ECE 65: Components & Circuits Lab

Lecture 17

Transistor Amplifiers – Introduction

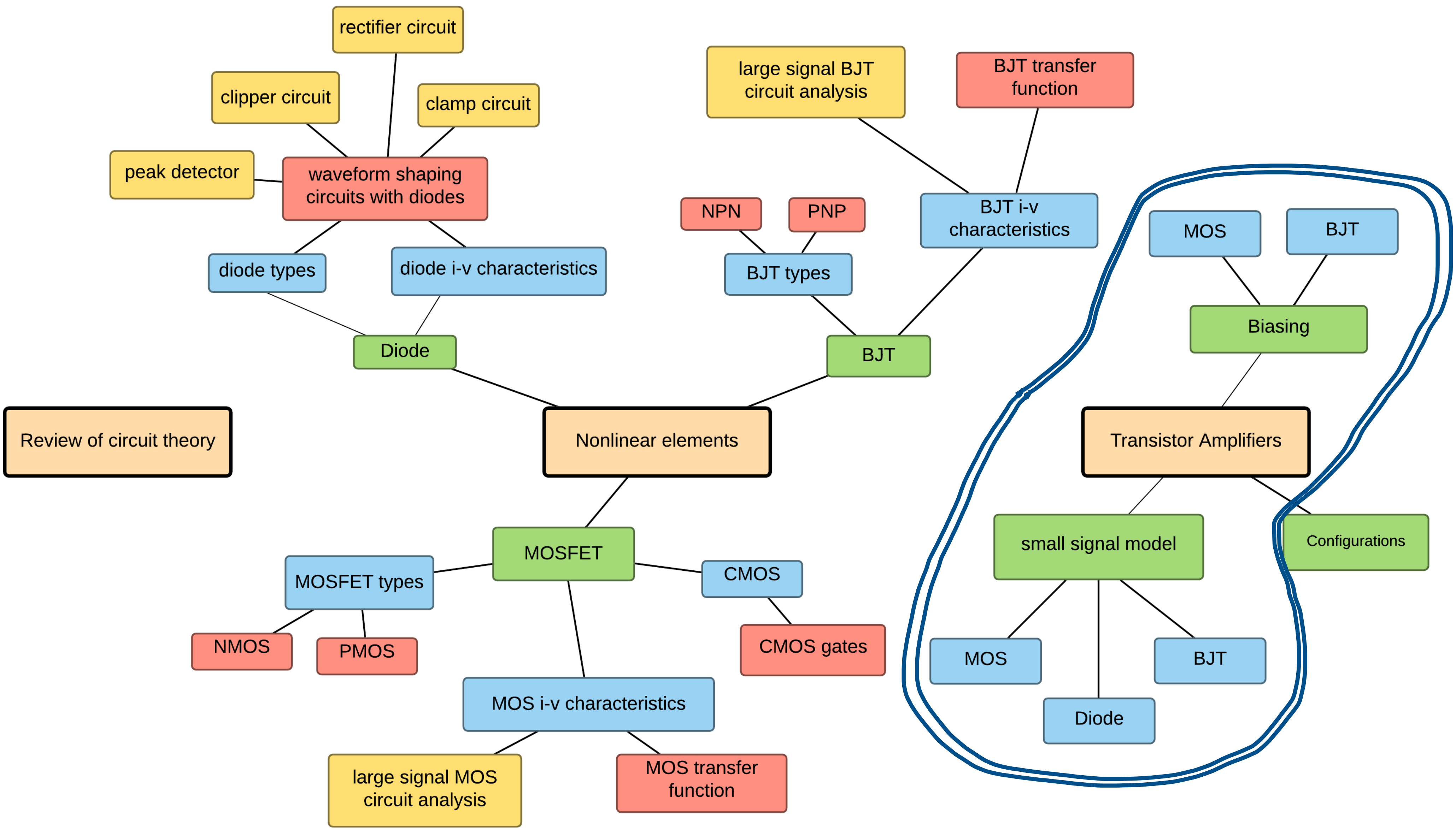
Reference notes: sections 5.1, 5.2

Sedra & Smith (7th Ed): sections 7.1

Saharnaz Baghdadchi

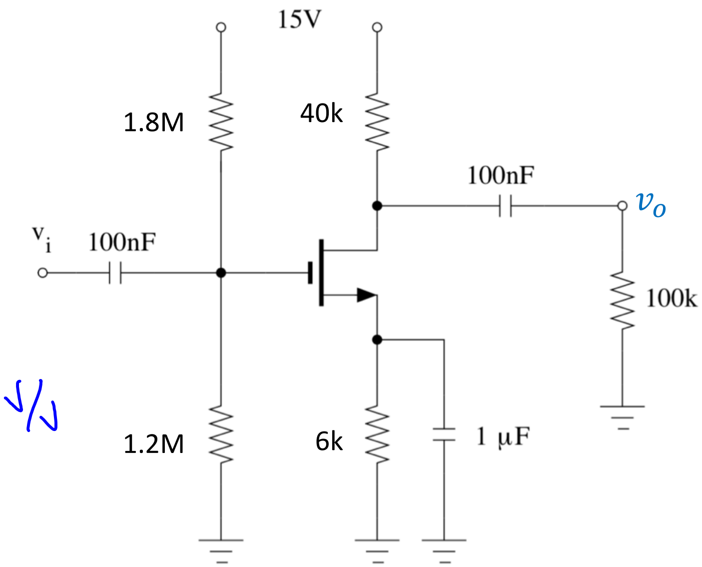
Course map

5. Transistor Amplifiers – Bias and small signal

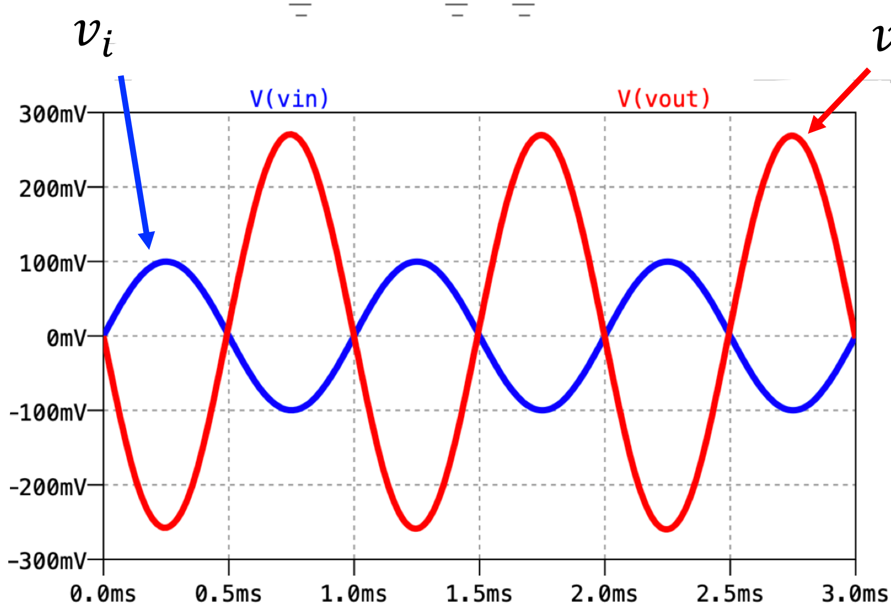


Transistor Amplifiers

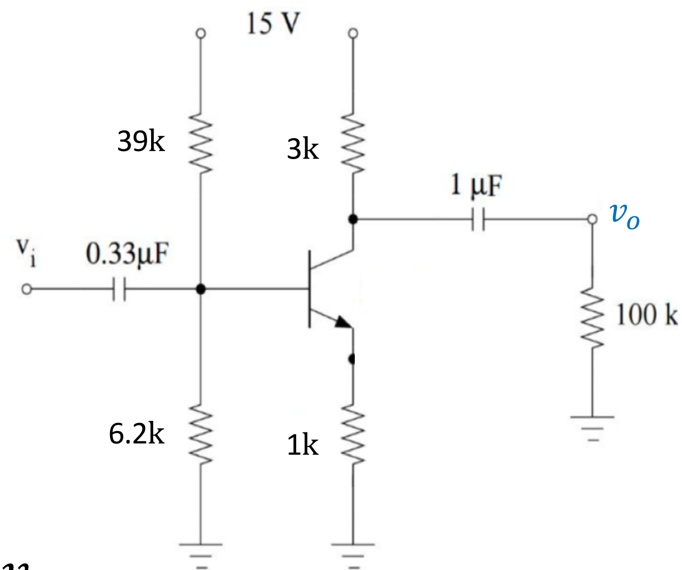
MOSFET as an amplifier

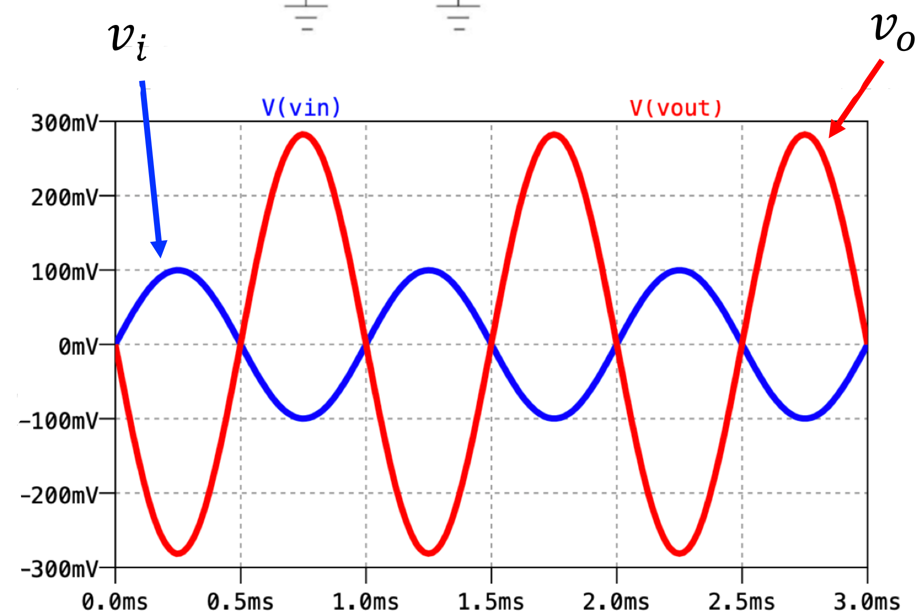


$\left|\frac{V_o}{V_i}\right| \approx 3 \; V/V$

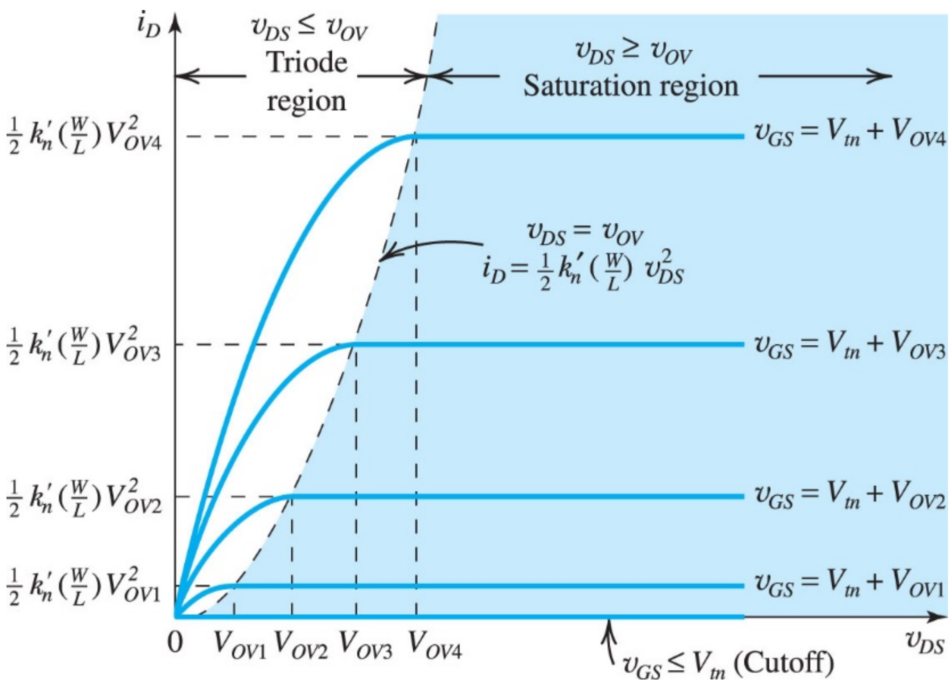


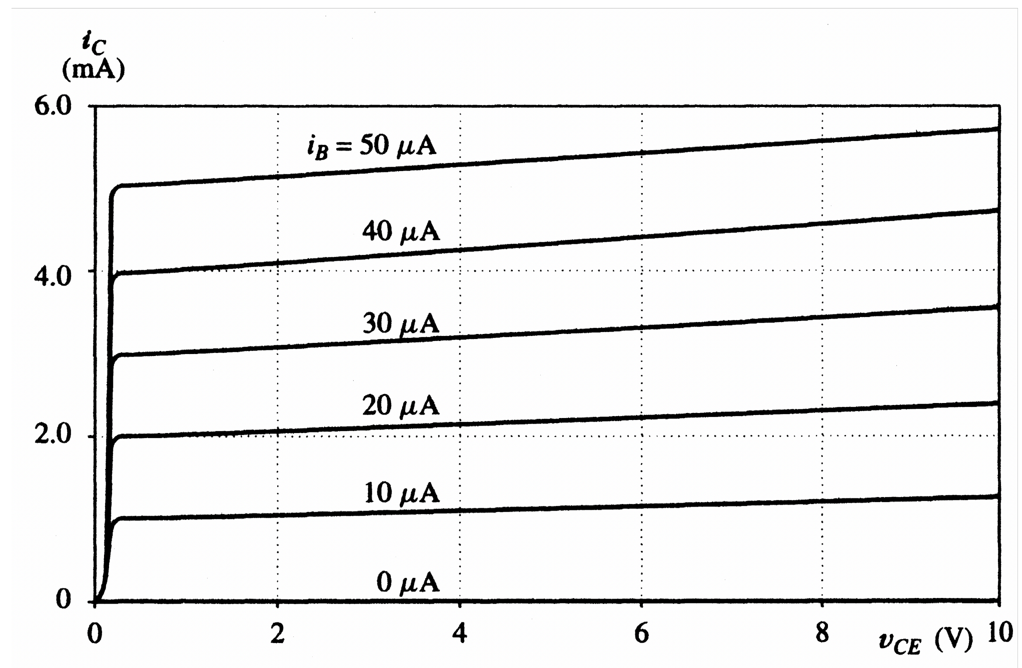
BJT as an amplifier





In the active region, BJT and MOSFET operate as a voltage-controlled current source

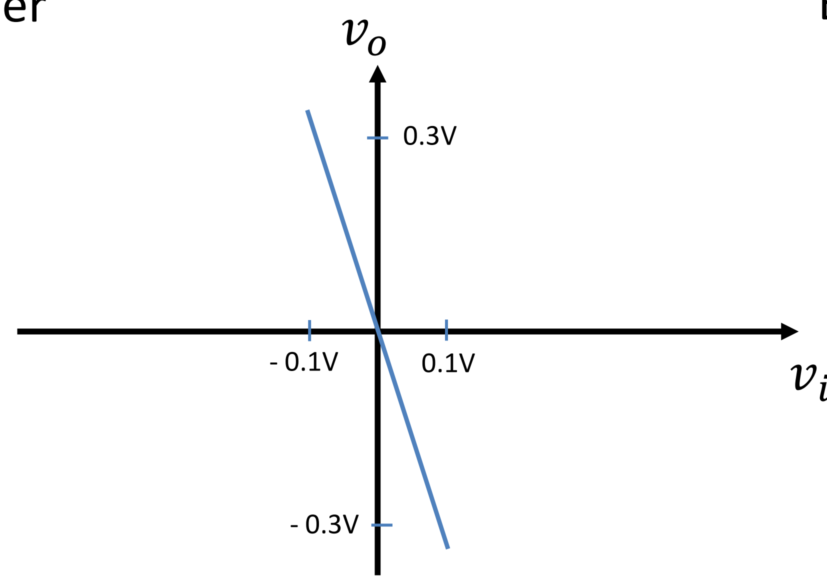


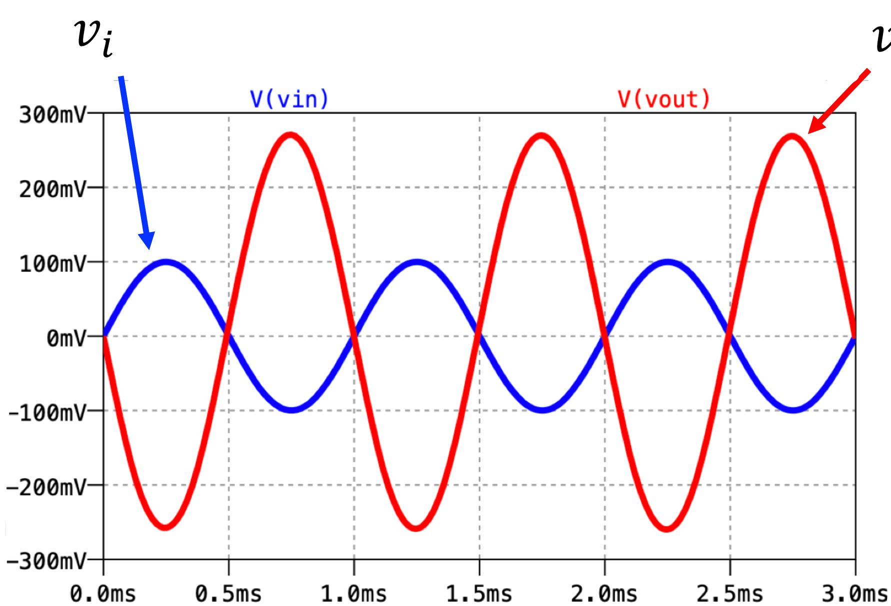


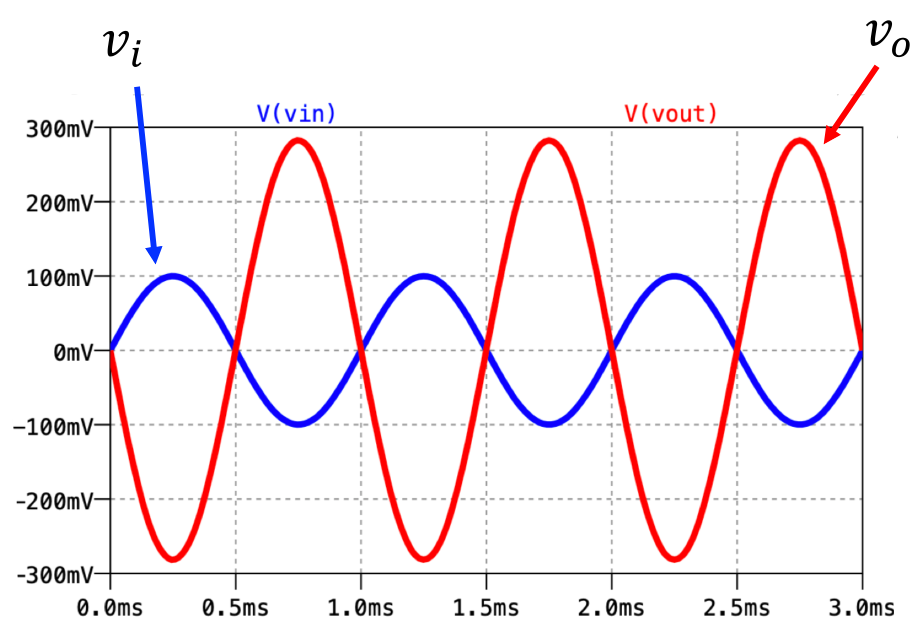
Transistor Amplifiers

MOSFET as an amplifier

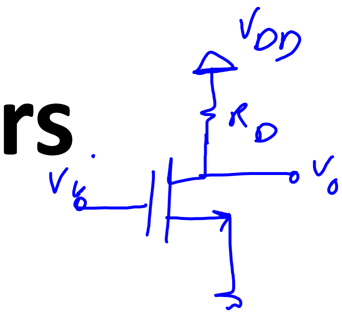
BJT as an amplifier



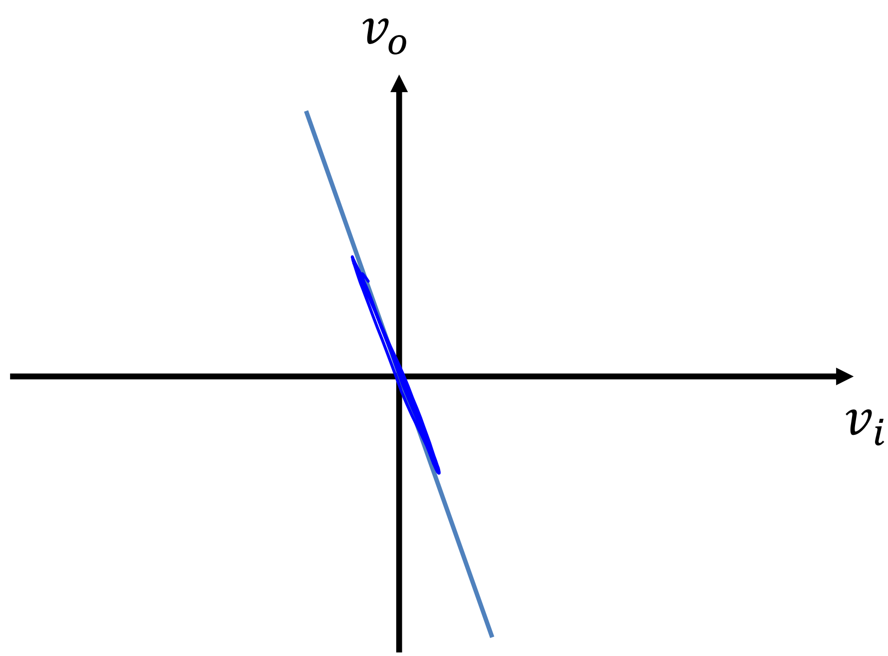




Foundation of Transistor Amplifiers

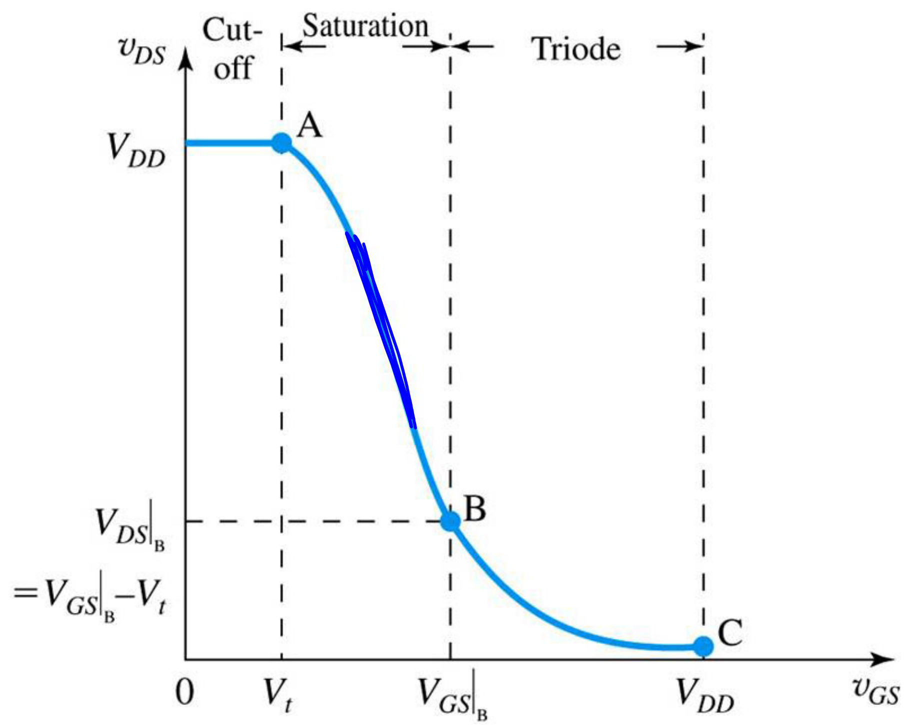


A voltage amplifier requires
$v_o/v_i = \text{const.}$



v_o/v_i can be negative (minus sign represents a 180º phase shift)

MOS transfer function is NOT linear

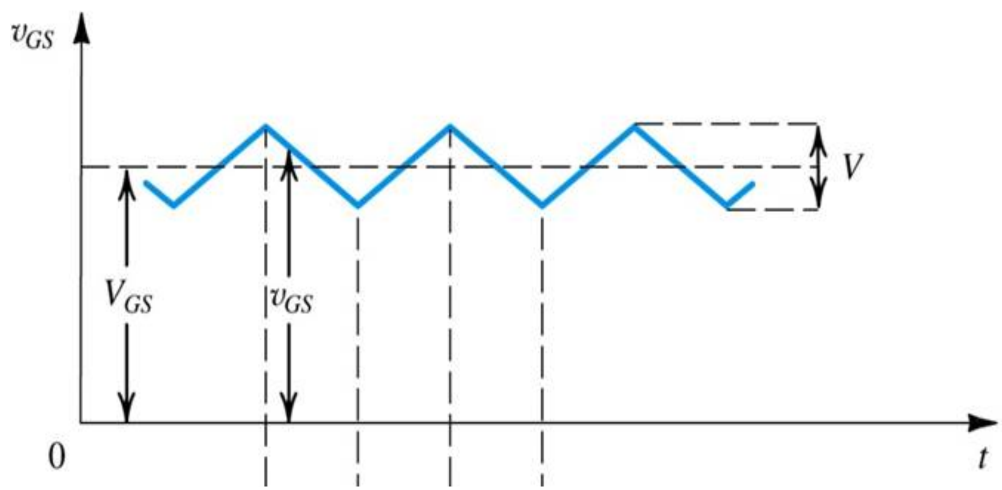


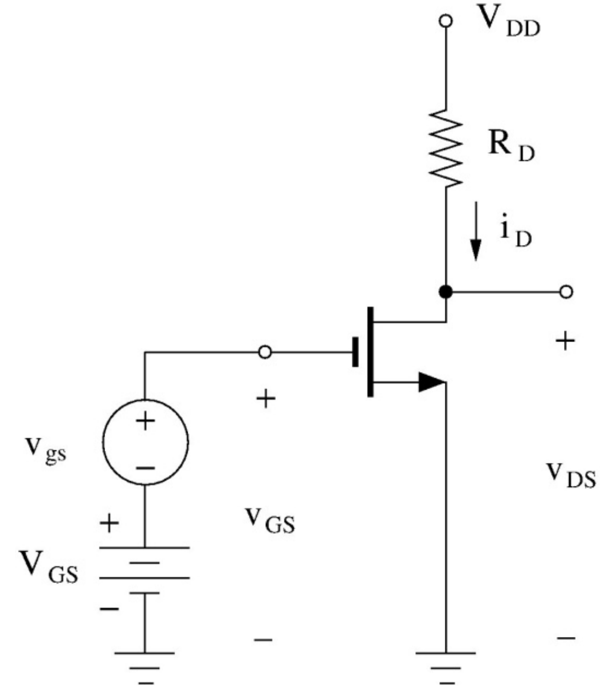
In saturation, however, transfer function looks linear (but shifted)

Foundation of Transistor Amplifiers

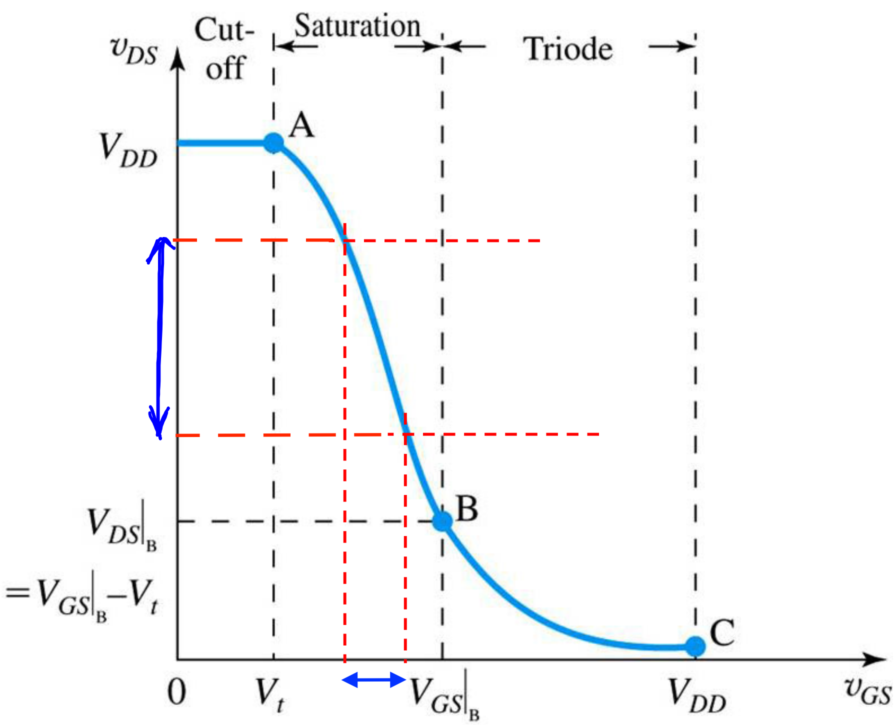
Let us consider the response, if NMOS remains in saturation at all times and v_{GS} is a combination of a **constant value** (V_{GS}) and a **signal** (v_{gs}):

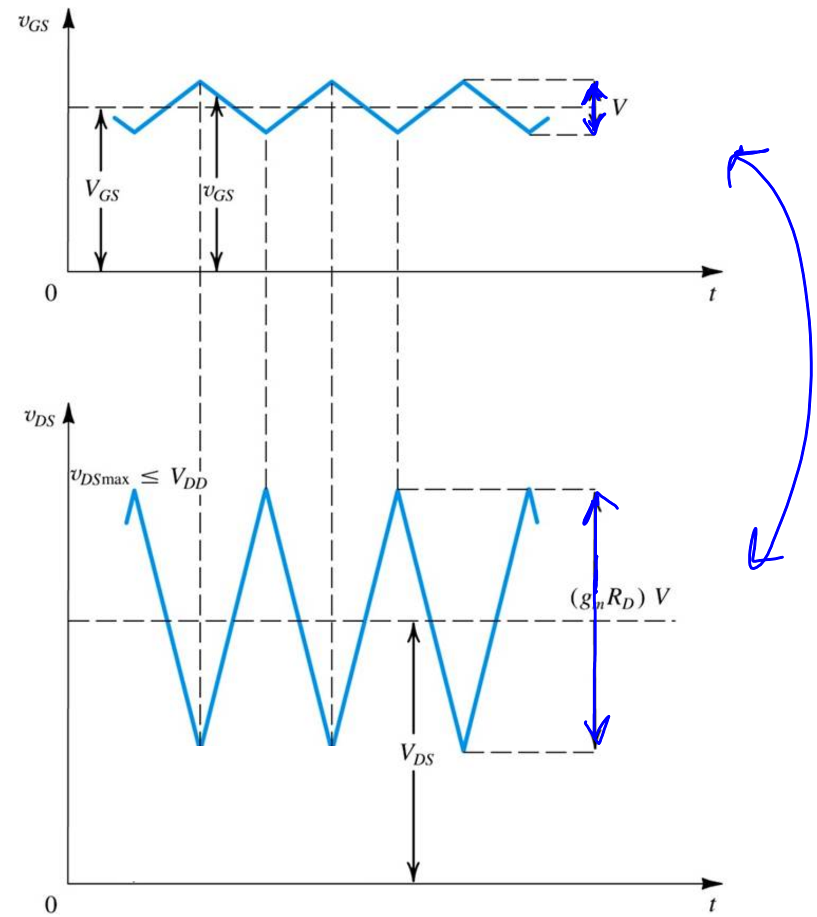
$$v_{GS} = V_{GS} + v_{gs}$$



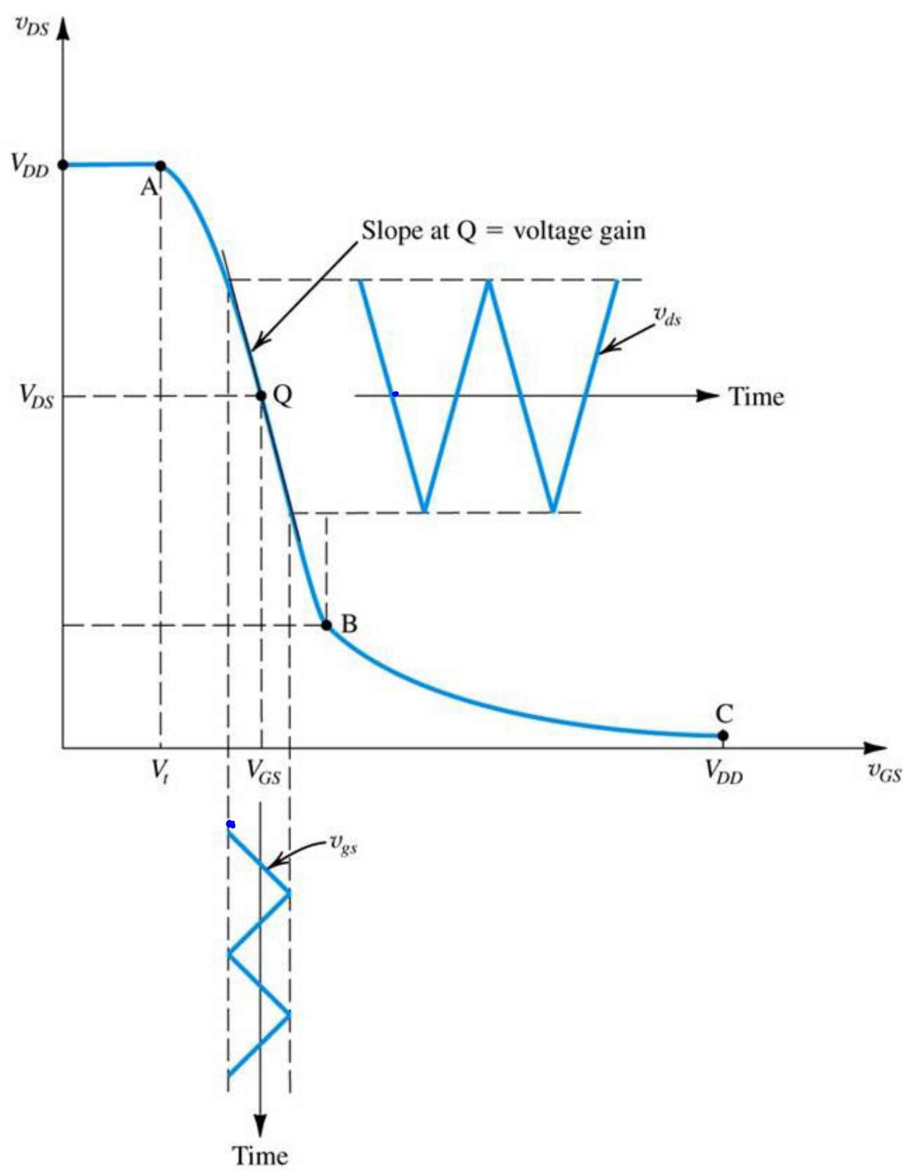


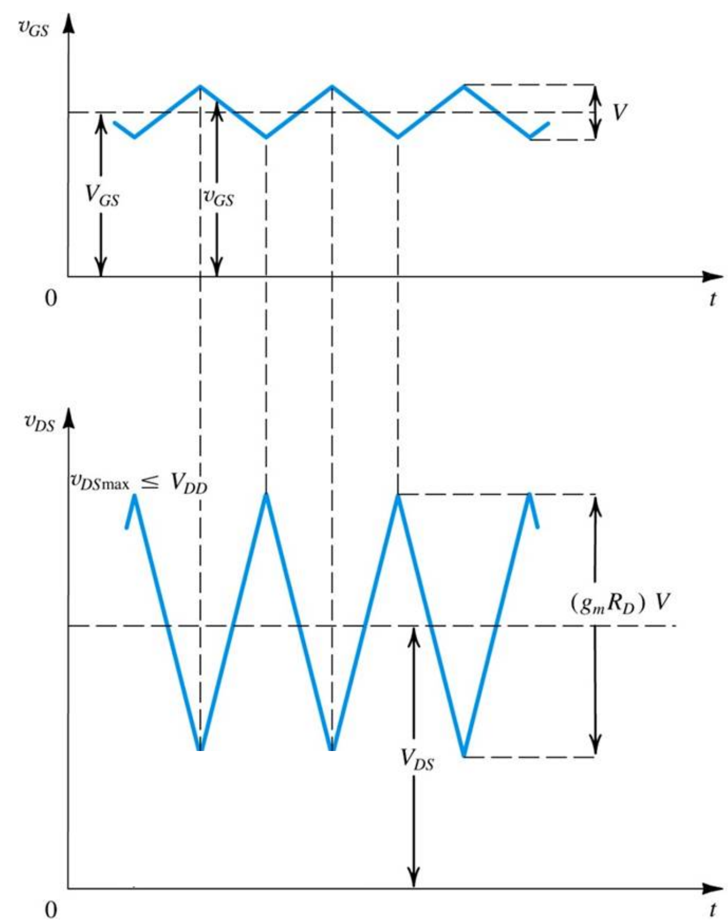
The response to a combination of $v_{GS} = V_{GS} + v_{gs}$ can be found from the transfer function



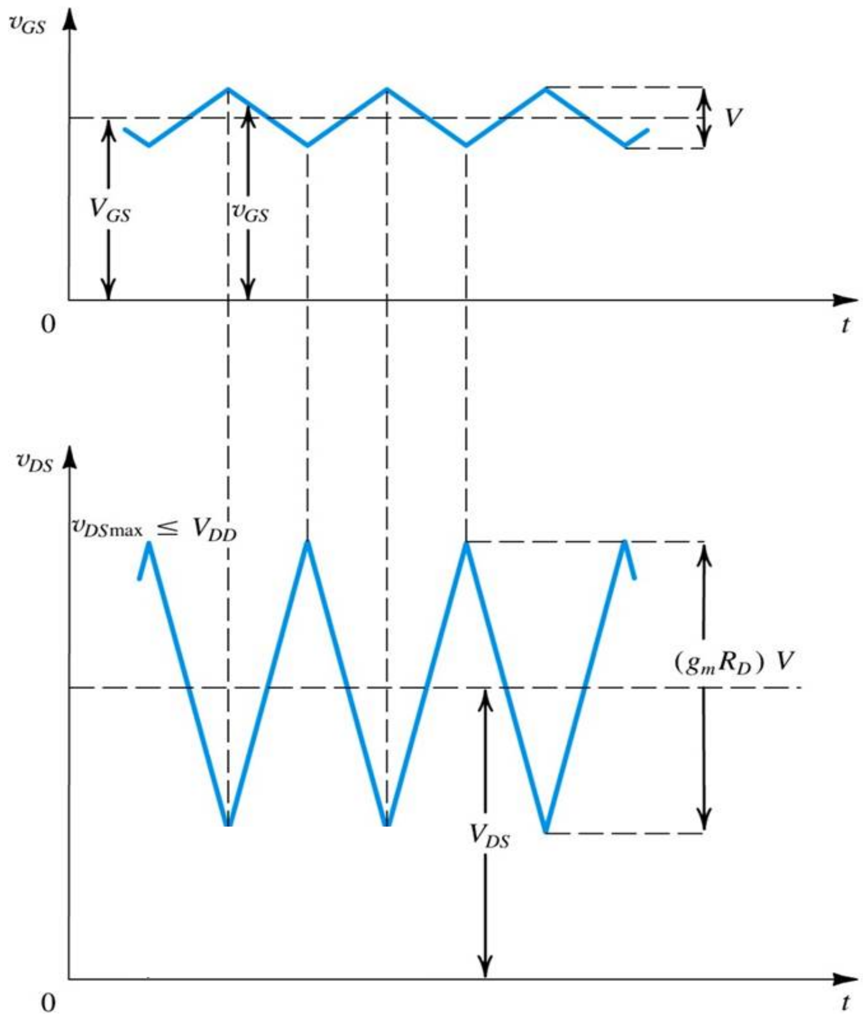


The response to a combination of $v_{GS} = V_{GS} + v_{gs}$ can be found from the transfer function





Response to the signal appears to be linear



Response ($v_o = v_{DS}$) is also made of a constant part (V_{DS}) and a signal response part (v_{ds}).

Constant part of the response, V_{DS}, is ONLY related to V_{GS}, the constant part of the input (Q point on the transfer function of previous slide).

- i.e., if $v_{gs} = 0$, then $v_{ds} = 0$

The shape of the time varying portion of the response (v_{ds}) is similar to v_{gs}.

- i.e., v_{ds} is proportional to the input signal, v_{gs}

Although the overall response is non-linear, the transfer function for the signal is linear!

Constant: Bias | Signal and response

$$v_{GS} = \boxed{V_{GS}} + \boxed{v_{gs}}$$

$$v_{DS} = \boxed{V_{DS}} + \boxed{v_{ds}}$$

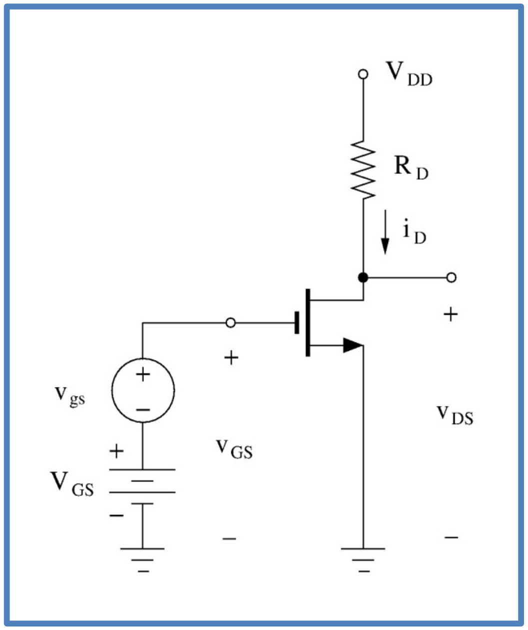
$$i_D = \boxed{I_D} + \boxed{i_d}$$

Under small signal approximation $\longrightarrow$

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

$$i_d = g_m v_{gs}$$

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



NMOS $(V_{OV} = v_{GS} - V_{tn})$

Cut-Off: $V_{OV} < 0$ $\qquad$ $i_D = 0$

Triode: $V_{OV} \geq 0$ and $v_{DS} \leq V_{OV}$ $\qquad$ $i_D = 0.5\mu_n C_{ox} \frac{W}{L}\left[2V_{OV}v_{DS} - v_{DS}^2\right]$

Saturation: $V_{OV} \geq 0$ and $v_{DS} \geq V_{OV}$ $\qquad$ $i_D = 0.5\mu_n C_{ox} \frac{W}{L} V_{OV}^2 \left[1 + \lambda v_{DS}\right]$

Lecture 17 reading quiz

If in a MOSFET amplifier $V_{DS} = 1\ V$ and $V_{OV} = 0.6\ V$ where $V_{GS} = 1\ V$ and $V_t = 0.4\ V$ and the voltage gain of the amplifier ($A_v = \frac{v_{ds}}{v_{gs}}$) is $-10\ V/V$, Which one of the given input AC signals can be amplified with this amplifier?

$$\hat{v}_{ds} = |A_v|\ \hat{v}_{gs} \qquad v_{DS} = V_{DS} + v_{ds} = V_{DS} + |A_v|\ v_{gs}$$

To use a MOSFET device as an amplifier, it should operate in the saturation region.

NMOS will be in saturation if $v_{DS} \geq V_{OV}$

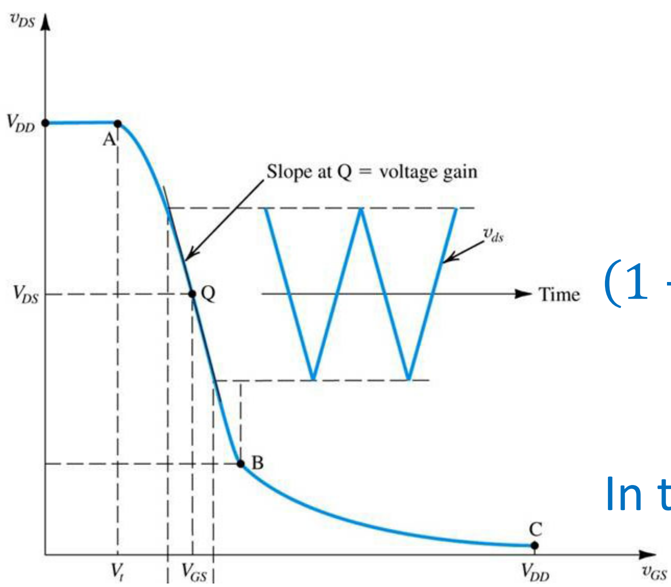
$$\hat{v}_{gs} = 30\ mV$$

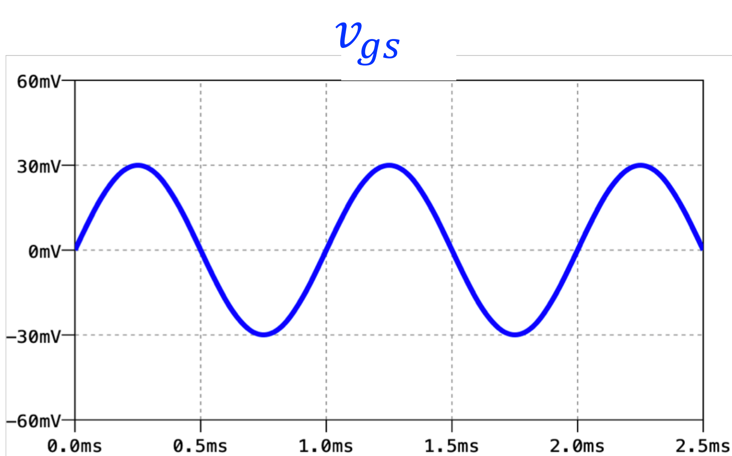
$$\hat{v}_{ds} = 30 \times 10 = 300\ mV$$

$$(1 - 0.3)V \leq v_{DS} \leq (1 + 0.3)V$$

$$\boxed{0.7\ V \leq v_{DS} \leq (1.3)V}$$

In this range, $v_{DS} \geq V_{OV} = 0.6\ V$





Simulation results for the Clicker Question 1

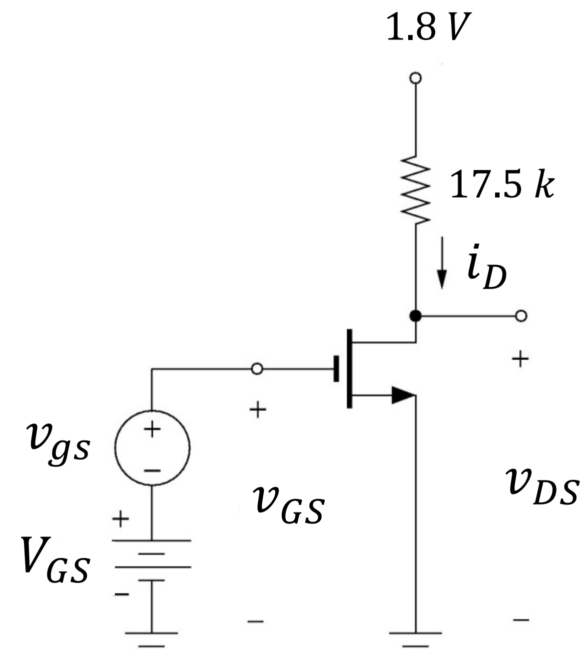
In the following circuit, $V_{GS} = 0.6\ V, V_t = 0.4\ V, k_n = 4\ mA/V^2$ and $\lambda = 0$.

Draw the graph of v_{GS}, v_{DS}, and I_D for

1. $v_{gs} = 0.005\ sin(2\pi f t)\ (V)$

2. $v_{gs} = 0.010\ sin(2\pi f t)\ (V)$

Use $f = 1$ kHz.



Simulation results for the Clicker Question 1

In the following circuit, $V_{GS} = 0.6\ V, V_t = 0.4\ V, k_n = 4\ mA/V^2$ and $\lambda = 0$.

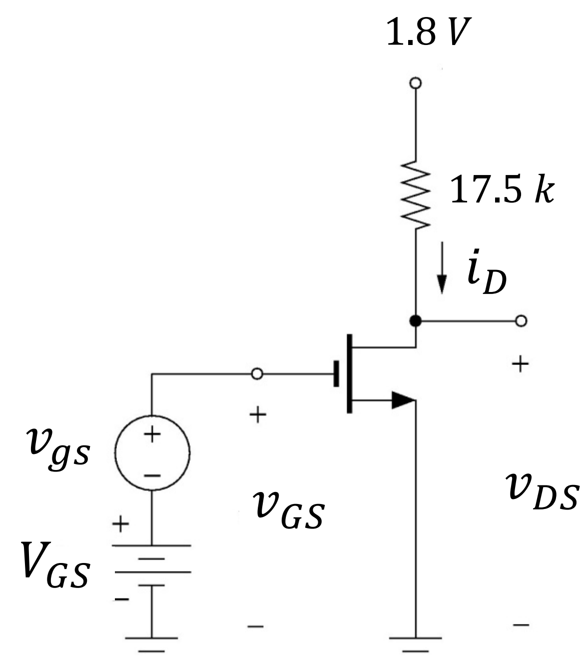
Draw the graph of v_{GS}, v_{DS}, and I_D for

Bias point, or the operation point, or the Q point:

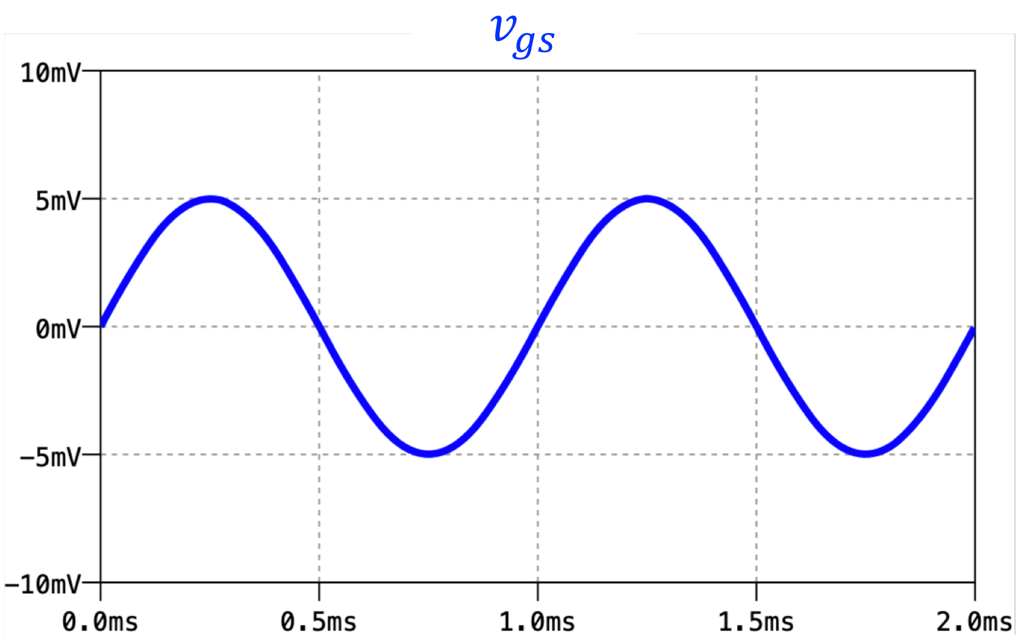
$$V_{GS} = 0.6\ V$$

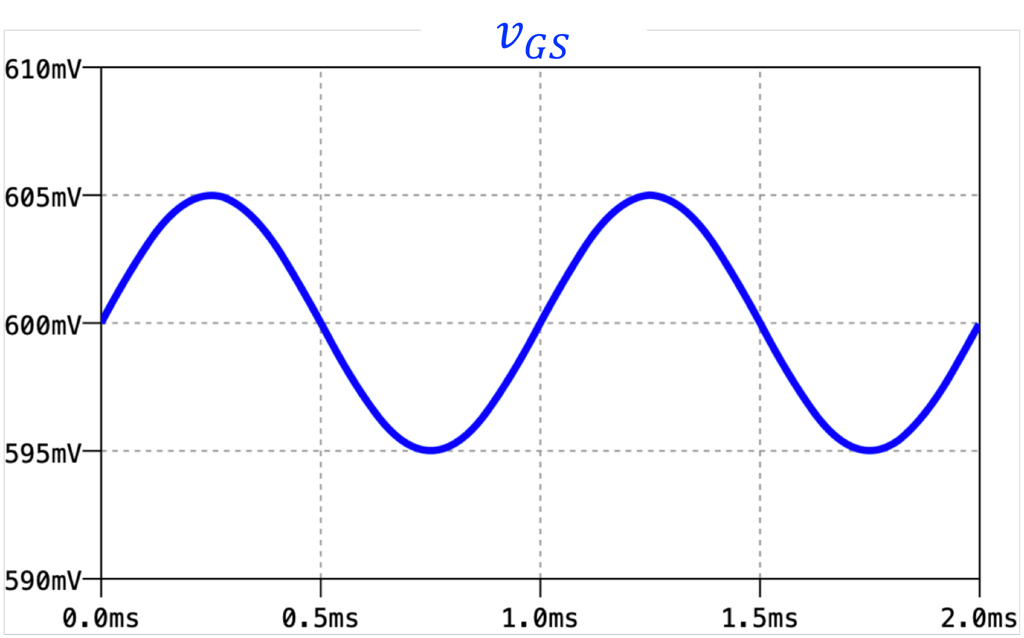
$$V_{DS} = 0.4\ V$$

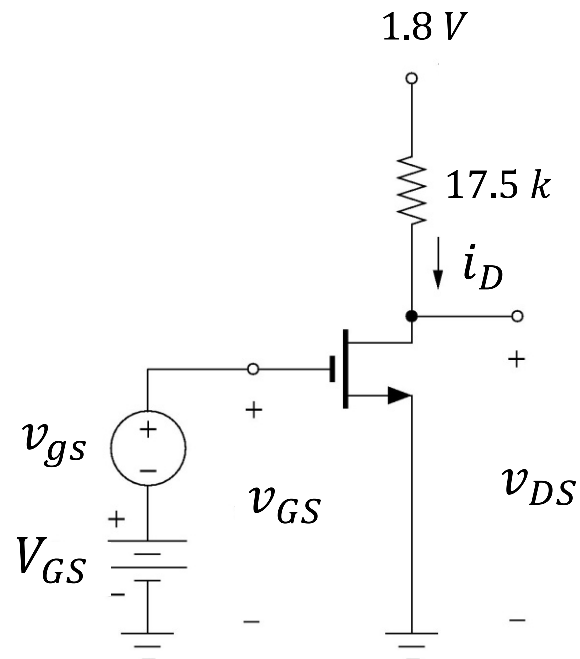
$$I_D = 0.08\ mA$$



$$v_{gs} = 0.005\ sin(2\pi f t)\ (V)$$





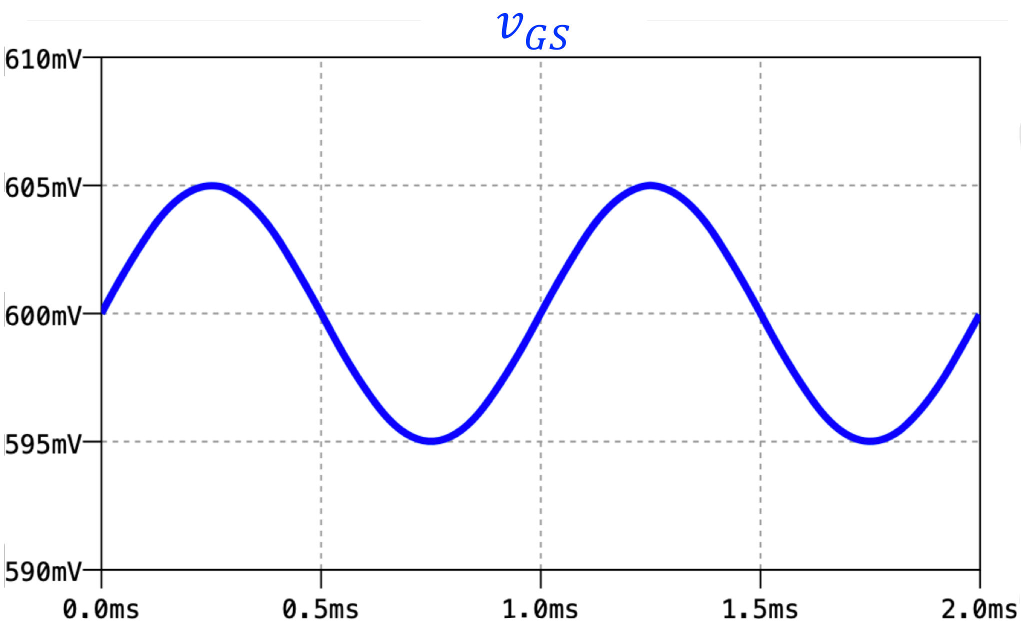


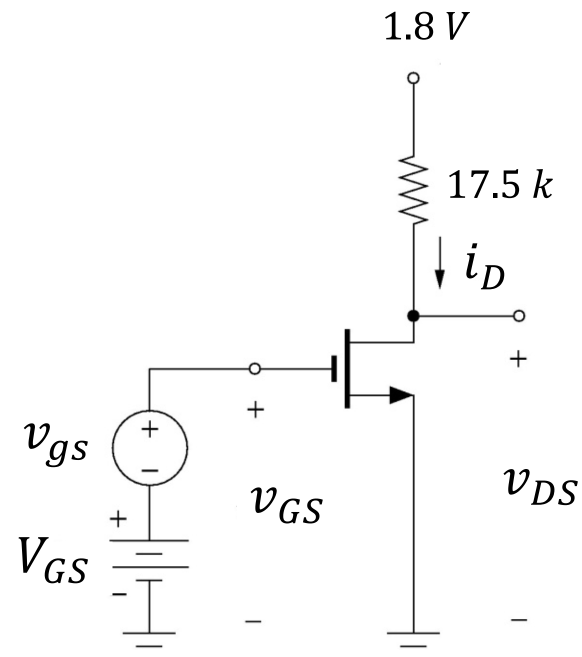
@ Q: $V_{GS} = 0.6\ V$

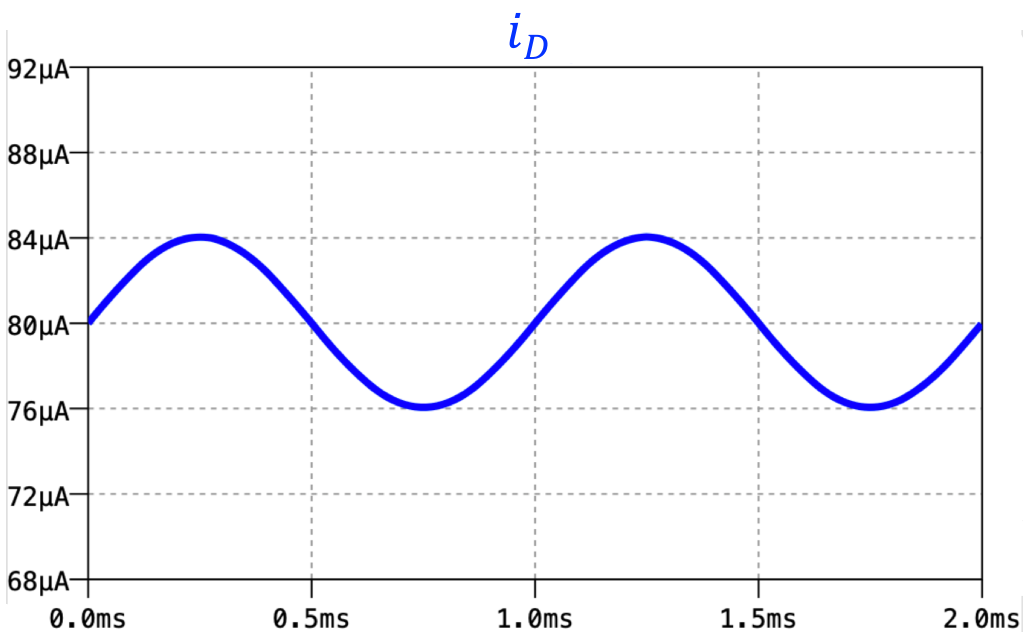
$V_{DS} = 0.4\ V$

$I_D = 0.08\ mA$

$$v_{gs} = 0.005\ sin(2\pi f t)\ (V)$$







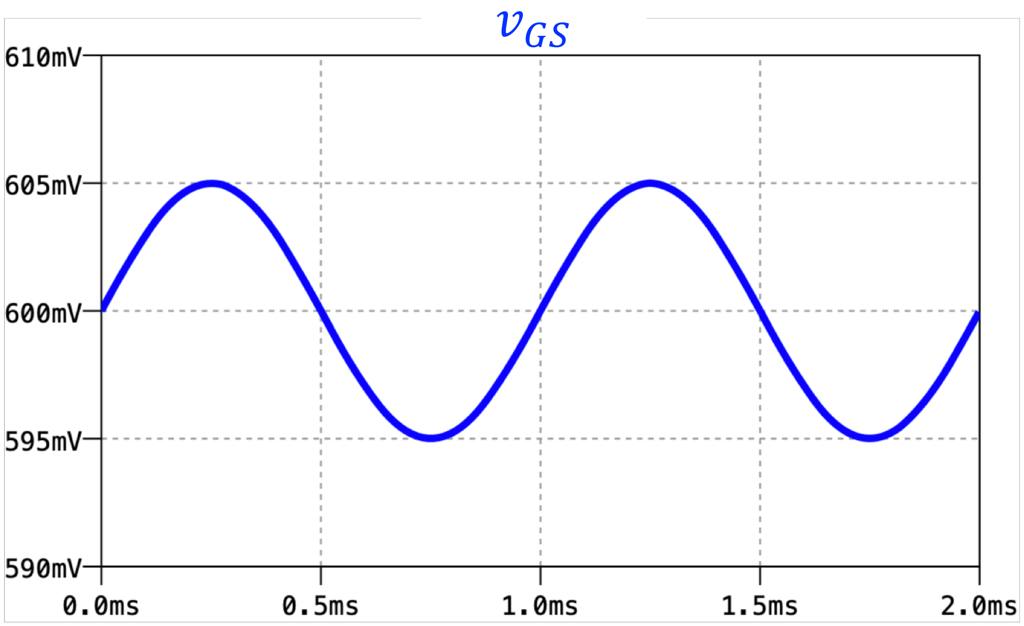
@ Q: $V_{GS} = 0.6\ V$

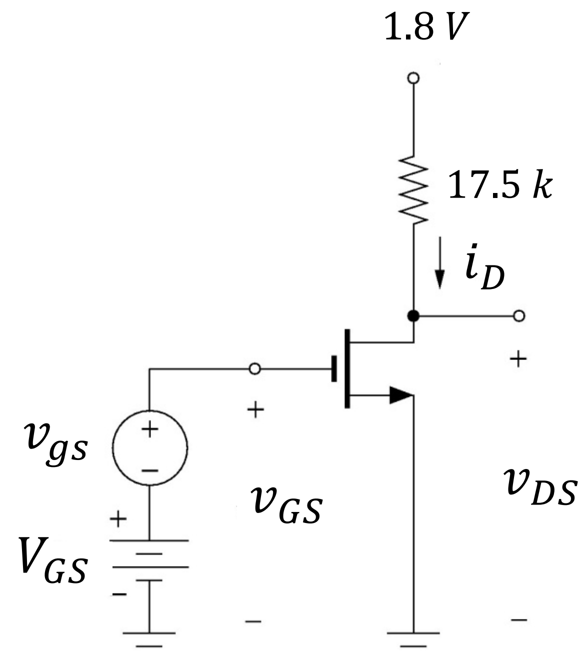
$V_{DS} = 0.4\ V$

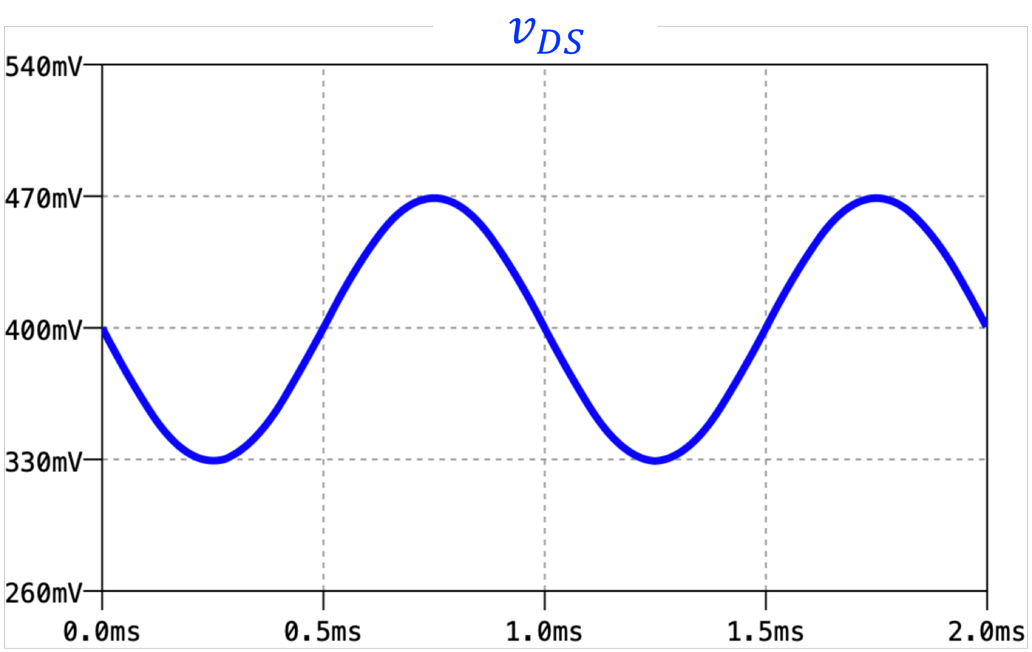
$I_D = 0.08\ mA$

$$g_m = \frac{i_d}{v_{gs}} = 0.08\ \ mA/V$$

$$v_{gs} = 0.005\, sin(2\pi f t)\ (V)$$







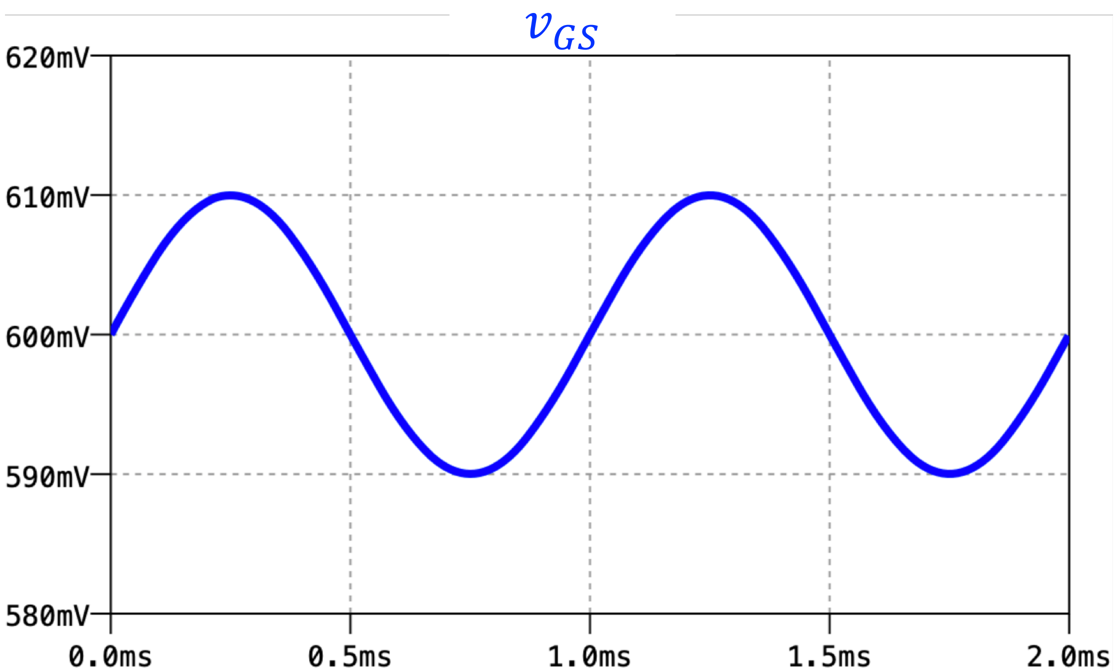
@ Q: $V_{GS} = 0.6\ V$

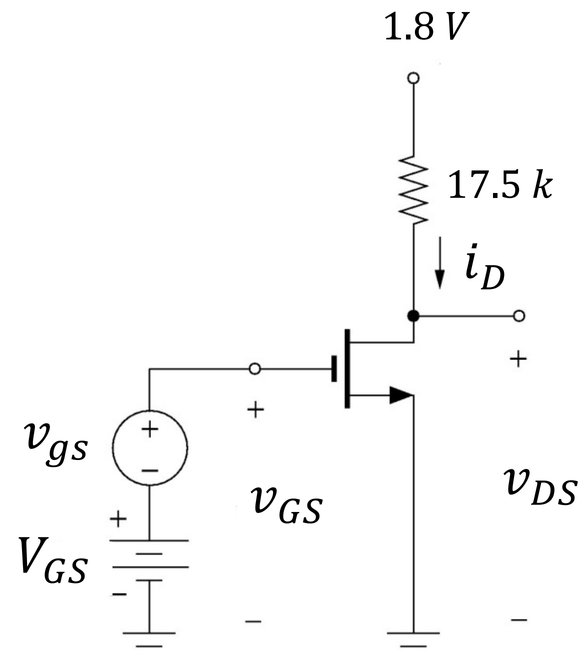
$V_{DS} = 0.4\ V$

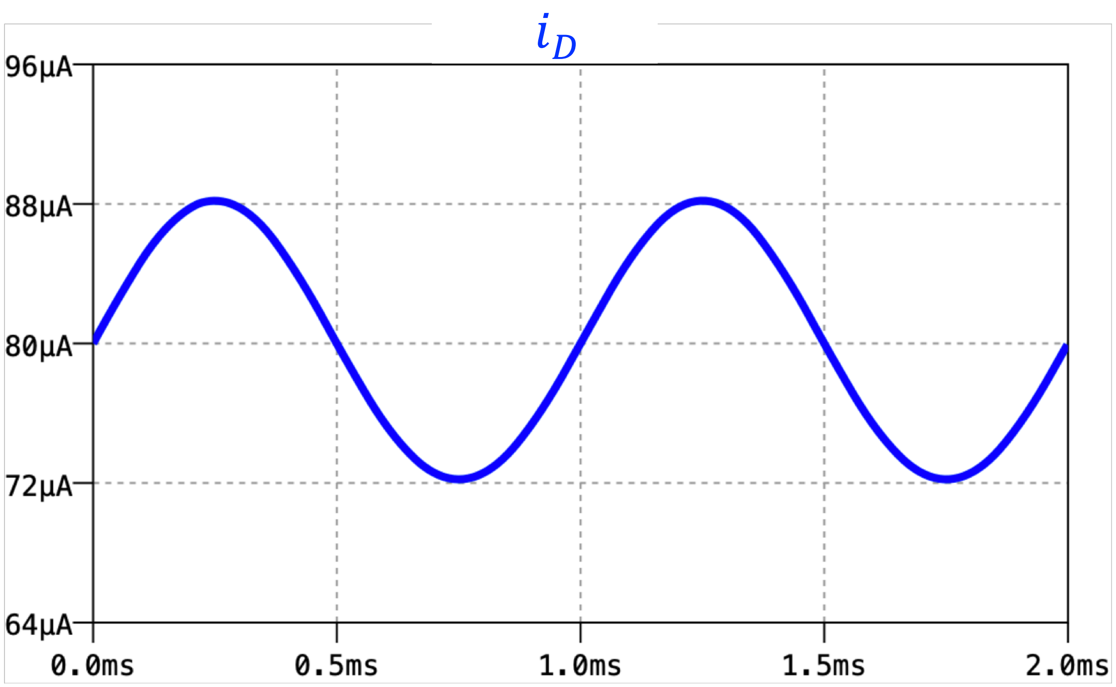
$I_D = 0.08\ mA$

$$A_v = \frac{v_{ds}}{v_{gs}} = -14\ V/V$$

$$v_{gs} = 0.01\, sin(2\pi f t)\ (V)$$







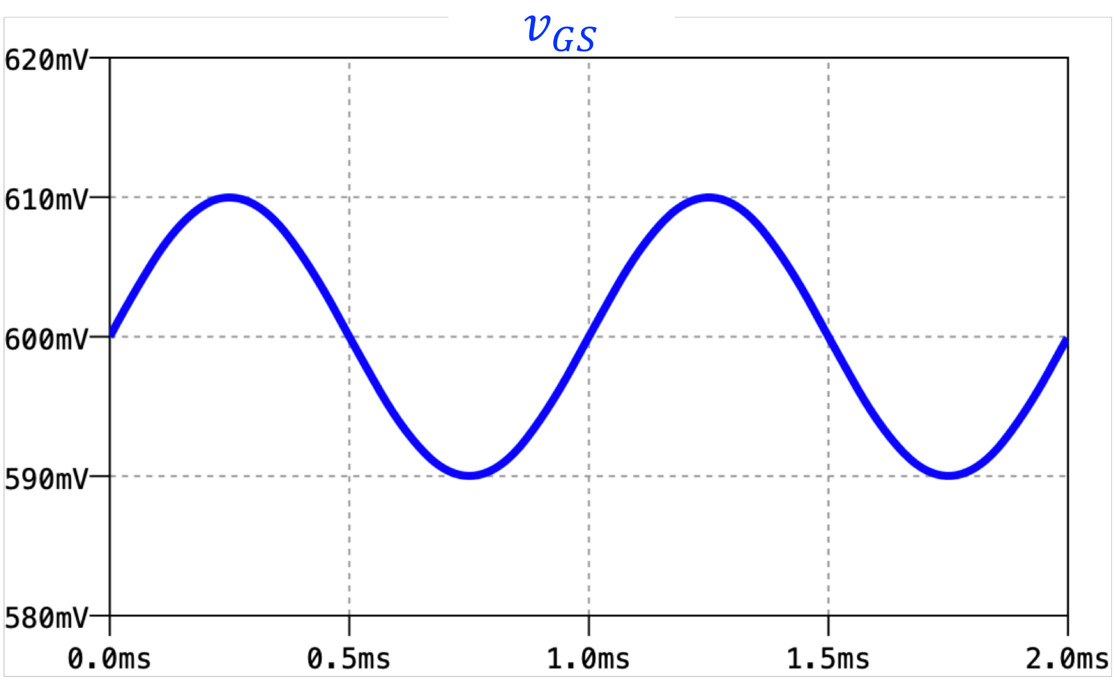
@ Q: $V_{GS} = 0.6\ V$

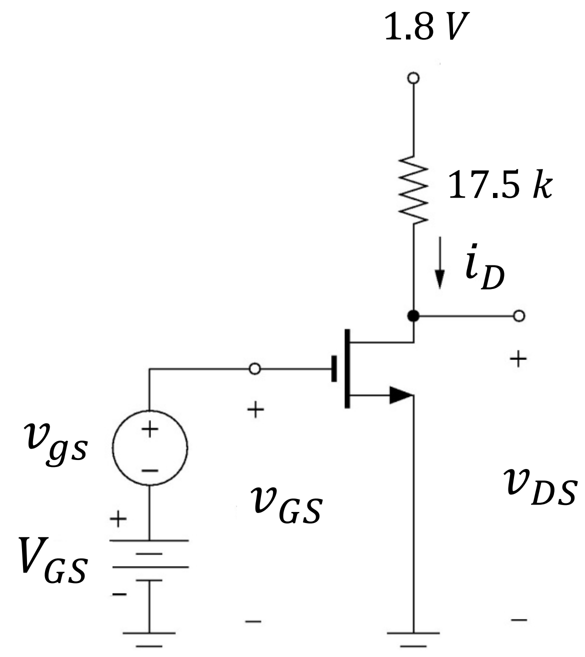
$V_{DS} = 0.4\ V$

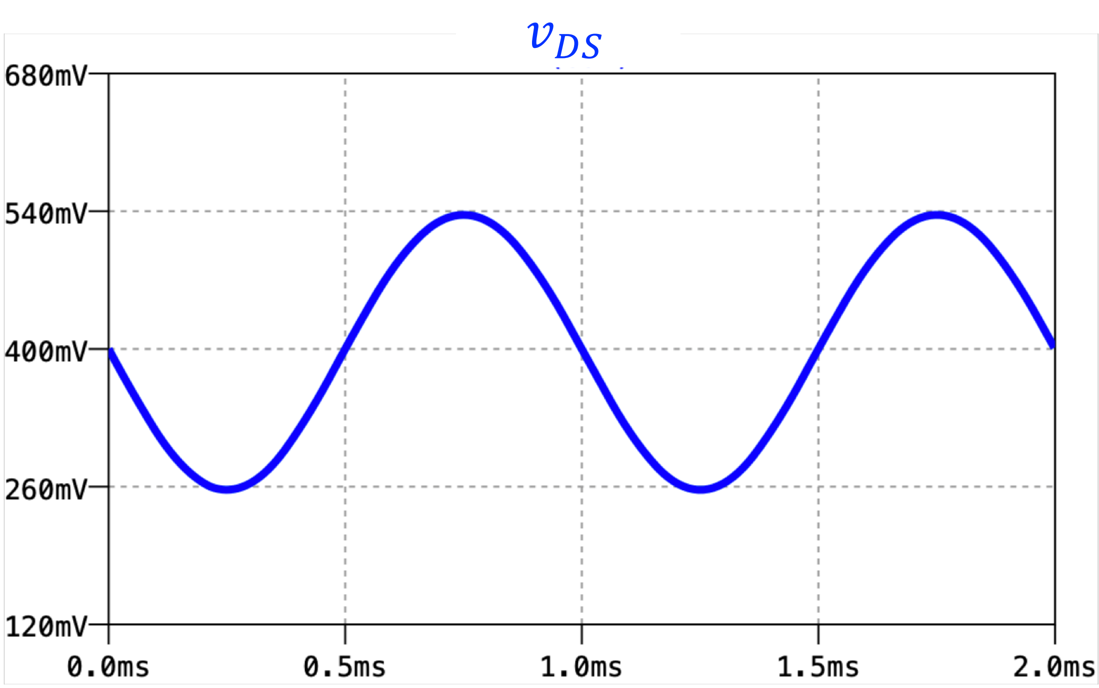
$I_D = 0.08\ mA$

$$g_m = \frac{i_d}{v_{gs}} = 0.08\ \ mA/V$$

$$v_{gs} = 0.01\, sin(2\pi f t)\ (V)$$







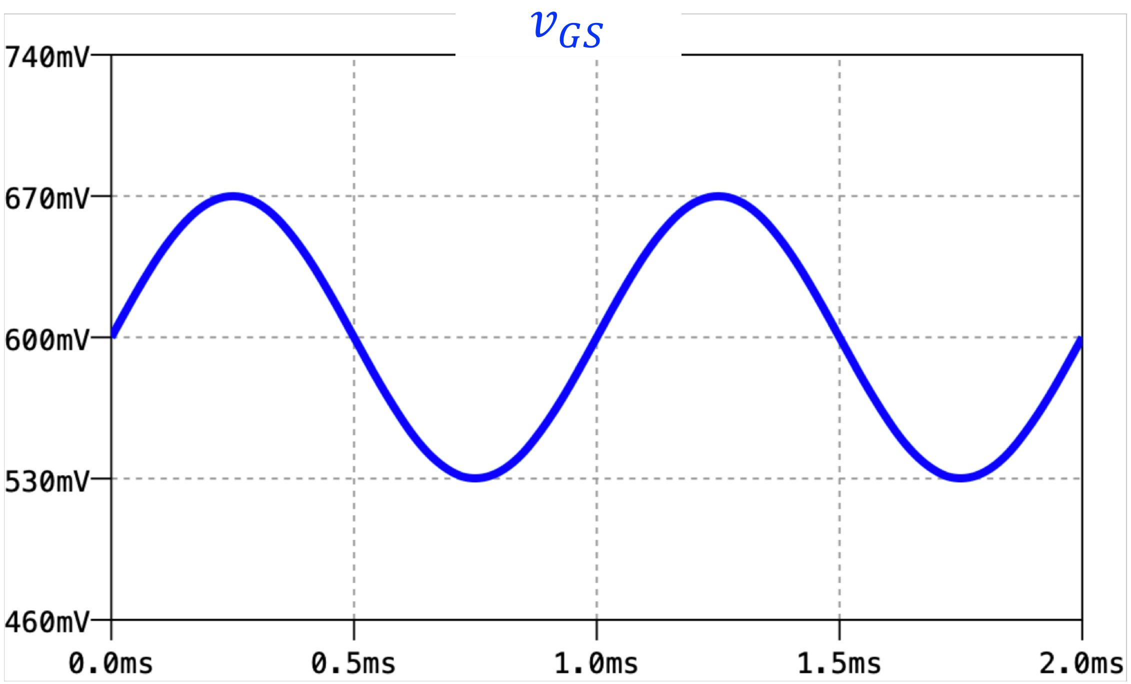
@ Q: $V_{GS} = 0.6\ V$

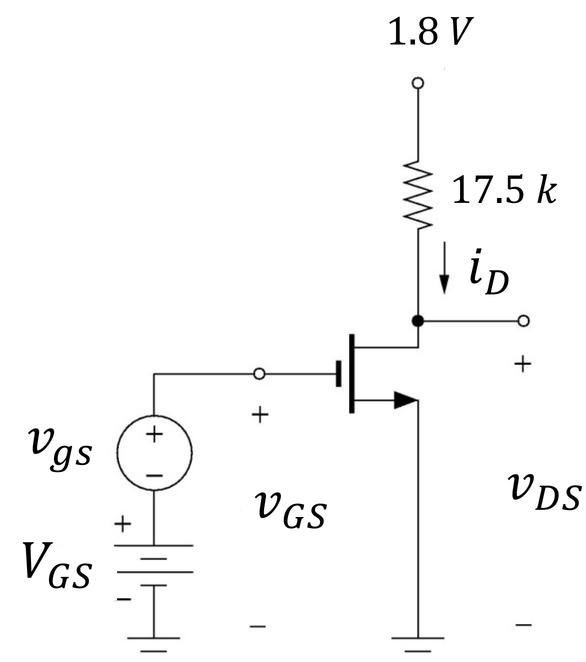
$V_{DS} = 0.4\ V$

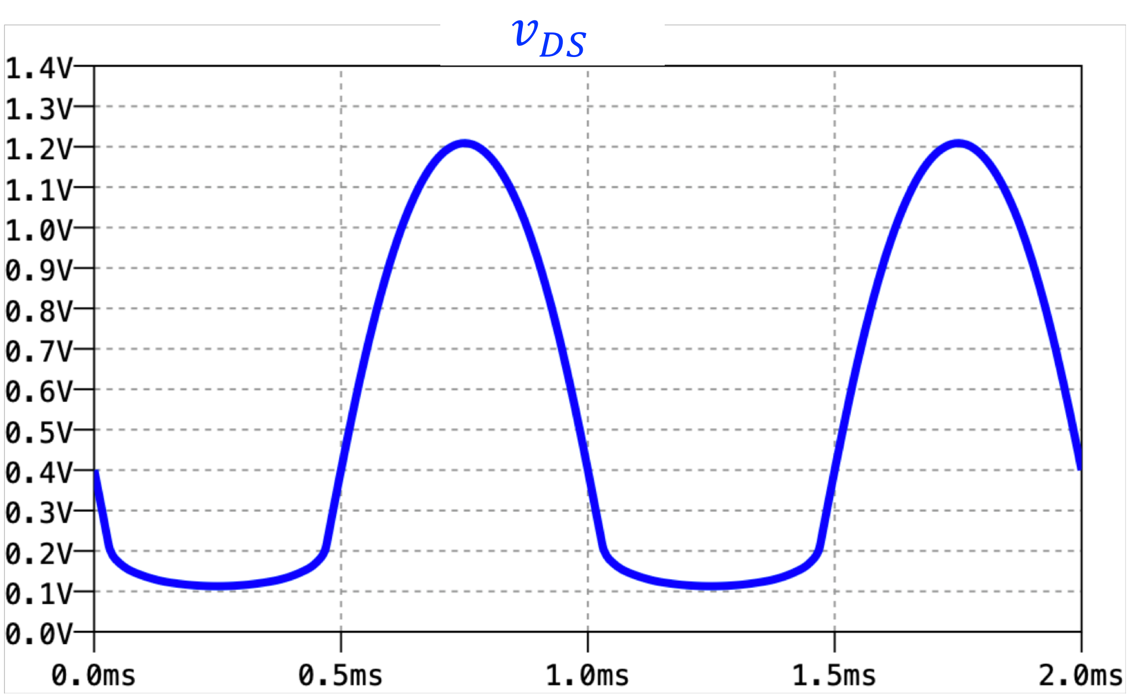
$I_D = 0.08\ mA$

$$A_v = \frac{v_{ds}}{v_{gs}} = -14\ V/V$$

$v_{gs} = 0.07 \sin(2\pi f_1 t) \quad (V)$







@ Q: $V_{GS} = 0.6\ V$

$V_{DS} = 0.4\ V$

$I_D = 0.08\ mA$

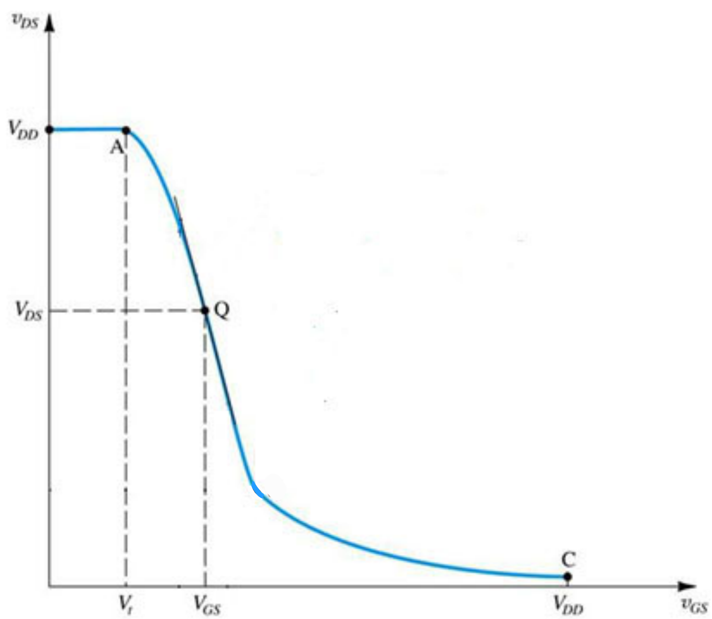
$V_{OV} = 0.2\ V$

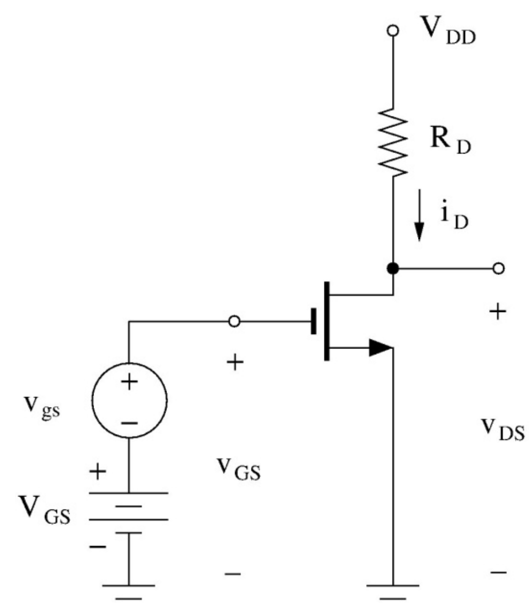
Clicker Question 1.

In the following circuit, $V_{GS} = 0.6\ V, V_{DD} = 1.8\ V, R_D = 17.5\ k\Omega, V_t = 0.4\ V, k_n = 4\ mA/V^2$ and $\lambda = 0$.

What is the maximum symmetrical signal swing allowed at the drain (what is the maximum allowable peak amplitude of v_{ds})?

A. 0.4 V
B. 0.6 V
C. 0.2 V





Hints:

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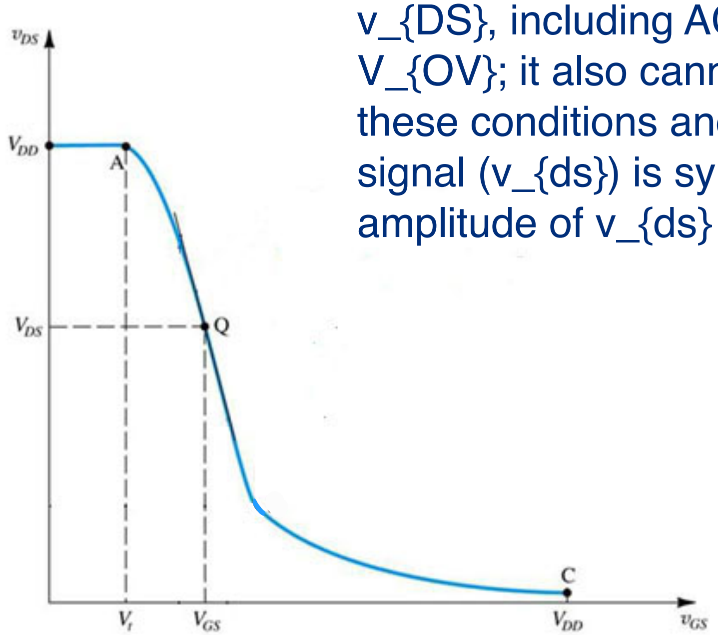
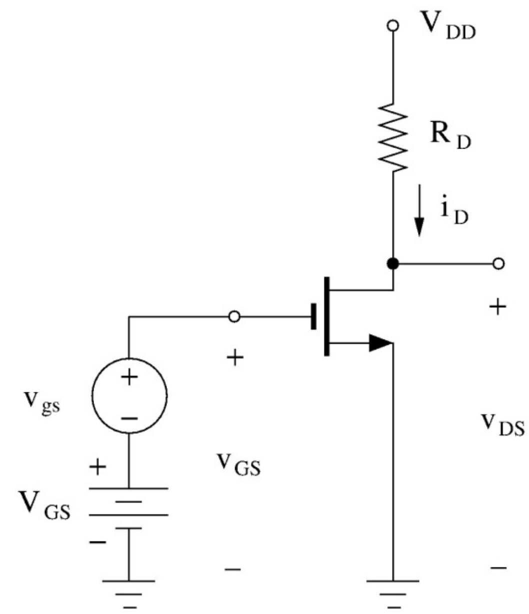
What is the maximum symmetrical signal swing allowed at the drain (what is the maximum allowable peak amplitude of v_{ds})?

A. 0.4 V
B. 0.6 V
C. 0.2 V

- Find V_{OV} and V_{DS}.

- After adding an AC signal, v_{gs}, an AC signal v_{ds} will be superimposed on V_{DS}. The total v_{DS}, including AC and DC should not go below V_{OV}; it also cannot exceed V_{DD}. Knowing these conditions and assuming that the AC output signal (v_{ds}) is symmetric, how large the amplitude of v_{ds} can be?





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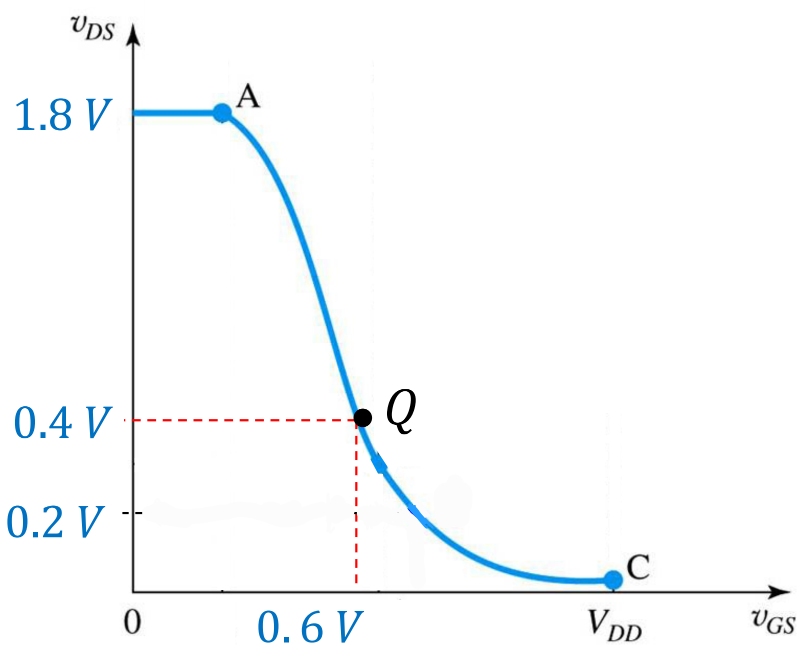

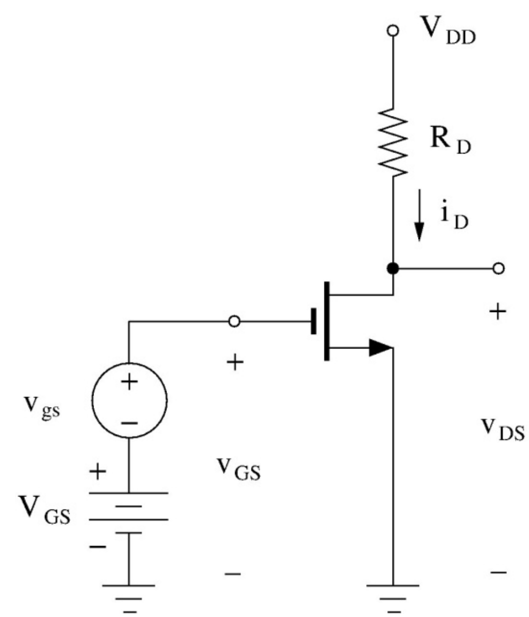

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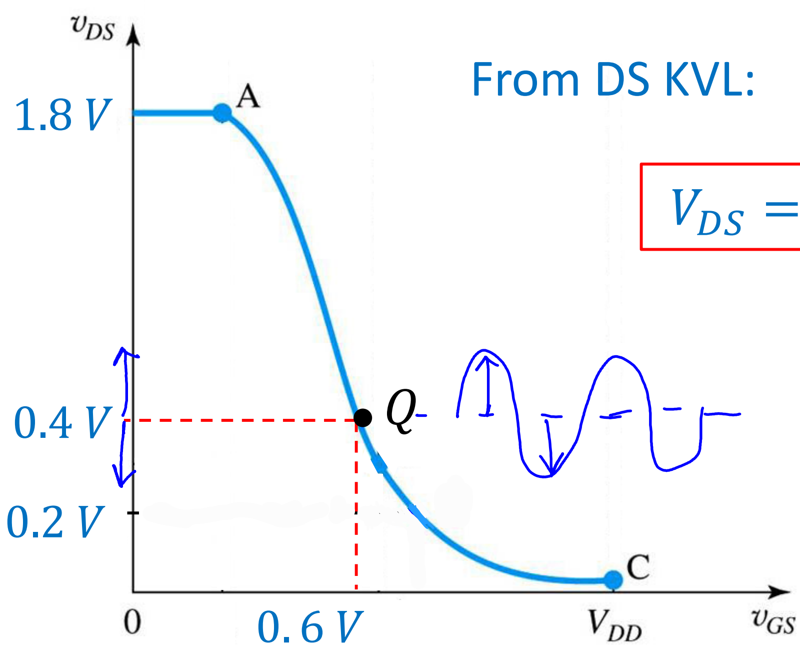
What is the maximum symmetrical signal swing allowed at the drain (what is the maximum allowable peak amplitude of v_{ds})?

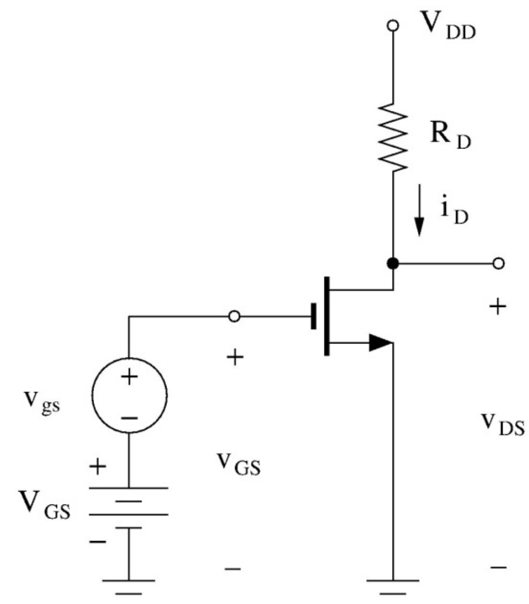
$$V_{OV} = V_{GS} - V_t = 0.6\ V - 0.4\ V = 0.2\ V$$

$$I_D = 0.5\ k_n (V_{OV})^2 = 0.08\ mA$$

From DS KVL: $I_D = \dfrac{V_{DD} - V_{DS}}{R_D}$

$$\boxed{V_{DS} = 0.4\ V}$$





@ Q: $V_{GS} = 0.6\ V$

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$I_D = 0.08\ mA$

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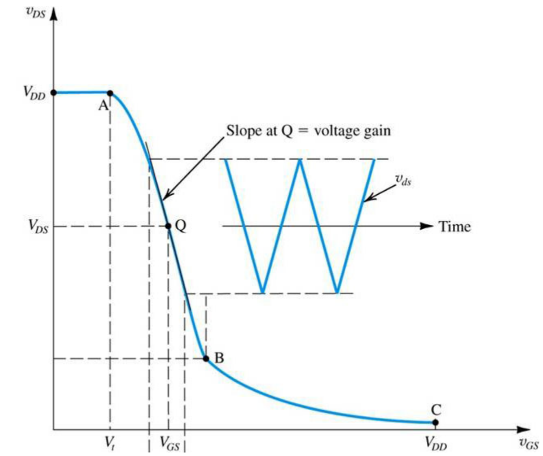
In the following circuit, $V_{GS} = 0.6\ V, V_{DD} = 1.8\ V, R_D = 17.5\ k\Omega, V_t = 0.4\ V, k_n = 4\ mA/V^2$ and $\lambda = 0$.

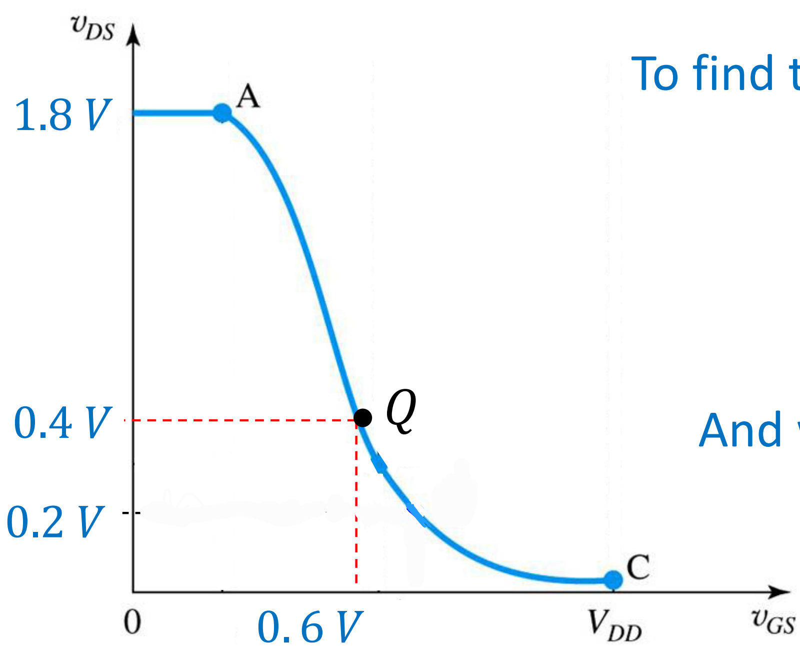
What is the maximum symmetrical signal swing allowed at the drain



$@\ Q$: $V_{GS} = 0.6\ V$

$V_{DS} = 0.4\ V$

$I_D = 0.08\ mA$



To find the max allowable peak amplitude of $\hat{v}_{ds}$:

$$V_{DS} - \hat{v}_{ds} \le v_{DS} \le V_{DS} + \hat{v}_{ds}$$

$$0.4\ \text{V} - \hat{v}_{ds} \le v_{DS} \le 0.4\ \text{V} + \hat{v}_{ds}$$

And we know that

$$0.2\ V \le v_{DS} \le 1.8\ V$$

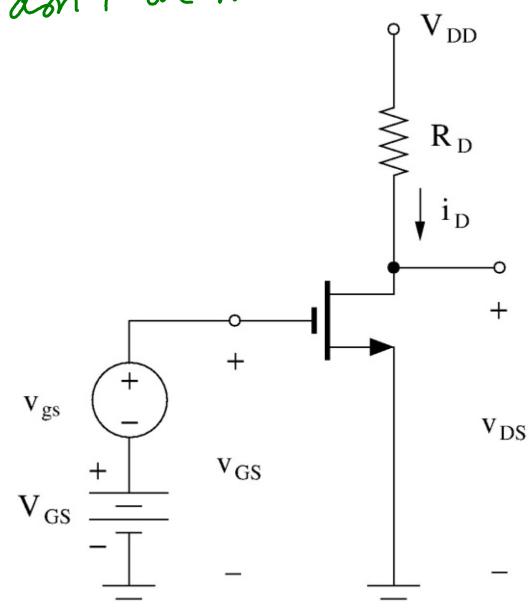
$$\hat{v}_{ds} = 0.2\ V$$

Clicker Question 1.

In the following circuit, $V_{GS} = 0.6\,V, V_{DD} = 1.8\,V, R_D = 17.5\,k\Omega, V_t = 0.4\,V, k_n = 4\,mA/V^2$ and $\lambda = 0$.

What is the maximum symmetrical signal swing allowable at the drain (what is the maximum allowable peak amplitude of v_{ds})?

Question: doesn't V_{ov} change when v_{GS} changes? so, don't we need to take that into account?



Answer: Yes, to be more precise,

total AC+DC $\boxed{v_{DS_{min}}} \geq \boxed{v_{GS_{max}}} - V_t$

$v_{DS_{min}} \geq \underbrace{\boxed{V_{GS}}}_{\text{DC part}} + \underbrace{\boxed{\hat{v}_{gs}}}_{\text{peak amplitude of the AC part of the total } v_{GS}} - V_t$

$\underbrace{\boxed{v_{DS_{min}}}}_{\text{total } v_{DS}} = \underbrace{\boxed{V_{DS}}}_{\text{DC part}} - \underbrace{\boxed{\hat{v}_{ds}}}_{\text{peak amplitude of AC part}} \geq V_{GS} + \hat{v}_{gs} - V_t \implies 0.4 - \hat{v}_{ds} \geq 0.6 - 0.4 + \hat{v}_{gs}$

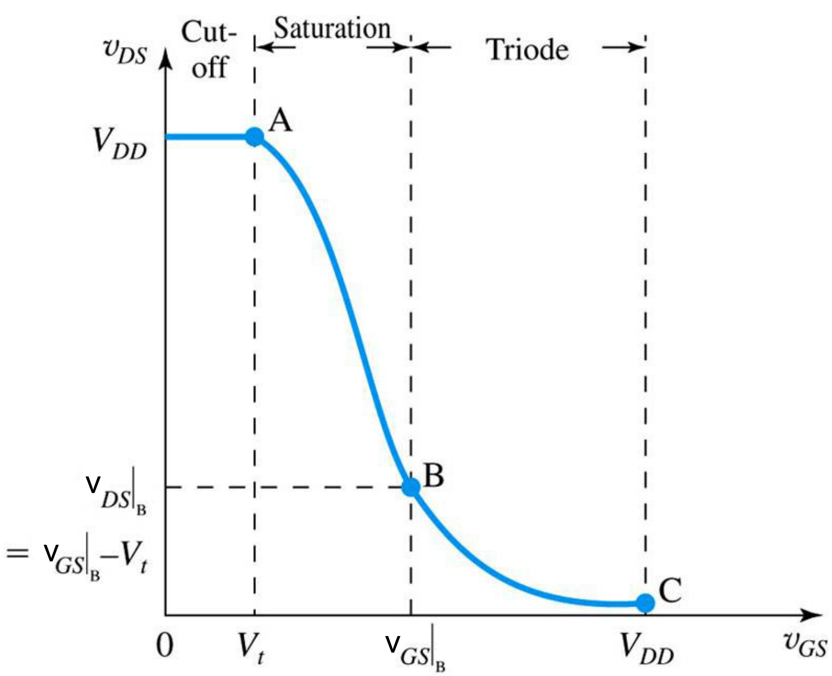
$\hat{v}_{ds} = A\,\hat{v}_{gs} \longrightarrow \hat{v}_{ds} \leq 0.2\left(\frac{|A|}{|A|+1}\right)$, We will learn how to calculate the gain value next week.

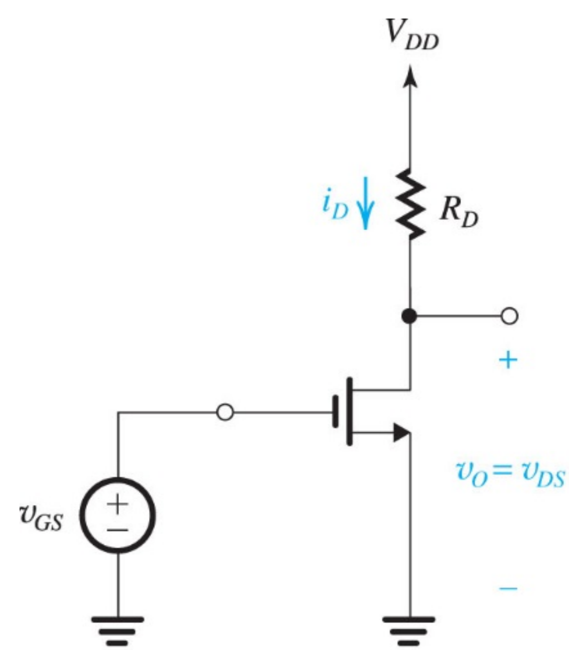
Discussion Question 1.

In the following circuit,

$V_{DD} = 5\,V, R_D = 20\,k\Omega, V_t = 0.5\,V, k_n = 10\,mA/V^2$ and $\lambda = 0$.

Determine the coordinates of the saturation-region segment (AB) of the curve for the voltage transfer function.





Discussion Question 1.

$V_{DD} = 5\ V, R_D = 20\ k\Omega, V_t = 0.5\ V, k_n = 10\ mA/V^2$ and $\lambda = 0$.

@A: $v_{GS} = V_t = 0.5\ V$

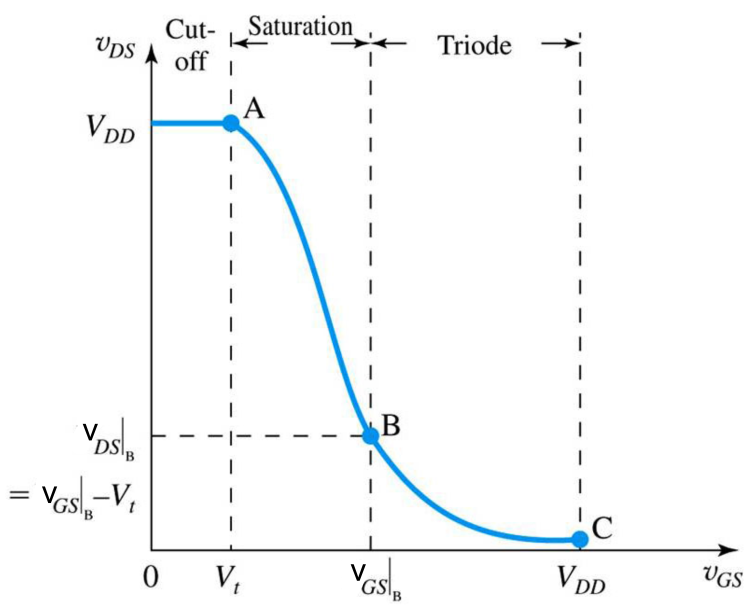
$v_{DS} = V_{DD} = 5\ V$

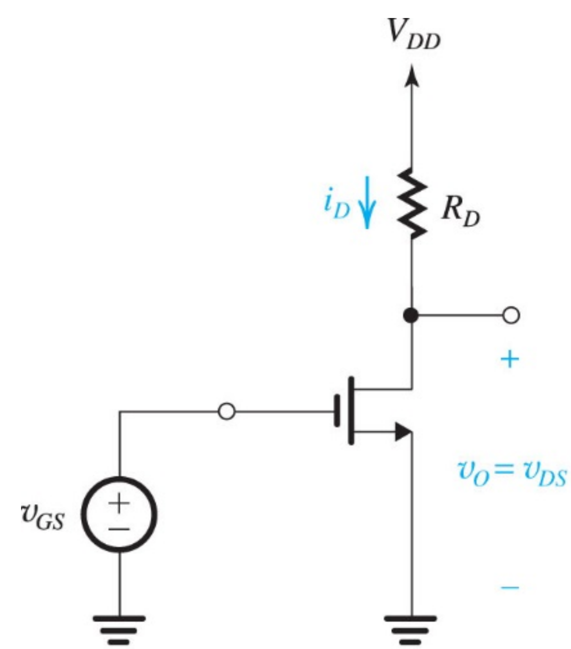
@B: The edge of saturation

$v_{GS} = v_{GS}\big|_B$

$v_{DS} = v_{DS}\big|_B$

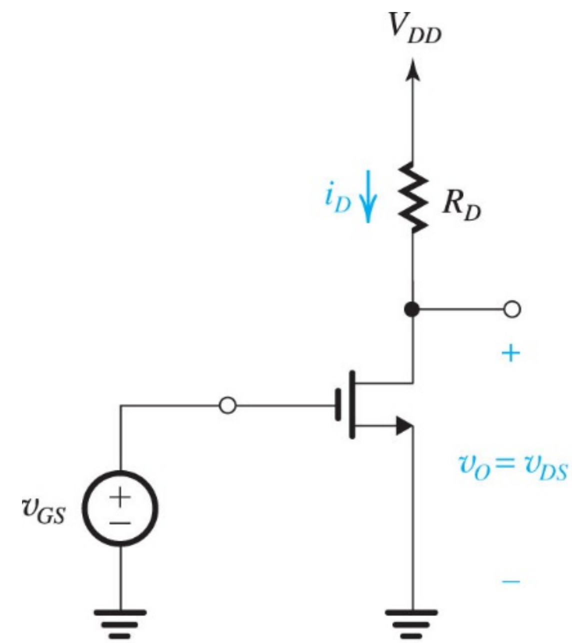
$v_{DS}\big|_B = v_{GS}\big|_B - V_t$





Discussion Question 1.

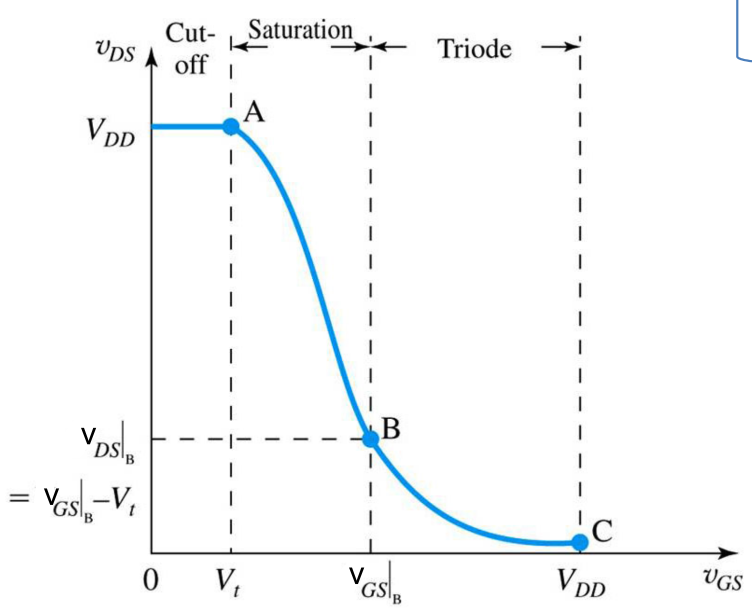
$V_{DD} = 5\,V, R_D = 20\,k\Omega, V_t = 0.5\,V, k_n = 10\,mA/V^2$ and $\lambda = 0$.



When NMOS is in saturation: $i_D = 0.5\,k_n(v_{GS} - V_t)^2$

From the DS KVL: $V_{DD} = R_D i_D + v_{DS}$

@B:
$$\begin{cases} i_D\big|_B = 0.5\,k_n\left(v_{GS}\big|_B - V_t\right)^2 \\ V_{DD} = R_D\,i_D\big|_B + v_{DS}\big|_B \end{cases}$$



$$\rightarrow \quad V_{DD} = 0.5\,R_D k_n\left(v_{GS}\big|_B - V_t\right)^2 + v_{DS}\big|_B$$

Since $v_{DS}|_B = v_{GS}|_B - V_t$

$$V_{DD} = 0.5\,R_D k_n\left(v_{GS}\big|_B - V_t\right)^2 + v_{GS}\big|_B - V_t$$

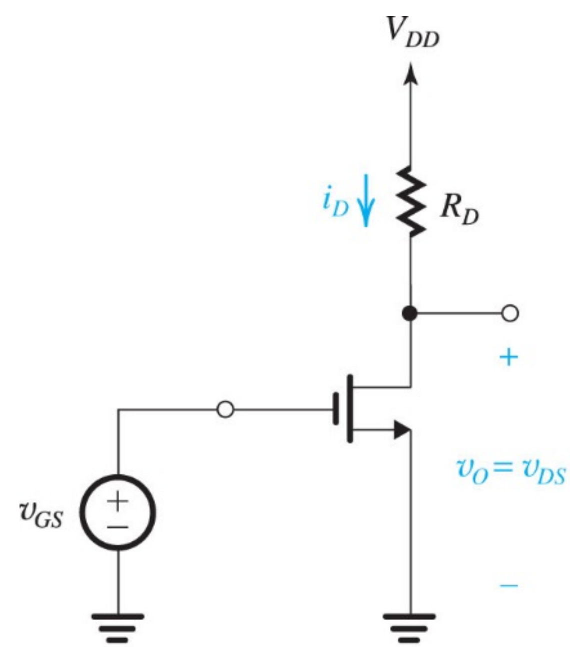
Discussion Question 1.

$V_{DD} = 5\ V, R_D = 20\ k\Omega, V_t = 0.5\ V, k_n = 10\ mA/V^2$ and $\lambda = 0$.

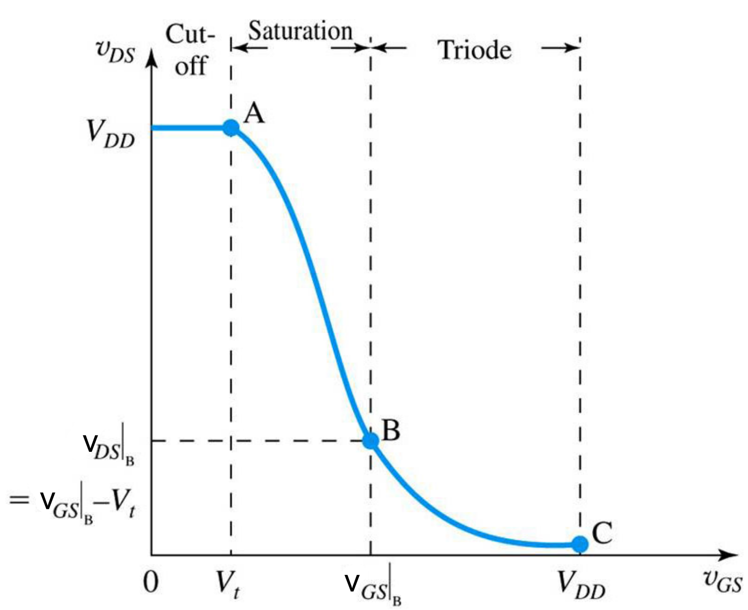
$$V_{DD} = 0.5\ R_D k_n \left(v_{GS}\Big|_B - V_t \right)^2 + v_{GS}\Big|_B - V_t$$

$$Z = v_{GS}\Big|_B - V_t$$

$$5 = 0.5 \times 20\ (k\Omega) \times 10\ (mA/V^2) \times (Z)^2 + Z$$



$$Z = \begin{cases} \boxed{0.22\ \text{V}} \\ -0.23\ \text{V} \end{cases}$$



$$Z = v_{GS}\Big|_B - V_t > 0$$

$$v_{GS}\Big|_B - V_t = 0.22\ V$$

$$v_{GS}\Big|_B = 0.72\ V$$

$$v_{DS}\Big|_B = 0.22\ V$$