ECE 65: Components & Circuits Lab

Lecture 18

MOSFET Amplifier small signal model

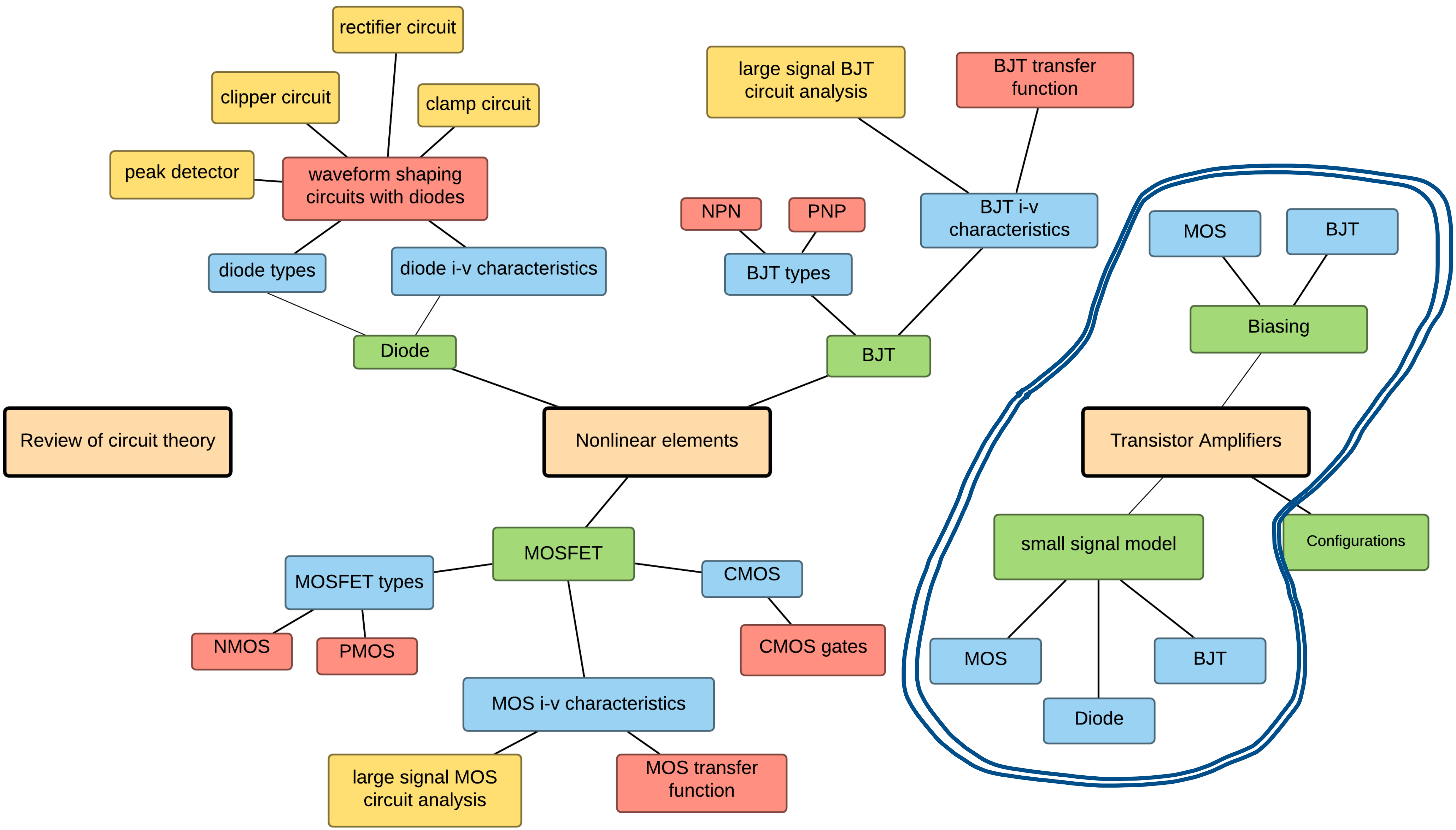
Reference notes: sections 5.1, 5.2

Sedra & Smith (7th Ed): sections 7.1

Saharnaz Baghdadchi

Course map

5. Transistor Amplifiers – Bias and small signal



Review of definitions

Signal: We want the response of the circuit to this input.

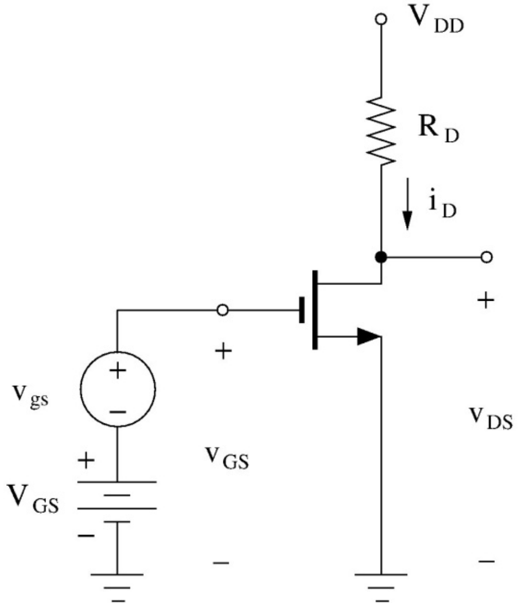
Bias: State of the system when there is no signal.

- Bias is constant in time (may vary extremely slowly compared to signal).
- Purpose of the bias is to ensure that MOS is in saturation at all times.

Derivation of MOS small signal model

$\lambda = 0$

The DC Bias point: $v_{gs} = 0$



$$I_D = \frac{1}{2} k_n (V_{GS} - V_t)^2 = \frac{1}{2} k_n {V_{OV}}^2$$

$$k_n = \mu_n C_{ox} \left(\frac{W}{L}\right)_n$$

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

In the presence of the input signal, v_{gs}:

The total instantaneous gate-to-source voltage is: $v_{GS} = V_{GS} + v_{gs}$

$$i_D = \frac{1}{2} k_n \left(V_{GS} + v_{gs} - V_t\right)^2$$

$$i_D = \frac{1}{2} k_n \left(V_{GS} + v_{gs} - V_t\right)^2$$

$$= \frac{1}{2} k_n (V_{GS} - V_t)^2 + k_n (V_{GS} - V_t)\, v_{gs} + \frac{1}{2} k_n \left(v_{gs}\right)^2$$

Consider the case:

$$\frac{1}{2} k_n \left(v_{gs}\right)^2 \ll k_n (V_{GS} - V_t)\, v_{gs}$$

or

$$v_{gs} \ll 2\,(V_{GS} - V_t)$$

In this case, v_{gs} is small enough and the **Small Signal Condition** is satisfied.
we can neglect the $\frac{1}{2} k_n \left(v_{gs}\right)^2$ term in the i_D equation and

$$i_D \simeq I_D + i_d$$

$$\begin{cases} i_D \simeq \frac{1}{2} k_n (V_{GS} - V_t)^2 + k_n (V_{GS} - V_t)\, v_{gs} \\ i_D \simeq I_D + i_d \end{cases}$$

$$\boxed{I_D = \frac{1}{2} k_n (V_{GS} - V_t)^2}$$

$$\boxed{i_d = k_n (V_{GS} - V_t)\, v_{gs}}$$

The MOSFET transconductance g_m is defined as

$$g_m \equiv \frac{i_d}{v_{gs}} = k_n (V_{GS} - V_t)$$

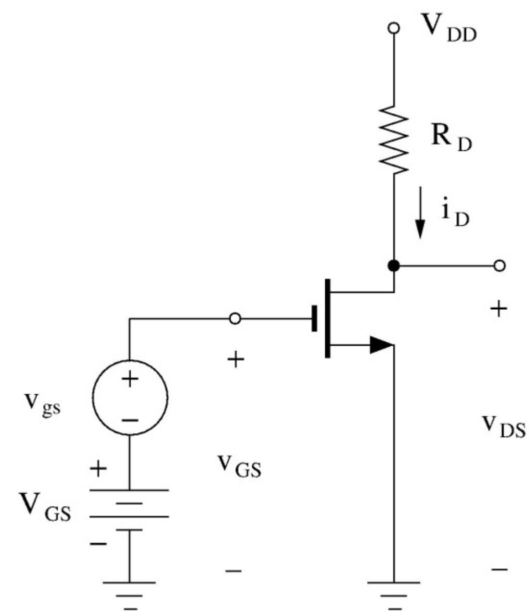
$$\boxed{g_m = k_n V_{OV} = \frac{2\, I_D}{V_{OV}}}$$

$$\boxed{i_d = g_m v_{gs}}$$

$$v_{DS} = V_{DD} - R_D i_D$$

$$= V_{DD} - R_D(I_D + i_d)$$

$$\left\{\begin{array}{l} v_{DS} = V_{DD} - R_D I_D - R_D i_d \\ \\ v_{DS} = V_{DS} + v_{ds} \end{array}\right.$$



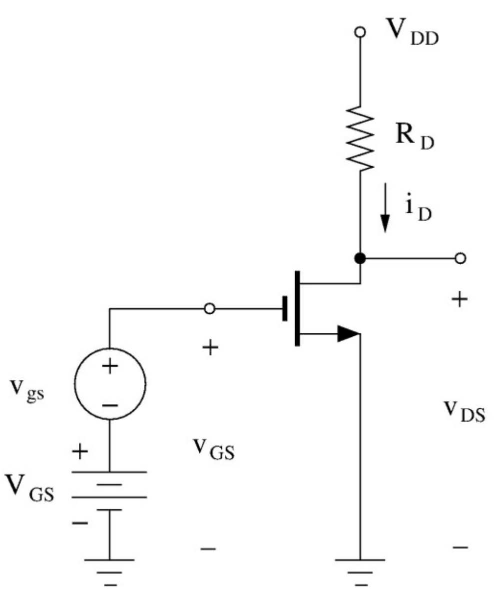
$$\boxed{V_{DS} = V_{DD} - R_D I_D}$$

$$v_{ds} = -\,i_d R_D = -g_m\, v_{gs}\, R_D$$

Amplifier voltage gain is $\boxed{A_v = \dfrac{v_{ds}}{v_{gs}} = -g_m\, R_D}$

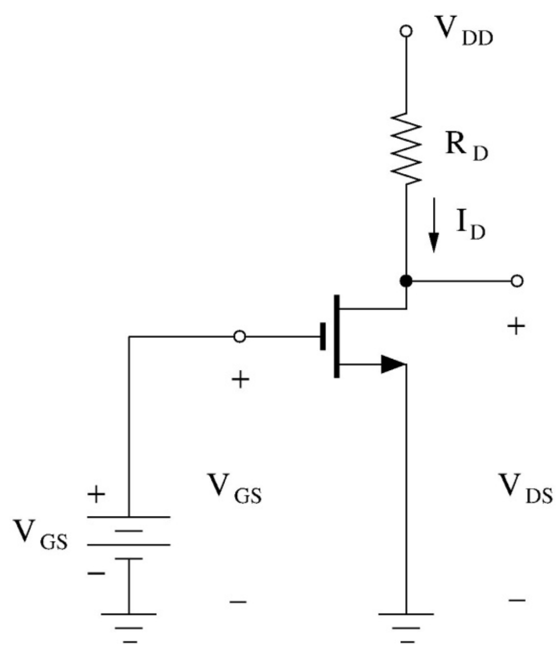
Bias and Signal circuits under small signal approximation

Bias & Signal



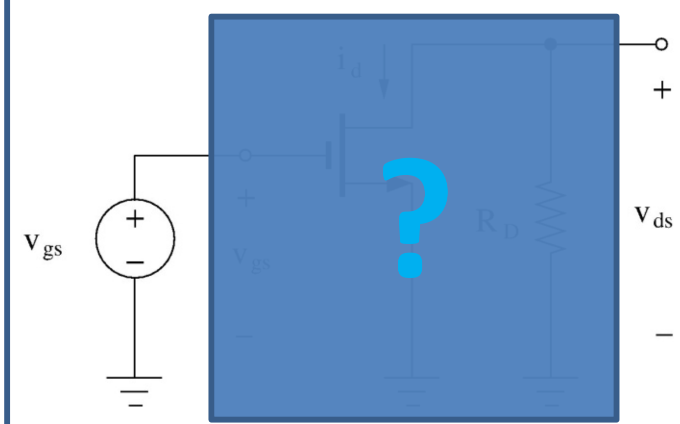
$$v_{GS}\,, i_D\,, v_{DS}\,, \ldots$$

Bias



$$V_{GS}\,, I_D\,, V_{DS}\,, \ldots$$

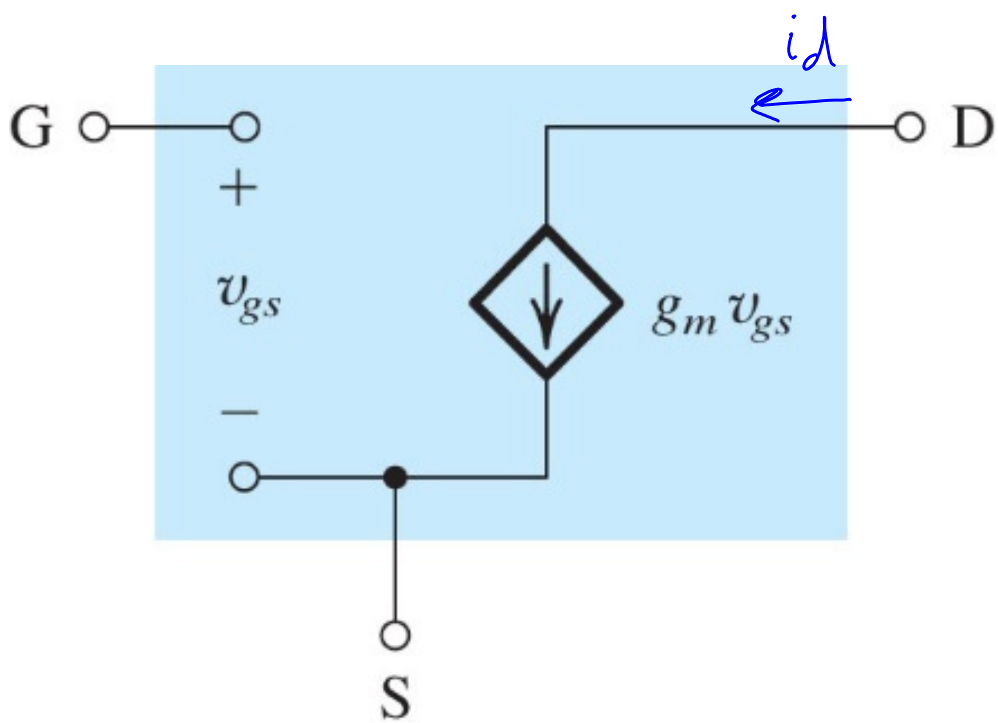
Signal only
= (Bias + Signal) - Bias



$$v_{gs}\,, i_d\,, v_{ds}\,, \ldots$$

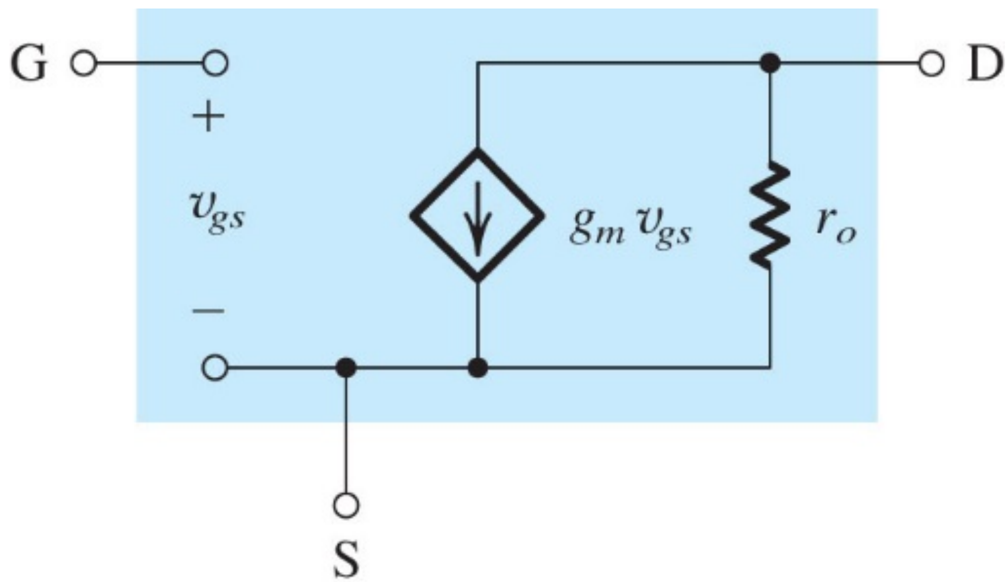
MOS small signal model

$$i_g = 0 \qquad\qquad i_d = g_m v_{gs}$$



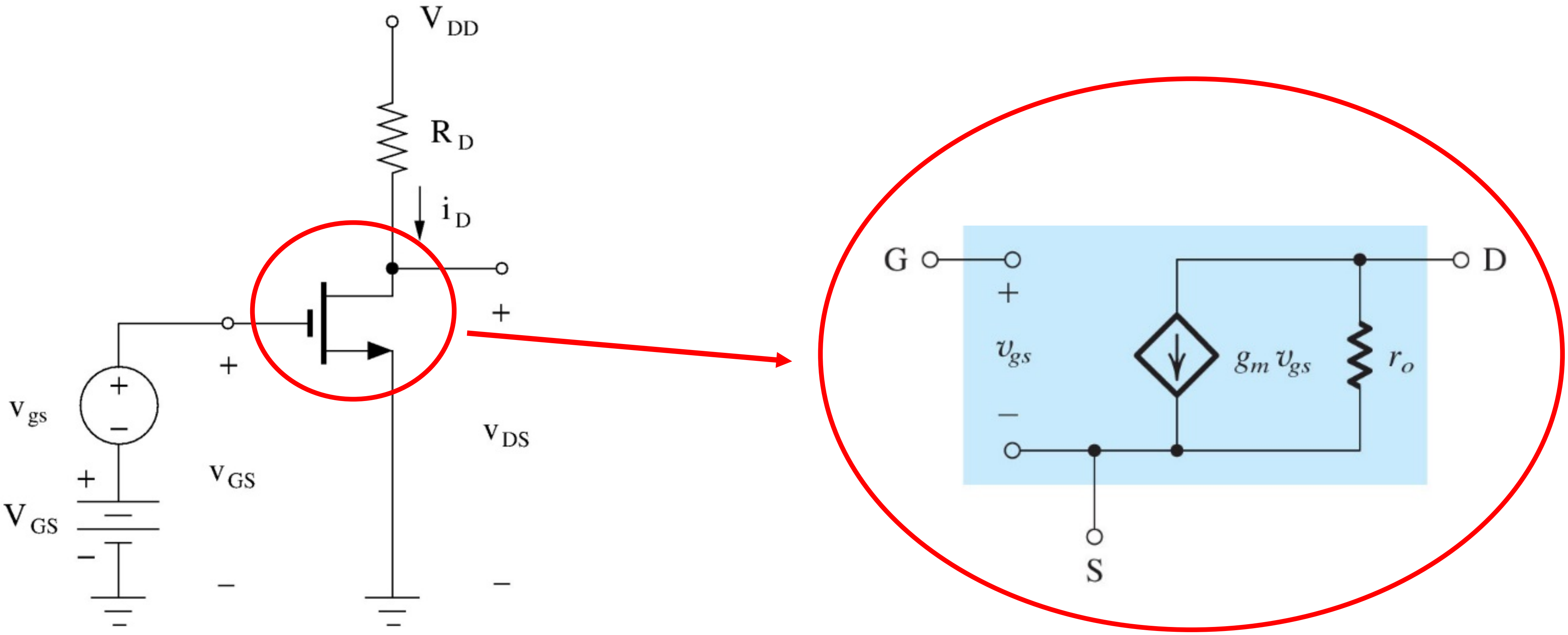
MOS small signal model

$$i_g = 0 \qquad\qquad i_d = g_m v_{gs} + \frac{v_{ds}}{r_o}$$



$$\boxed{g_m = \frac{2\, I_D}{V_{OV}}} \qquad\qquad \underline{r_o \approx \frac{1}{\lambda . I_D}}$$

MOS Small Signal Model



What about the rest of the circuit element?

Other circuit elements in the small signal equivalent circuit

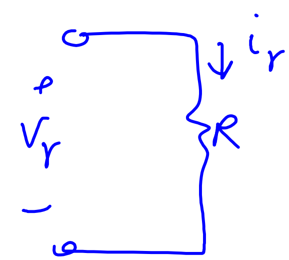
A resistor remains as a resistor in the signal circuit.

$$v_R = V_R + v_r$$

Bias + Signal: $v_R = Ri_R$

Bias: $V_R = RI_R$

Signal: $v_r = v_R - V_R = Ri_r \Longrightarrow \boxed{v_r = Ri_r}$



Other circuit elements in the small signal equivalent circuit

A capacitor remains as a capacitor in the signal circuit.

Unless we perform the frequency analysis of amplifier circuits, <u>the capacitors will be short in the signal equivalent circuit</u>.

Reminder:

A capacitor acts as an open circuit in the bias circuit.

Other circuit elements in the small signal equivalent circuit

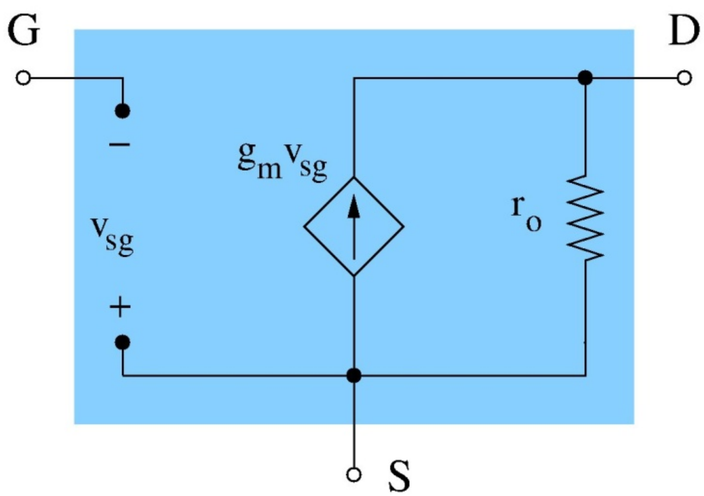
A DC voltage source becomes a <u>short</u> circuit.

For example, V_{DD} , V_{SS} will be effectively grounded.

A DC current source becomes an <u>open</u> circuit.

PMOS small signal model is identical to NMOS

PMOS



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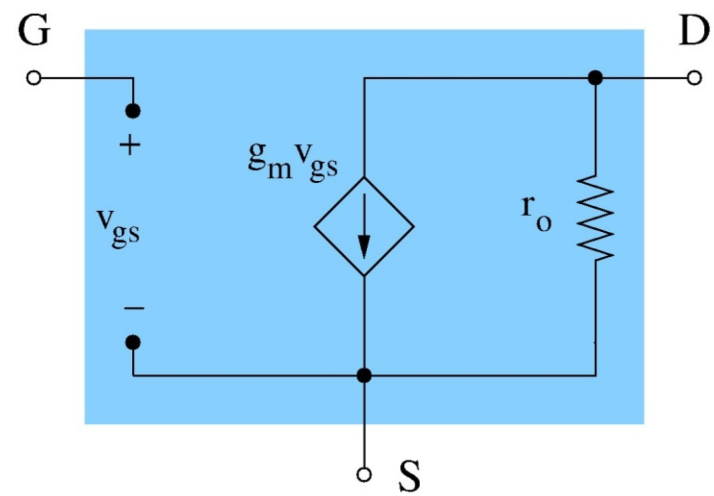
NMOS or PMOS ✓



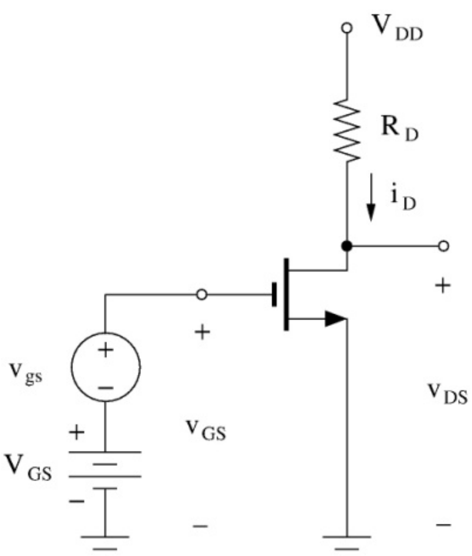
PMOS small-signal circuit model is identical to NMOS

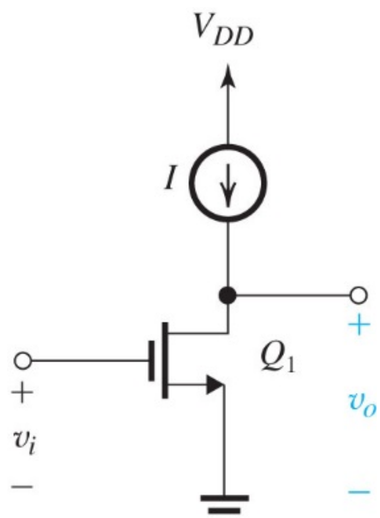
We will use NMOS circuit model for both!

How to add signal to the bias

1. Direct Coupling

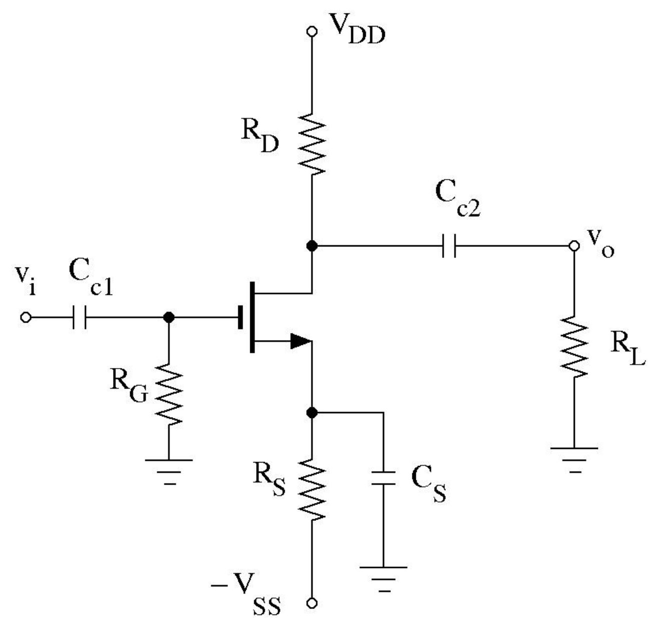
The signal is directly applied to the transistor.





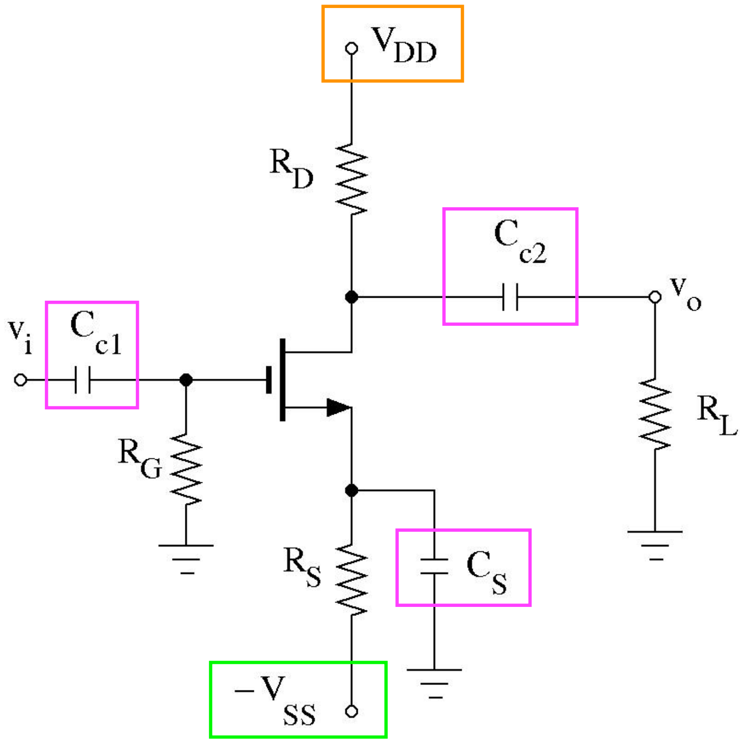
2. Capacitive Coupling

A capacitor is used to couple the signal to the transistor.

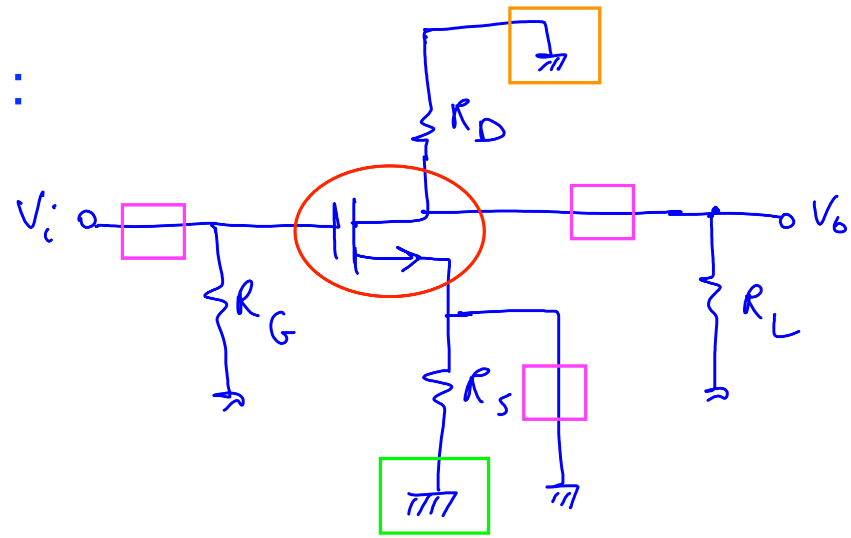


Example 1:

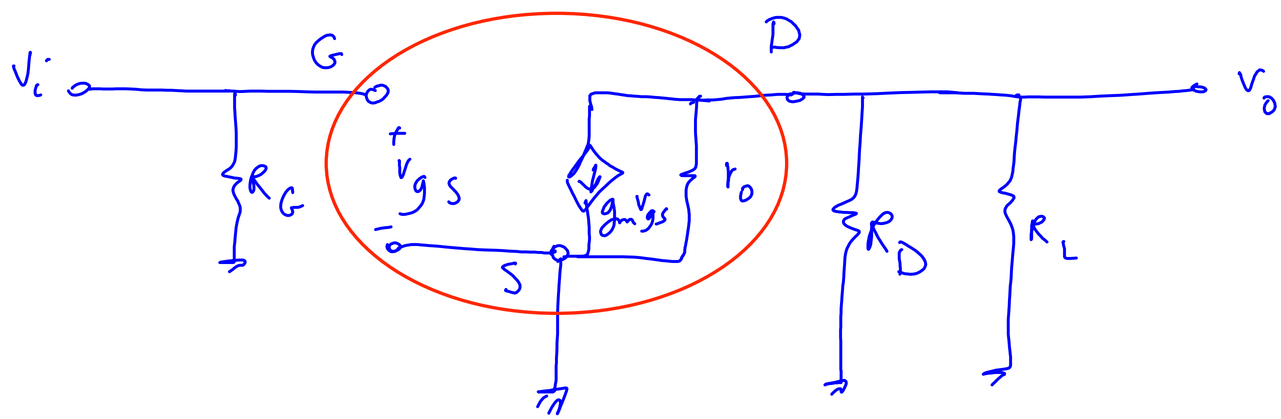
Draw the signal circuit (assume capacitors are short for signal).



step 1:

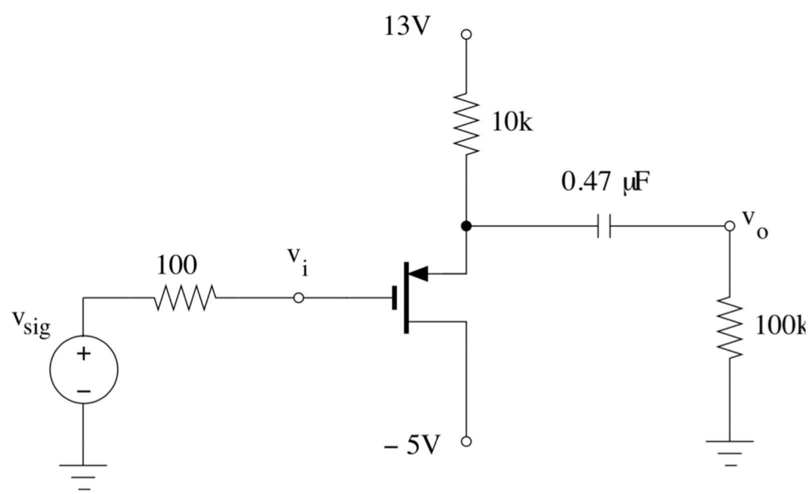


step 2:



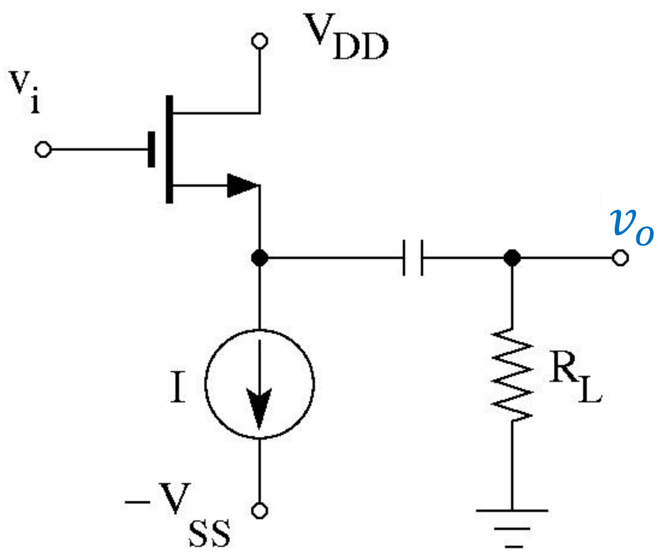
Lecture 18 reading quiz

Find the transconductance, g_m , in this circuit ($V_{tn} = |V_{tp}| = 4\ V$, $k_n = k_p = 0.4\ mA/V^2$, $\lambda = 0.01\ V^{-1}$. Assume $\lambda = 0$ for the bias circuit.



Discussion question 1.

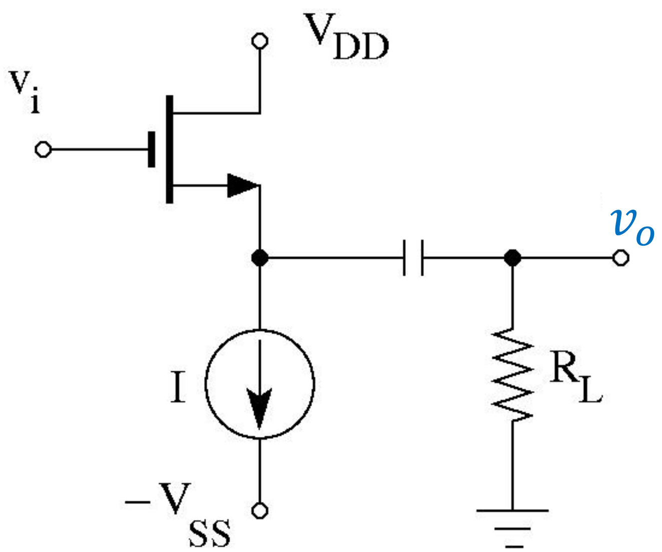
Draw the signal circuit (assume capacitors are short for signal).



Hints:

Discussion question 1.

Draw the signal circuit (assume capacitors are short for signal).



- Label all the node voltages and i_D on the given circuit.

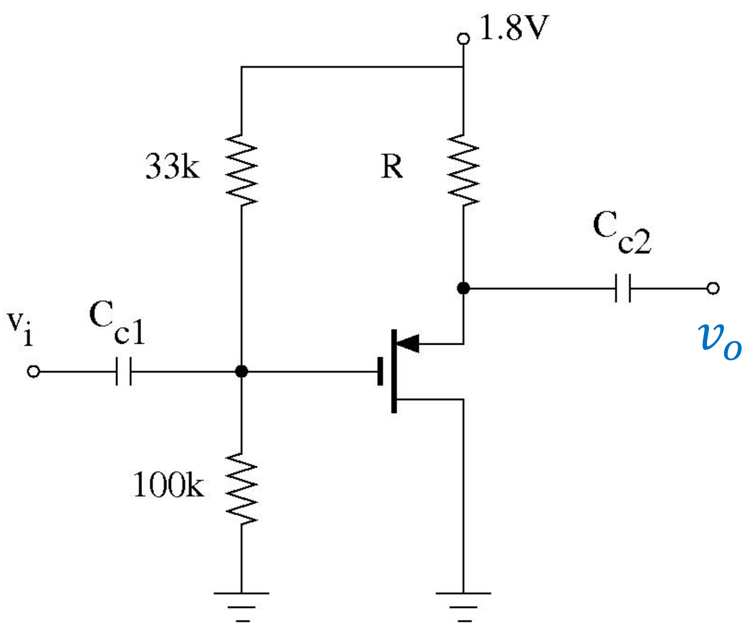
- Draw the small signal model for the MOSFET, and label all the node voltages.

- Add the other circuit elements to the small signal circuit according to how they are connected to the gate, drain, and course terminals of the MOSFET in the given circuit.

- The capacitors will be short and the DC voltage sources will be set to zero in the signal circuit.

Discussion question 2.

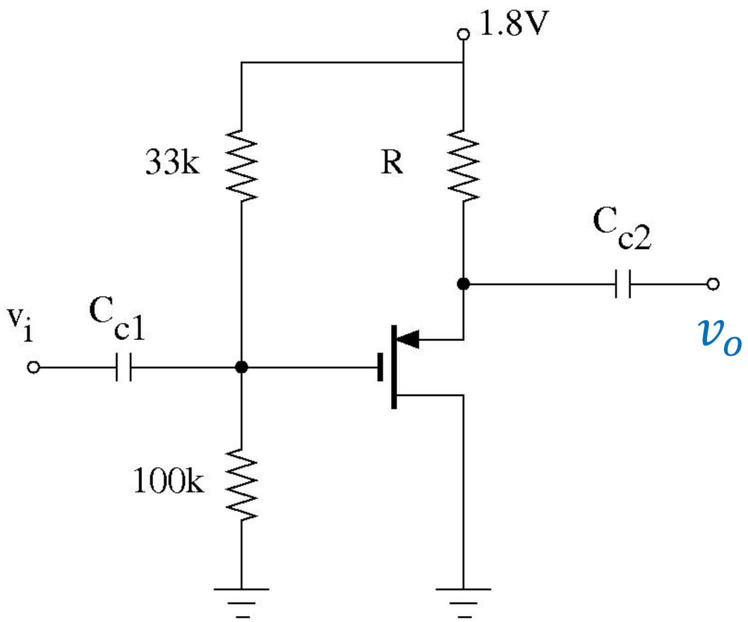
Draw the signal circuit (assume capacitors are short for signal).



Hints:

Discussion question 2.

Draw the signal circuit (assume capacitors are short for signal).



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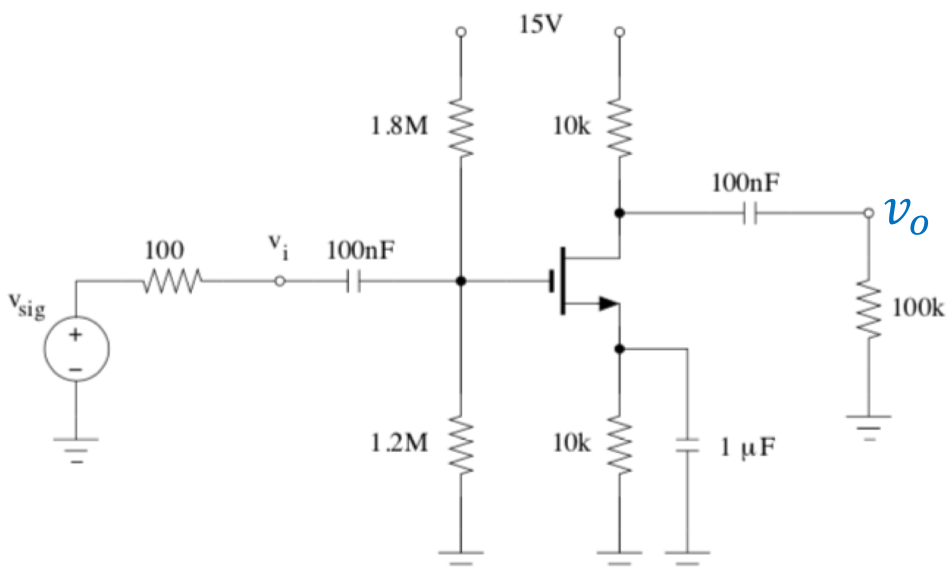
Discussion question 3.

Find the small signal parameters and draw the signal circuit (assume capacitors are short for signal).

$V_{tn} = 1\,V$, $k_n = 0.8\,mA/V^2$. $\lambda = 0.01\,V^{-1}$.

Ignore the channel-width modulation effect in biasing calculations.



Hints:

Discussion question 3.

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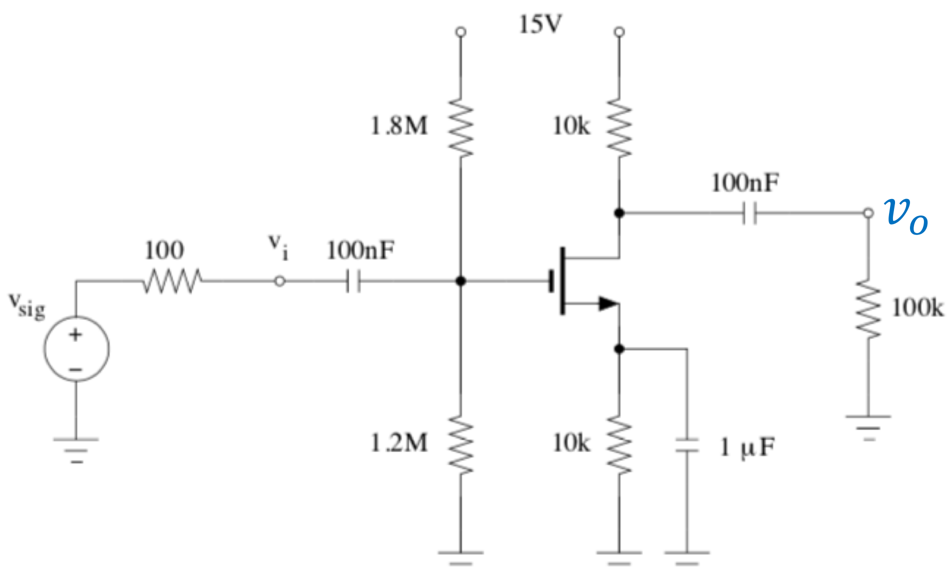

- The small signal parameters (g_m and r_o) depend on the Bias point of the circuit (DC node voltages and currents). Write down the equations for g_m and r_o.

- Draw the Bias circuit and solve it to find the DC node voltages and I_D. The capacitors will be open and the signal sources will be set to zero in the Bias circuit.