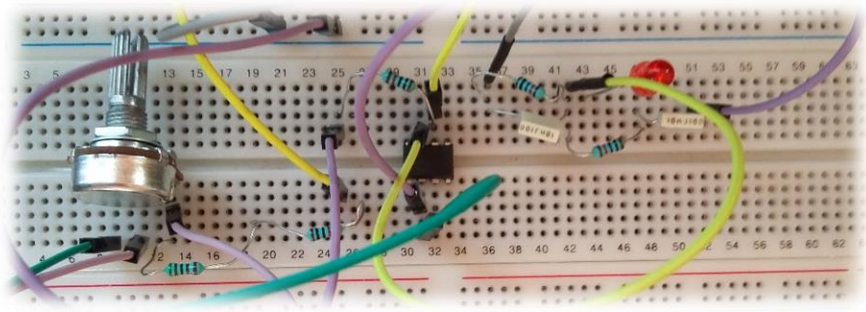

FUNDAMENTAL ELECTRONIC CIRCUITS

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C6 – Power amplifiers – class A, B, AB

Contents

To begin with

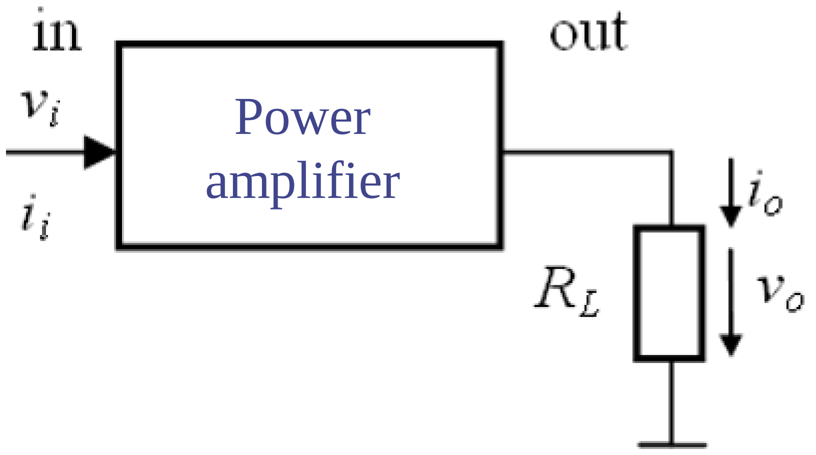
- What is a power amplifier? How is it different from a voltage amplifier?
- Where are power amplifiers used? What requirements do they need to meet?
- How is the performance of a power amplifier measured? Who gives the name/class?
- Power amplifiers w/ BJT or MOSFET?

Both are possible, but we're studying BJT power amplifiers only.

➢ What is a power amplifier?

= a circuit which provides little or no voltage gain, but **significant** current gain

= large signal or output amplifier

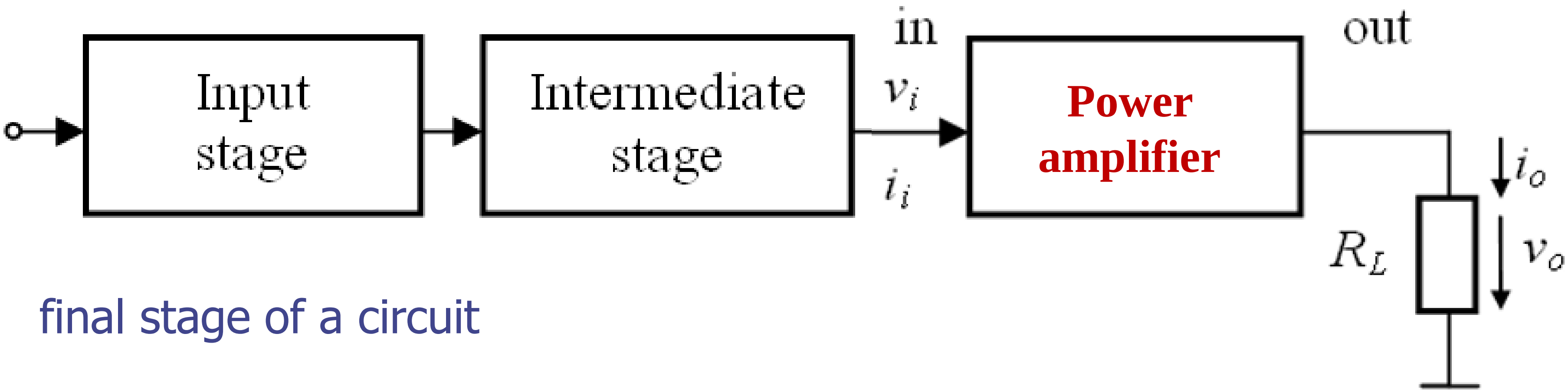


$v_o \approx v_i \qquad A_v \approx 1$

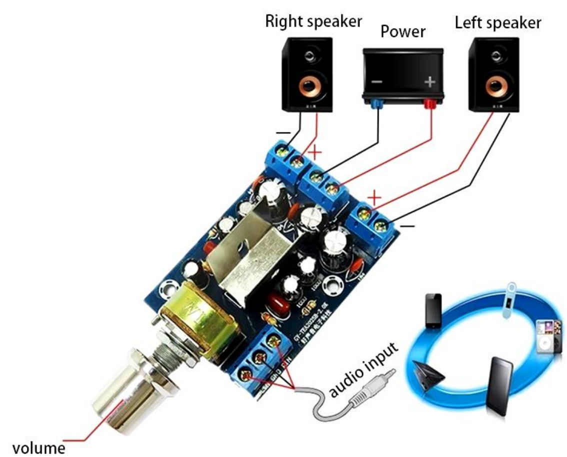
$i_o > i_i \qquad A_i > 1$

$$p_o = v_o \cdot i_o$$
$$p_i = v_i \cdot i_i$$
$$p_o > p_i$$

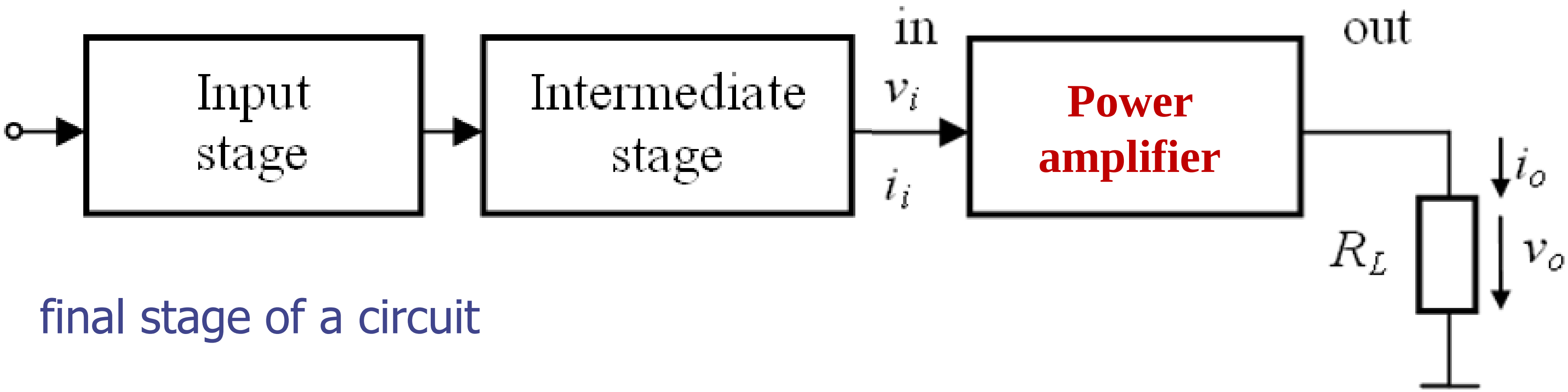
➢ Placement & usage



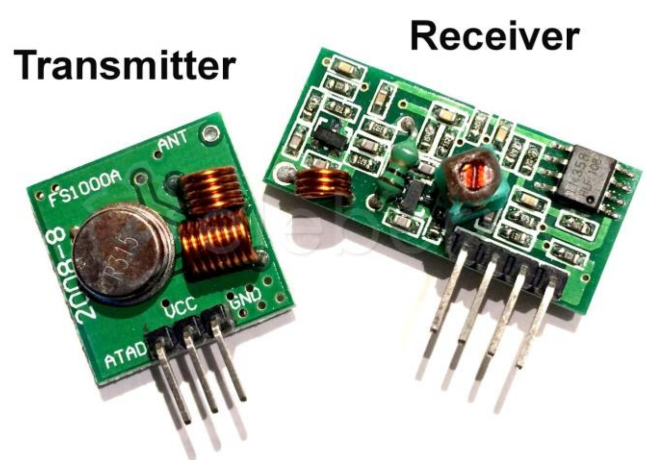
- final stage of a circuit
- usage: audio systems (loudspeakers, headphones) – to increase sound volume



➢ Placement & usage



- final stage of a circuit
- usage: radiofrequency (RF) transmitters – to increase the power of the transmitted signal (communications systems)



Requirements

- low output resistance (can deliver output signal without loss of gain)
- (very) high efficiency (enhances battery life)
- good linearity (non distorted output signal)

$$THD = \frac{\sqrt{V_{RMS2}^2 + V_{RMS3}^2 + V_{RMS4}^2 + \cdots}}{V_{RMS1}}$$

$THD < 1\%$ for Hi-Fi amplifiers

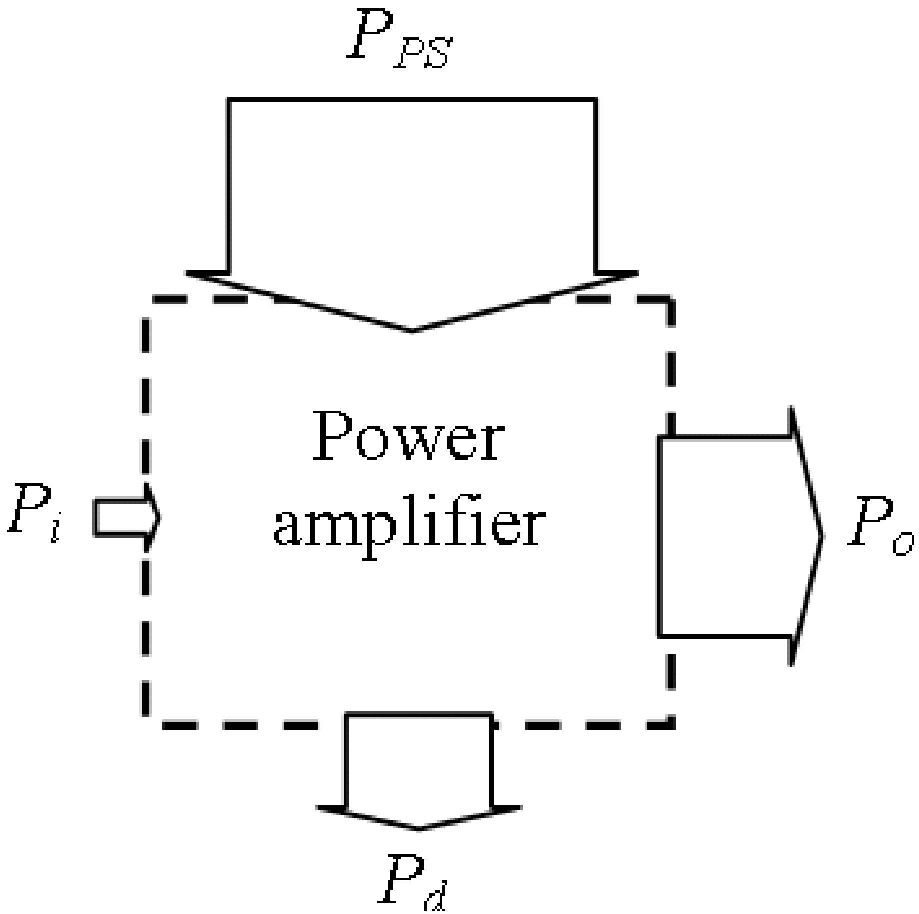
RMS voltage ≡ effective voltage

THD – total harmonic distortion

RMS – root mean square

V_{RMSi} - RMS value of the ith harmonic of the original signal, i = 2, 3, 4, ...

➢ Power transfer



$$P_i + P_{PS} = P_d + P_o$$

P_i - power from the input source
P_{PS} - power drawn from the power supplies
P_d - dissipated power (heat)
P_o - power delivered at the output (on R_L)

$$P_i << P_{PS}$$

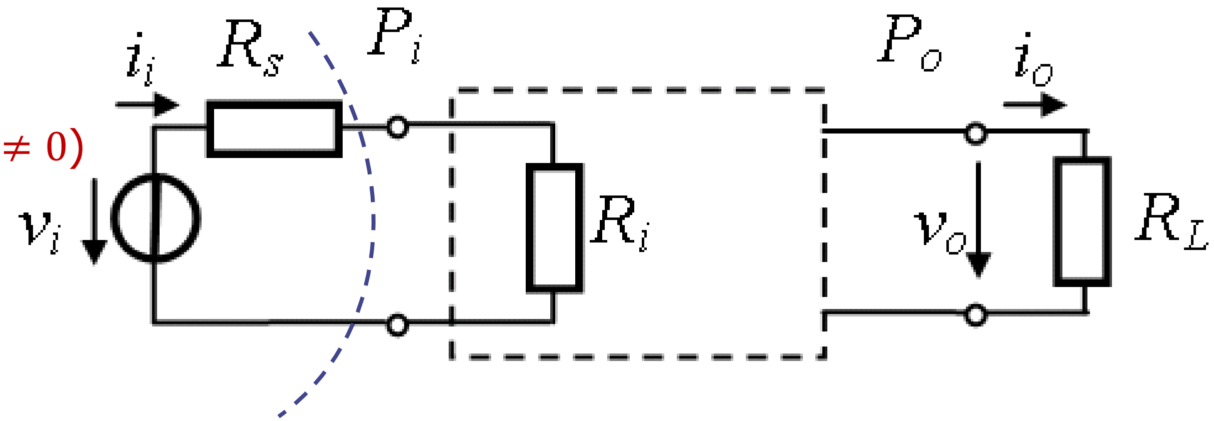
$$\eta = \frac{P_o}{P_{PS}}$$

efficiency of the stage

η [%] or $\eta \in (0, 1)$

Power gain

real input voltage source ($R_s \neq 0$)



Assume sinusoidal regime, average power:

$$P_o = \left(\frac{\hat{V}_o}{\sqrt{2}}\right)^2 \frac{1}{R_L} = \frac{\hat{V}_o^{\,2}}{2R_L}$$

$$P_i = R_i \left(\frac{\hat{I}_i}{\sqrt{2}}\right)^2 = R_i \frac{\hat{V}_i^{\,2}}{2(R_i + R_s)^2}$$

$$A_p = \frac{P_o}{P_i} = \left(\frac{\hat{V}_o}{\hat{V}_i}\right)^2 \frac{(R_i + R_s)^2}{R_i R_L}$$

If $R_i >> R_s$ $\quad A_p \approx \left(\frac{\hat{V}_o}{\hat{V}_i}\right)^2 \frac{R_i}{R_L}$

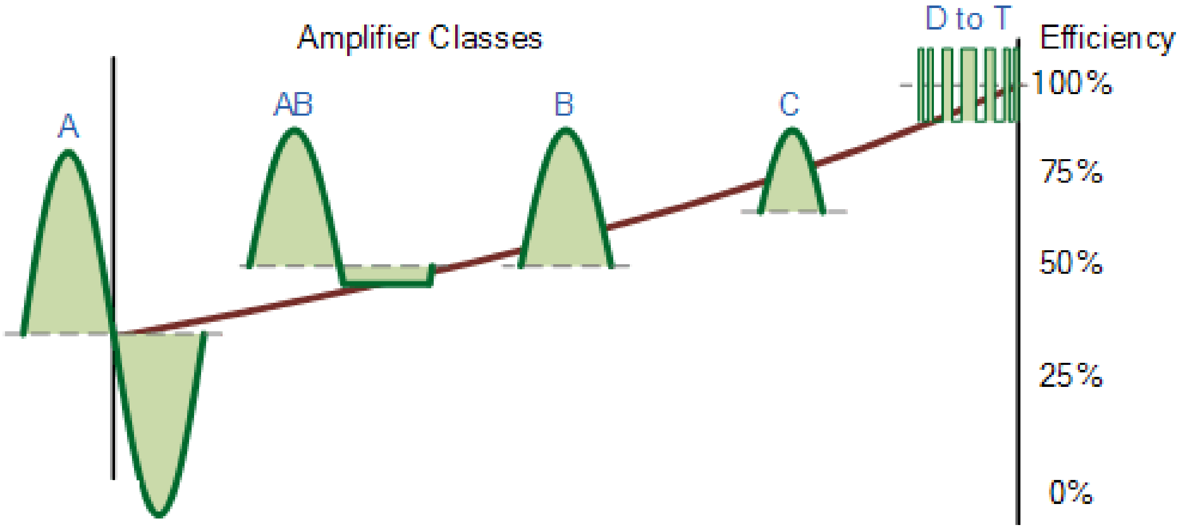
➢ Power amplifier classes

The classes are defined in relation to the interval of time in which the amplifier device (transistor) is active, expressed as a fraction of the period of the input signal.

Classes: A, B, AB, C, D, E, F, G, I, S, T, etc

efficiency of the stage

$$\eta = \frac{P_o}{P_{PS}}$$



The less time T is active during a period, the higher the efficiency

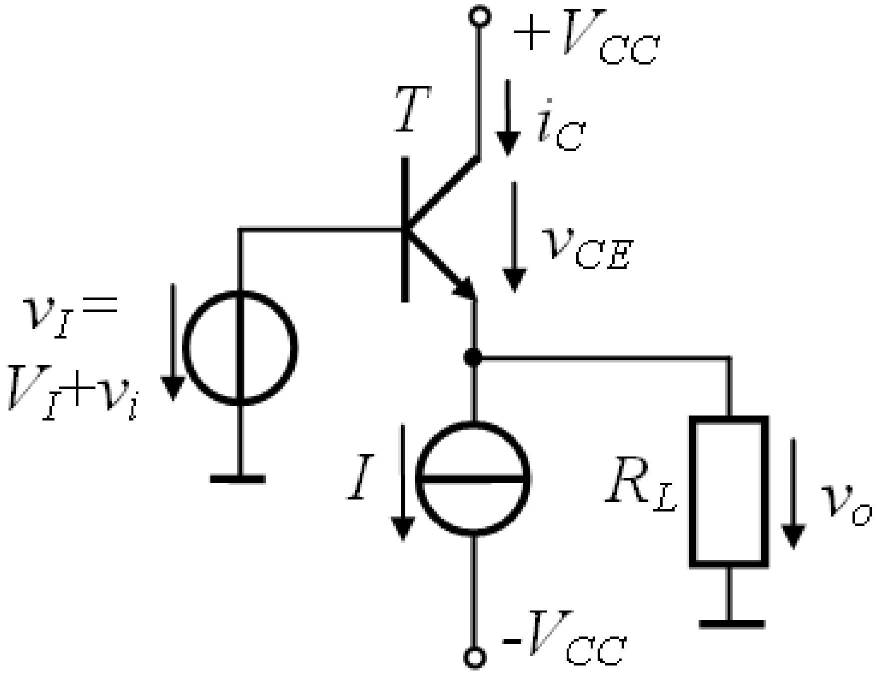
Power amplifier classes

Class	Conduction interval	Max. efficiency	Notes
A	$t_c = T$	25%	Small-signal amplifiers
B	$t_c = T/2$	78.5%	Audio amplifiers; crossover distortions
AB	$T/2 < t_c < T$	78.5%	Audio amplifiers; no crossover distortions
C	$t_c < T/2$	90%	RF transmitters
D	switching mode	80%-95%	PWM and passive filtering
E	switching mode	90%	RF transmitters
G	more efficient version of class AB		
H	similar to class G	100%	Power supply modulated by the signal
I	similar to class B, switching mode		Interleaved PWM amplifier
S, T	similar to class D, switching mode		

Classes A, B, AB – C6, Lab 7, Seminar 4; Class D – C13 (in 2025 ☺)

Class A power amplifier

➢ Class A - circuit



Type of configuration?

emitter **follower** for variable input voltage

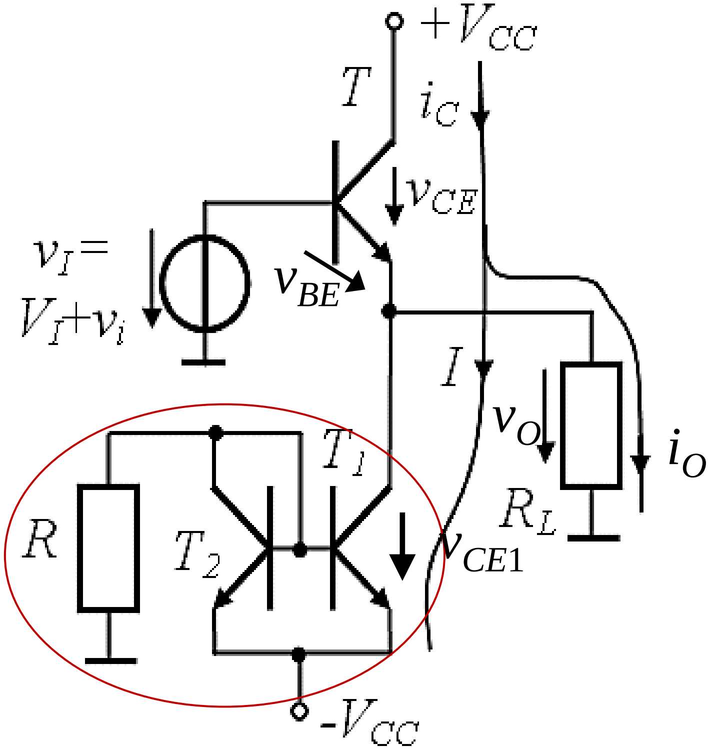
common collector (CC) topology

$V_I = 0.7$ V – to bias T

$v_o \approx v_i$

How can we implement the current source?

Class A – operation



$$v_O = v_I - v_{BE} = v_I - 0.7$$

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

$v_I \uparrow, \ v_O \uparrow, \ v_{CE} \downarrow$

$$v_{Omax} = V_{CC} - v_{CEsat} \approx V_{CC}$$

T – reaches saturation

$$v_{Imax} = v_{Omax} + 0.7 \approx V_{CC} + 0.7$$

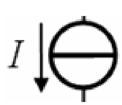
$v_I \downarrow, \ v_O \downarrow, \ v_{CE1} \downarrow$

$$v_{Omin} = -V_{CC} + v_{CE1sat} \approx -V_{CC}$$

T_1 – reaches saturation

$$v_{Imin} = v_{Omin} + 0.7 \approx -V_{CC} + 0.7$$

Current source



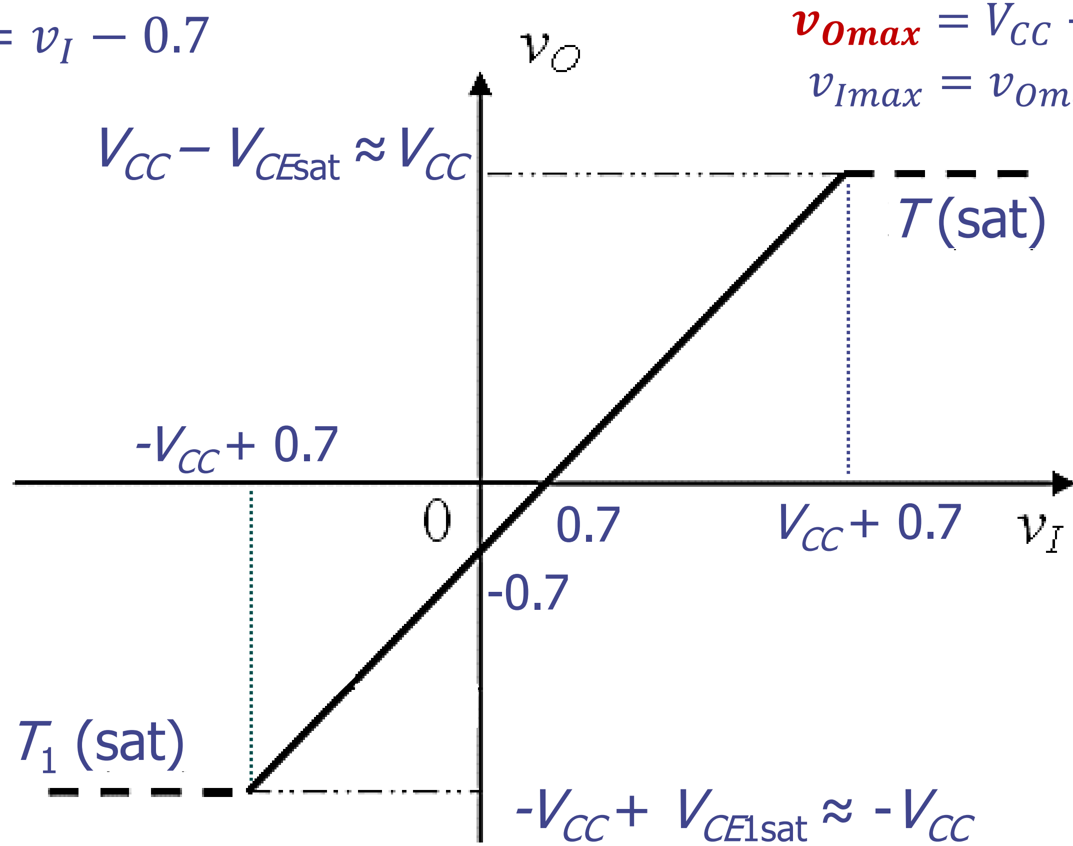
$$I = \frac{V_{CC} - V_{BE2}}{R}$$

➢ Class A – VTC

$v_O = v_I - v_{BE} = v_I - 0.7$

$\boldsymbol{v_{Omax}} = V_{CC} - v_{CEsat} \approx \boldsymbol{V_{CC}}$

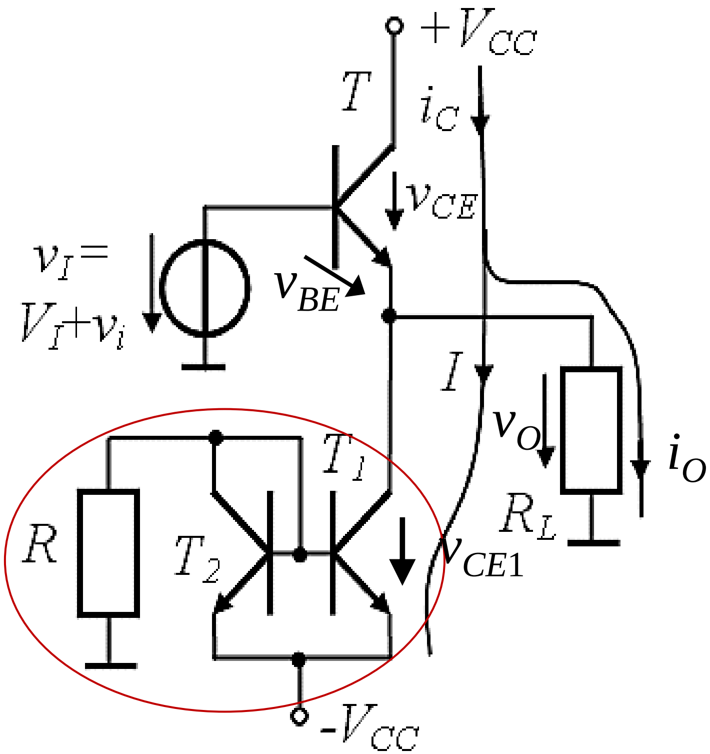
$v_{Imax} = v_{Omax} + 0.7 \approx V_{CC} + 0.7$



$\boldsymbol{v_{Omin}} = -V_{CC} + v_{CE1sat} \approx \boldsymbol{-V_{CC}}$

$v_{Imin} = v_{Omin} + 0.7 \approx -V_{CC} + 0.7$

➢ Class A – maximum output voltage swing



$$\boldsymbol{i_C} = I + i_O = I + \frac{v_O}{R_L}$$

$$\boldsymbol{i_{Cmax}} = I + \frac{v_{Omax}}{R_L} = I + \frac{V_{CC}}{R_L}$$

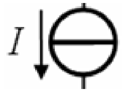
$$\boldsymbol{i_{Cmin}} = I + \frac{v_{Omin}}{R_L} = I - \frac{V_{CC}}{R_L}$$

T – (a_F) implies $i_{Cmin} > 0$

$$I - \frac{V_{CC}}{R_L} > 0$$

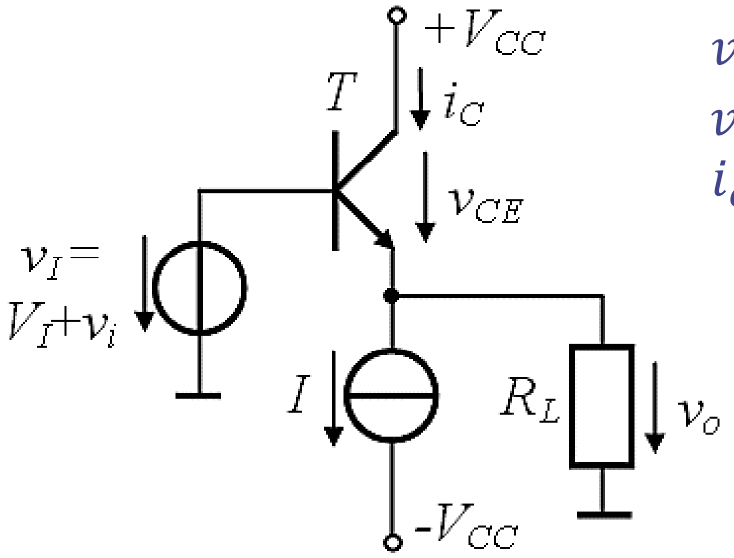
$$\boldsymbol{R_L I > V_{CC}}$$

Current source



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

➢ Class A – powers



$$v_i(t) = \hat{V}_i \sin \omega t$$
$$v_o(t) = \hat{V}_o \sin \omega t$$
$$i_o(t) = \hat{I}_o \sin \omega t$$

$$\hat{I}_o = \frac{\hat{V}_o}{R_L}$$

Average power from the power supplies

$$P_{PS} = P_{PS+} + P_{PS-} = V_{CC} i_{C,\,average} + V_{CC} I$$

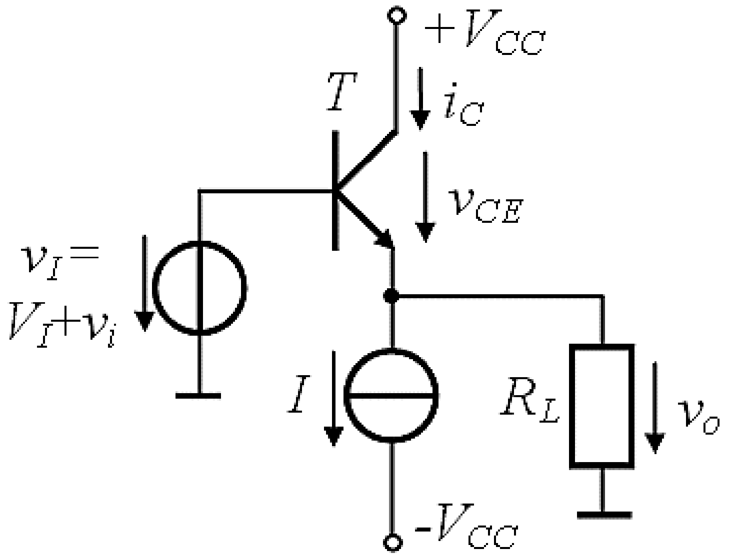
$$i_C(t) = I + \frac{v_o(t)}{R_L} = I + \frac{\hat{V}_o \sin \omega t}{R_L}$$

$$i_{C,average} = I$$

$$P_{PS} = 2V_{CC} I$$

Same power is consumed regardless the magnitude of the input voltage (even if no input variable voltage is applied) => reduced circuit efficiency.

Class A – powers



Instantaneous output power

$$p_o(t) = i_o(t) v_o(t) = \frac{{v_o}^2(t)}{R_L} = \frac{\hat{V}_o^2 (\sin \omega\, t)^2}{R_L}$$

Average output power

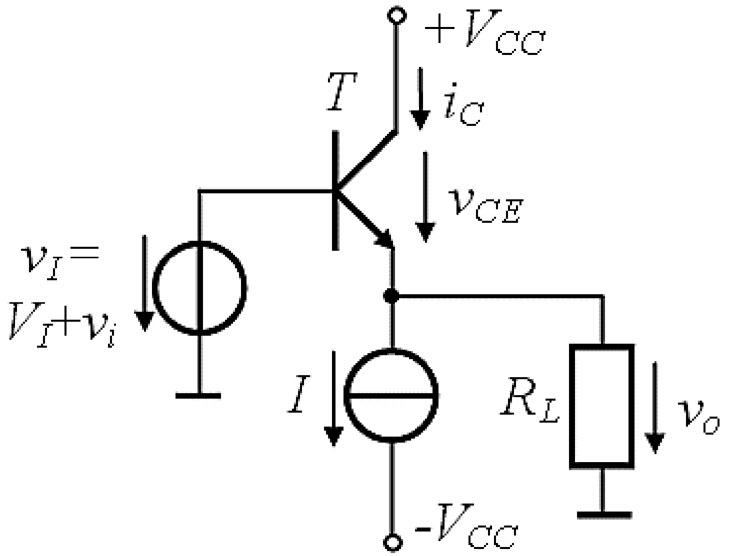
$$P_o = \frac{1}{T} \int_0^T \frac{\hat{V}_o^2}{R_L} \left(\sin \frac{2\pi}{T} t \right)^2 dt$$

For sinusoidal output voltage and current:

$$P_o = v_{o\_rms} i_{o\_rms} = \frac{\hat{V}_o}{\sqrt{2}} \frac{\hat{I}_o}{\sqrt{2}} = \frac{\hat{V}_o \hat{I}_o}{2} = \frac{\hat{V}_o^2}{2R_L}$$

$$P_o = \frac{\hat{V}_o^2}{2R_L}$$

Class A – efficiency



Average efficiency

$$\eta = \frac{P_o}{P_{PS}} = \frac{\frac{\hat{V}_o^2}{2R_L}}{2V_{CC}I} = \frac{\hat{V}_o^2}{4V_{CC}R_L I}$$

Maximum average efficiency

$\hat{V}_o = V_{CC}$ $\eta_{\max}$

R_L as small as possible, but keeping the maximum output swing ($R_L I \geq V_{CC}$)

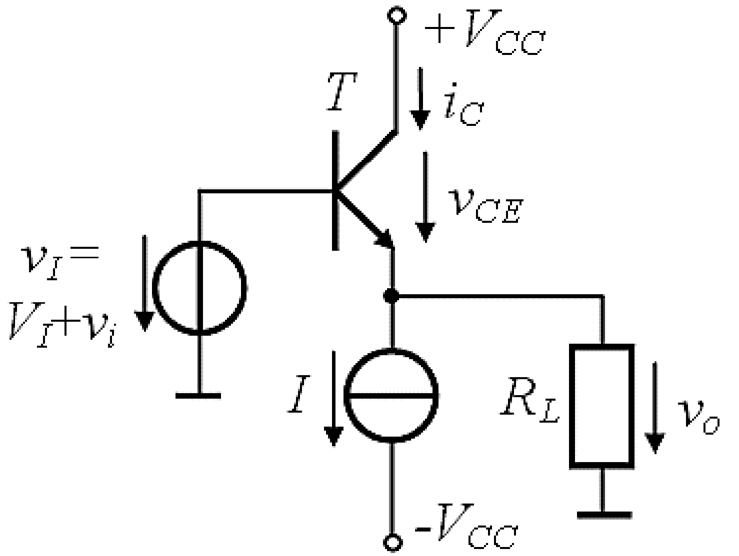
$R_L I = V_{CC}$

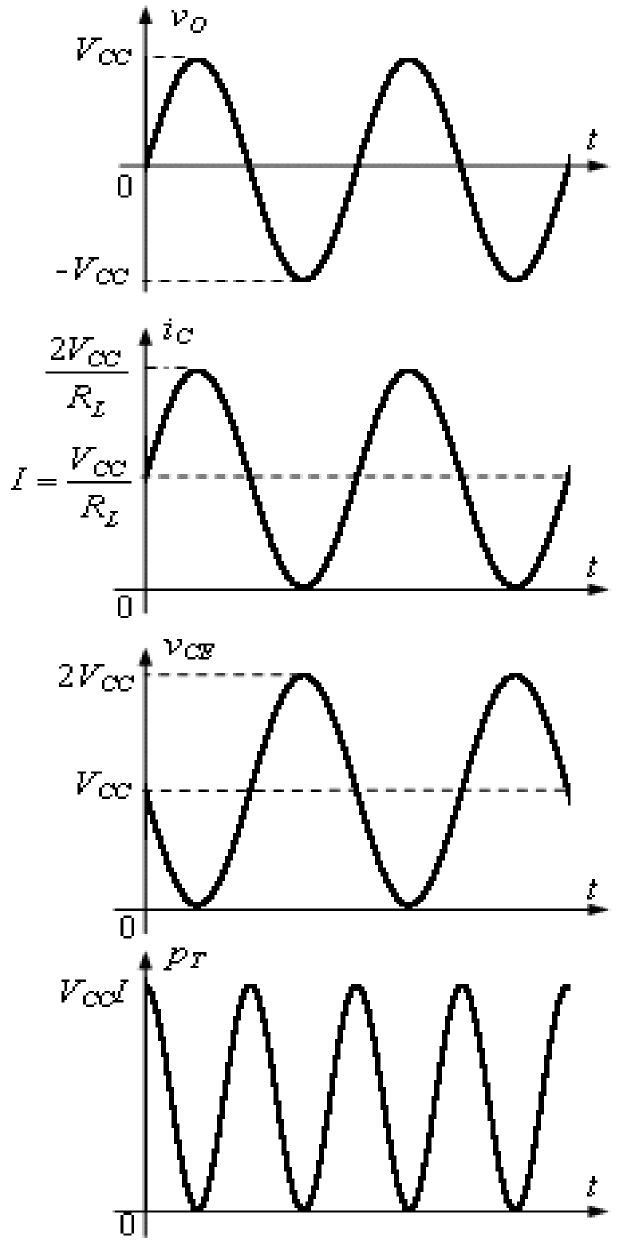
$$\eta_{max} = \frac{P_o}{P_{PS}} = \frac{V_{CC}^2}{4V_{CC}V_{CC}} = \frac{1}{4}$$

$\eta_{\max} = 25\%$

IRL $\eta \leq 20\%$

➢ Class A – waveforms





$$v_o(t) = V_{CC} \sin \omega t$$

$$i_C(t) = I + \frac{v_o(t)}{R_L}$$

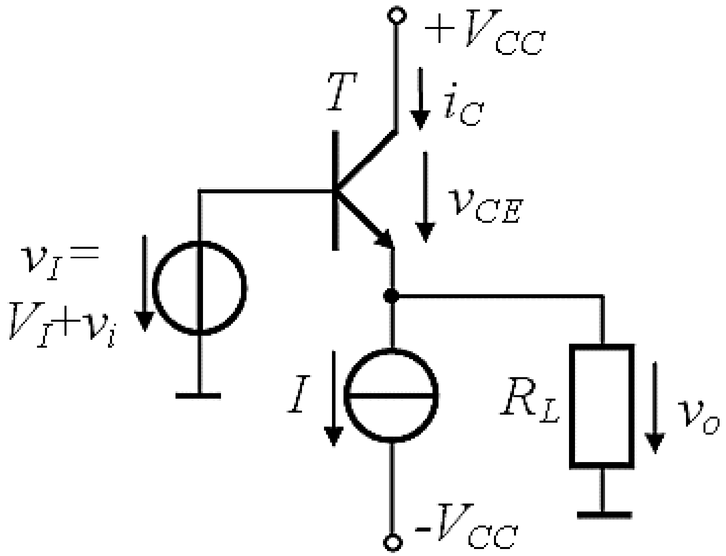
$$v_{CE}(t) = V_{CC} - v_o(t)$$

$$p_T = i_C(t) v_{CE}(t)$$

Assume the criteria for maximum efficiency are met:

$$\hat{V}_O = V_{CC}$$
$$R_L I = V_{CC}$$

➢ Class A – summary



$$P_o = \frac{\hat{V}_o^2}{2R_L}$$

$$P_{PS} = 2V_{CC}I$$

$$\eta_{\max} = \frac{1}{4} = 25\%$$

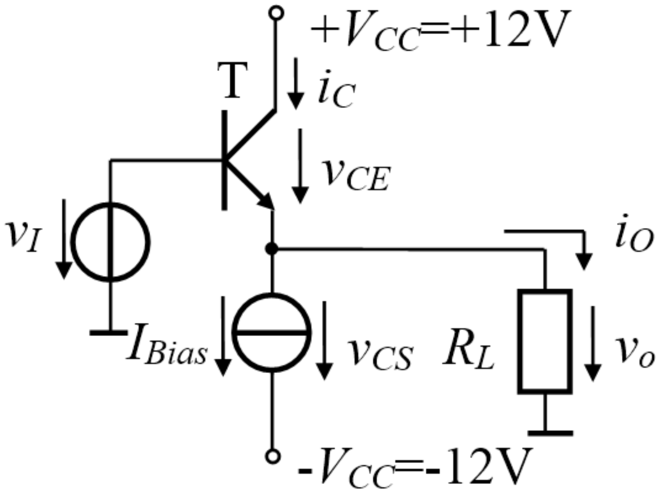
- emitter **follower** for variable input voltage

- common collector (CC) topology

- *T* – always on

$$v_o \approx v_i$$

➢ Class A – example



$v_{BE,on}$ = 0.7 V, I_{bias} = 0.2 A, R_L =75 Ω,
$v_I(t)$ = 0.7+6sinωt [V]

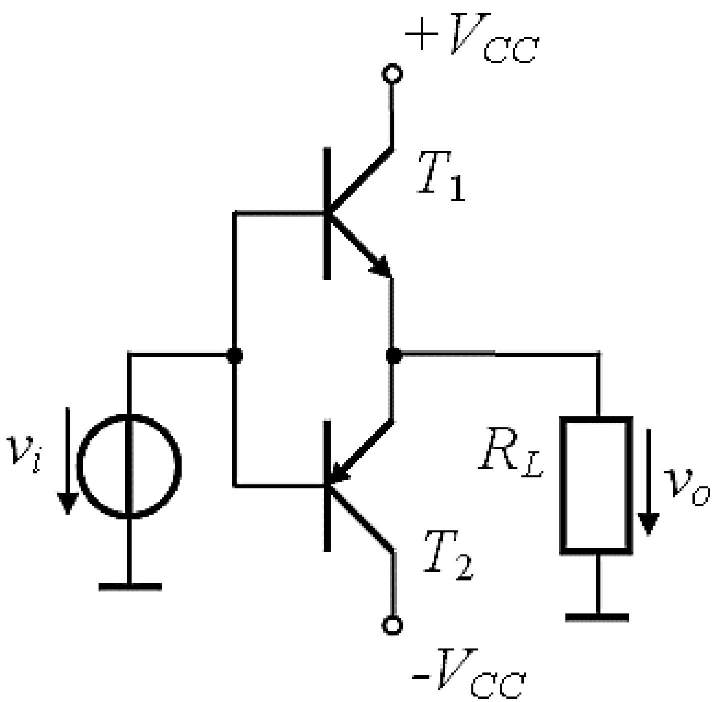
a) Plot the VTC $v_O(v_I)$. The current source is active for v_{CS} > 0V. Indicate the transistor state (*off*, a_F, *exc*) for every region of the VTC.

b) Plot $v_I(t)$, $v_O(t)$, $i_O(t)$, $v_{CE}(t)$ and $i_C(t)$.

c) What is the average value of the power dissipated by the load and average efficiency?

d) Explain why the average efficiency is less than the maximum average efficiency possible for this stage.

➢ Class B – circuit



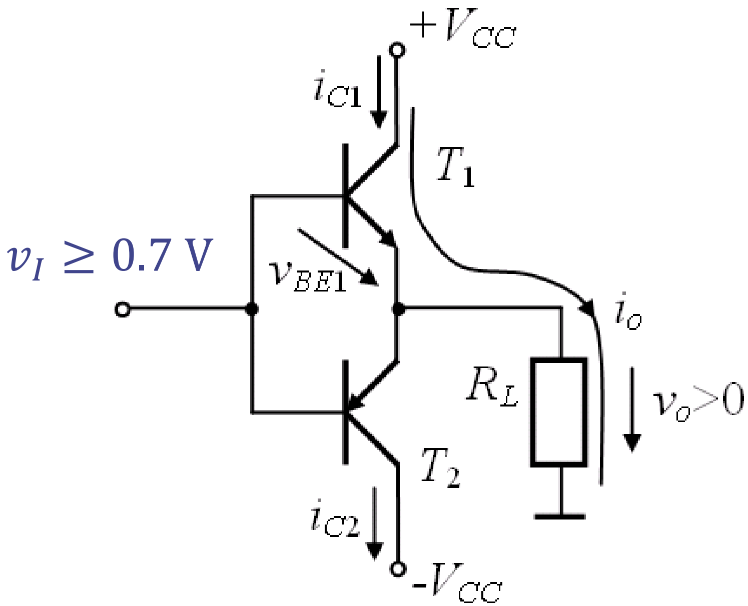
- each transistor conducts for half a period
- complementary pair of transistors
- push-pull arrangement

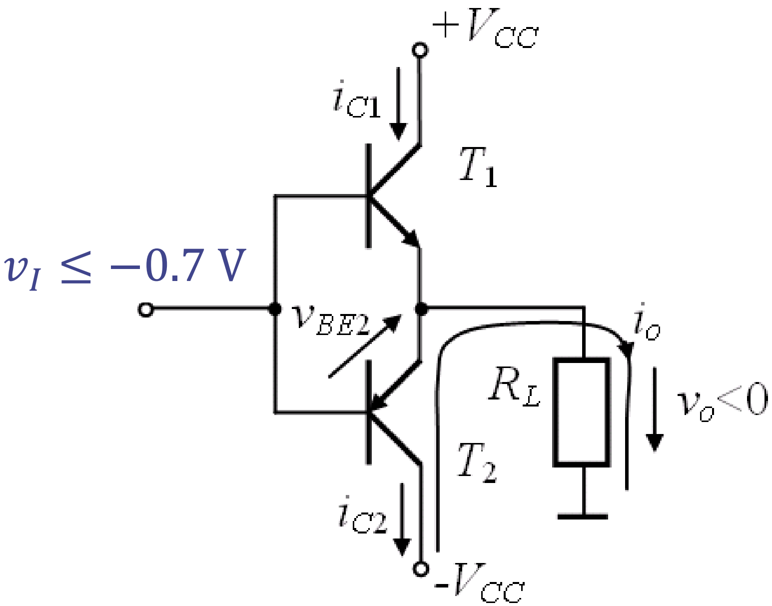
$v_O = ?$
$v_{Omax} = ?$
$v_{Omin} = ?$

Can T_1, T_2 be (on)/(off) at the same time?

➢ Class B – operation

$v_I \in (-0.7\text{ V};\ +0.7\text{ V})$ $T_{1,2}$ – (off) $v_O = 0\text{ V}$ $i_O = 0$





$v_I \geq 0.7\text{ V}$ T_1 – (on), T_2 – (off)

$v_O = v_I - v_{BE1} = v_I - 0.7\text{ V}$

$i_O > 0$ $i_{C1} = i_O$ $i_{C2} = 0$

$v_{Omax} = V_{CC} - v_{CE1sat} \approx V_{CC}$

$v_I \leq -0.7\text{ V}$ T_1 – (off), T_2 – (on)

$v_O = v_I - v_{BE2} = v_I + 0.7\text{ V}$

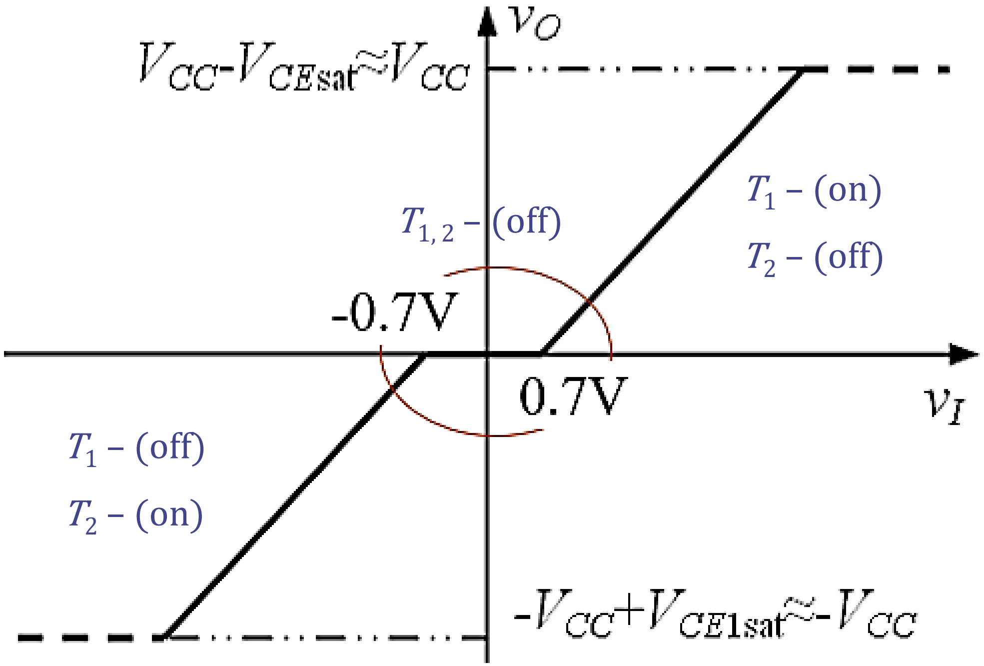
$i_O < 0$ $i_{C2} = -i_O$ $i_{C1} = 0$

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

➢ Class B – VTC

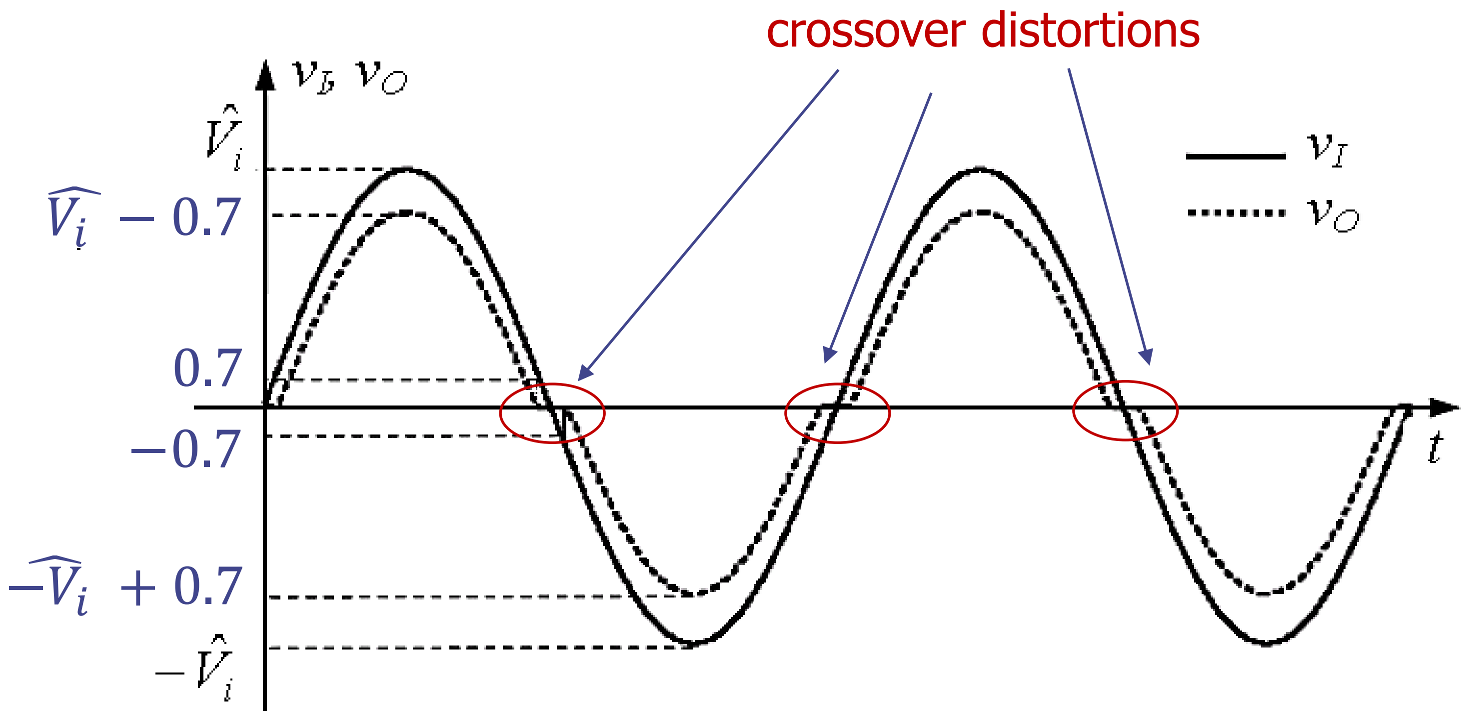
$$v_{Omax} = V_{CC} - v_{CE1sat} \approx V_{CC}$$

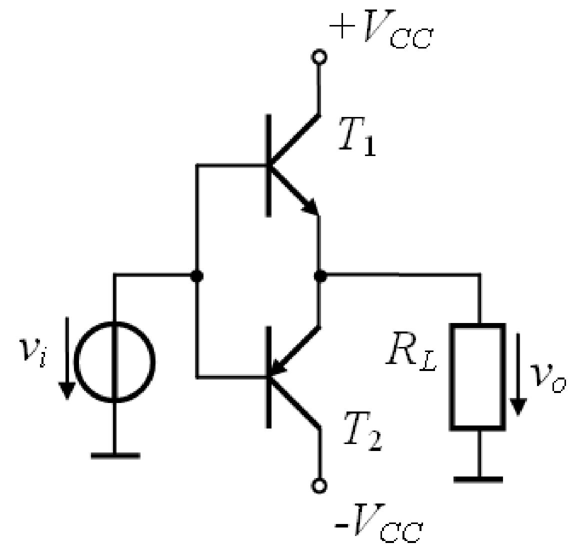
$$v_o = \begin{cases} v_I - 0.7\text{ V}, & v_I \geq 0.7\text{ V} \\ 0, v_I \in (-0.7\text{ V};\ +0.7\text{ V}) \\ v_I + 0.7\text{ V}, & v_I \leq -0.7\text{ V} \end{cases}$$



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

➢ Class B – waveforms





➢ Class B – waveforms

- assume $\hat{V}_o$ – high enough to neglect crossover distortions

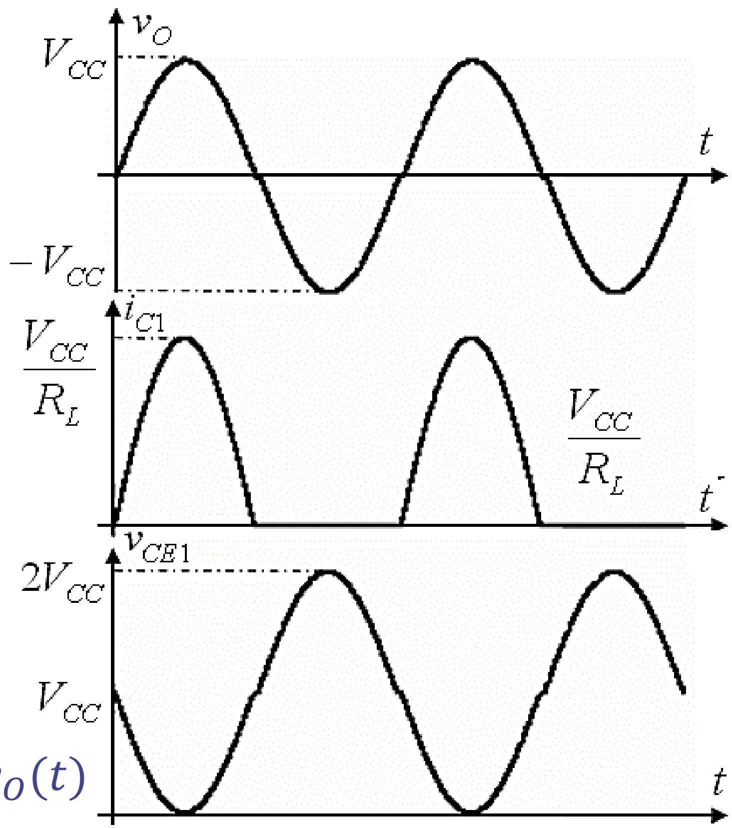
$$v_o(t) = \hat{V}_o \sin \omega t$$

$$\hat{V}_o = V_{CC}$$

$$i_{C1}(t) = v_O(t)/R_L$$

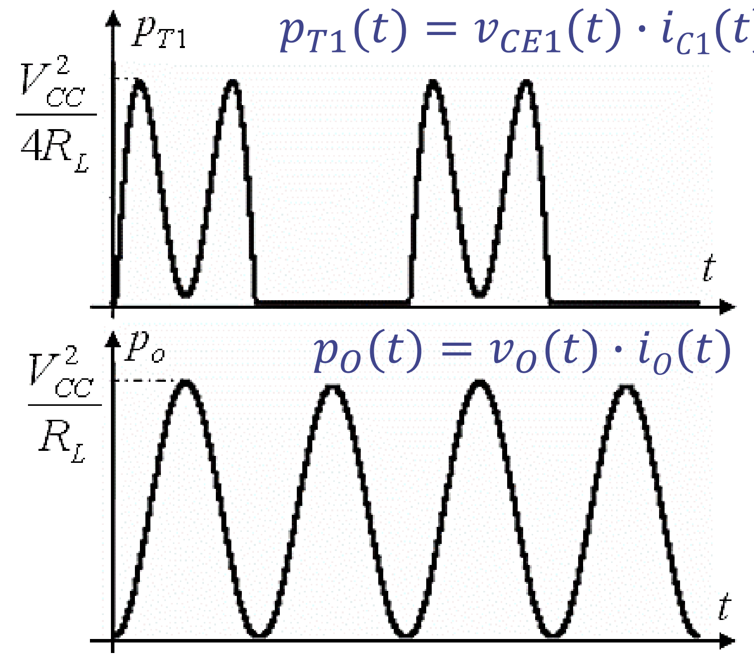
T_1 – (on)

$$v_{CE1}(t) = V_{CC} - v_O(t)$$



$$p_{T1}(t) = v_{CE1}(t) \cdot i_{C1}(t)$$

$$p_O(t) = v_O(t) \cdot i_O(t)$$



➢ Class B – powers & efficiency

Average power from the power supplies

$$P_{PS}^{+} = \frac{1}{T}\int_0^T V_{CC}\, i_{C1}(t)dt = \frac{1}{T}\int_0^{T/2} V_{CC}\frac{\hat{V}_o \sin\omega t}{R_L}dt = \frac{1}{T}\frac{V_{CC}\hat{V}_o}{R_L}\int_0^{T/2}\sin\frac{2\pi}{T}t\,dt$$

$$P_{PS}^{+} = \frac{1}{\pi}\frac{V_{CC}\hat{V}_o}{R_L}$$

$$P_{PS} = P_{PS}^{+} + P_{PS}^{-} = \frac{2}{\pi}\frac{V_{CC}\hat{V}_o}{R_L}$$

For $\hat{V}_o = V_{CC}$

$$P_{PS\max} = \frac{2}{\pi}\frac{V_{CC}^2}{R_L}$$

Average output power

$$P_O = V_{Orms}I_{Orms} = \frac{\hat{V}_O^2}{2R_L}$$

For $\hat{V}_O = V_{CC}$

$$P_{O\max} = \frac{V_{CC}^2}{2R_L}$$

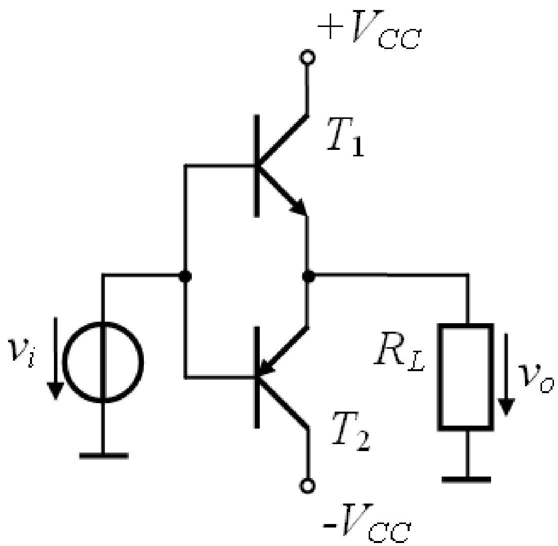
Average efficiency

$$\eta = \frac{P_O}{P_{PS}} = \frac{\hat{V}_O^2}{2R_L}\frac{\pi}{2}\frac{R_L}{V_{CC}\hat{V}_O} = \frac{\pi}{4}\frac{\hat{V}_O}{V_{CC}}$$

For $\hat{V}_o = V_{CC}$

$$\eta_{\max} = \frac{\pi}{4} = 78.5\%$$

➢ Class B – summary



$$P_{O\max} = \frac{V_{CC}^2}{2R_L}$$

$$P_{PS\max} = \frac{2}{\pi}\frac{V_{CC}^2}{R_L}$$

$$\eta_{\max} = \frac{\pi}{4} = 78.5\%$$

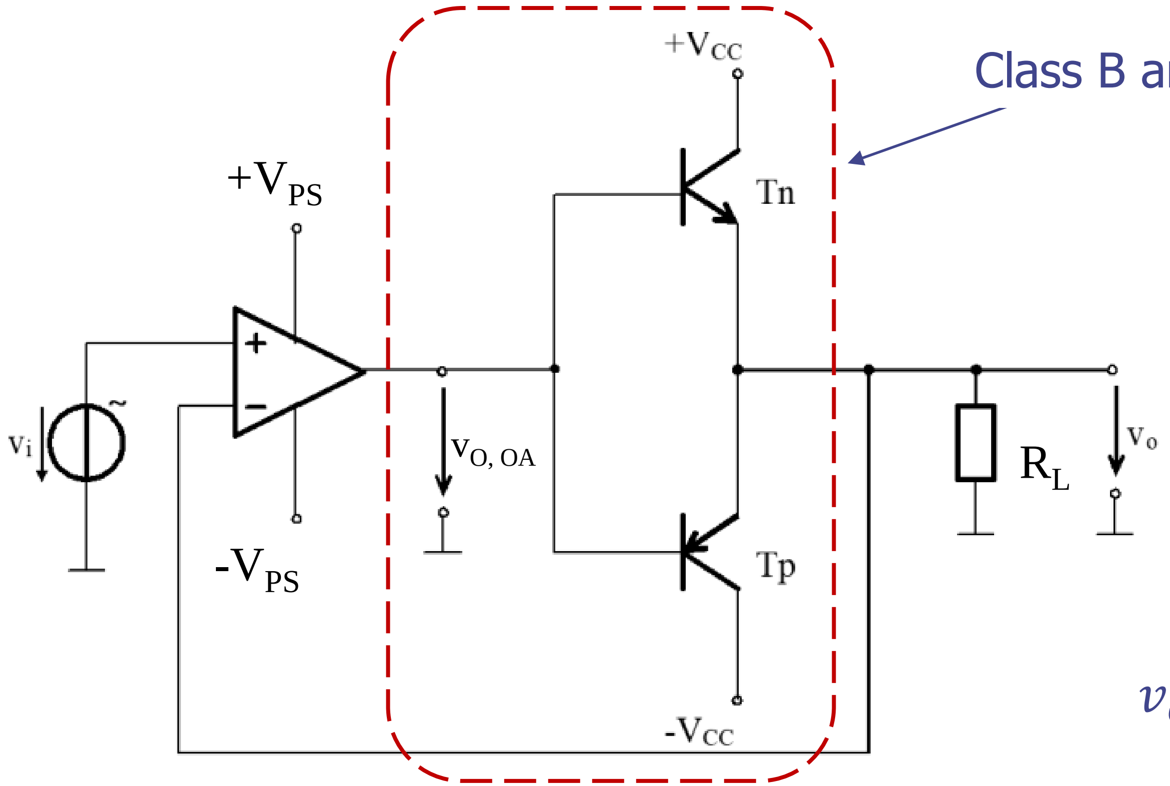
- each transistor conducts for half a period
- crossover distortions - how do we get rid of them?

Make them too small to matter – class B w/ additional OpAmp and global NF

OR

Eliminate them by compensating the ± 0.7 V – class AB

Class B w/ additional OpAmp and global NF



Class B amplifier

$$v_{O,\mathrm{OA}} = a \cdot v_D$$

$$v_D = V^+ - V^- = v_i - v_o$$

a - open-loop gain of the OpAmp

$$a_{LM741} = 2 \cdot 10^5$$

When $v_{O,\mathrm{OA}} \in (-0.7\ \mathrm{V};\ +0.7\ \mathrm{V})$

$T_{n,p}$ – (off) $v_O = 0$

no feedback

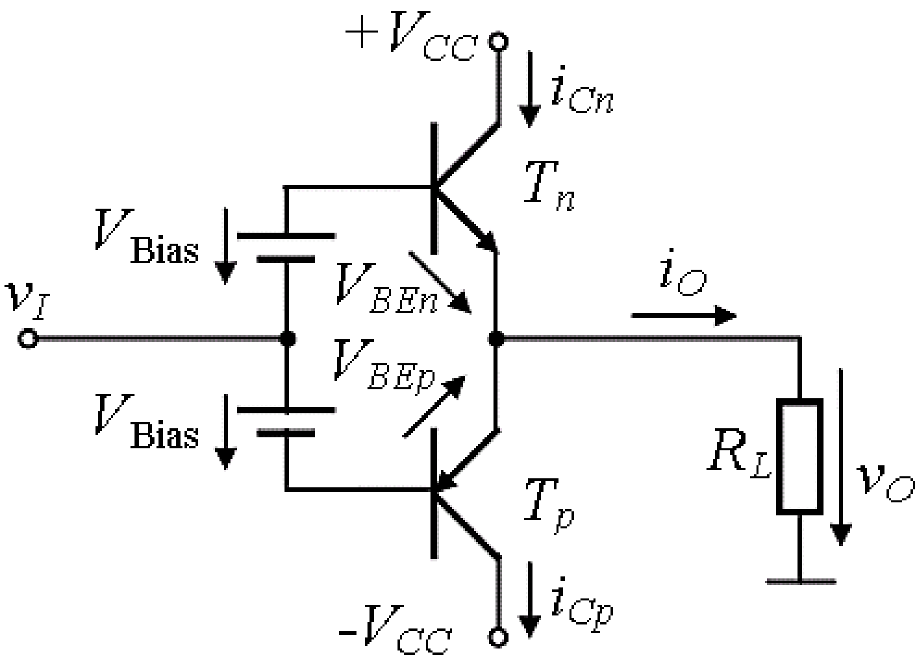
$$v_{O,\mathrm{OA}} = a \cdot v_i$$

$$v_i \in (-0.7\ \mathrm{V}/a;\ +0.7\ \mathrm{V}/a)$$

When $v_\mathrm{i} > -0.7\ \mathrm{V}/a$ T_n – (on), T_p – (off),
$v_\mathrm{i} < -0.7\ \mathrm{V}/a$ T_n – (off), T_p – (on),
the NF loop is active and $v_D = 0$ $v_O = v_i$

VTC? Crossover distortions?

➢ Class AB – circuit



The complementary transistors are biased with a small current.

$$V_{Bias} \approx 0.7\ \text{V}$$

$$I = I_S e^{\frac{V_{Bias}}{V_T}}$$

No more crossover distortions!

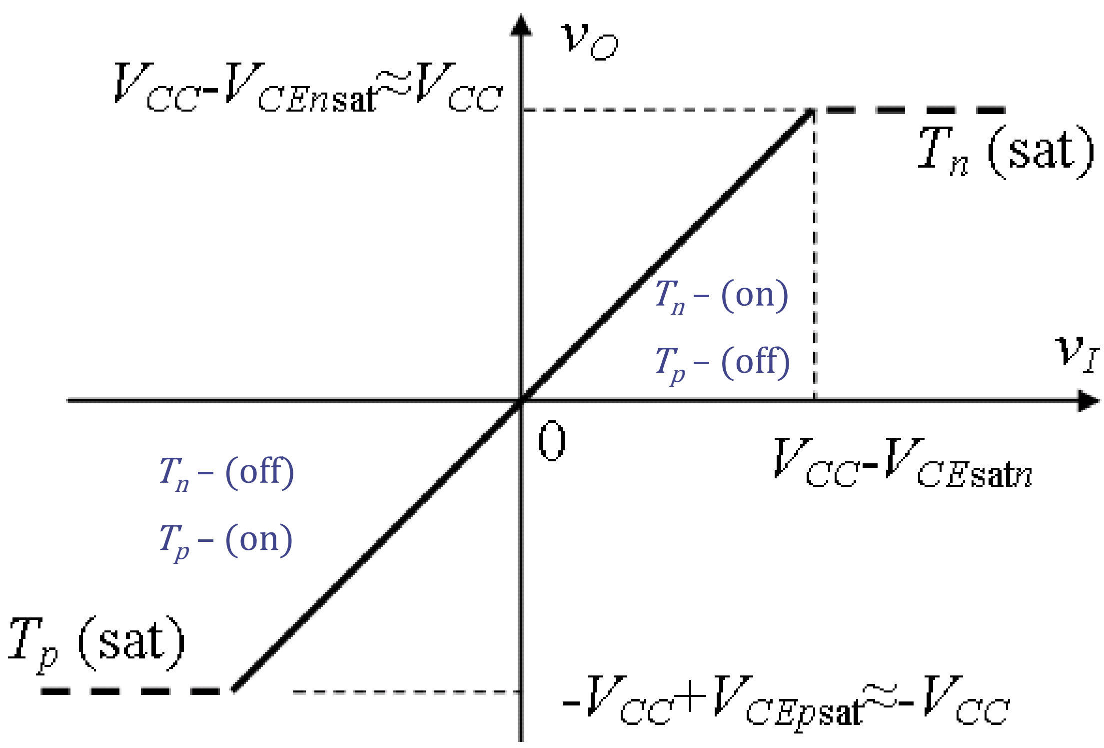
v_I - positive $\quad v_O(t) = v_I(t) + V_{Bias} - V_{BEn} \approx v_I(t)$

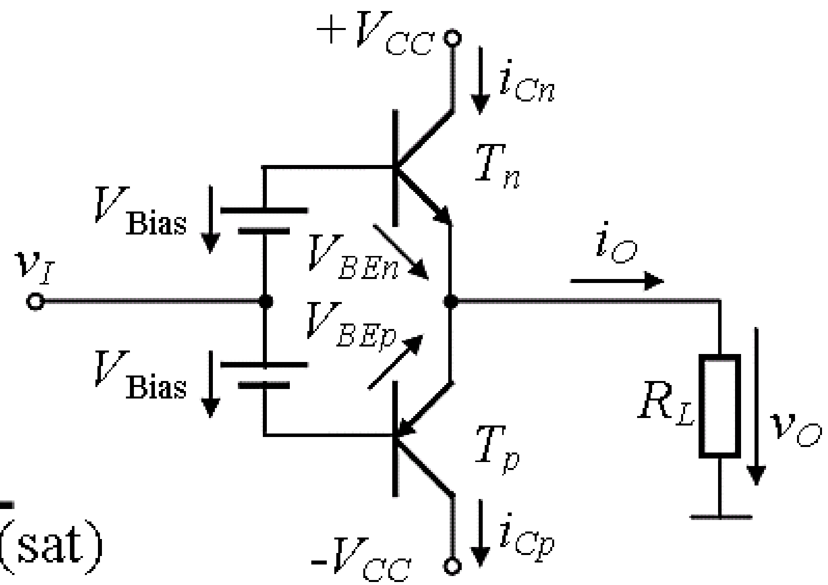
v_I - negative $\quad v_O(t) = v_I(t) - V_{Bias} - V_{BEp} \approx v_I(t)$

Class AB power amplifier

➢ Class AB – VTC

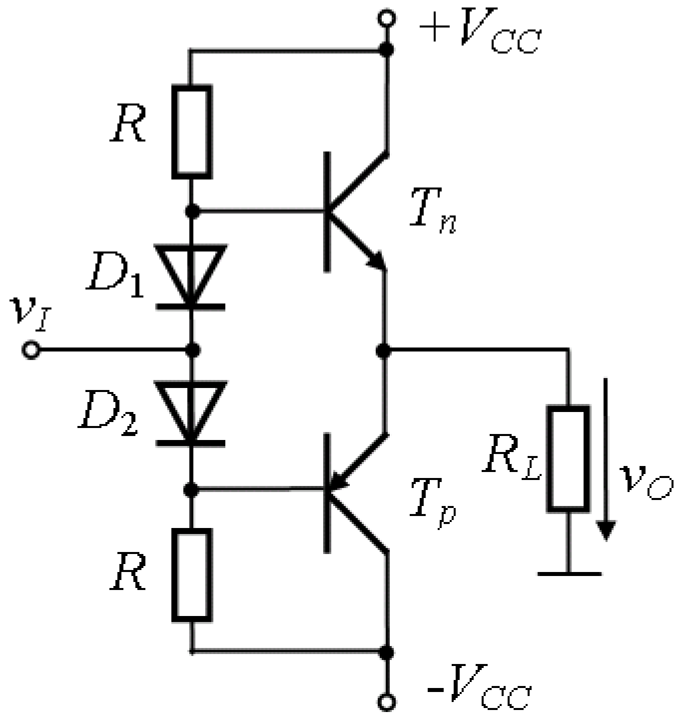
$v_O(t) = v_I(t)$

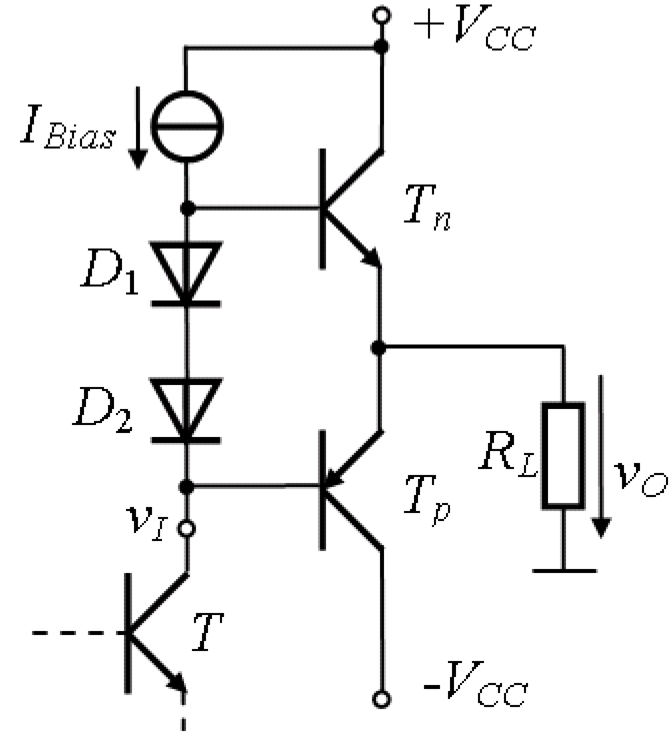




Solutions to generate V_{Bias}?

- Class AB – biasing using diodes





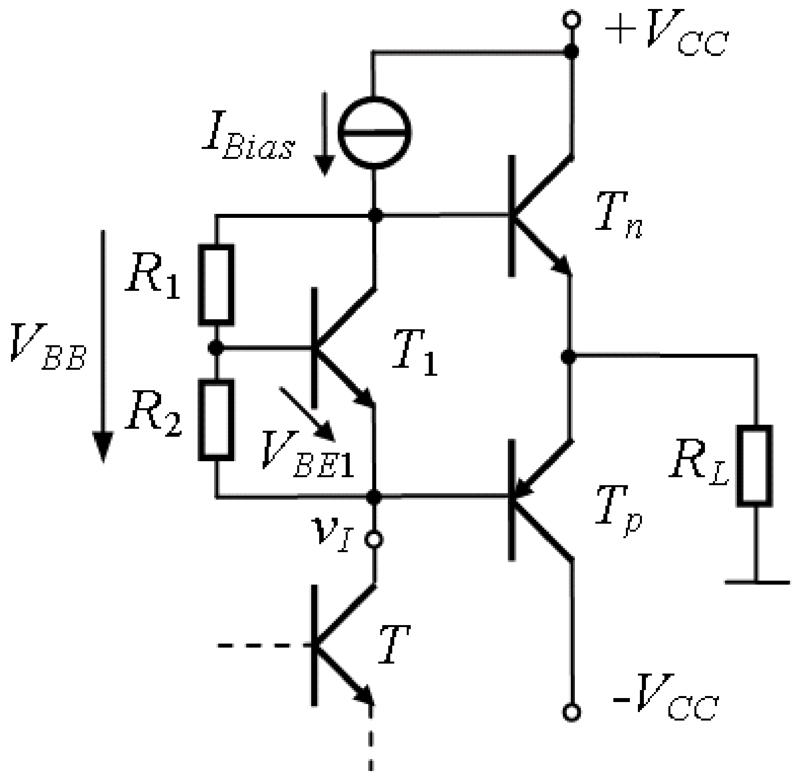
R should allow the currents in the diodes and in the bases of the transistors, even for maximum output current

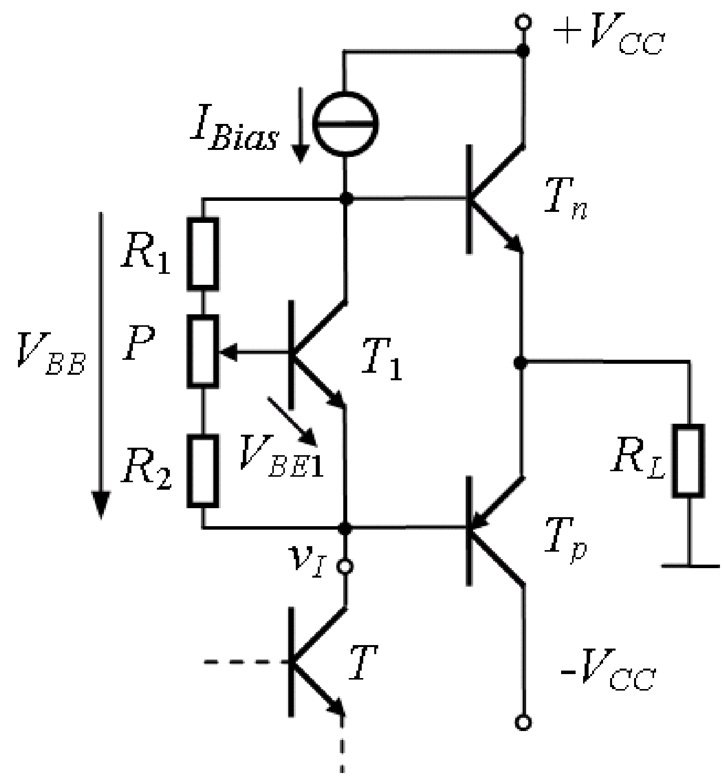
Sizing *R* – see Seminar 4

T - driver transistor from previous amplifier stage

OPTIONAL

- Class AB – biasing using V_{BE} multiplier

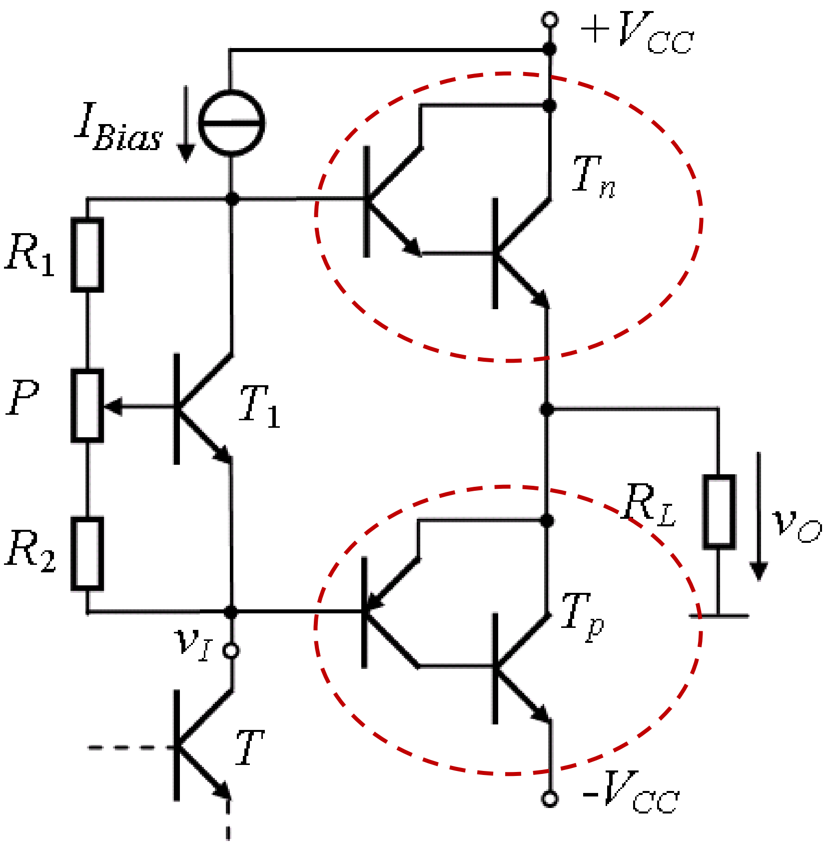


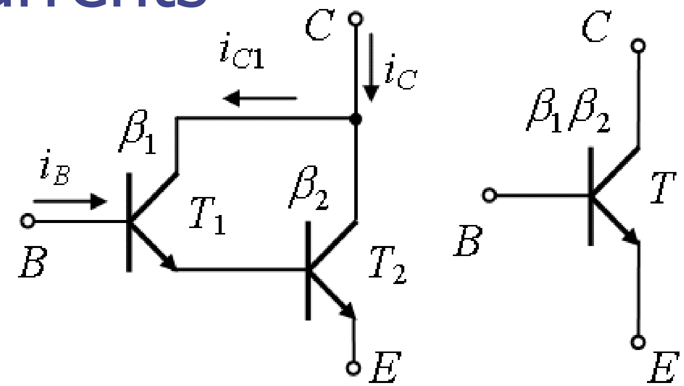


$$V_{BB} = \left(1 + \frac{R_1}{R_2}\right) V_{BE1}$$

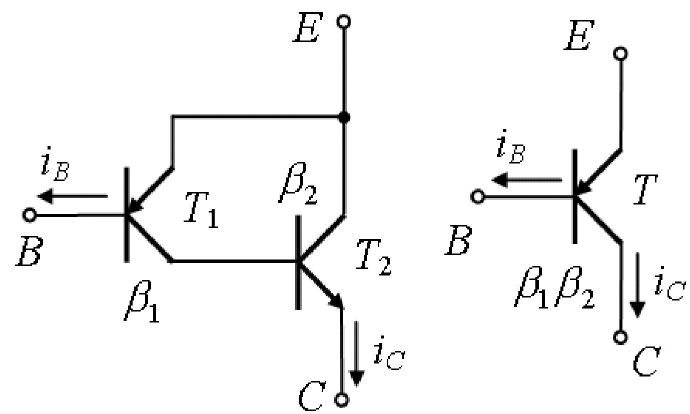
OPTIONAL

➢ Class AB – high output currents





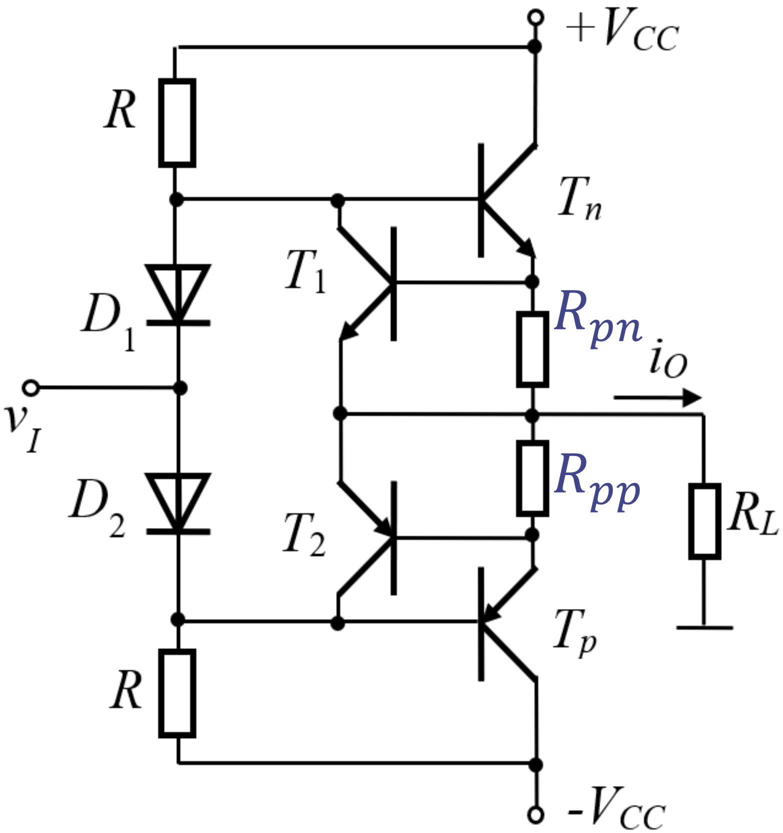
Darlington *npn* configuration



Compound *pnp* configuration
(preferred in IC)

OPTIONAL

➢ Class AB – short-circuit protection



Elements for short-circuit protection:

- T_1, R_{pn} when $v_o > 0$
- T_2, R_{pp} when $v_o < 0$

When $v_o > 0$

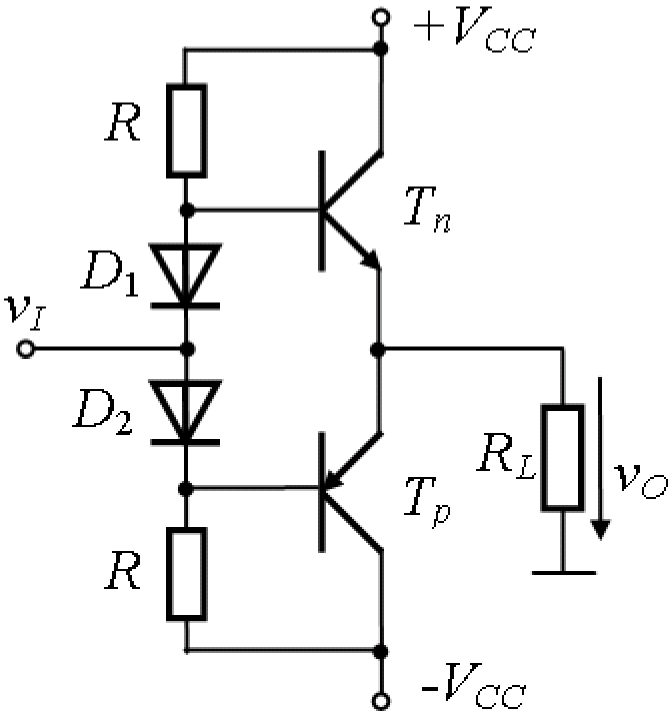
If $R_{pn} i_O < 0.7\ \text{V}$

$$T_1 - (\text{off});\quad i_O = \frac{v_O}{R_L}$$

If i_O increases, T_1 turns (on) when $R_{pn} i_O = 0.7\ \text{V}$

$$i_{Omax} = \frac{V_{BE1,on}}{R_{pn}} = \frac{0.7\ \text{V}}{R_{pn}}$$

➢ Class AB – summary



$$v_O(t) = v_I(t)$$

Powers & efficiency – same as for class B

$$P_{O\max} = \frac{V_{CC}^2}{2R_L}$$

$$P_{PS\max} = \frac{2}{\pi}\frac{V_{CC}^2}{R_L}$$

$$\eta_{\max} = \frac{\pi}{4} = 78.5\%$$

- no more crossover distortions – assuming perfect match between $V_{D,\ on}$ and V_{BE}

Summary

- Intro
- Class A power amplifier
- Class B power amplifier
- Class AB power amplifier

Next week: Feedback circuits