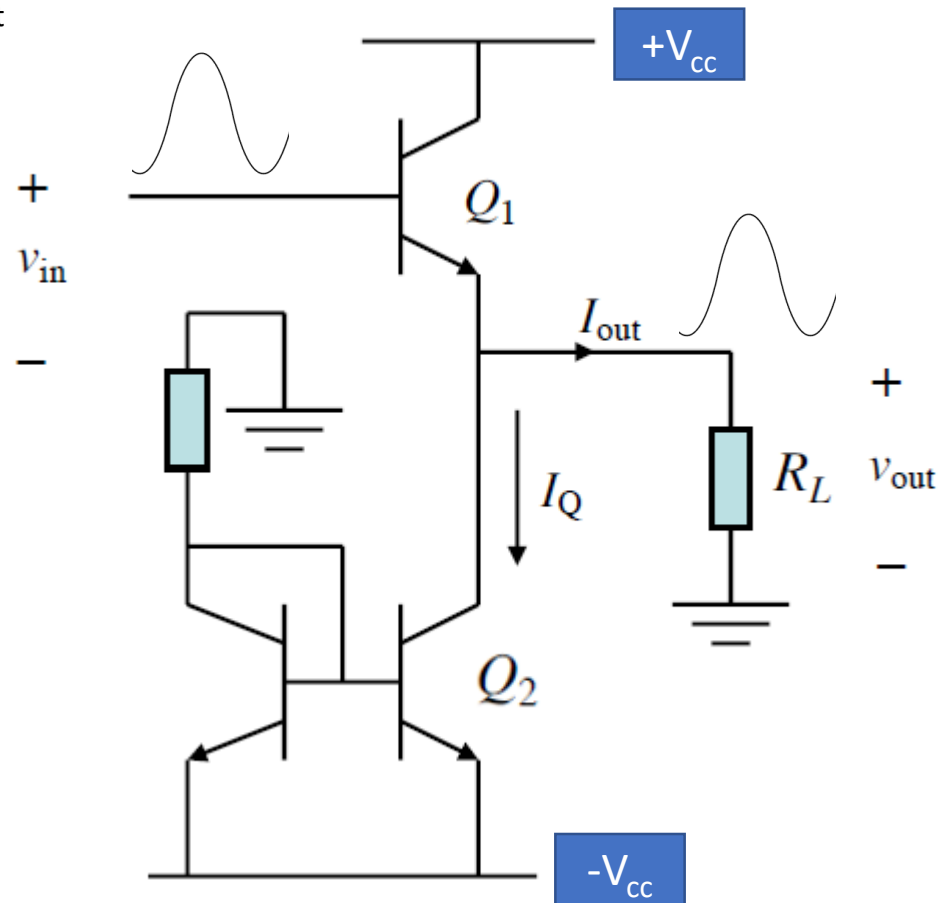
Emitter Follower: Large Signal Analysis

+ve cycle

$$I_{E1} = I_Q + I_{out}$$

-ve cycle

$$I_{E1} + I_{out} = I_Q$$



$$\text{For } Q_1 : \begin{cases} v_{in} = v_{be1} + v_{out} \\ v_{be1} = \frac{kT}{q} \ln \frac{I_{c1}}{I_{s1}} \end{cases} \quad \text{if } Q_1 \text{ is active.}$$

Also,

$$\begin{aligned} I_{c1} &= I_Q + \frac{v_{out}}{R_L} \\ &= I_Q + I_{out} \end{aligned} \quad \text{if } Q_2 \text{ is active.}$$

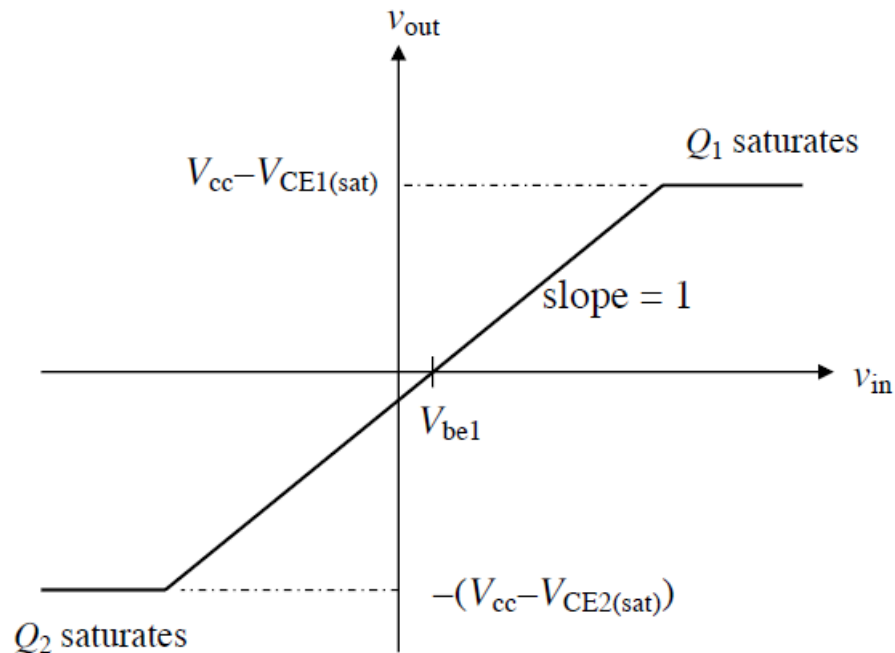
Hence,

$$v_{in} = \frac{kT}{q} \ln \left(\frac{I_Q + I_{out}}{I_{s1}} \right) + v_{out}$$

Weak nonlinearity

Emitter Follower: Signal Clipping

- We note that the good linearity is only maintained if both Q_1 and Q_2 are kept in active region.
- If Q_1 saturates, the output voltage clips at the top.
- If Q_2 saturates, the output voltage clips at the bottom.

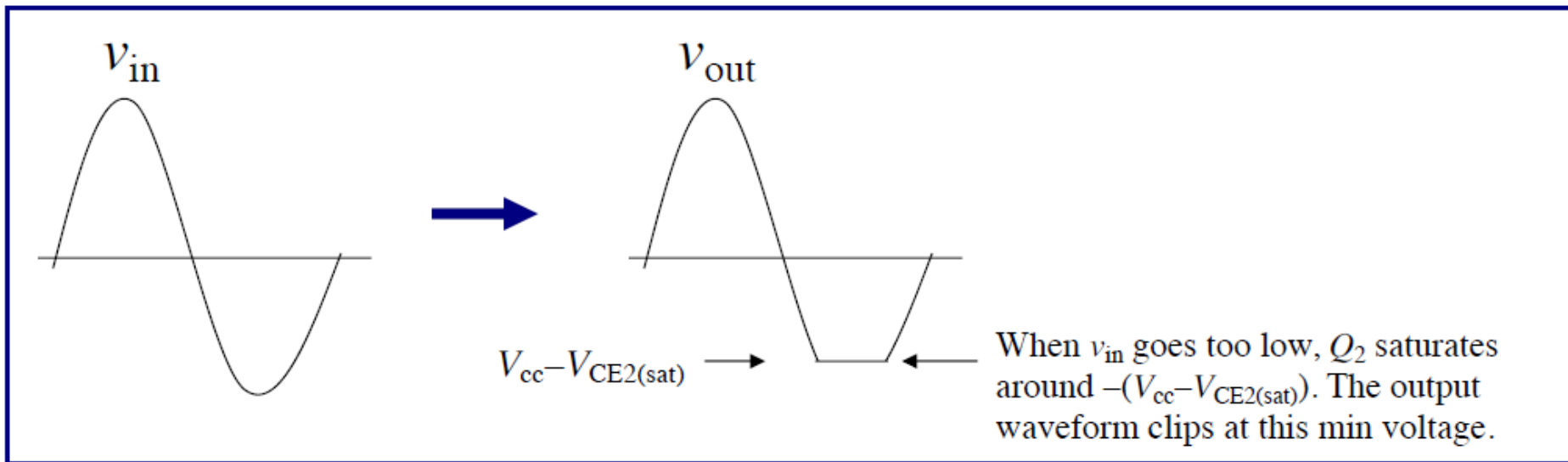
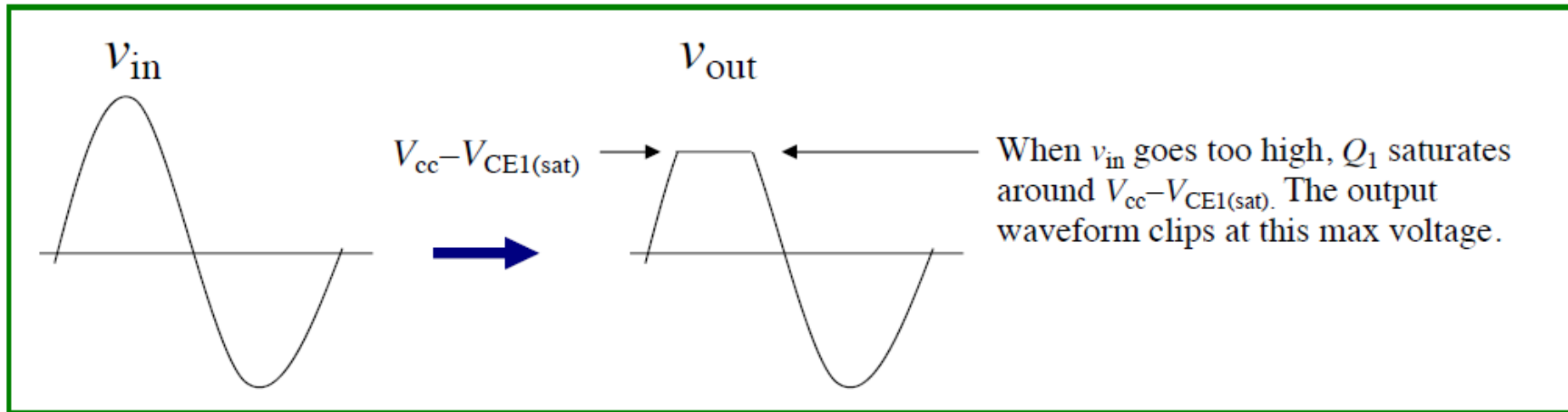


**Operating range without
clippings caused by saturation:**

$$-(V_{cc} - V_{CE2(sat)} - V_{be1}) < v_{in} < V_{cc} - V_{CE1(sat)} + V_{be1}$$

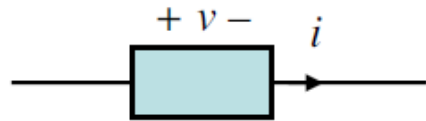
Clipping may also happen if V_{be} increases too much due to very large load current I_{out} .

Emitter Follower: Signal Clipping



Class A: Power Efficiency

Recall the basic equation of power dissipation in any device:



$$P_{av} = \frac{1}{T} \int_0^T v(t)i(t)dt$$

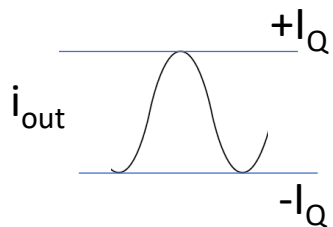
Efficiency = Output Power / Input Power

Output power: AC power to load

Input power: power taken from DC source

For the load resistor, assuming no clipping occurs, i.e., i_{out} and v_{out} are sinewaves, we have the average power output:

$$\begin{aligned} P_{av} &= \frac{1}{T} \int_0^T \hat{i}_{out} \hat{v}_{out} \sin^2 2\pi ft \, dt \\ &= \frac{1}{2\pi} \int_0^{2\pi} \hat{i}_{out} \hat{v}_{out} \sin^2 \theta \, d\theta \\ &= \frac{1}{2} \hat{i}_{out} \hat{v}_{out} \end{aligned}$$

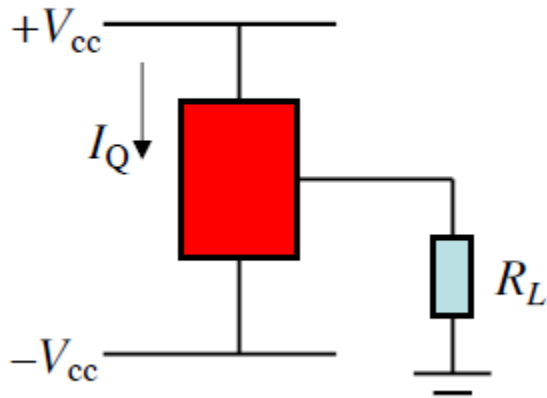


At max load without severe clipping, $I_Q = \hat{i}_{out}$ and $\hat{v}_{out} = V_{cc} - V_{CE(sat)}$

the max power output is $P_{out,max} = \frac{1}{2} I_Q (V_{cc} - V_{CE(sat)}) \approx \frac{1}{2} I_Q V_{cc}$

Class A: Power Efficiency

To find the total power drawn from the power supply:



Average current and voltage drawn from supply by the class A output stage is

$$I_{av} = I_Q$$
$$V_{av} = 2V_{cc}$$

Thus, power supplied to the output stage is

$$P_{supply} = 2V_{cc}I_Q$$

Hence, the max efficiency is

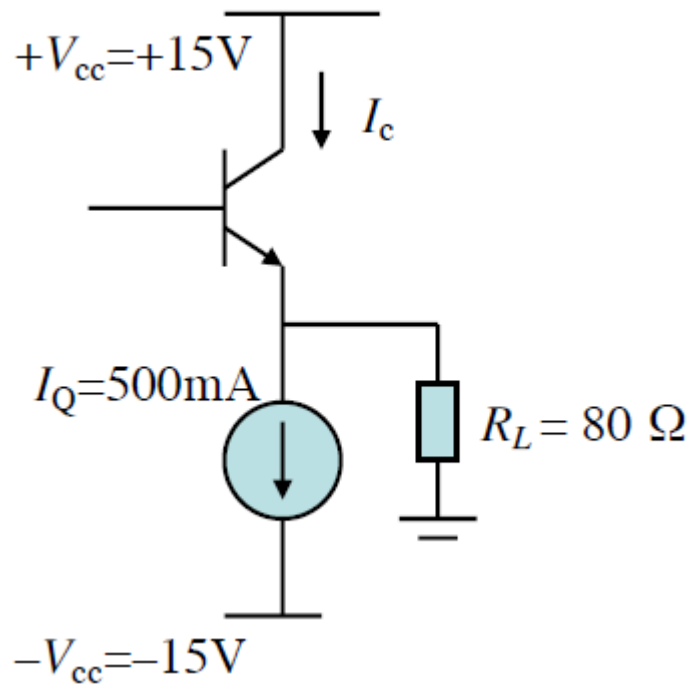
$$\eta_{max} = \frac{\frac{1}{2}I_Q(V_{cc} - V_{CE(sat)})}{2V_{cc}I_Q} \approx \frac{\frac{1}{2}I_QV_{cc}}{2V_{cc}I_Q} = 25\%$$

**Class A has a poor efficiency,
but very low distortion — *high-fidelity!***

ONLY 25% !!

Example: Power Efficiency

- Suppose we wish to find the efficiency of the following Class A power amplifier.



Here, $I_Q = 500 \text{ mA}$, $V_{cc} = 15 \text{ V}$ and $V_{CE(sat)} = 0.2 \text{ V}$

Suppose $R_L = 80 \Omega$ and $v_{in(peak)} = 12 \text{ V}$

$$v_{out(peak)} = 12 \text{ V}$$

$i_{out(peak)} = 150 \text{ mA}$ which is less than I_Q :

No clipping occurs!

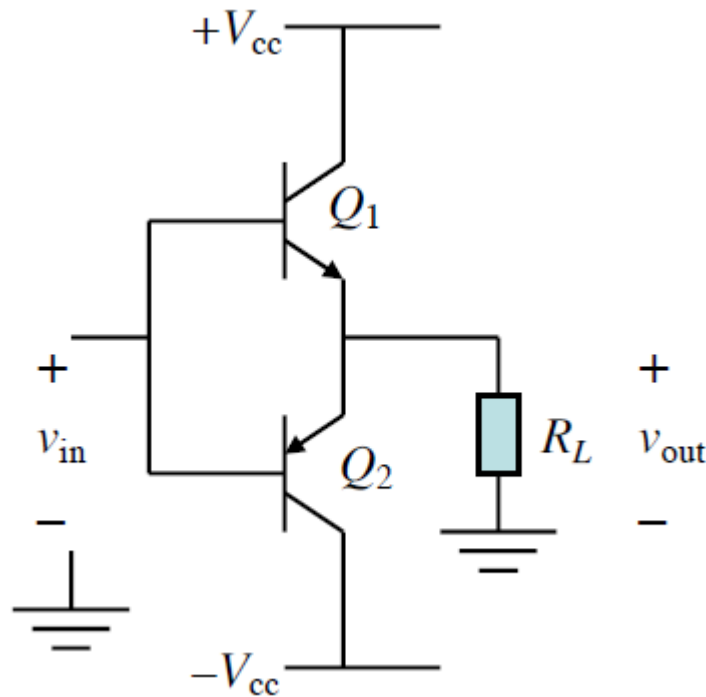
$$P_{out} = 0.5 \times 12 \times 0.15 = 0.9 \text{ W}$$

$$P_{in} = 2 \times 15 \times 0.5 = 15 \text{ W}$$

$$\text{Efficiency } \eta = 6 \%$$

Push-Pull (Class B)

- The main disadvantage of Class A power amplifier is the poor efficiency because of the large dissipation even at zero output.
- To improve efficiency, we may try to eliminate the dissipation at zero output. That means, we aim to design an amplifier whose dissipation is zero when $v_{in} = 0$.



Solution: Class B push-pull output stage

Use two complementary active devices.
Each conducts for half cycle.

Basically, it is emitter follower circuit.

Q_1 and Q_2 are cutoff at $v_{in} = 0$.

Actually, Q_1 and Q_2 are cutoff for $|v_{in}| < 0.7V$

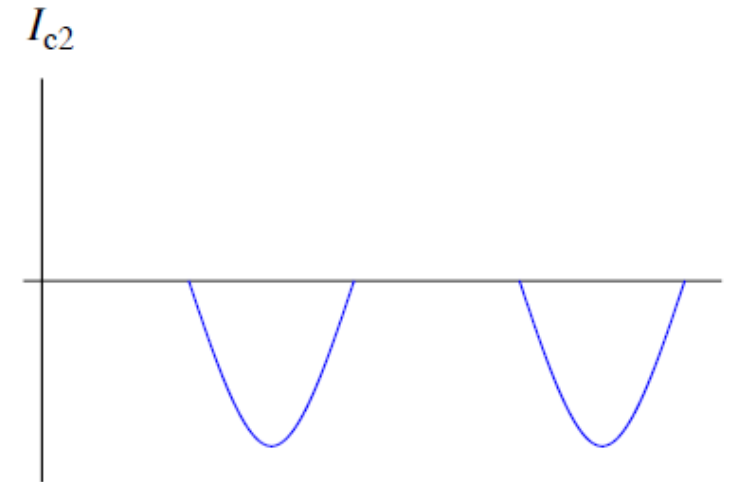
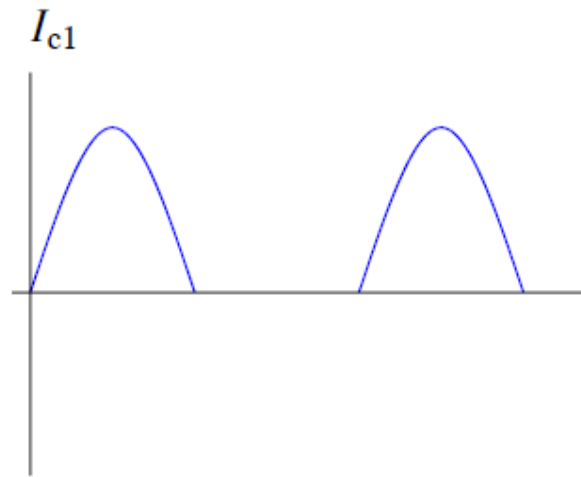
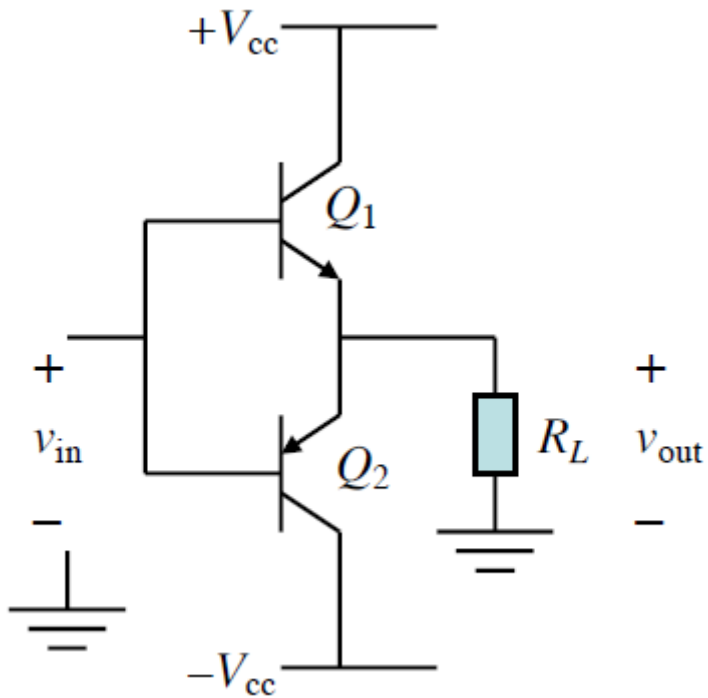
Q_1 conducts when $v_{in} > 0.7V$

Q_2 conducts when $v_{in} < -0.7V$

Clipping occurs similar to class A if $|v_{out}|$ is too large, exceeding the supply $|V_{cc} - V_{CE(sat)}|$

Push-Pull (Class B): Power Efficiency

- Each device only conducts for half cycle, i.e., 180°. So, the current waveform for each device is a half-sinusoid.



Push-Pull (Class B): Power Efficiency

Efficiency = Output Power / Input Power

Output power: AC power to load

Input power: power taken from DC source

- For simplicity of analysis, we ignore the crossover distortion.

Supply current

$$\begin{aligned} I_{\text{supply}} &= \frac{1}{T} \int_0^T i_{C1} dt \\ &= \frac{1}{2\pi} \int_0^\pi \hat{i}_{\text{out}} \sin \theta d\theta \\ &= \frac{1}{\pi} \hat{i}_{\text{out}} = \frac{1}{\pi} \frac{\hat{v}_{\text{out}}}{R_L} \end{aligned}$$

Input power

$$\begin{aligned} P_{\text{supply}} &= 2V_{cc} I_{\text{supply}} \\ &= \frac{2V_{cc} \hat{v}_{\text{out}}}{\pi R_L} \end{aligned}$$

Output power

$$\begin{aligned} P_{\text{load}} &= \frac{1}{2} \hat{v}_{\text{out}} \hat{i}_{\text{out}} \\ &= \frac{1}{2} \frac{\hat{v}_{\text{out}}^2}{R_L} \end{aligned}$$

Efficiency

$$\eta = \frac{P_{\text{load}}}{P_{\text{supply}}} = \frac{\frac{1}{2} \frac{\hat{v}_{\text{out}}^2}{R_L}}{\frac{2}{\pi} \frac{V_{cc}}{R_L} \hat{v}_{\text{out}}} = \frac{\pi}{4} \frac{\hat{v}_{\text{out}}}{V_{cc}}$$

Push-Pull (Class B): Power Efficiency

The best efficiency is when the output voltage is the greatest possible without clipping.

$$\hat{v}_{\text{out,max}} = V_{cc} - V_{\text{CE(sat)}}$$

Thus, the maximum efficiency is

$$\eta_{\text{max}} = \frac{\pi}{4} \frac{V_{cc} - V_{\text{CE(sat)}}}{V_{cc}} \approx 78\%$$

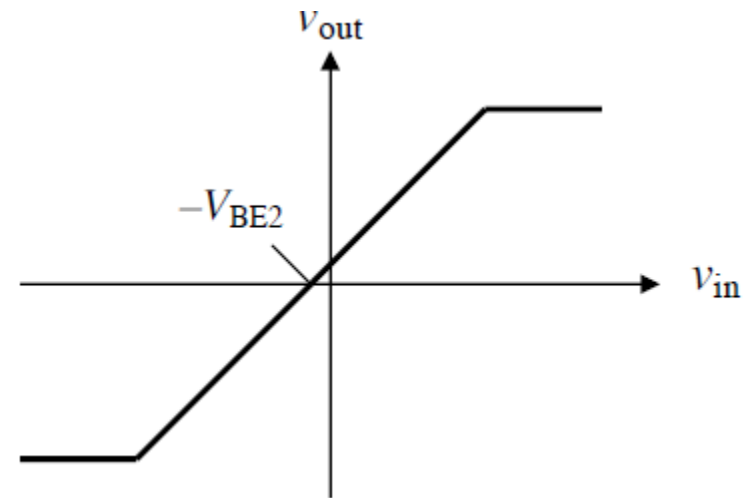
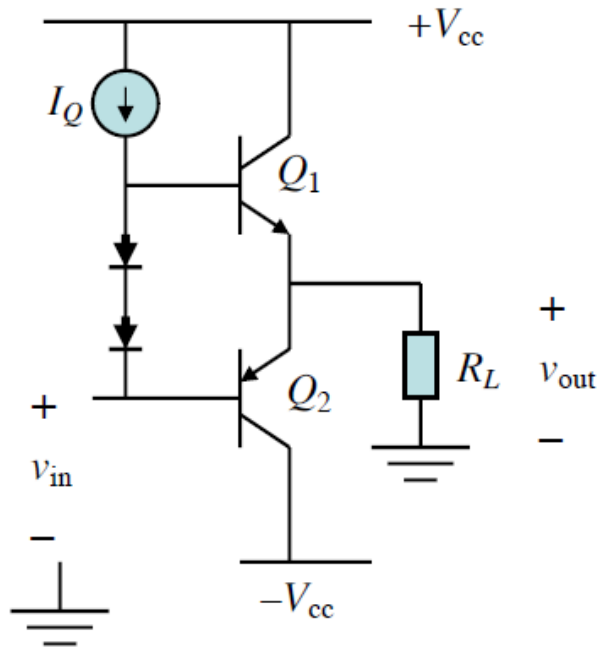
MUCH BETTER THAN CLASS A AMPLIFIER!

- Problem is distortion
- To have high efficiency & low distortion – need class AB amplifier

Appendix

Class AB amplifier

- To eliminate the crossover distortion, we may bias the active devices so that they conduct a small quiescent current near the crossover $v_{in} = 0$. **Don't let them cutoff!**



Class AB amplifier

- Here, for $v_{in} < 0$, $Q2$ turns on and out follows. But since the diodes maintain a constant total bias voltage across the BE junctions of both $Q1$ and $Q2$, V_{BE} of $Q2$ decreases by the same amount that V_{BE} of $Q1$ increases. Thus, $Q1$ stays on, but only allows a very small current to flow.
- Similarly, for $v_{in} > 0$, we have the same situation, with $Q1$ and $Q2$ interchanged.

