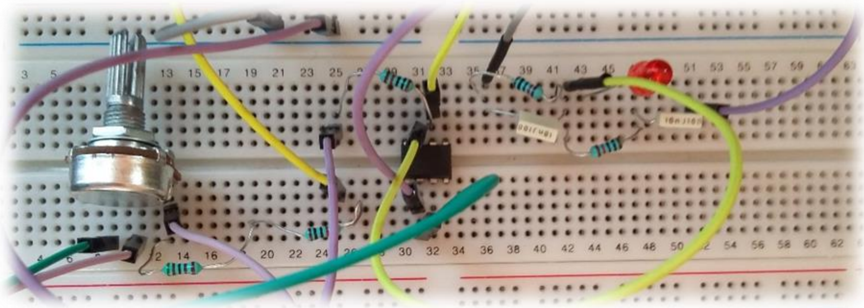


FUNDAMENTAL ELECTRONIC CIRCUITS

Assist. prof. Laura-Nicoleta IVANCIU, Ph.D.

C2 – Transistor amplifiers. DC biasing.

Contents

- Transistor amplifiers - intro
- MOSFET dc biasing
- BJT dc biasing

Operating regions for transistors

- Two extreme regions, passive:

 - **cutoff (off)**

$I_O = 0$; $V_O > 0$; ideal switch in off state

 - **extreme conduction (exc)**

$I_O = I_{Oex}$; $V_O = 0$; ideal switch in on state

completed

$V_{CT} < V_{Thn}$ or $V_{CT} > V_{CTex}$ - **switching transistor**

- An intermediate region, active:

active forward region **(a_F)**

$V_{Thn} < V_{CT} < V_{CTex}$ – **permanent conduction (amplifier)**

➢ To begin with

What signal (voltage/current, AC/DC) is used at the input of a transistor amplifier?

Is the output signal bigger/smaller? Same phase or inverted?

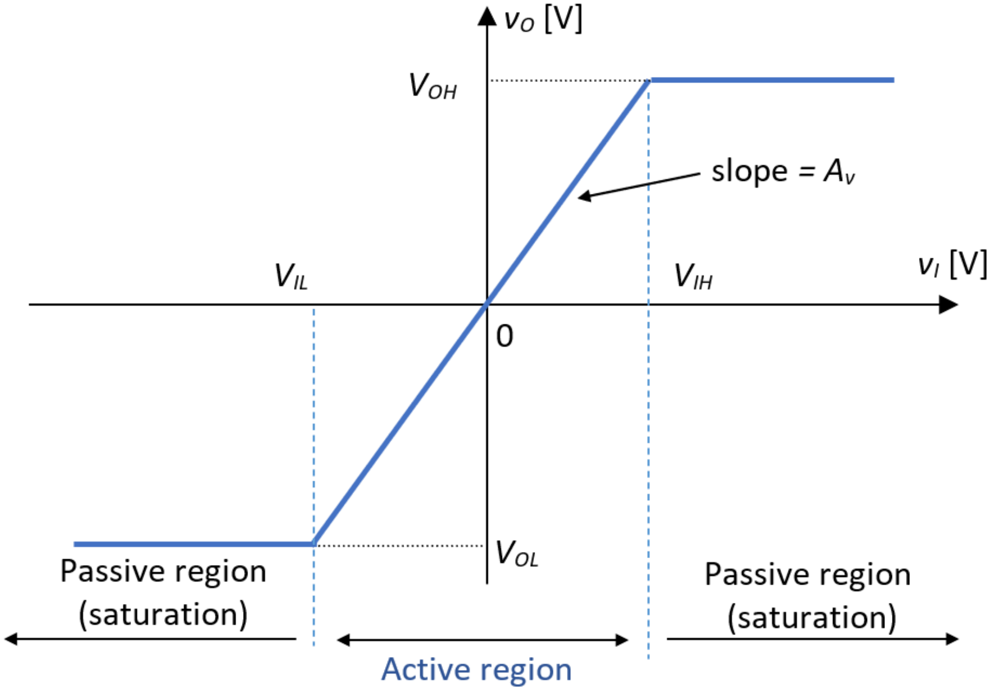
How many transistors in a basic transistor amplifier?

Who determines the gain of the amplifier?

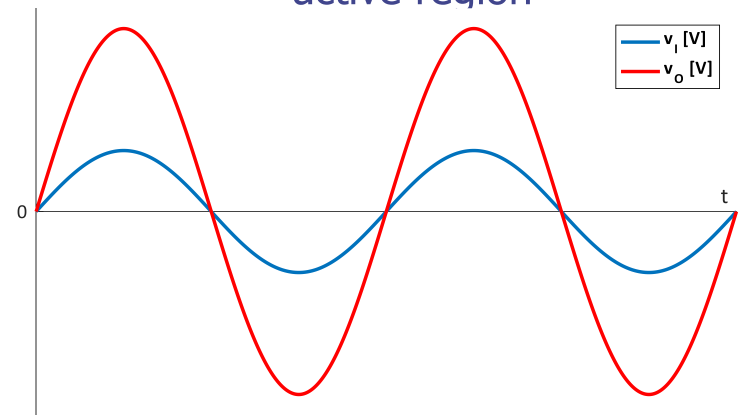
How do we make sure the transistor stays in a_F?

Transistor amplifiers - intro

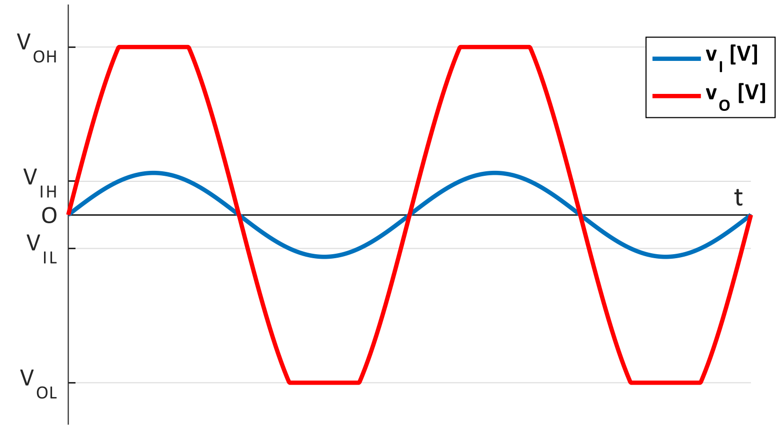
➢ OpAmp – revisited



active region



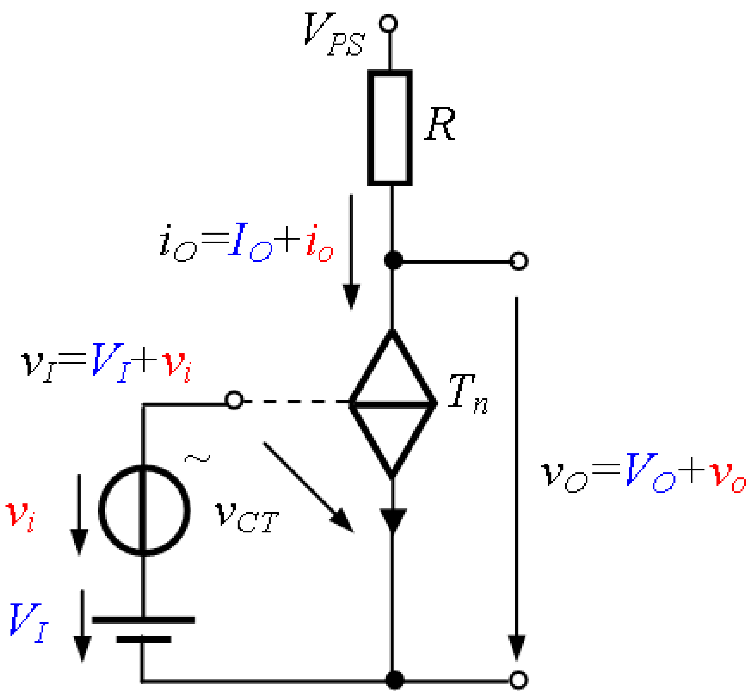
active and passive (saturation)



Input signal – low enough for the OpAmp to operate in the linear, active region

➢ Transistors as amplifiers – concept circuit

In (a_F), the transistor operates **around** a dc **operating point** (aka bias point, quiescent point), denoted ***Q* (*V*$_O$; *I*$_O$)**



DC signals

V_{PS} – dc supply

V_I – dc component of the input

V_O – dc output voltage, **I_O** – dc output current

***Q* (*V*$_O$; *I*$_O$)** is computed/determined by V_{PS} and V_I

AC signals

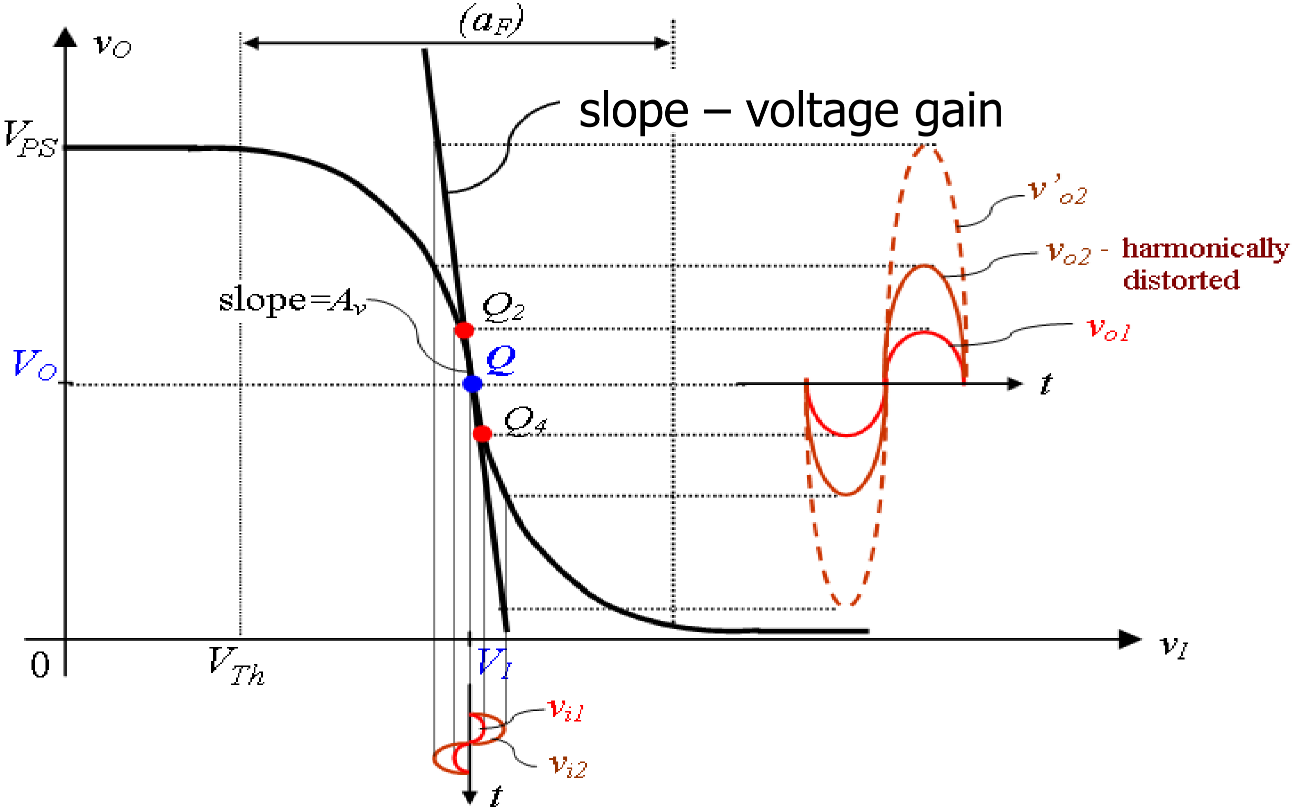
v_i – ac input voltage (to be amplified)

v_o – ac output voltage (amplified voltage)

i_o – ac output current

The ac (variable) signal is superimposed on the dc components.

➢ VTC of an inverting transistor amplifier circuit



Voltage gain: $A_v = \frac{v_o}{v_i}$

The **middle region** of the VTC can be approximated as linear.

Input signal – small enough to be inside the linear region.

Small signal: operation of the amplifier in the **narrow linear region around *Q***

Transistor amplifiers - intro

To use the transistor as an amplifier:

- the transistor - biased as close as possible to the middle of the active region
- the instantaneous (mobile) operating point - in the active region
- the input variable signal - small (linear region around *Q*)

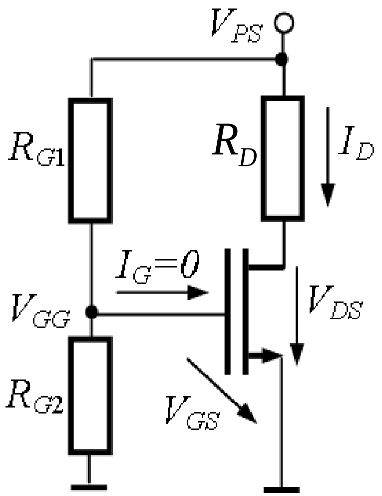
To bias ≡ to provide appropriate dc current and/or voltage

Q **– operating point**

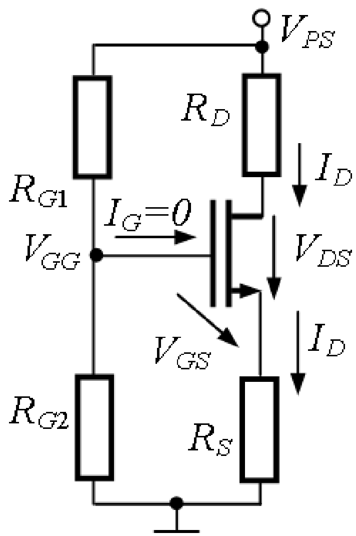
- stable and predictibile
- independent of transistor parameters

Methods for setting *Q* in the middle of the active region?

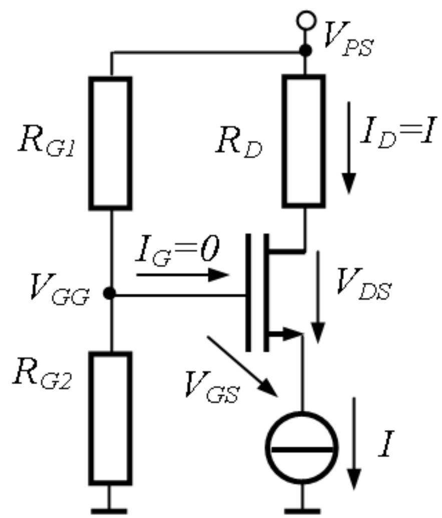
➢ MOSFET dc biasing - methods



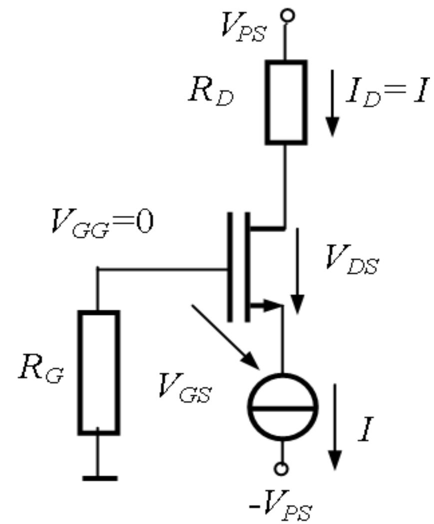
3 resistors
single supply



4 resistors
single supply



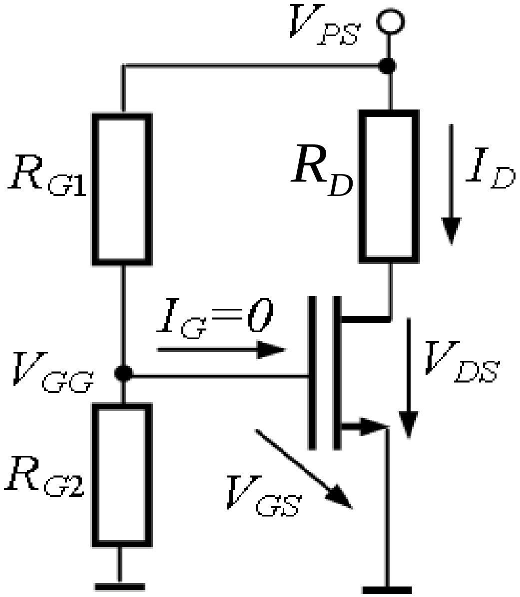
current source
single supply



current source
differential supply

MOSFET dc biasing

➢ 3 resistors, single supply



$$V_{GG} = V_{GS} = \frac{R_{G2}}{R_{G1}+R_{G2}} V_{PS}$$

$$I_D = \beta(V_{GS} - V_{Th})^2$$

$$V_{DS} = V_{PS} - I_D R_D$$

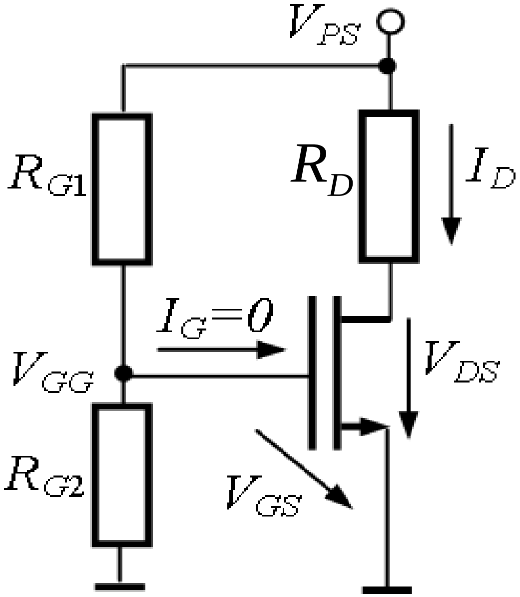
$Q\,(V_{DS};\ I_{DS}) = ?$

☺ very simple

☹ I_D depends on the transistor parameters, β and V_{Th}

☹ cannot assure the stability of Q

➢ 3 resistors, single supply - example



$R_{G1} = 7.6\ \mathrm{M\Omega}$

$R_{G2} = 2.4\ \mathrm{M\Omega}$

$R_D = 29.1\ \mathrm{K\Omega}$

$V_{PS} = 5\ \mathrm{V}$

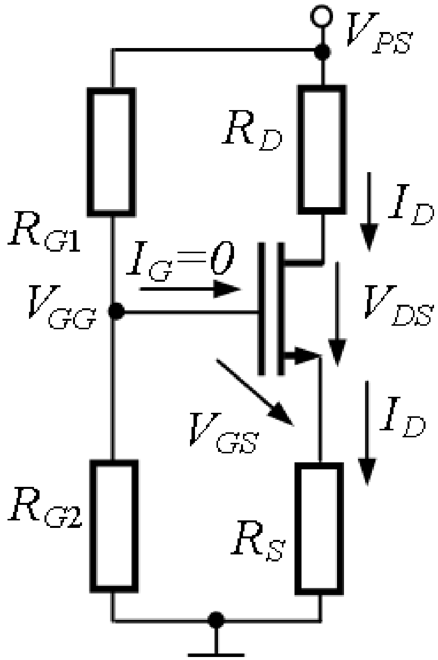
$V_{Th} = 0.8\ \mathrm{V}$

$\beta = 500 \mu A/V^2$

$Q\,(V_{DS}\,;\ I_{DS}) = Q\,(2.67\ \mathrm{V}\,;\ 80\ \mu\mathrm{A})$

MOSFET dc biasing

➢ 4 resistors, single supply



$$V_{GG} = \frac{R_{G2}}{R_{G1}+R_{G2}} V_{PS}$$

$$\begin{cases} V_{GS} = V_{GG} - I_D R_S \\ I_D = \beta(V_{GS} - V_{Th})^2 \end{cases}$$

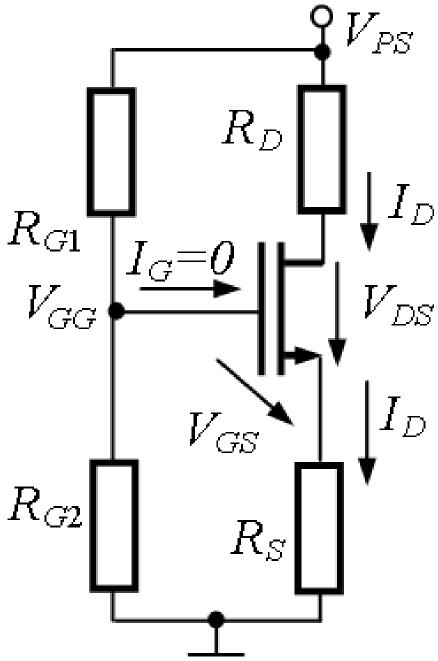
$$V_{DS} = V_{PS} - I_D(R_D + R_S)$$

$Q\,(V_{DS};\, I_{DS}) = ?$

- 2 unknowns, V_{GS} and I_D
- 2nd order system of equations
- select suitable value for I_D so that T - a_F

MOSFET dc biasing

- 4 resistors, single supply



$$V_{GG} = \frac{R_{G2}}{R_{G1}+R_{G2}} V_{PS}$$

$$\begin{cases} V_{GS} = V_{GG} - I_D R_S \\ I_D = \beta(V_{GS} - V_{Th})^2 \end{cases}$$

$$V_{DS} = V_{PS} - I_D(R_D + R_S)$$

$Q\,(V_{DS};\, I_{DS}) = ?$

- V_{GS} also depends on I_D

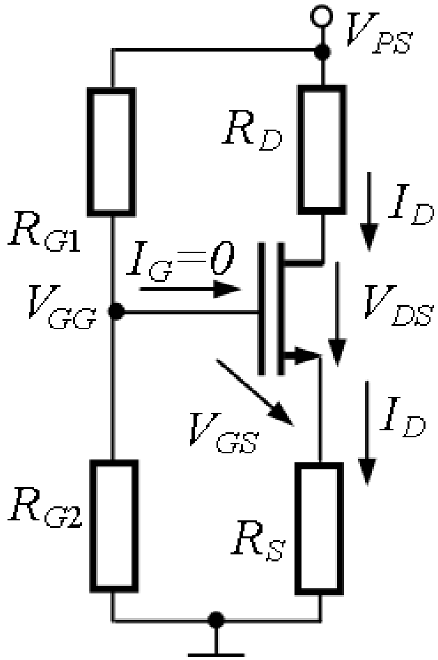
$I_D\uparrow$, $R_S I_D\uparrow$, $V_{GS}\downarrow$, $I_D\downarrow$ - negative feedback due to R_S

☺ Q – more stable when certain parameters change

☹ increased computational complexity

MOSFET dc biasing

4 resistors, single supply – example 1



R_{G1} = 3 MΩ

R_{G2} = 1 MΩ

R_D = 3 KΩ

R_S = 1 KΩ V_{PS} = 20 V

V_{Th} = 2 V

β = 0.5 mA/V²

$$V_{GS} = V_{GG} - I_D R_S$$

$$I_D = \beta(V_{GS} - V_{Th})^2$$

$$V_{GG} = \frac{R_{G2}}{R_{G1} + R_{G2}} V_{PS} = 5\ \text{V}$$

$I_D^2 - 8I_D + 9 = 0$ I_{D1} = 6.65 mA; I_{D2} = 1.35 mA

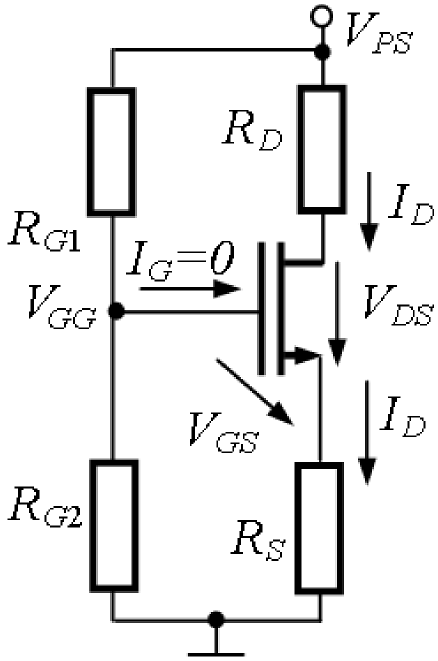
I_{D1} is not suitable; results in $V_{GS} < 0$

$$V_{DS} = V_{PS} - I_D(R_D + R_S) = 14.6\ \text{V}$$

$$I_D = I_{D2} = 1.35\ \text{mA}$$

$Q\,(V_{DS};\, I_{DS}) = Q\,(14.6\ \text{V};\ 1.35\ \text{mA})$

➢ 4 resistors, single supply – example 2



$V_{PS} = 20$ V
$V_{Th} = 2$ V
$\beta = 0.5$ mA/V^2

Size the resistors so that $\boldsymbol{I_D} = 1$ mA.

Usually, $V_{DS} \approx V_{RD} \approx V_{RS} \approx 1/3 * V_{PS}$

$V_{RS} \approx 1/3 * V_{PS} \approx 7$ V

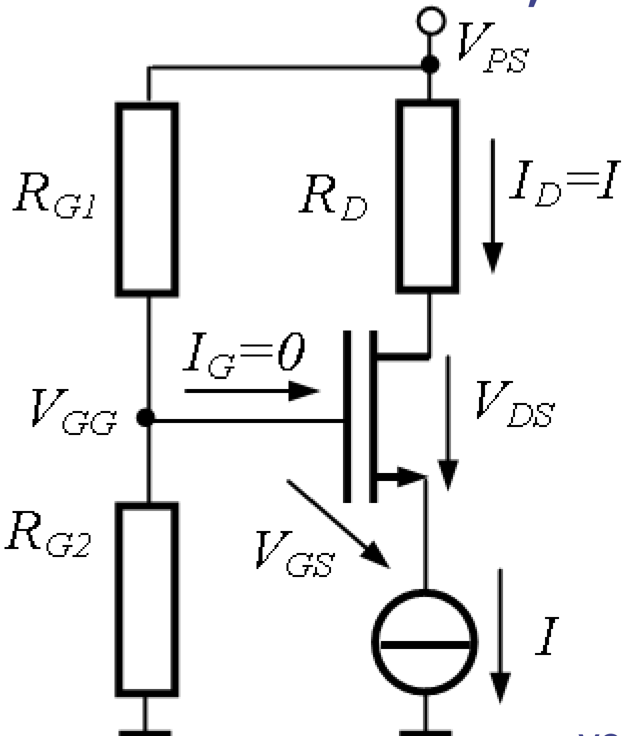
$R_S = 7\ \text{K}\Omega;\ R_D = 6\ \text{K}\Omega$

$$V_{GG} = V_{GS} + V_S = 4 + 7 = 11\ \text{V}$$

$$R_{G1} = 180\ \text{K}\Omega; \quad R_{G2} = 220\ K\Omega$$

MOSFET dc biasing

➢ Current source, single supply



$$I_D = I$$

$$V_{GG} = \frac{R_{G2}}{R_{G1} + R_{G2}} V_{PS}$$

$$V_{PS} = R_D I + V_{DS} - V_{GS} + V_{GG}$$

$$V_{DS} = V_{PS} - R_D I + V_{GS} - V_{GG}$$

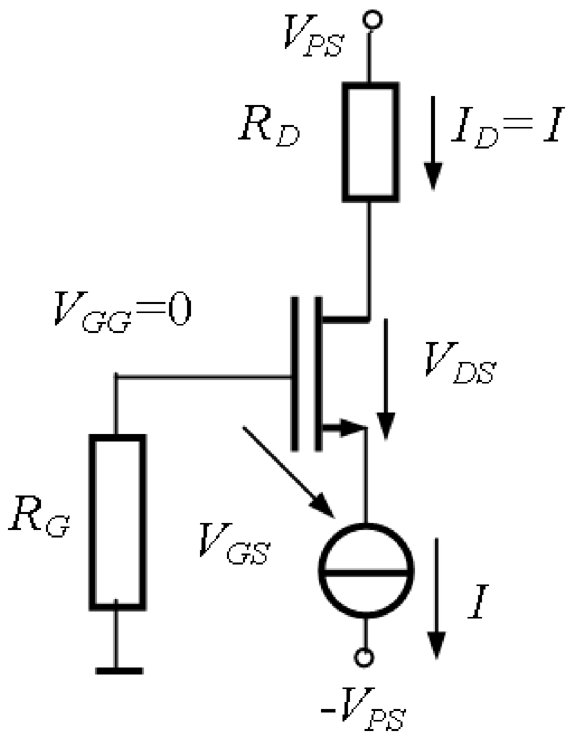
$Q\,(V_{DS};\ I_{DS}) = ?$

- voltage drop across the current source: $V_{GG} - V_{GS}$
- used in integrated circuits

☺ I_D does not depend on the transistor parameters, β and V_{Th}

MOSFET dc biasing

➢ Current source, differential supply



$Q\,(V_{DS};\ I_{DS}) = ?$

$$I_D = I$$

$$V_{PS} = R_D I + V_{DS} - V_{GS} + V_{GG}$$

$$V_{GG} = 0$$

$$V_{DS} = V_{PS} - R_D I + V_{GS}$$

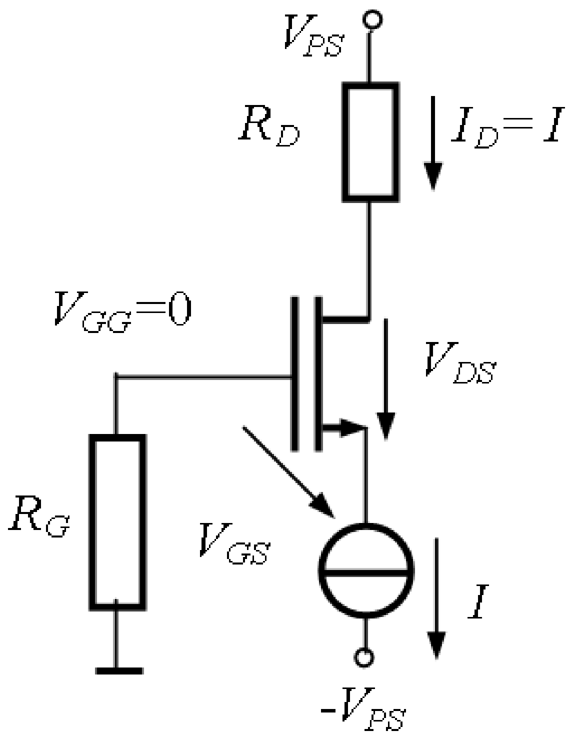
$$V_{GS} = V_{Th} + \sqrt{\frac{I_D}{\beta}} \qquad \beta = \frac{k}{2}\frac{W}{L}$$

- voltage drop across the current source: $V_{PS} - V_{GS}$
- used in integrated circuits

☺ I_D does not depend on the transistor parameters, β and V_{Th}

MOSFET dc biasing

➢ Current source, differential supply - example



$\pm V_{PS} = \pm 12\text{V}$

$R_G = 500\ \text{K}\Omega,\ R_D = 4.7\ \text{K}\Omega,\ I = 1.6\ \text{mA}$

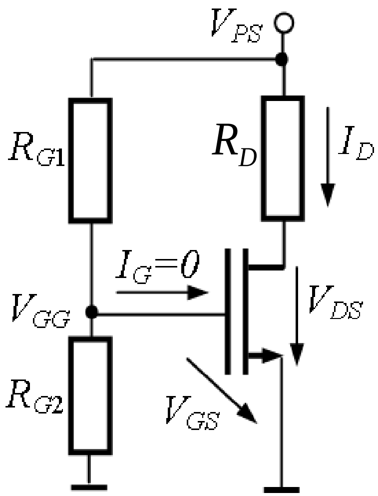
$k = 0.1\frac{\text{mA}}{\text{V}^2},\ W/_L = 2,\ V_{Th} = 0.5\ \text{V}$

$Q\,(V_{DS};\ I_{DS}) = ?$

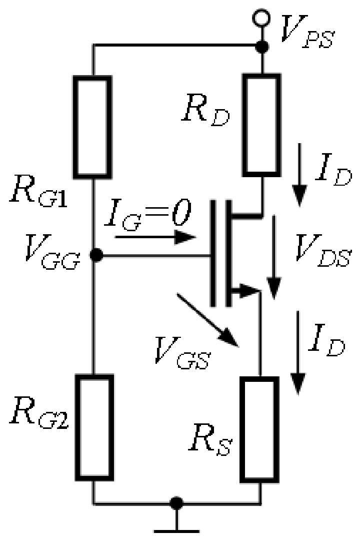
Voltage drop across the current source?

DC potentials in the three terminals of *T?*

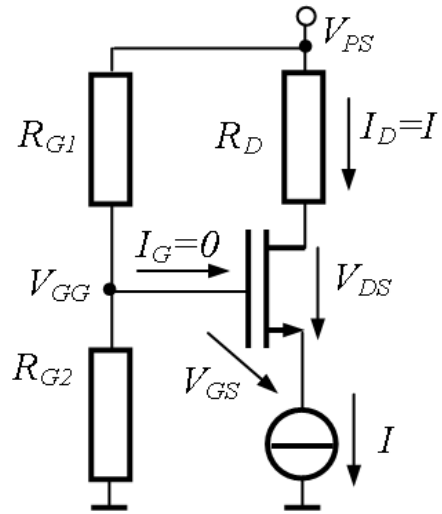
➢ MOSFET dc biasing – methods summary



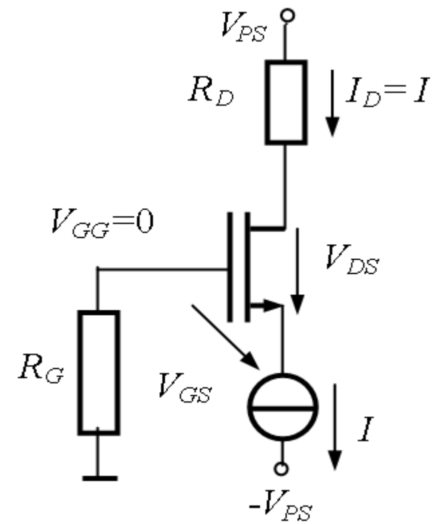
3 resistors
single supply



4 resistors
single supply



current source
single supply



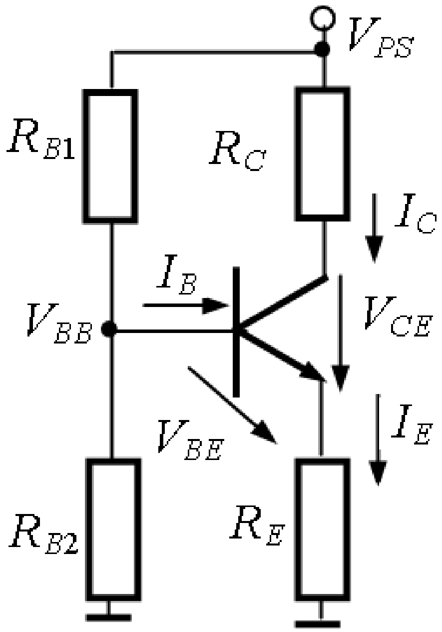
current source
differential supply

- ☺ very simple
- ☹ $I_D = f(\beta, V_{Th})$
- ☹ Q – not stable

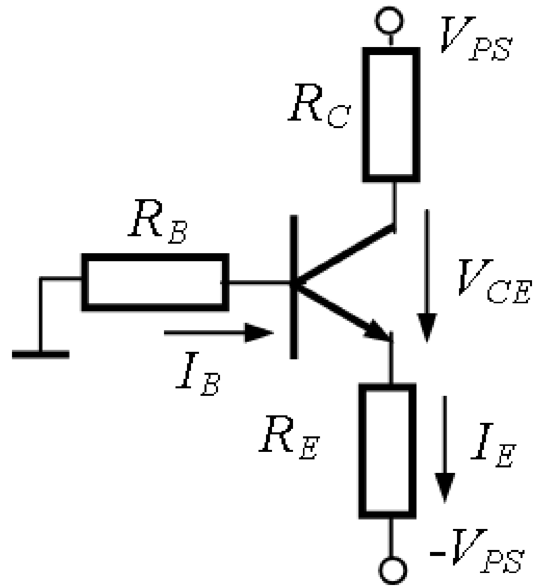
- ☺ Q – more stable
- ☹ complex calculus

- ☺ I_D – independent of β and V_{Th}
- ☹ need current source

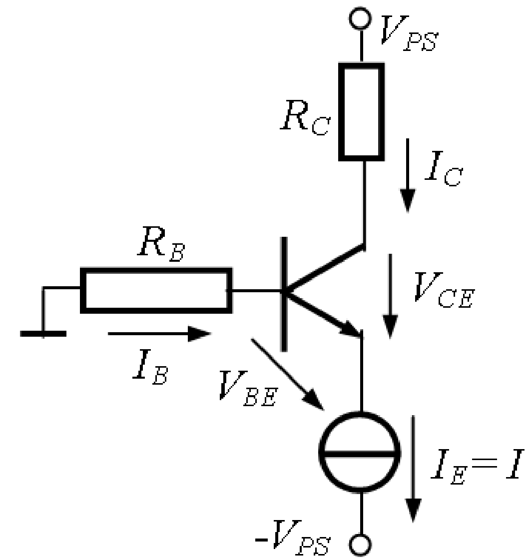
➢ BJT dc biasing – methods



4 resistors
single supply

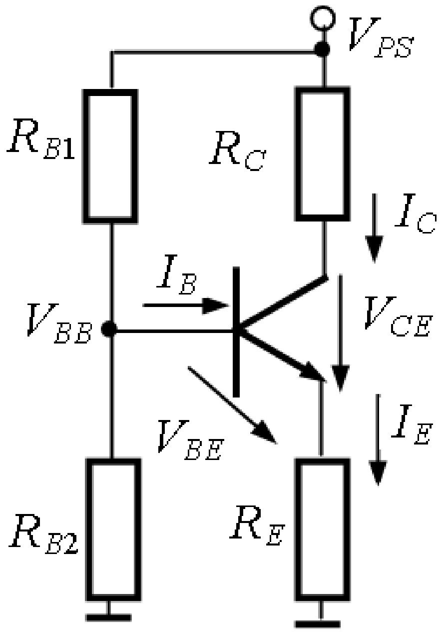


3 resistors
differential supply



current source
differential supply

➢ 4 resistors, single supply



$$I_C = \beta I_B$$

$$I_E = I_C + I_B = (\beta + 1) I_B = \frac{\beta+1}{\beta} I_C$$

$$I_E \approx I_C$$

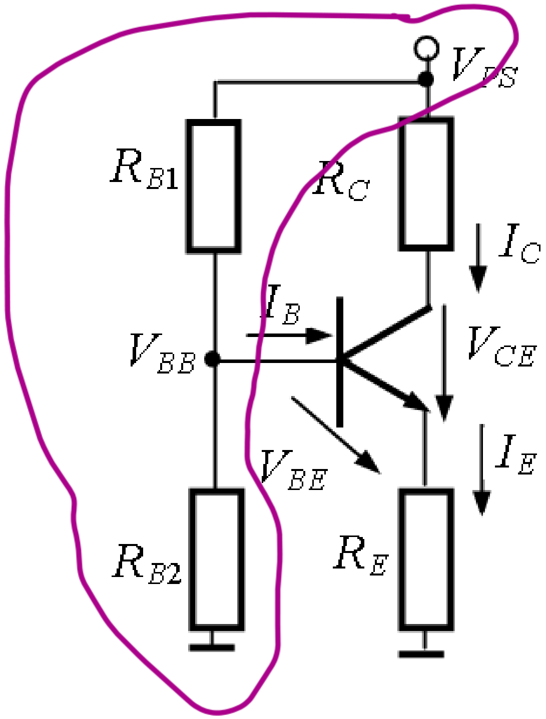
✓ Approximate calculation:

- neglect I_B
- assume R_{B1}, R_{B2} – voltage divider

✓ Precise calculation – make use of I_B

$Q\,(V_{CE};\ I_C) = ?$

➢ 4 resistors, single supply – approximate calculation



Assume $I_B \ll I_{RB1,\ RB2}$

$$V_{BB} = \frac{R_{B2}}{R_{B1} + R_{B2}} V_{PS}$$

$$I_C \approx I_E = \frac{V_{BB} - V_{BE}}{R_E}$$

$$V_{CE} = V_{PS} - I_C R_C - I_E R_E \approx V_{PS} - I_C (R_C + R_E)$$

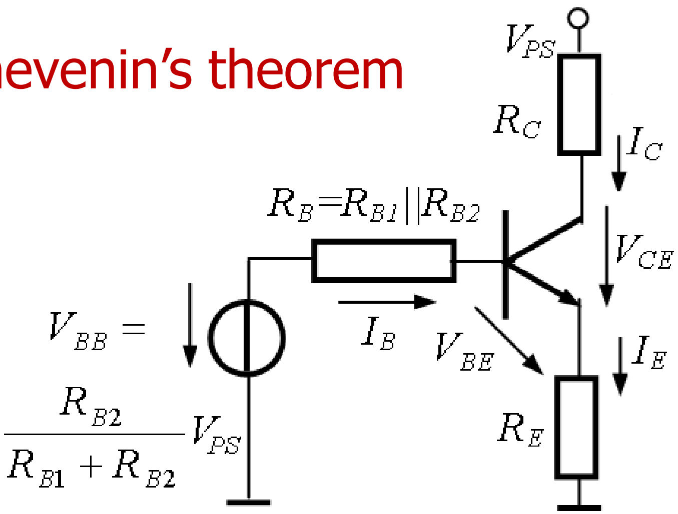
$Q\,(V_{CE};\ I_C) = ?$

$\boldsymbol{I_C}\uparrow$, $I_E\uparrow$, $R_E I_E\uparrow$, $V_{BE}\downarrow$, $\boldsymbol{I_C}\downarrow$ - negative feedback due to R_E

☺ Q – stable

➢ 4 resistors, single supply – precise calculation

Thevenin's theorem



$Q\,(V_{CE};\, I_C) = ?$

$$V_{BB} = R_B I_B + V_{BE} + R_E I_E$$

$$I_B = \frac{I_E}{\beta + 1}$$

$$V_{BB} - V_{BE} = \frac{R_B I_E}{\beta + 1} + R_E I_E$$

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + R_B/(\beta + 1)}$$

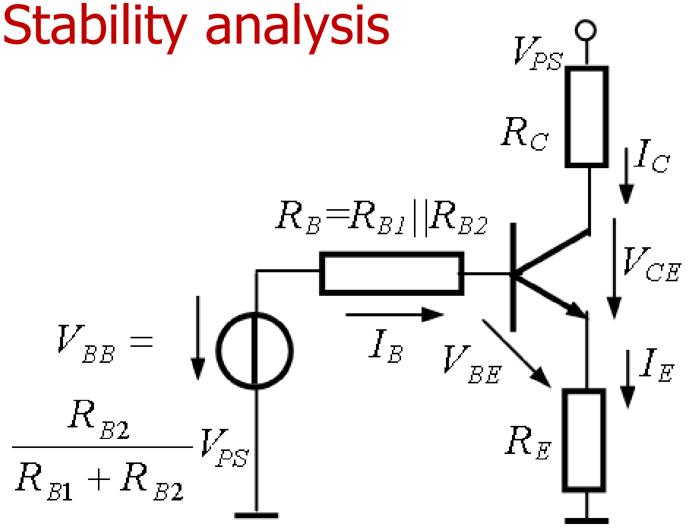
$$I_C = I_E + I_B \approx I_E$$

$$V_{CE} = V_{PS} - I_C R_C - I_E R_E$$
$$V_{CE} \approx V_{PS} - I_C (R_C + R_E)$$

➢ 4 resistors, single supply – precise calculation

OPTIONAL

Stability analysis



$$I_E = \frac{V_{BB} - V_{BE}}{R_E + R_B/(\beta + 1)}$$

To have I_E - insensitive to β variations

$$R_E >> \frac{R_B}{(\beta + 1)} \qquad R_E > 10\frac{R_B}{\beta}$$

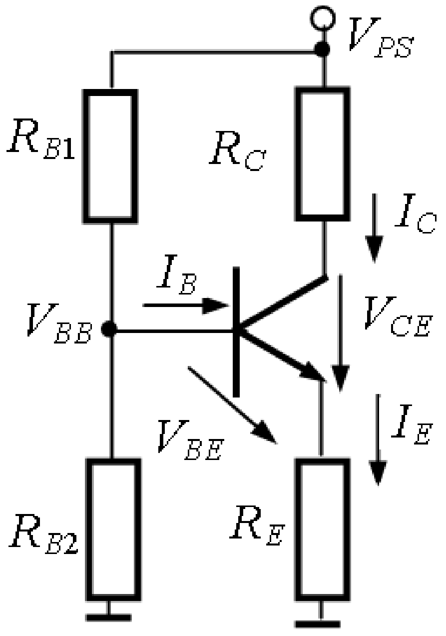
- R_{B1}, R_{B2} - small values for Q – independent on β
- R_{B1}, R_{B2} - high values for high input resistance of the voltage amplifier

To have I_E - insensitive to temperature variations due to V_{BE}

$V_{BB} >> 0.1\text{V}$

a ΔV_{BE} of 0.1 V can be neglected compared to $V_{BB} = 3\ldots5$ V

4 resistors, single supply – example 1



V_{PS} = 15 V; R_{B1} =10 KΩ; R_{B2} = 4.7 KΩ;

R_E =1.5 KΩ; R_C =1.8 KΩ; β =150

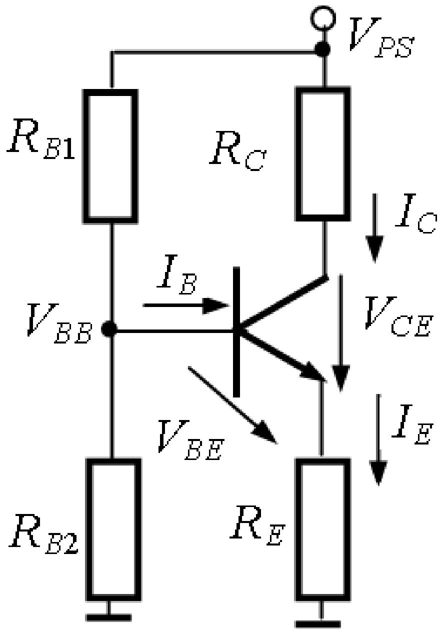
Approximate calculation

I_C = ?	I_C = 2.73 mA
V_{CE} =?	V_{CE} = 6 V
V_C = ?	V_C = 10.1 V
V_E = ?	V_E = 4.1 V

Precise calculation

I_C = ?	I_C = 2.7 mA

4 resistors, single supply – example 2



Size the resistors so that *T* is biased in a_F @ I_C= 2mA, for V_{PS}=12 V, β=100

Usually $V_{BB} = \frac{1}{3}V_{PS} = \frac{1}{3} \cdot 12 = 4\text{V}$

$$R_E = \frac{V_{BB} - V_{BE}}{I_E} = \frac{(1/3) \cdot 12 - 0.7}{2} = 1.65\ \text{K}\Omega$$

$$V_{BB} = \frac{R_{B2}}{R_{B1} + R_{B2}} V_{PS} = \frac{1}{3} V_{PS} \qquad R_{B1} = 2R_{B2}$$

$$R_E > 10\frac{R_B}{\beta} \qquad \frac{R_{B1}R_{B2}}{R_{B1} + R_{B2}} < 10R_E \qquad R_{B2} < 24.75\text{K}\Omega$$

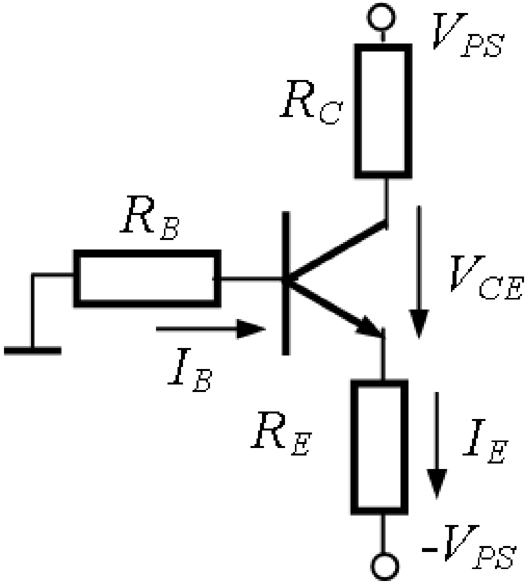
Choose $R_{B2} = 22\ \text{K}\Omega;\ R_{B1} = 44\ \text{K}\Omega$

Verification (precise calculation):

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + R_B/(\beta + 1)} = 1.84\ \text{mA}$$

Adjust $R_E = 1.5\ \text{K}\Omega$ so that $I_E = 2\text{mA}$

➢ 3 resistors, differential supply



$$R_B I_B + V_{BE} + R_E I_E - V_{PS} = 0$$

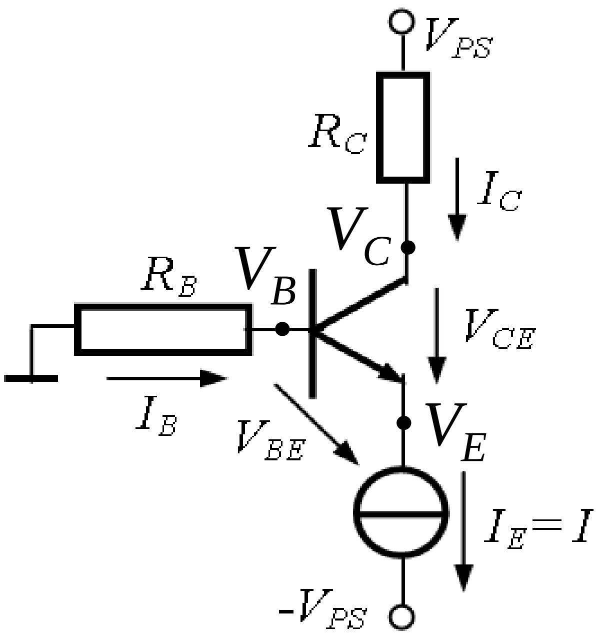
$$I_B = I_E/(\beta + 1)$$

$$I_E = \frac{0 - V_{BE} - (-V_{PS})}{R_E + R_B/(\beta + 1)} = \frac{V_{PS} - V_{BE}}{R_E + R_B/(\beta + 1)}$$

$$V_{CE} = 2V_{PS} - R_C I_C - R_E I_E$$

$Q\,(V_{CE};\, I_C) = ?$

➢ Current source, differential supply



$$I_E = I; I_C \approx I_E; I_B = \frac{I_C}{\beta}$$

$$V_C = V_{PS} - R_C I_C$$

$$V_B = 0 - R_B I_B = -R_B I_B$$

$$V_E = V_B - V_{BE} = V_B - 0.7\text{V}$$

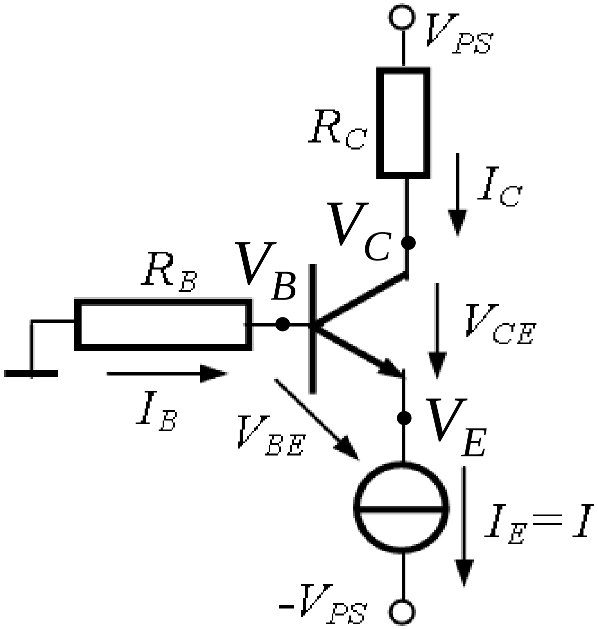
$$V_{CE} = V_C - V_E$$

$Q\,(V_{CE};\ I_C) = ?$

Voltage across the current source:

$$V_E - (-V_{PS}) = V_E + V_{PS}$$

➢ Current source, differential supply - example



$\pm V_{PS} = \pm$ 9 V; $R_B = 180$ KΩ;

R_C = 3.3 KΩ; $\beta = 100$; $I = 2$ mA

$I_C = ?$ $V_C = ?$ $V_B = ?$ $V_E = ?$

$V_{CE} = ?$

Voltage across the current source = ?

Summary

- Transistor amplifiers - intro
- MOSFET dc biasing
- BJT dc biasing

Next week: MOSFET basic amplifiers.