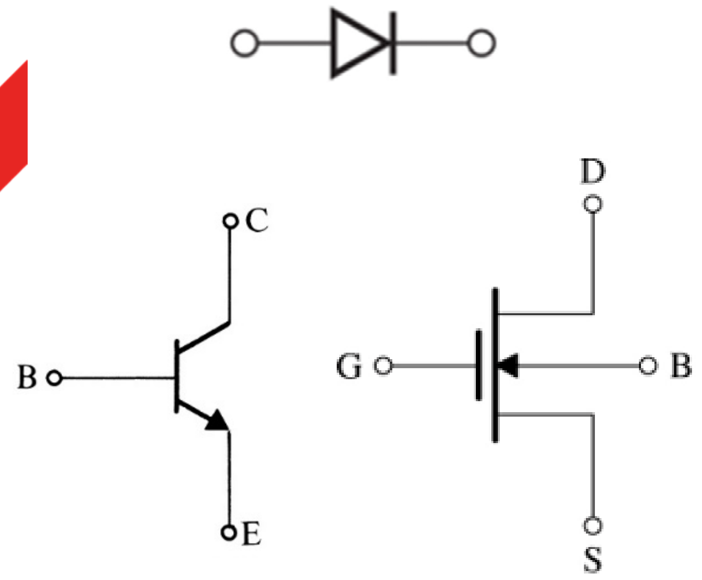
ELEC2005
Electrical and Electronic Systems

MOSFETS– PART 2

DAVID PAYNE

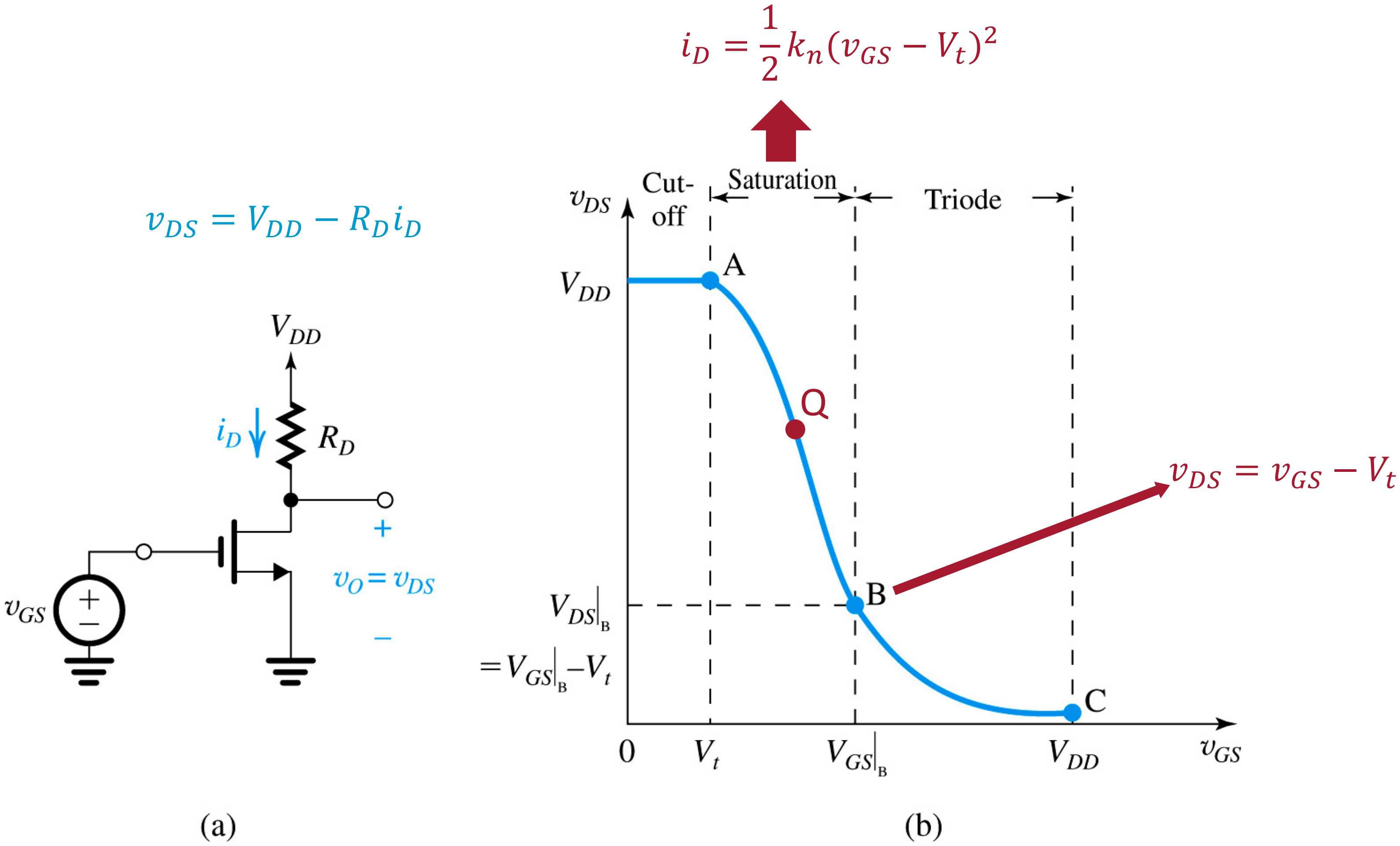


Lecture 6

1. **MOSFET Amplifiers**
2. MOSFET Small Signals
3. Examples

MOSFET

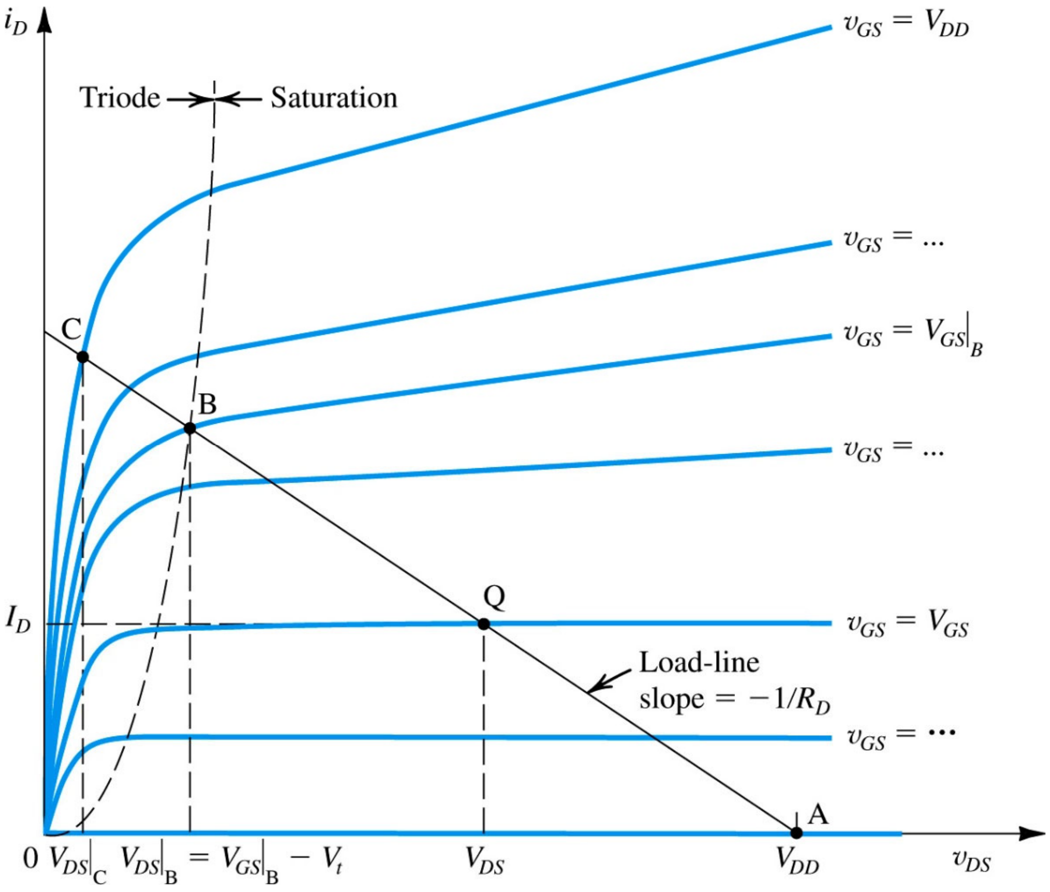
HOW TO MAKE AN AMPLIFIER OR SWITCH

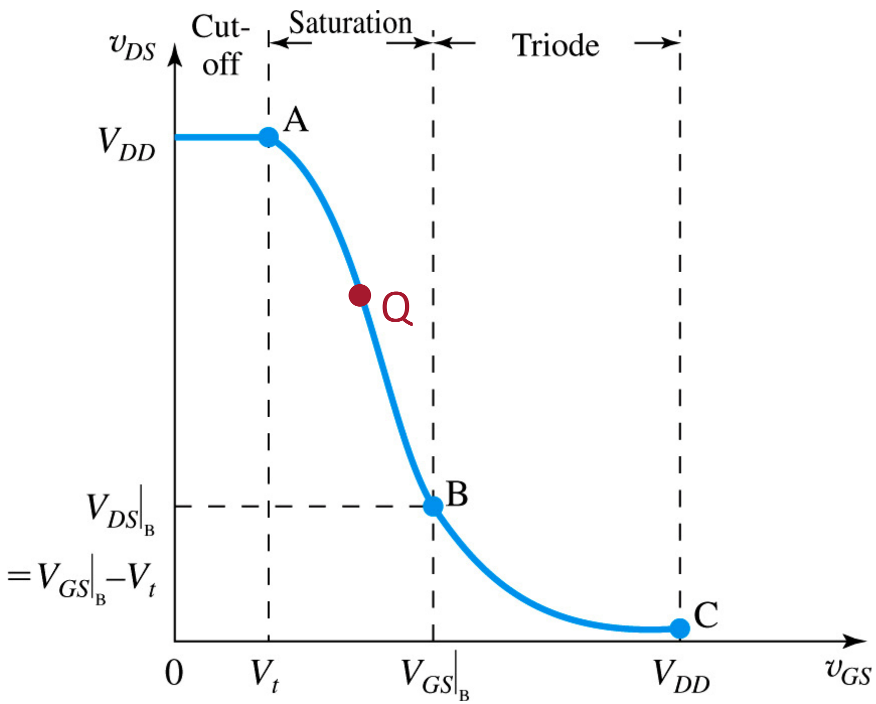


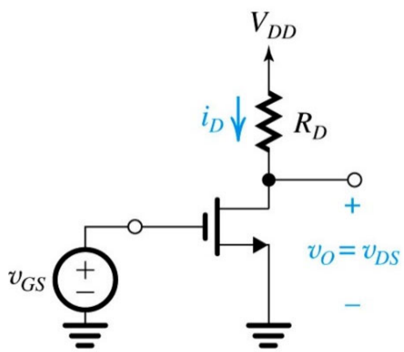
(a) Simple MOSFET amplifier with input v_{GS} and output v_{DS}. **(b)** The voltage transfer characteristic (VTC) of the amplifier in **(a)**. The three segments of the VTC correspond to the three regions of operation of the MOSFET.

MOSFET

GRAPHICAL METHOD TO FIND OP MODE







b)

MOSFET

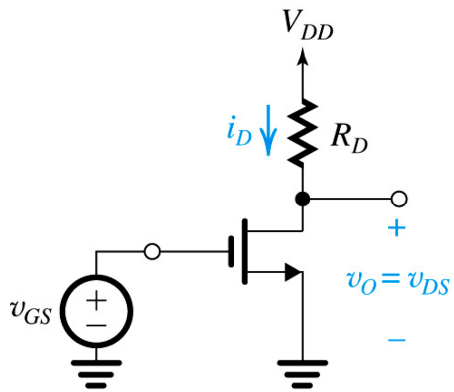
VOLTAGE GAIN

$$\upsilon_{DS} = V_{DD} - i_D R_D$$

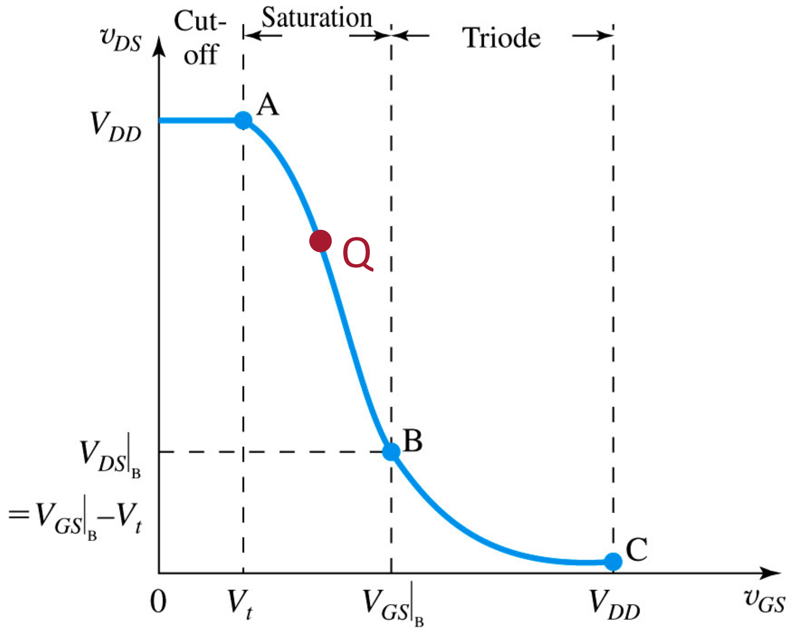
In saturation (Q):

$$i_D = \frac{1}{2} k_n (\upsilon_{GS} - V_t)^2$$

$$\upsilon_{DS} = V_{DD} - \frac{1}{2} R_D k_n (\upsilon_{GS} - V_t)^2$$



(a)



(b)

Gain:

$$A_\upsilon = \frac{\partial \upsilon_{DS}}{\partial \upsilon_{GS}} = -k_n R_D (\upsilon_{GS} - V_t) = -k_n R_D V_{OV}$$

as max $i_D = \frac{V_{DD}}{R_D}$

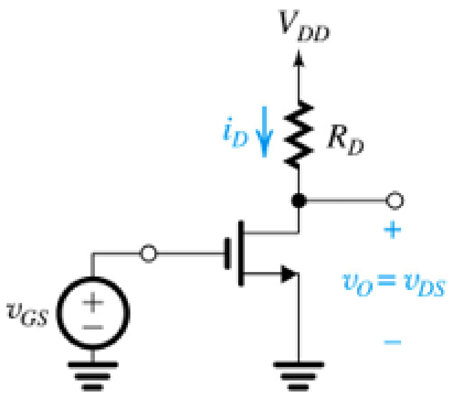
$$i_D = \frac{1}{2} k_n V_{OV}^2 \rightarrow A_\upsilon = -\frac{i_D R_D}{V_{OV}/2}$$

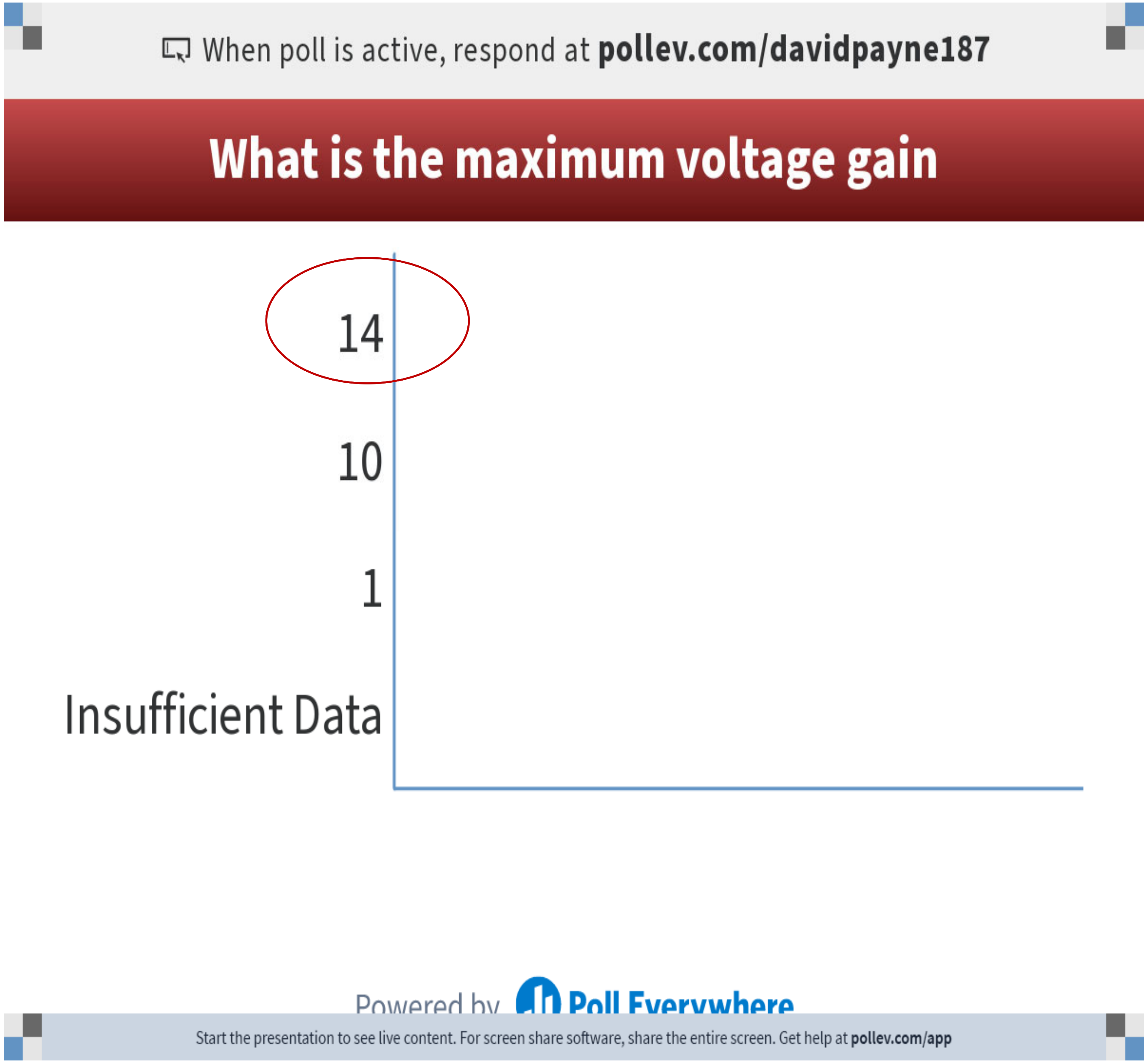
$$|A_{\upsilon,\max}| = \frac{V_{DD}}{V_{OV}/2}$$

typically ~ 10

Class Exercise

A MOSFET amplifier's supply voltage is 7V. If $V_{GS\ max}$=2V and V_{tn}=1V, what is the maximum voltage gain?

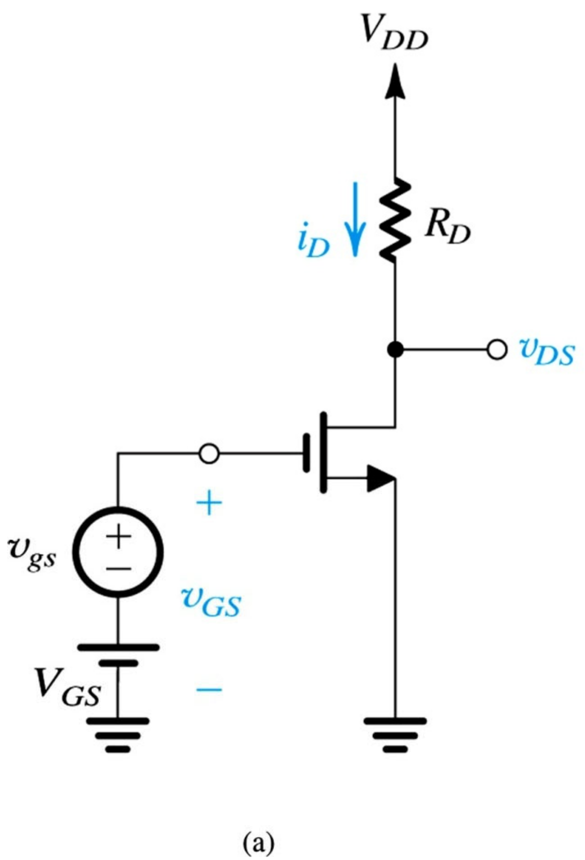


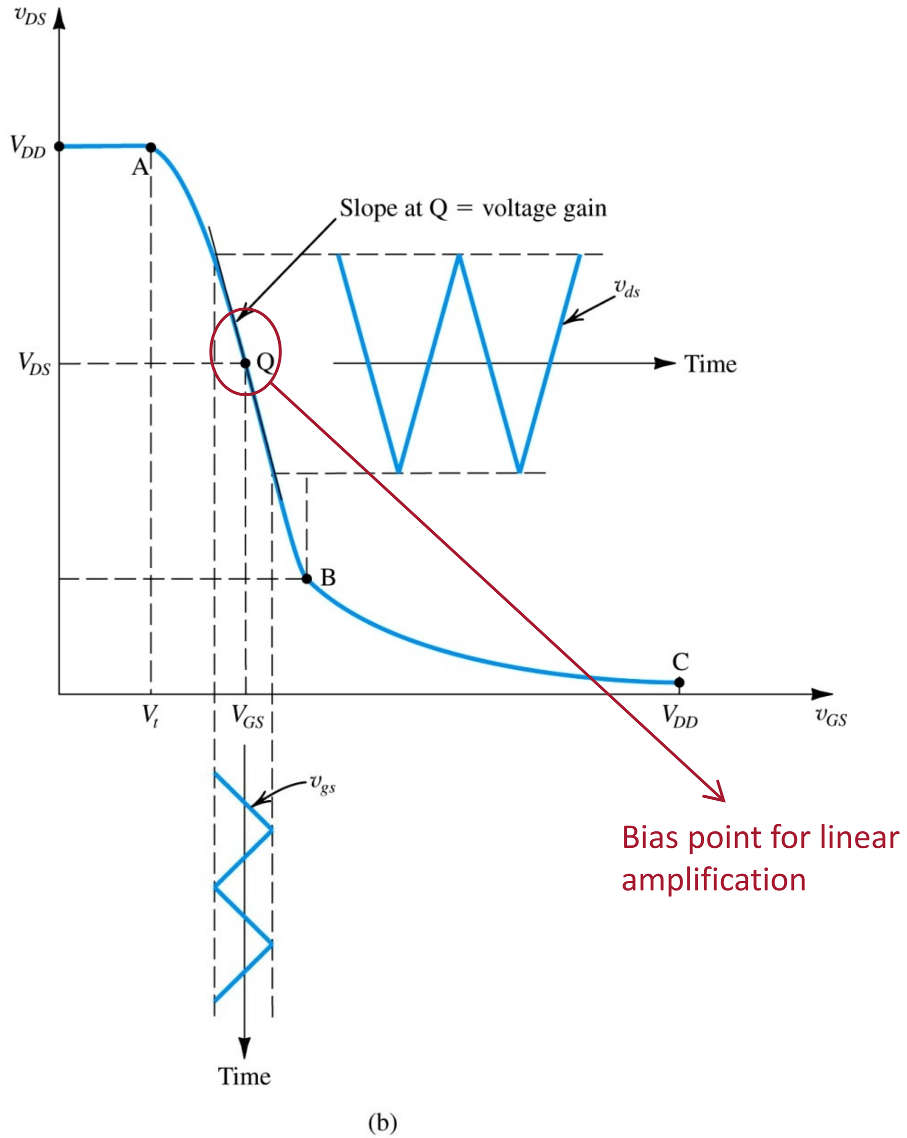


MOSFET

SMALL SIGNALS

DC voltages (V_{GS} and V_{DD}) set the bias point (Q) and AC signal v_{gs} is amplified.





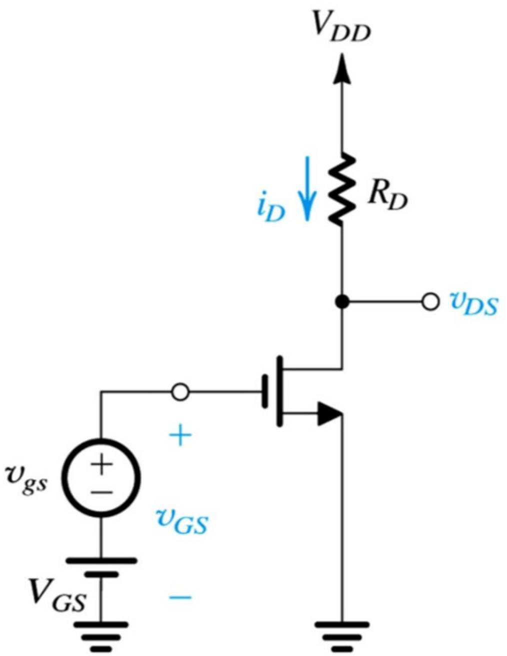
MOSFET

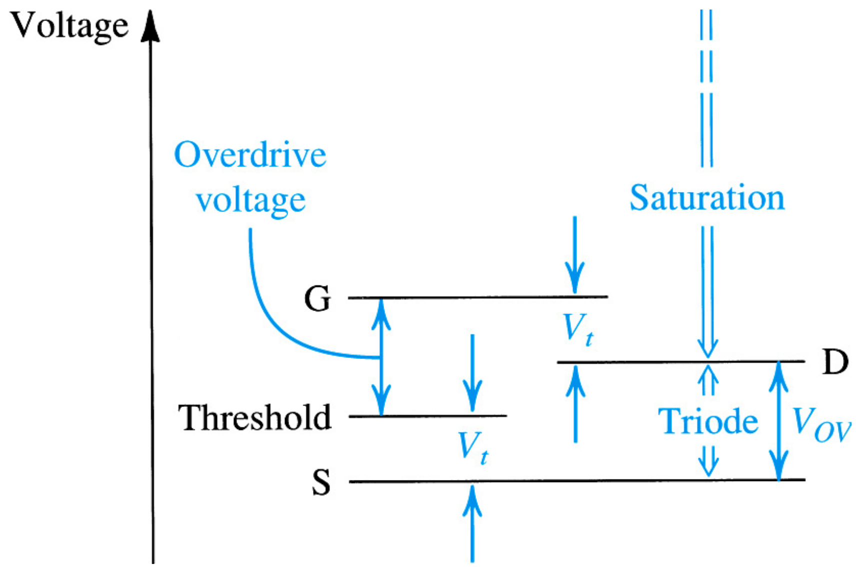
EXAMPLE-01

Consider the amplifier circuit shown below. The transistor is specified to have V_t = 0.4V, k'_n = 0.4 mA/V_2, W/L = 10 and λ = 0. Also let V_{DD} = 1.8V, R_D = 17.5kΩ, and V_{GS} = 0.6V

a) For v_{gs} = 0 (and hence v_{ds} = 0) find V_{OV}, I_D, V_{DS} and A_v,

b) DC bias point: what mode is the transistor in?





MOSFET

EXAMPLE-01

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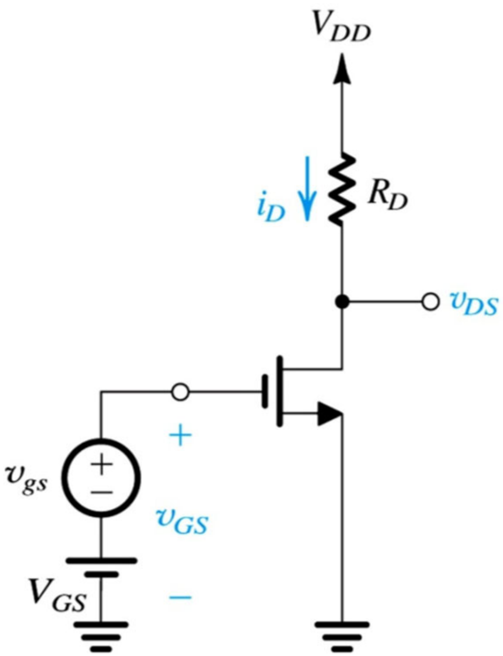


a) no small signal

$V_{ov} = V_{GS} - V_t = 0.6 - 0.4 = \underline{0.2}$

$I_D = \frac{1}{2} k_n (V_{ov})^2 = \frac{0.4 \times 10 \times 0.2^2}{2} = \underline{0.08mA}$

$V_{DS} = V_{DD} - I_D R_D = 1.8 - 1.4 = 0.4V$

$A_v = -k_n R_D V_{ov} = -4 \times 17.5k \times 0.2$
$= -14$

b) more than V_{ov}
∴ saturation

Saturation, with V_{OV}=0.2 V and I_D=0.08 mA, V_{DS}=0.4 V

$$A_v = -k_n R_D V_{OV} = -k'_n \frac{W}{L} R_D V_{OV} = -14$$

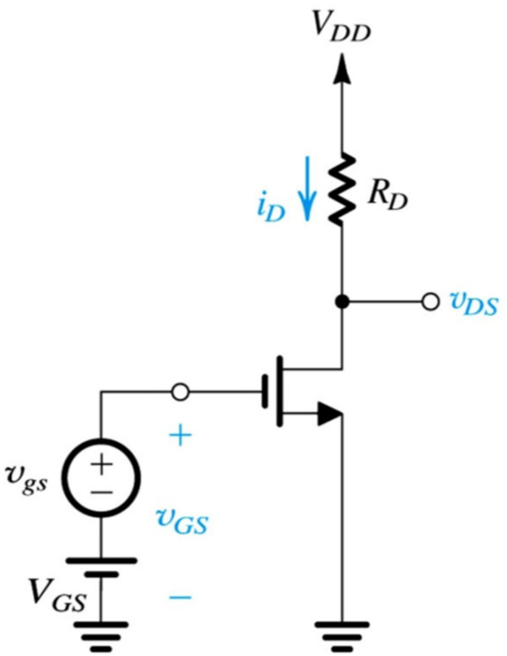
MOSFET

EXAMPLE-01

Consider the amplifier circuit shown below. The transistor is specified to have $V_t = 0.4V$, $k'_n = 0.4$ mA/V_2, $W/L = 10$ and $\lambda = 0$. Also let $V_{DD} = 1.8V$, $R_D = 17.5k\Omega$, and $V_{GS} = 0.6V$

c) What is the maximum symmetrical signal swing allowed at the drain? Hence find the maximum allowable amplitude of a sinusoidal v_{gs}.

d) What is the criterion for our gain calculation to be applicable?



c) We need to stay in saturation

so $V_{DS} > V_{OV}$ and $V_{GS} > V_t$

$V_{DS} - V_{OV} = 0.2V$ ← Max output swing

- Divide by gain to get input swing

$$\frac{0.2V}{|A_v|} = 14.2mV$$

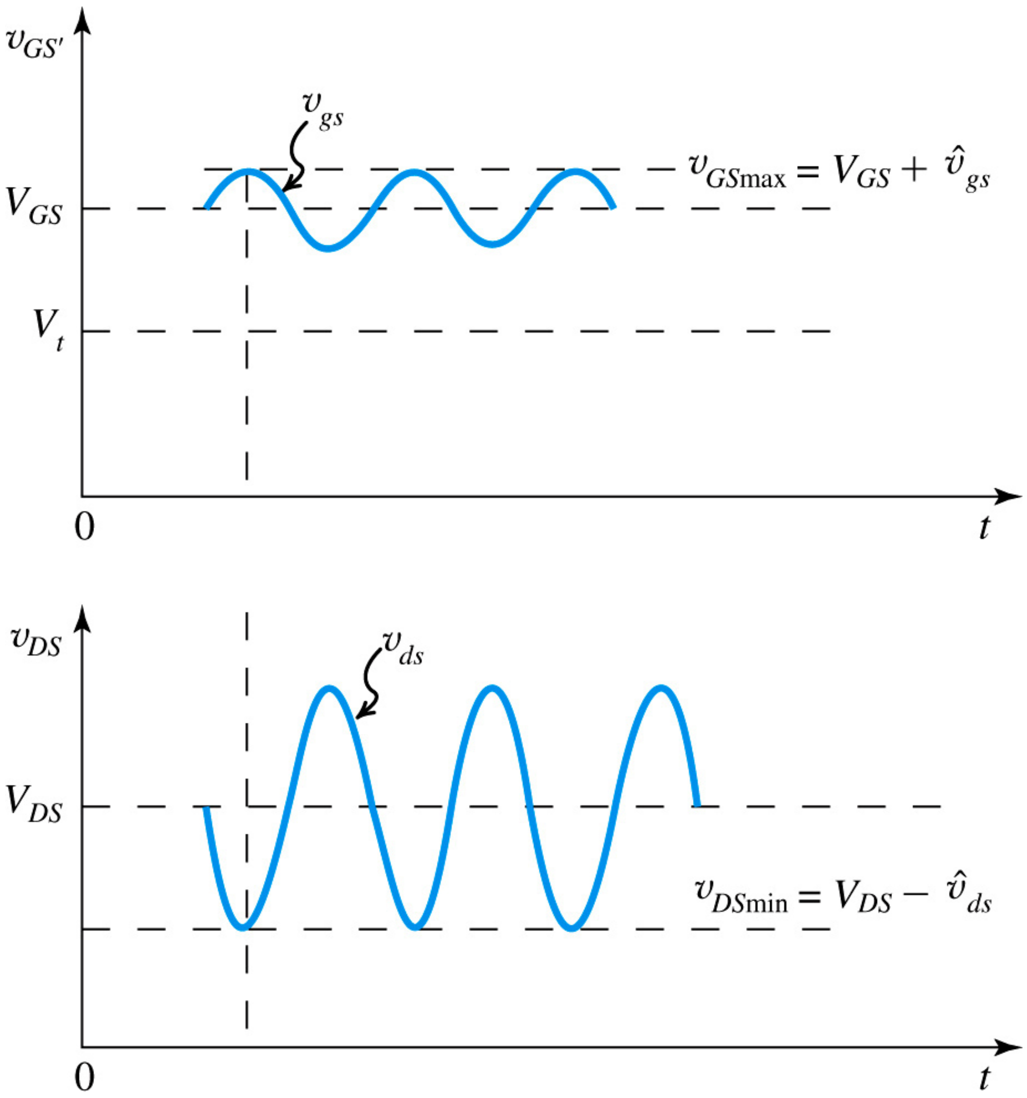
$v_{DS} > V_{OV}$, hence the allowed swing at V_{DS} is 0.2 V swing.

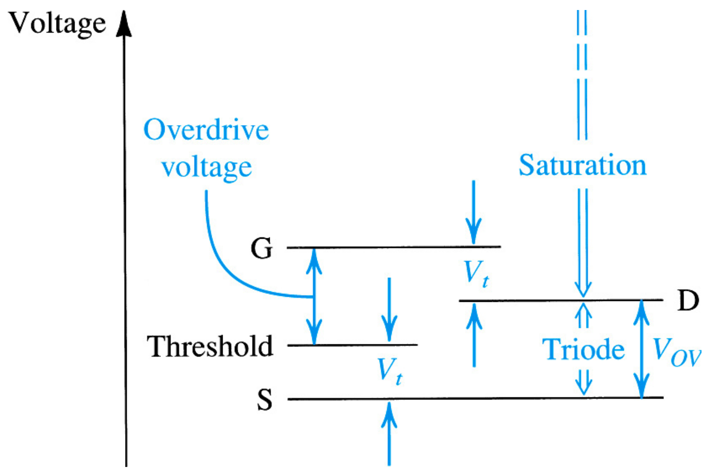
At first glance: $$v_{gs} \leq \frac{0.2}{|A_v|} = 14.2mV$$

$$\hat{v}_{ds} < 0.2 \text{ V}$$

MOSFET

EXAMPLE CONT'D





$$v_{DS\min} \geq v_{GS\max} - V_t$$

$$0.4\ \text{V} - \hat{v}_{ds} \geq 0.6\ \text{V} + \hat{v}_{gs} - 0.4\ \text{V}$$

express in terms of just vgs:

$$0.4 - |A_v| v_{gs} \geq 0.2 + v_{gs}$$

$$v_{gs}(|A_v|+1) \leq 0.2$$

$$v_{gs} \leq \frac{0.2}{|A_v| + 1} = 13.3mV$$

Lecture 6

1. MOSFET Amplifiers
2. **MOSFET Small Signals**
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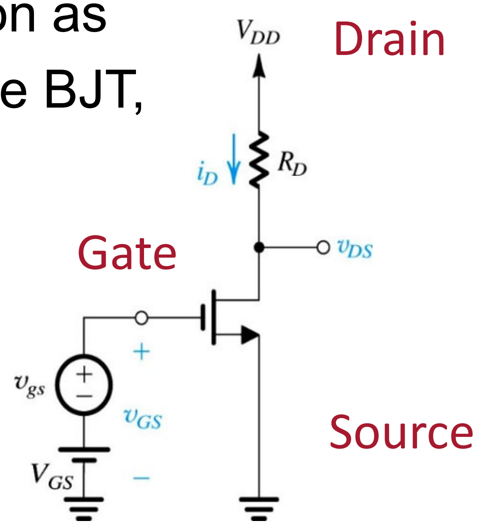
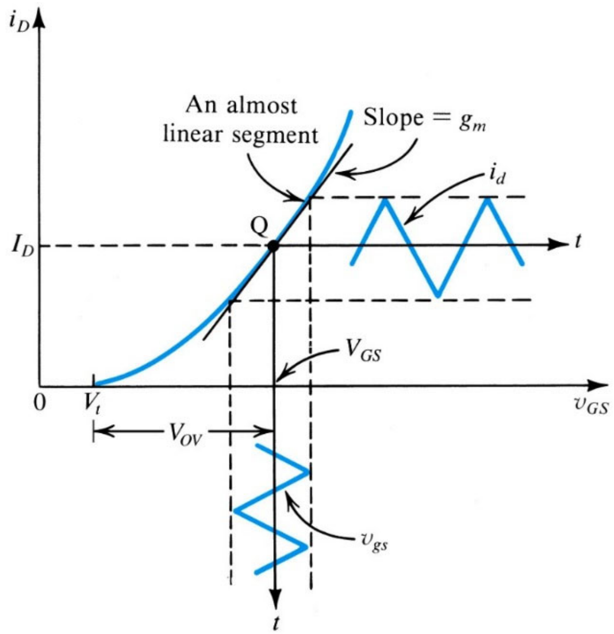
MOSFET

SMALL SIGNAL APPROXIMATION – SATURATION REGION

Similar technique for linearization as for the exponential diode and the BJT, but no need for Taylor series





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

$$i_D = I_D + i_d$$

$$i_D = \frac{1}{2}k_n(v_{GS} - V_t)^2$$

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

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

$$i_D \cong \underbrace{\frac{1}{2}k_n(V_{GS} - V_t)^2}_{I_D} + \underbrace{\overbrace{k_n(V_{GS} - V_t)}^{g_m}v_{gs}}_{i_d}$$

Transconductance

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

MOSFET

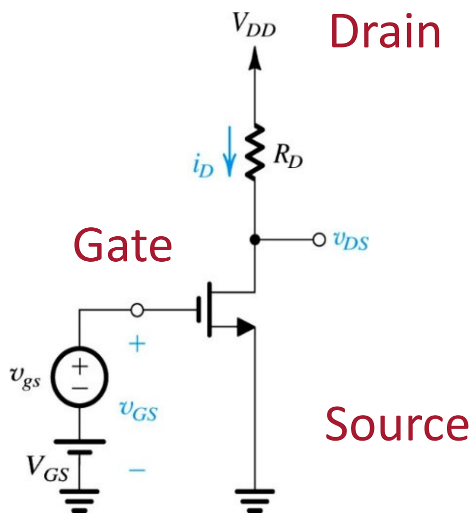
SMALL SIGNAL APPROX – SATURATION REGION

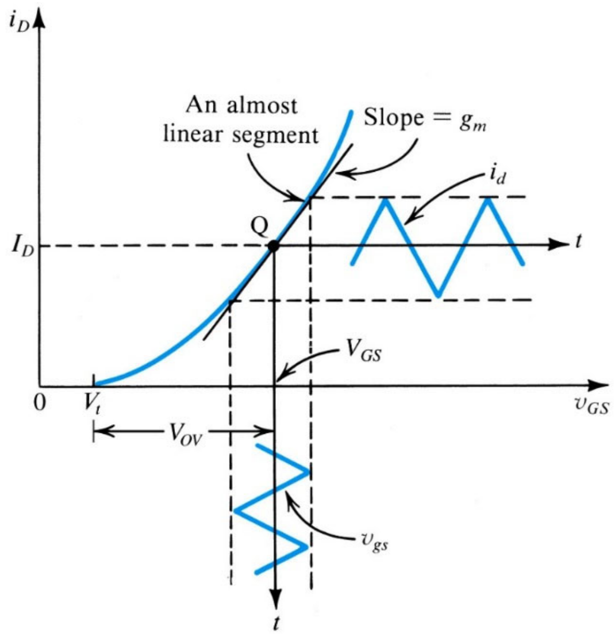
$$i_D \cong \underbrace{\frac{1}{2}k_n(V_{GS}-V_t)^2}_{I_D}+\underbrace{\overbrace{k_n(V_{GS}-V_t)}^{g_m}v_{gs}}_{i_d}$$

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

$$i_D = I_D + i_d$$

$$i_D = \frac{1}{2}k_n(v_{GS}-V_t)^2$$





$$g_m = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}$$

Calculated at the DC operating point

Transconductance

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

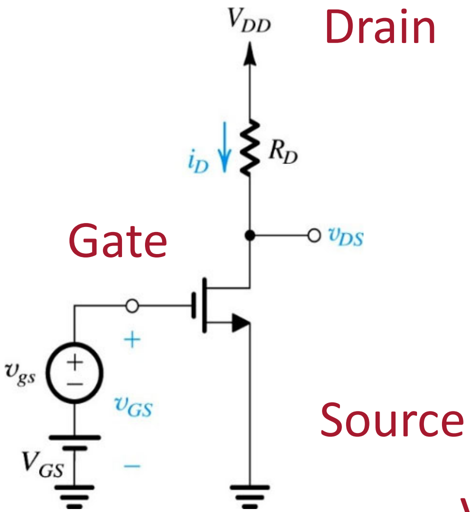
MOSFET

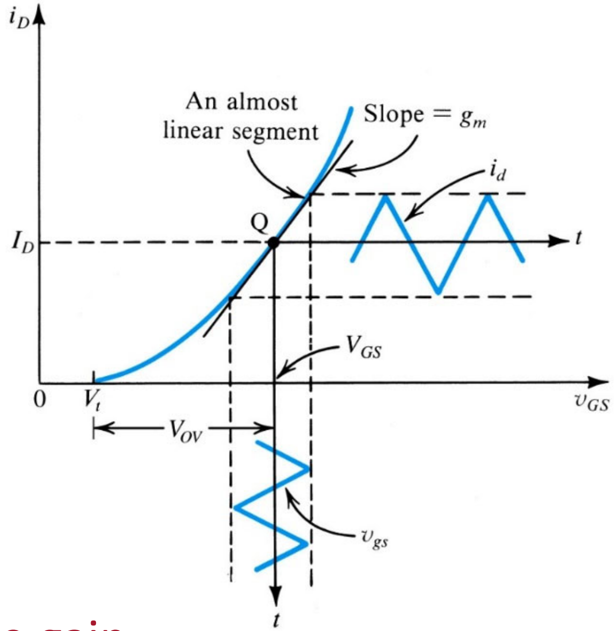
SMALL SIGNAL APPROX – SATURATION REGION

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

$$i_D = I_D + i_d$$

$$i_D = \frac{1}{2}k_n(v_{GS} - V_t)^2$$





Transconductance

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

Voltage gain:

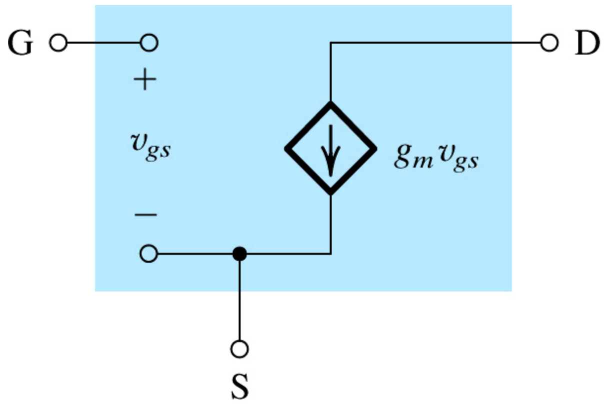
$$\boxed{A_\upsilon = \frac{\partial \upsilon_{DS}}{\partial \upsilon_{GS}} = \frac{\upsilon_{ds}}{\upsilon_{gs}} = -g_m R_D = -k_n V_{OV} R_D}$$

$$\upsilon_{DS} = V_{DD} - R_D i_D = V_{DD} - R_D\underbrace{(I_D + i_d)}_{\text{Linear approx.}} = \underbrace{V_{DS}}_{\text{DC}} - \underbrace{R_D i_d}_{\text{AC}}$$

$$\upsilon_{ds} = -R_D i_d = -R_D g_m \upsilon_{gs}$$

MOSFET

SMALL SIGNAL MODEL – SATURATION REGION

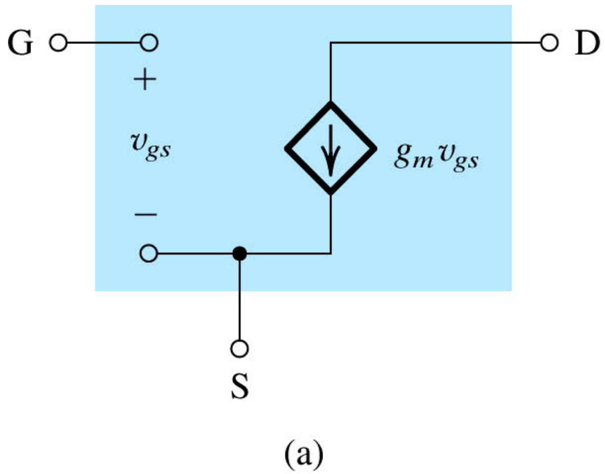


(a)

$$g_m = k_n(V_{GS} - V_t) = \frac{2I_D}{V_{GS} - V_t}$$

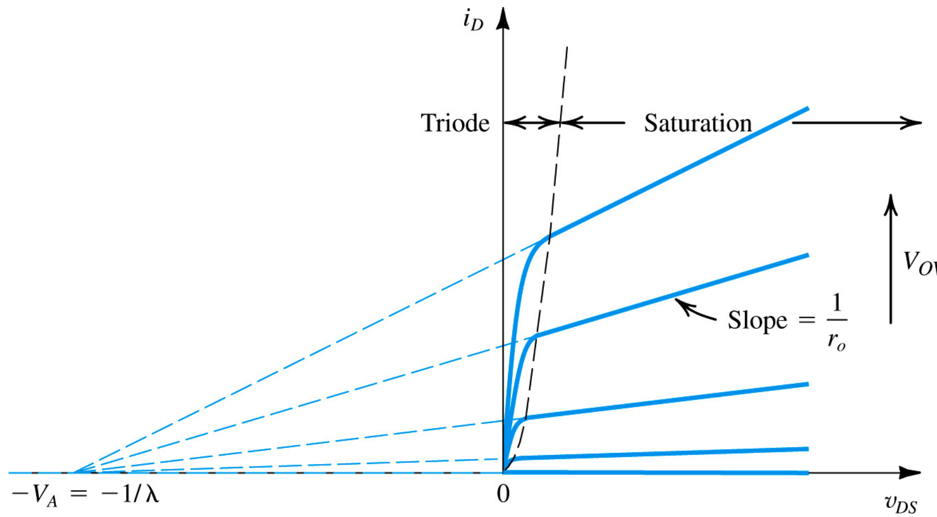
MOSFET

SMALL SIGNAL MODEL – SATURATION REGION



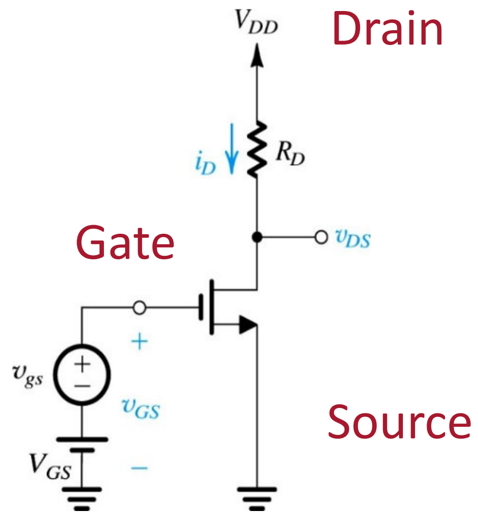
$$g_m = k_n(V_{GS} - V_t) = \frac{2I_D}{V_{GS} - V_t}$$

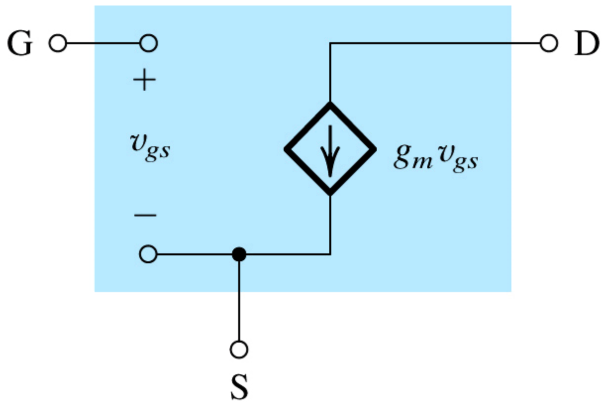
$$r_o = \frac{|V_A|}{I_D}$$

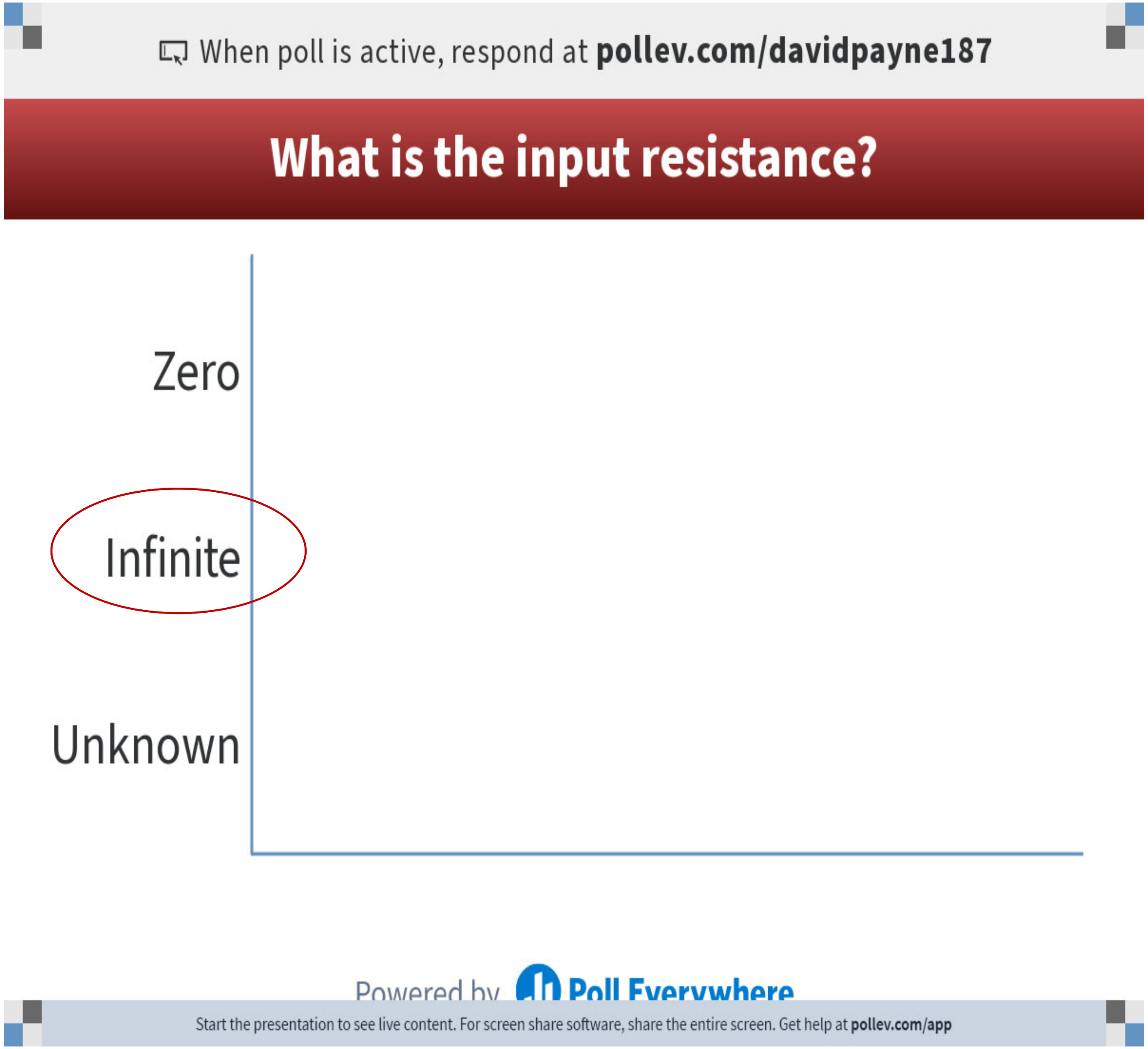


Class Exercise

What is the input resistance of this circuit?



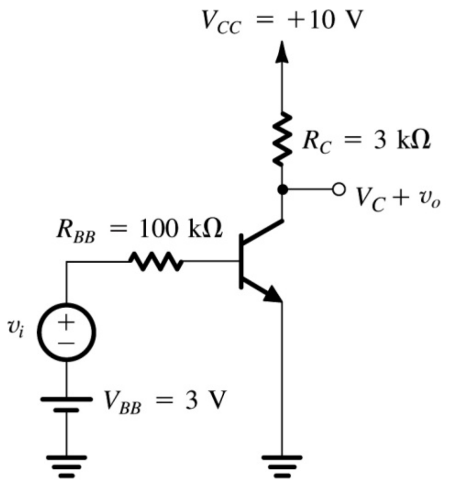




Reminder - BJTs

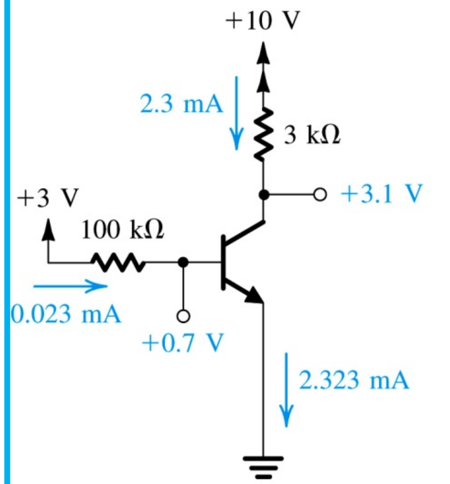
SMALL SIGNAL FOR BJTS

Amplifier circuit



(a)

Step 1: DC operating point



(b)

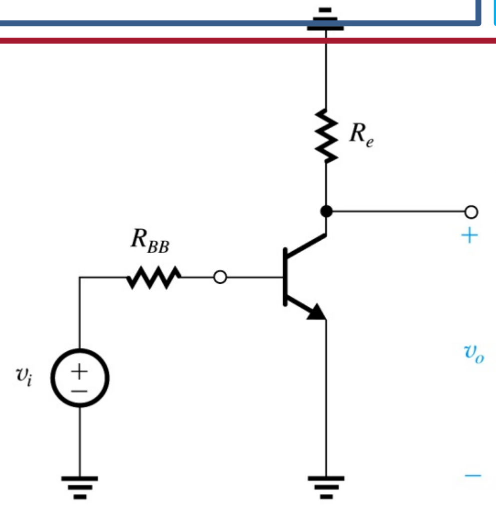
Step 2: Small signal parameters

$$g_m = \frac{I_C}{V_T} = \frac{2.3\text{ mA}}{25\text{ mV}} = 92\text{ mA/V}$$

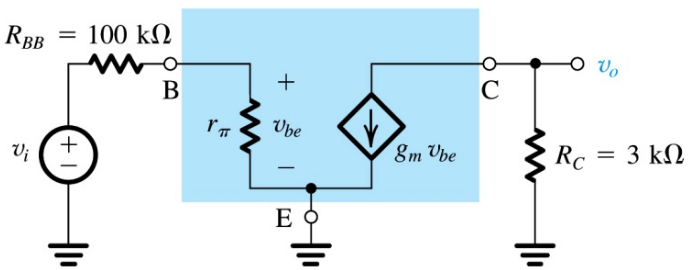
$$r_\pi = \frac{\beta}{g_m} = \frac{100}{92}\text{ k}\Omega = 1.09\text{ k}\Omega$$

$$r_e = \frac{V_T}{I_E} = \frac{25\text{ mV}}{(2.3/0.99)\text{ mA}} = 10.8\ \Omega$$

Step 3: Small signal equiv. circuit



(c)



(d)

Step 4: Small signal analysis

$$\upsilon_{be} = \upsilon_i \frac{r_\pi}{R_{BB} + r_\pi} = 0.011\upsilon_i$$

$$\upsilon_o = -R_C g_m \upsilon_{be} = -3.04\upsilon_i$$

$$A_\upsilon = \frac{\upsilon_o}{\upsilon_i} = -3.04$$

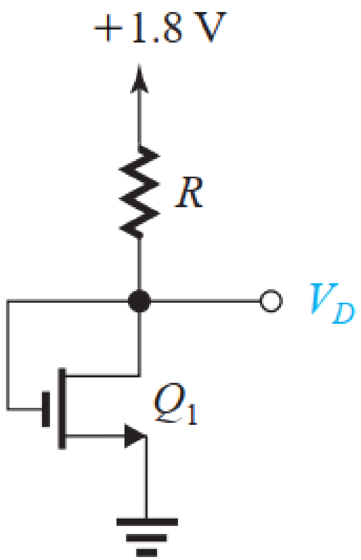
Lecture 6

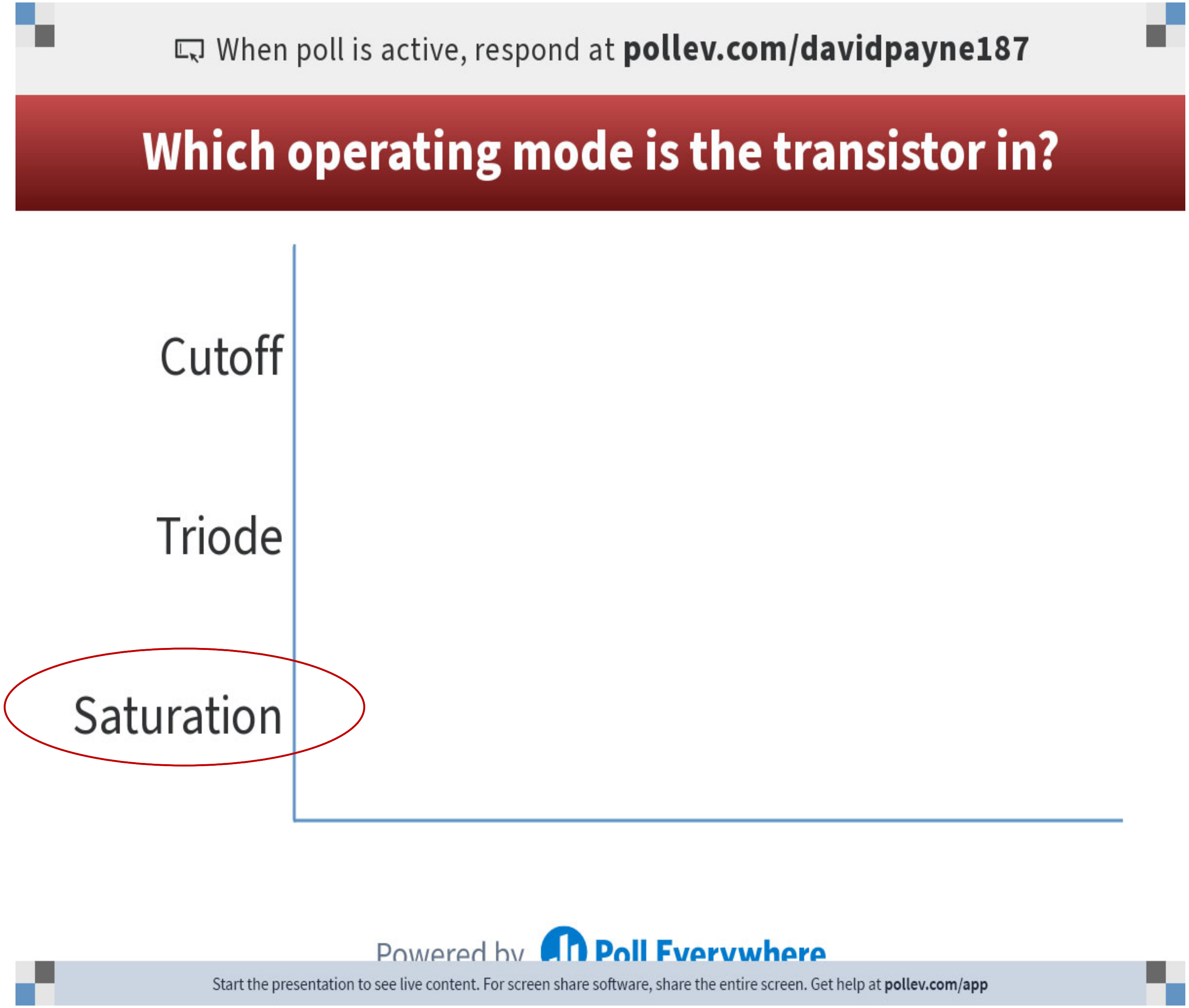
1. MOSFET Amplifiers
2. MOSFET Small Signals
3. **Examples**

Class Exercise

MACQUARIE University

Which operating mode is this transistor in if $V_D > V_t$?

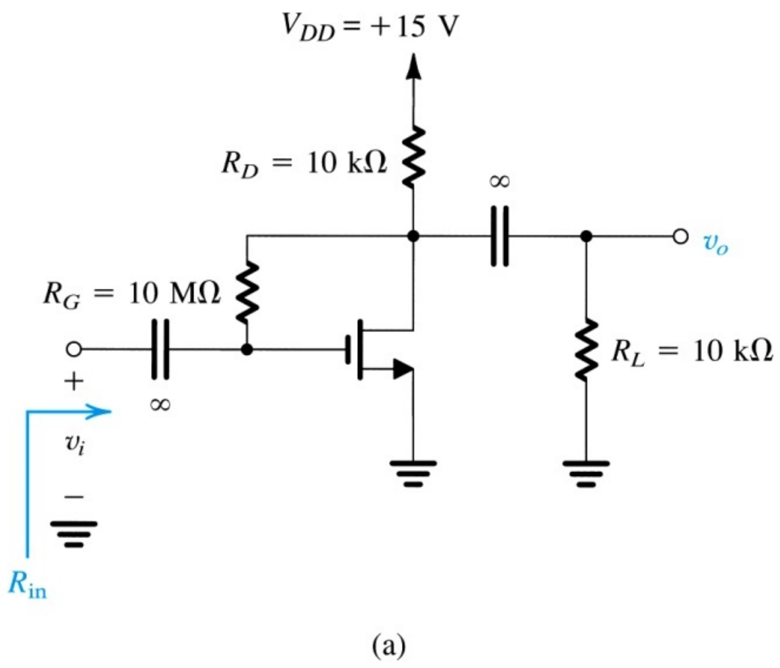




MOSFET

EXAMPLE-2

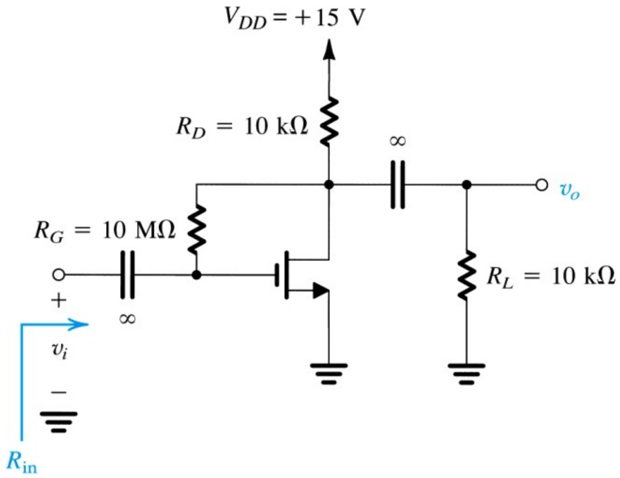
The circuit below shows a discrete common-source MOSFET amp, using a drain-to-gate resistor R_g for biasing. The input signal v_i is coupled to the gate via a large capacitor, the output signal at the drain is coupled to the load resistance RL via another large capacitor. We want to analyze this amplifier to determine its **small-signal voltage gain, its input resistance and the largest allowable input**.
The transistor has **V_t = 1.5V, K'_n (W/L) = 0.25mA/V^2 and V_A = 50V**. Assume the coupling capacitors to be large enough act as short circuits at the frequencies of interest.



Amplifier Circuit

MOSFET

EXAMPLE – STEP 1 – DC EQUIVALENT

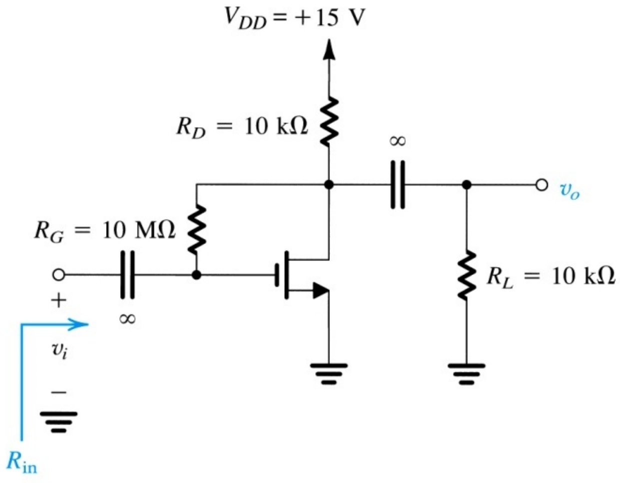


(a)

Amplifier Circuit

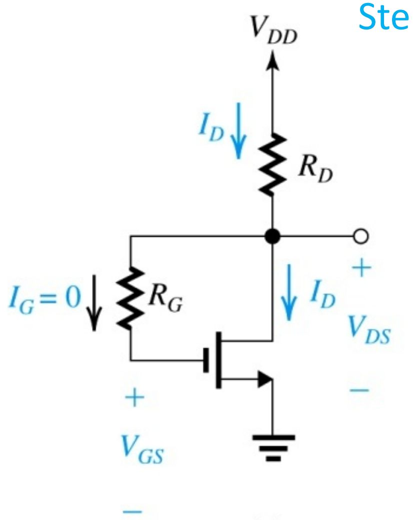
MOSFET

EXAMPLE – STEP 1 – DC EQUIVALENT



(a)

Amplifier Circuit



(b)

dc equivalent circuit

Step 1: DC operating point

$$i_D = \frac{1}{2} k_n (v_{GS} - V_t)^2$$

I_D=1.06 mA

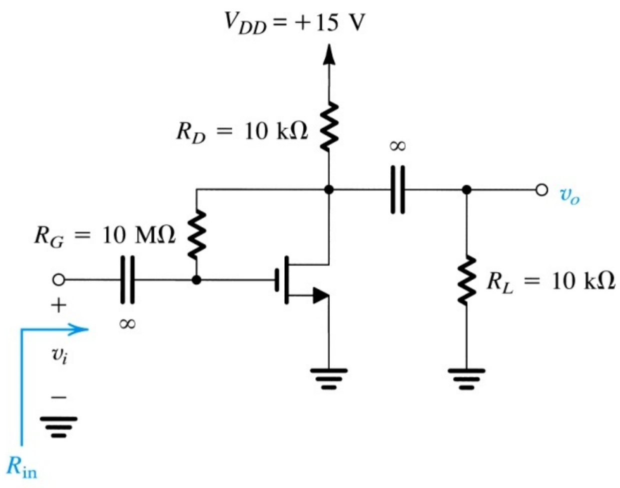
V_{DS}=V_{GS}=4.4 V

V_{OV}=2.9 V

MOSFET

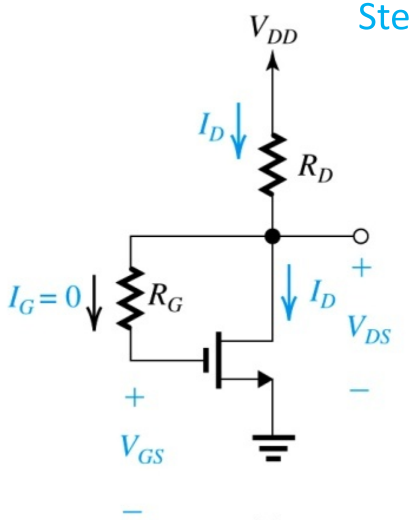
EXAMPLE – STEP 2 – SMALL SIGNAL PARAMETERS

Step 1: DC operating point



(a)

Amplifier Circuit



(b)

dc equivalent circuit

$$i_D = \frac{1}{2} k_n (v_{GS} - V_t)^2$$

I_D=1.06 mA

V_{DS}=V_{GS}=4.4 V

V_{OV}=2.9 V

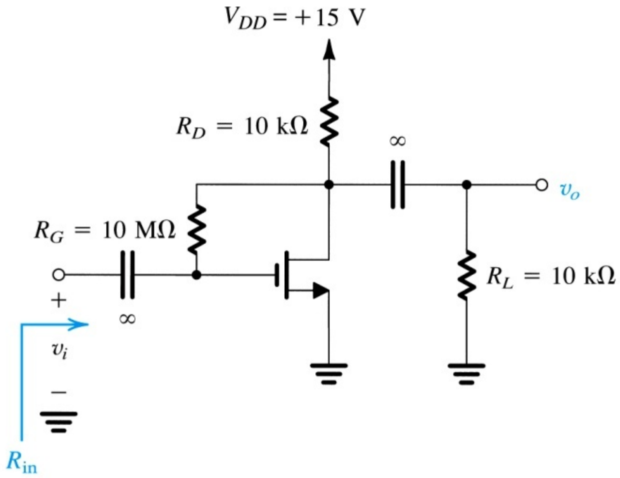
Step 2: Small signal parameters

g_m=$k_n V_{OV}$=0.725 mA/V

r_0=V_A/I_D=50V/1.06 mA=47 kΩ

MOSFET

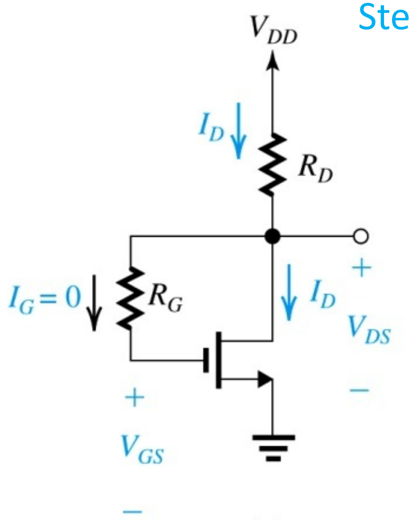
EXAMPLE – STEP 3 – AC EQUIVALENT



(a)

Amplifier Circuit

Step 1: DC operating point



(b)

dc equivalent circuit

$$i_D = \frac{1}{2}k_n(v_{GS} - V_t)^2$$

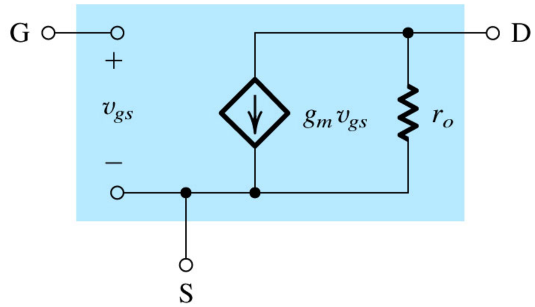
I_D=1.06 mA

V_{DS}=V_{GS}=4.4 V

V_{OV}=2.9 V

Step 2: Small signal parameters

MOSFET small signal model (from formula sheet)



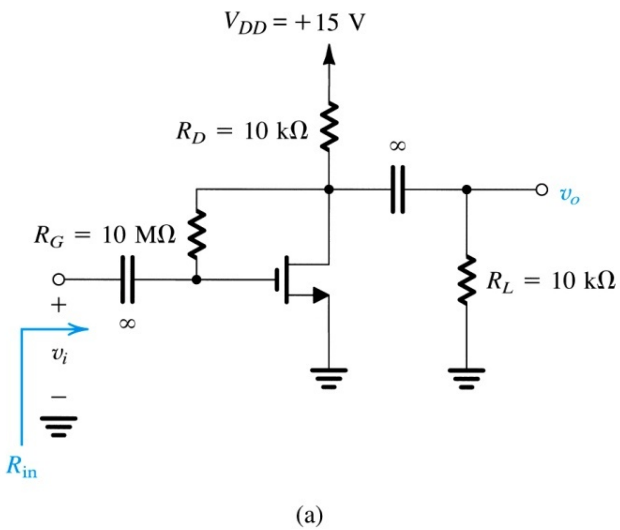
(b)

g_m=$k_n V_{OV}$=0.725 mA/V

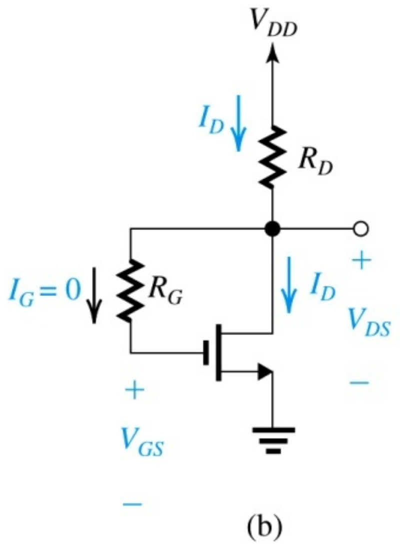
r_0=V_A/I_D=50V/1.06 mA=47 kΩ

MOSFET

EXAMPLE – STEP 3 – AC EQUIVALENT



Amplifier Circuit



dc equivalent circuit

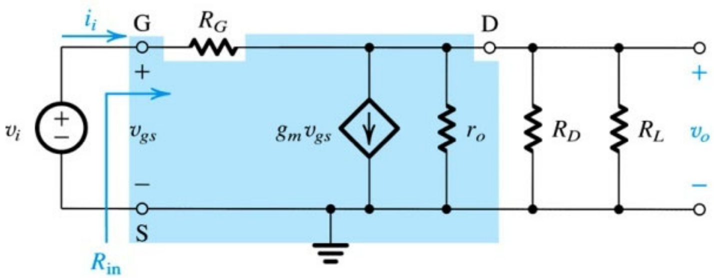
$$i_D = \frac{1}{2}k_n(v_{GS} - V_t)^2$$

I_D=1.06 mA

V_{DS}=V_{GS}=4.4 V

V_{OV}=2.9 V

Step 3: Small signal equiv. circuit



Ac small-signal equivalent circuit

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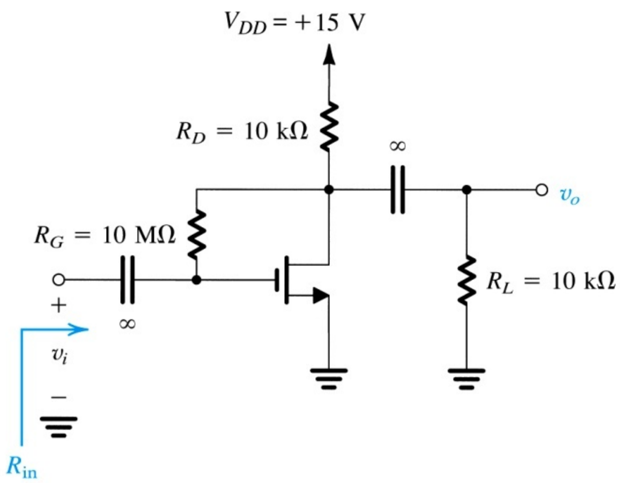
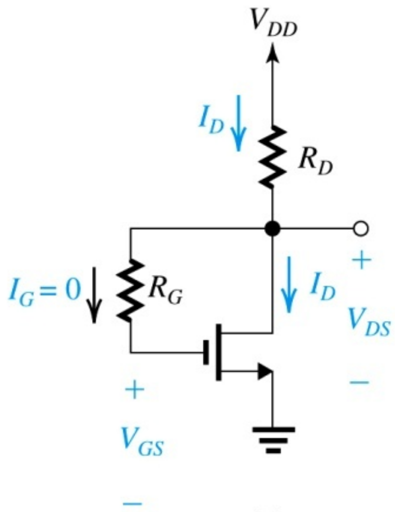
EXAMPLE – STEP 3 – AC EQUIVALENT SIMPLIFIED



(a)

Amplifier Circuit



(b)

dc equivalent circuit

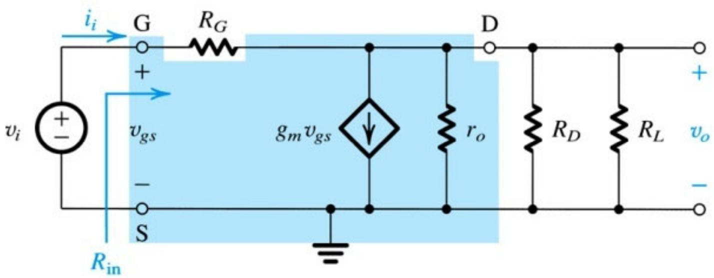
$$i_D = \frac{1}{2} k_n (v_{GS} - V_t)^2$$

I_D=1.06 mA

V_{DS}=V_{GS}=4.4 V

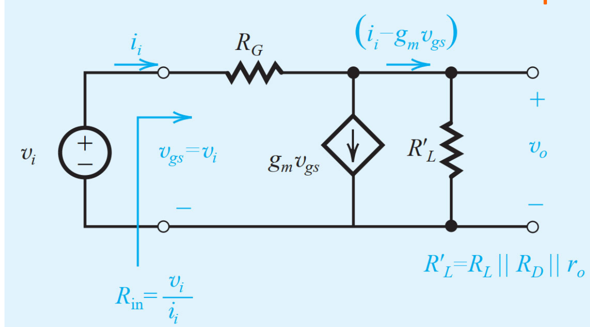
V_{OV}=2.9 V

Step 3: Small signal equiv. circuit



Ac small-signal equivalent circuit

Step 4: Small signal analysis



Ac small-signal equivalent circuit (simplified)

R'_L=4.52 K

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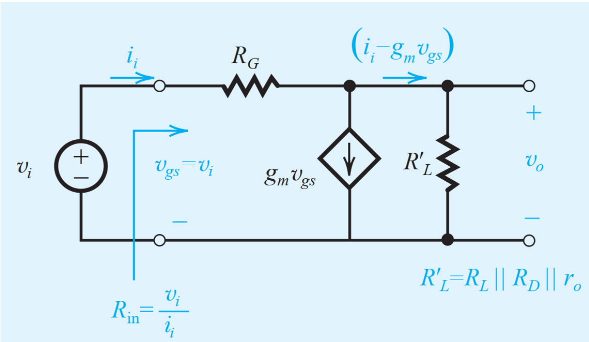
EXAMPLE – STEP 3 – AC EQUIVALENT SIMPLIFIED

Step 4: Small signal analysis



$V_o = (i_i - g_m V_{gs}) R'_L$ $\quad i_i = \frac{V_{gs} - V_o}{R_G}$

$\therefore \; V_o = \left(\frac{V_{gs} - V_o}{R_G} - g_m V_{gs}\right) R'_L$

rearrange to get $V_o = \frac{R'_L V_{gs} - V_o R'_L}{R_G} - g_m V_{gs} R'_L$

$$V_o (R_G + R'_L) = R'_L V_{gs} - g_m V_{gs} R'_L R_G$$

$$\therefore \; V_o = \frac{R'_L V_{gs} - g_m V_{gs} R'_L R_G}{R_G + R'_L} = R'_L \frac{\frac{V_{gs}}{R_G} - g_m V_{gs}}{1 + \frac{R'_L}{R_G}}$$

$V_{gs} = V_i \qquad A_v = \frac{V_o}{V_i}$

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EXAMPLE – STEP 4 – AC ANALYSIS

$$A_\upsilon = \frac{\upsilon_0}{\upsilon_i} = -g_m R_L' \frac{1-\left(\frac{1}{g_m R_G}\right)}{1+\left(\frac{R_L'}{R_G}\right)} \simeq -g_m R_L' = -3.3$$

$$R_{in} = \frac{V_i}{i_i} = \frac{V_i}{\frac{V_i - V_o}{R_G}} = \frac{R_G V_i}{V_i - V_o} = \frac{R_G}{1-A_v}$$

$$R_i = \frac{R_G}{1-A_\upsilon} = \frac{R_G}{1+g_m R_L'} = 2.33\ \text{M}\Omega$$

condition $V_{DS} > V_{ov}$ so at edge of region:

$$V_{DS_{min}} = V_{GS_{max}} - V_t$$

$$V_{DS} - A_v V_i = V_{GS} + V_i - V_t$$

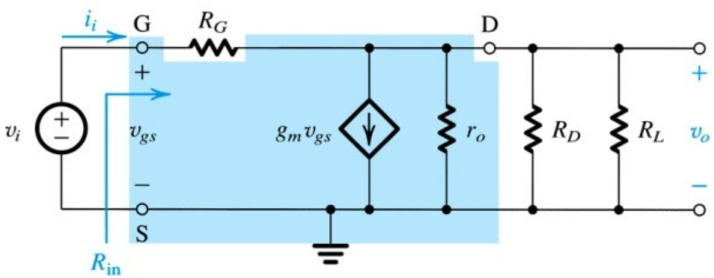
$$\therefore -A_v V_i = V_i - V_t$$

$$A_v V_i + V_i = V_t$$

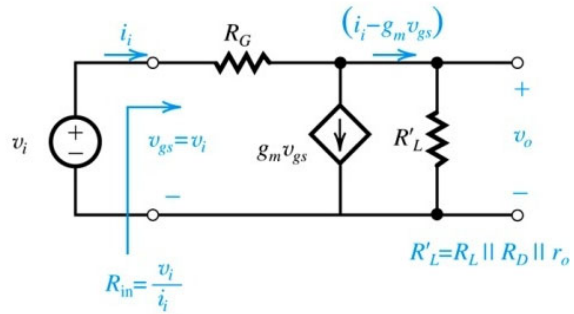
$$V_i(A_v + 1) = V_t$$

Original Circuit

Max, allowed swing at input: $\hat{\upsilon}_i = \dfrac{V_t}{|A_\upsilon|+1} = 0.35\ \text{V}$



Ac small-signal equivalent circuit



Ac small-signal equivalent circuit (simplified)

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EXAMPLE 3

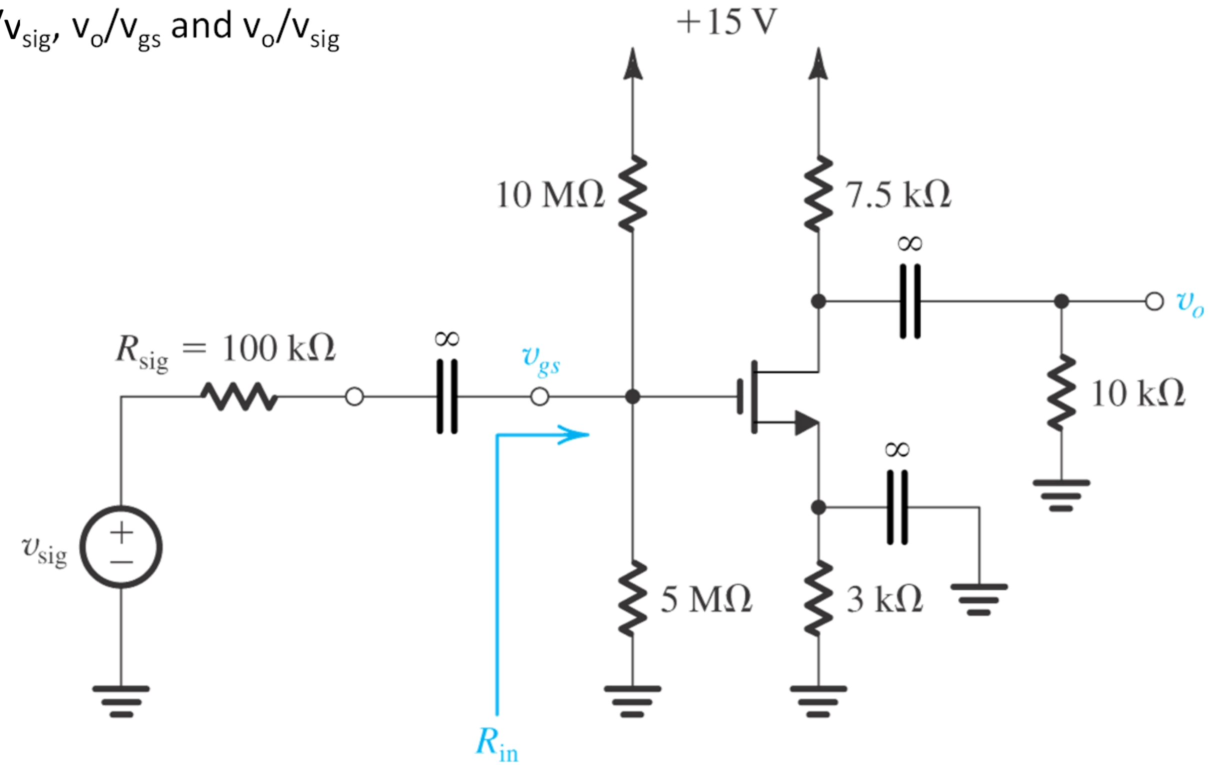
A discrete-circuit amplifier is shown bellow. The input signal v_{sig} is coupled to the gate through a very large capacitor. The transistor source is connected to ground at signal frequencies via a very large capacitor. The output voltage signal at the drain is coupled to a load resistance via a very large capacitor.

a) If the transistor has V_t = 1V and K_n = 2mA/V^2, verify that the bias circuit establishes V_{GS} = 2V, I_D = 1mA and V_D= +7.5 V. That is, assume these values and verify that they are consistent.

b) Find g_m and r_o if V_A = 100V

c) Draw the small signal equivalent circuit

d) Find R_{in}, v_{gs}/v_{sig}, v_o/v_{gs} and v_o/v_{sig}



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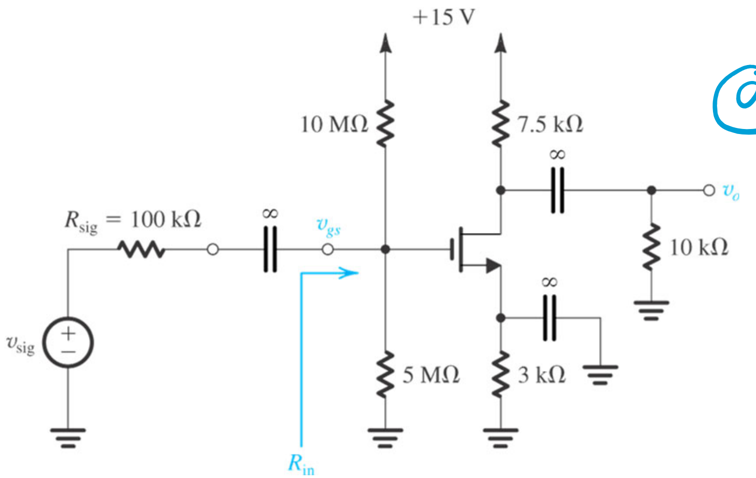
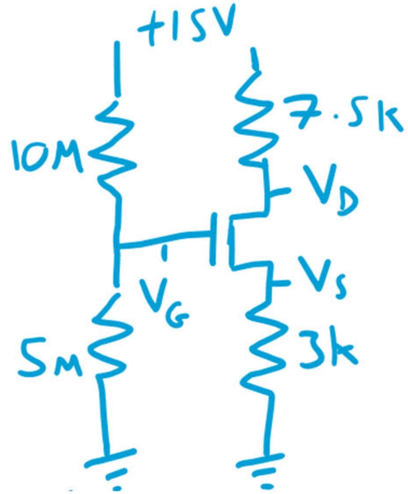
EXAMPLE 3



(a) Step 1: Draw DC equivalent



$$V_G = \frac{5}{15} \times 15 = 5V$$

← simple potential divider as no current to gate

$$V_S = 3 \times I_D$$

$$I_D = \frac{1}{2} k_n (\overbrace{5 - 3I_D}^{V_{GS}} - 1)^2 = \frac{1}{2} k_n (4 - 3I_D)^2$$

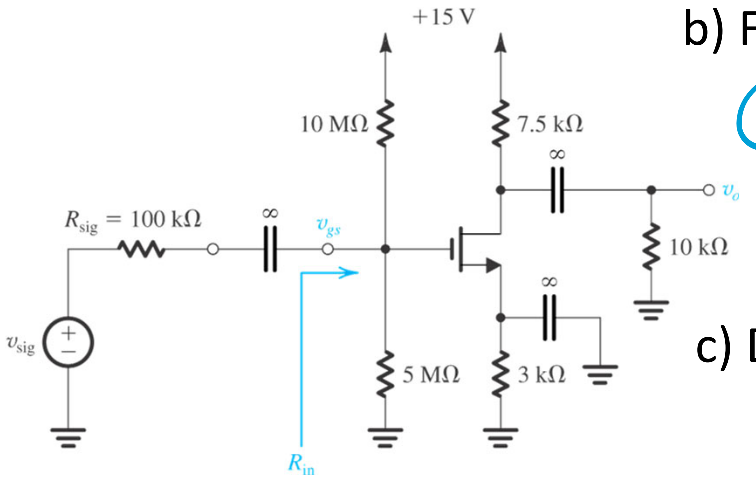
we get a quadratic for I_D: $I_D = 9I_D^2 - 25I_D + 16 = 0$ $\quad I_D \nearrow 1.77mA$, $\searrow \underline{\underline{1mA}}$

$V_S = 3 \times I_D = 3V \qquad V_{GS} = 5 - 3 = 2V$

$V_D = 15 - 7.5 = 7.5V$

MOSFET

EXAMPLE 3

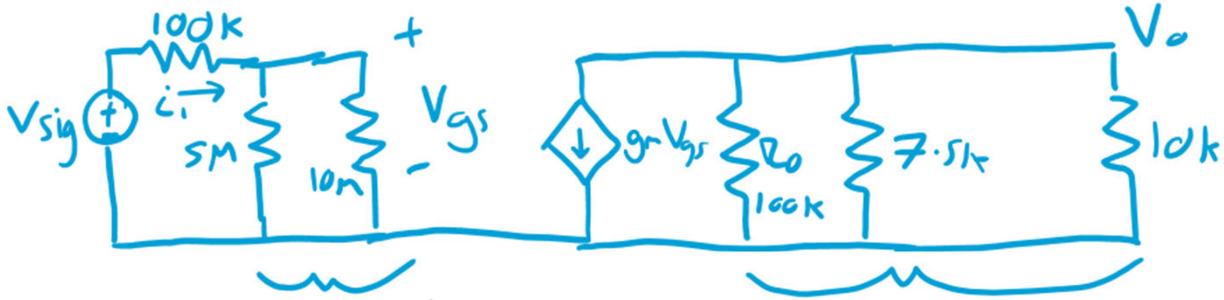


b) Find g_m and r_o if V_A = 100V

(b) Small signal parameters

$g_m = k_n V_{ov} = 2\,mA/V$ $\qquad r_o = \frac{V_A}{I_D} = 100k$

c) Draw the small signal equivalent circuit



can simplify to 3.33MΩ

can simplify

d) Find R_{in}, v_{gs}/v_{sig}, v_o/v_{gs} and v_o/v_{sig}

$R_{in} = \frac{V_{gs}}{i_i}$

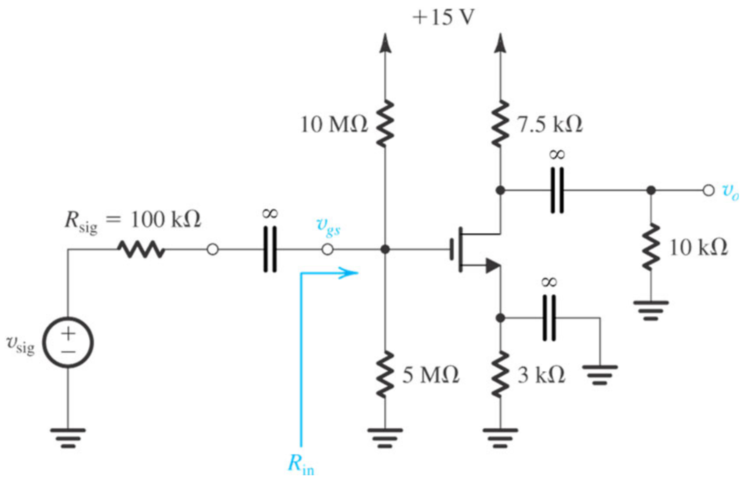
$i_i = \frac{V_{sig} - V_{gs}}{100k}$ so $R_{in} = \frac{V_{gs} \times 100k}{V_{sig} - V_{gs}} = \frac{100k}{\frac{V_{sig}}{V_{gs}} - 1}$

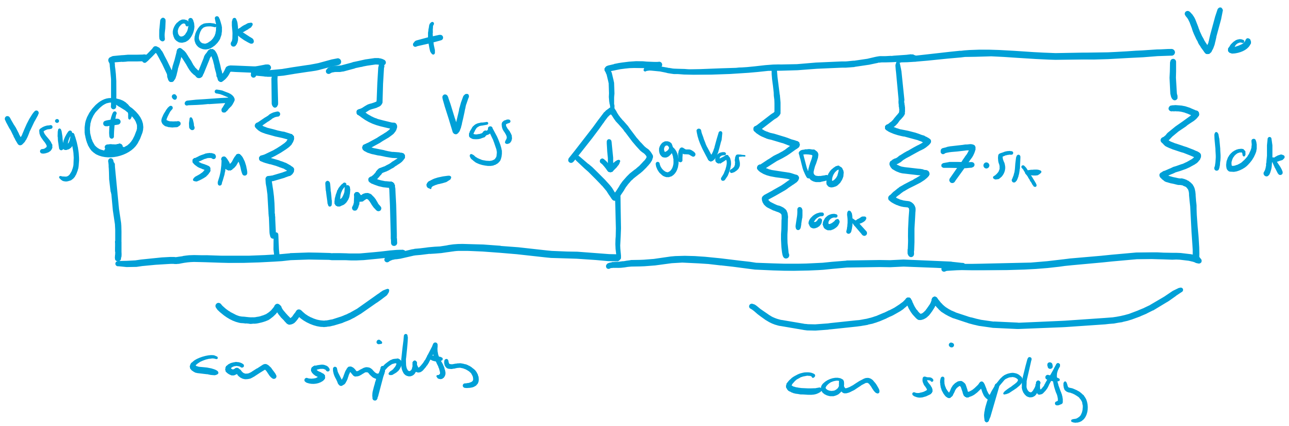
$V_{gs} = V_g - \overset{0}{V_s} = V_g = \frac{3.3M}{3.4M} V_{sig}$

So $R_{in} = \frac{100}{\frac{3.4}{3.3} - 1} = 3.33M\Omega$

MOSFET

EXAMPLE 3





(d) cont'd

$$\frac{V_{gs}}{V_{sig}} = \frac{\frac{3.3}{3.4} V_{sig}}{V_{sig}} = 0.97\ V/V$$

$$\frac{V_o}{V_{gs}} = -g_m(r_o \| R_D \| R_L) = -8.2$$

$$\frac{V_o}{V_{sig}} = -8.2 \times 0.97 = \underline{\underline{-7.95}}$$

This week

LAB + SECOND ASSIGNMENT

MACQUARIE University

MOSFET Lab:

- The worksheet is available on iLearn
- You will use the AD2 and your kit to make a MOSFET amplifier with biasing
- Complete as much of the lab as you can before attending the support session (prelab part is the minimum requirement)

2nd Assignment!

- The second assignment will be posted on Friday
- Submission is due early in week 8 (you have the semester break to work on it)