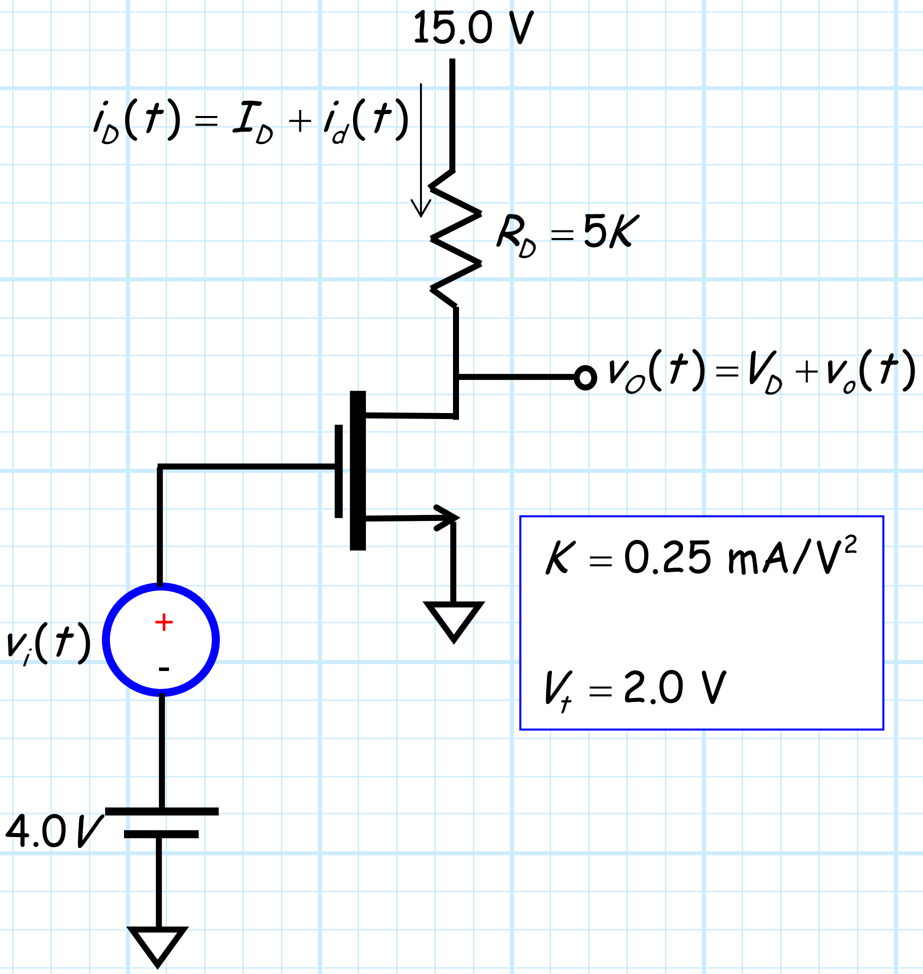
Example: MOSFET Amplifier Distortion

Recall this circuit from a **previous** handout:



We found that the small-signal **voltage gain** is:

$$A_{vo} = \frac{v_o(t)}{v_i(t)} = -5.0$$

Say the **input** voltage to this amplifier is:

$$v_i(t) = V_i \cos\omega t$$

Q: *What is the **largest** value that V_i can take without producing a **distorted** output?*

A: Well, we know that the **small-signal output** is:

$$\begin{aligned} v_o(t) &= A_{vo}\, v_i(t) \\ &= -5.0\, V_i \cos\omega t \end{aligned}$$

BUT, this is **not** the output voltage!

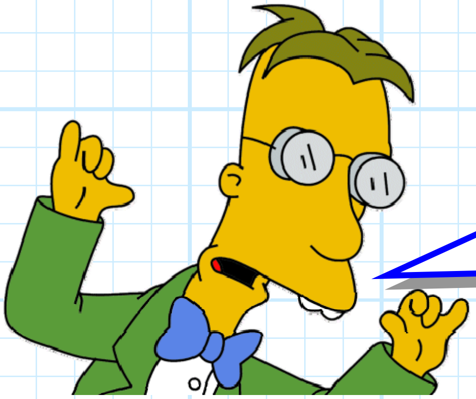
The **total** output voltage is the **sum** of the **small-signal** output voltage and the **DC** output voltage!

Note for this example, the **DC output** voltage is the **DC drain** voltage, and we recall we determined in an earlier handout that its value is:

$$V_O = V_D = 10 \text{ V}$$

Thus, the **total output voltage** is :

$$\begin{aligned} v_O(t) &= V_D + v_o(t) \\ &= 10.0 - 5.0\, V_i \cos\omega t \end{aligned}$$



It is very important that you realize there is a ***limit*** *on both how high and how low the* ***total*** *output voltage* $v_O(t)$ *can go!*

That's right! If the ***total*** *output voltage* $v_O(t)$ *tries to exceed these limits—even for a moment—theMOSFET will leave* ***saturation*** *mode.*

And leaving saturation mode results in ***signal distortion****!*

Let's break the problem down into **two** separate problems:

1) If **total** output voltage $v_O(t)$ becomes too **small**, the MOSFET will enter the **triode** mode.

2) If **total** output voltage $v_O(t)$ becomes too **large**, the MOSFET will enter **cutoff**.

We'll first consider **problem 1**.

For a MOSFET to remain in saturation, $v_{DS}(t)$ must remain **greater than** the excess gate voltage $\left(V_{GS}-V_t\right)$ for all time t.

$$v_{DS}(t) > V_{GS} - V_t$$

Since the source terminal of the MOSFET in **this** circuit is connected to ground, we know that $V_S = 0$ V. Therefore:

$$v_{DS}(t) = v_D(t) = v_O(t) \qquad \text{and} \qquad V_{GS} = V_G$$

And so the MOSFET will remain in saturation **only** if the total output voltage remains **larger** than $V_{GS} - V_t = V_G - V_t$!

$$v_O(t) > V_G - V_t$$

Thus, we conclude for this amplifier that the output "floor" is:

$$L_- = V_G - V_t$$

And since $V_G = 4.0\,V$ and $V_t = 2.0\,V$, we find:

$$L_- = V_G - V_t = 4 - 2 = 2.0\,V$$

Thus, to remain in saturation, the **total** output voltage must remain larger than the "floor" voltage L_- for all time t:

$$v_O(t) > L_- = 2.0\,V$$

Since this **total** voltage is:

$$v_O(t) = 10.0 - 5.0\,V_i \cos\omega t$$

we can determine the **maximum** value of small-signal **input** magnitude V_i:

$$10.0 - 5.0\,V_i \cos\omega t > 2.0$$

$$\Rightarrow 8.0 > 5.0\,V_i \cos\omega t$$

$$\Rightarrow V_i \cos\omega t < 1.6$$

Since $\cos\omega t$ can be as large as 1.0, we find that the **magnitude** of the **input** voltage can be **no larger** than 1.6 V, i.e.,

$$V_i < 1.6 \text{ V}$$

If the **input** magnitude exceeds this value, the MOSFET will (momentarily) leave the saturation region and enter the dreaded **triode** mode!

Now let's consider **problem 2**

For the MOSFET to remain in saturation, the **drain** current must be **greater** than zero (i.e., $i_D > 0$). Otherwise, the MOSFET will enter **cutoff** mode.

Applying **Ohm's Law** to the drain resistor, we find the **drain current** is:

$$i_D = \frac{V_{DD} - v_O}{R_C} = \frac{15 - v_O}{5}$$

it is evident that drain current is **positive** only if $v_O < 15 \text{ V}$.

In other words, the **upper** limit (i.e., the "ceiling") on the **total** output voltage is:

$$L_+ = V_{DD} = 15.0\,V$$

Since:

$$v_O(t) = 10.0 - 5.0\,V_i \cos\omega t$$

we can conclude that in order for the MOSFET to remain in **saturation** mode:

$$10 - 5.0\, V_i \cos\omega t > 15.0$$

Therefore, we find:

$$V_s \cos\omega t > \frac{-5.0}{5.0} = -1.0$$

Since $\cos\omega t \geq -1$, the above equation means that the **input** signal **magnitude** V_i can be **no larger** than:

$$V_i < 1.0 \text{ V}$$

If the input magnitude **exceeds** 1.0 V, the MOSFET will (momentarily) leave the saturation and enter the **cutoff** region!

In **summary**:

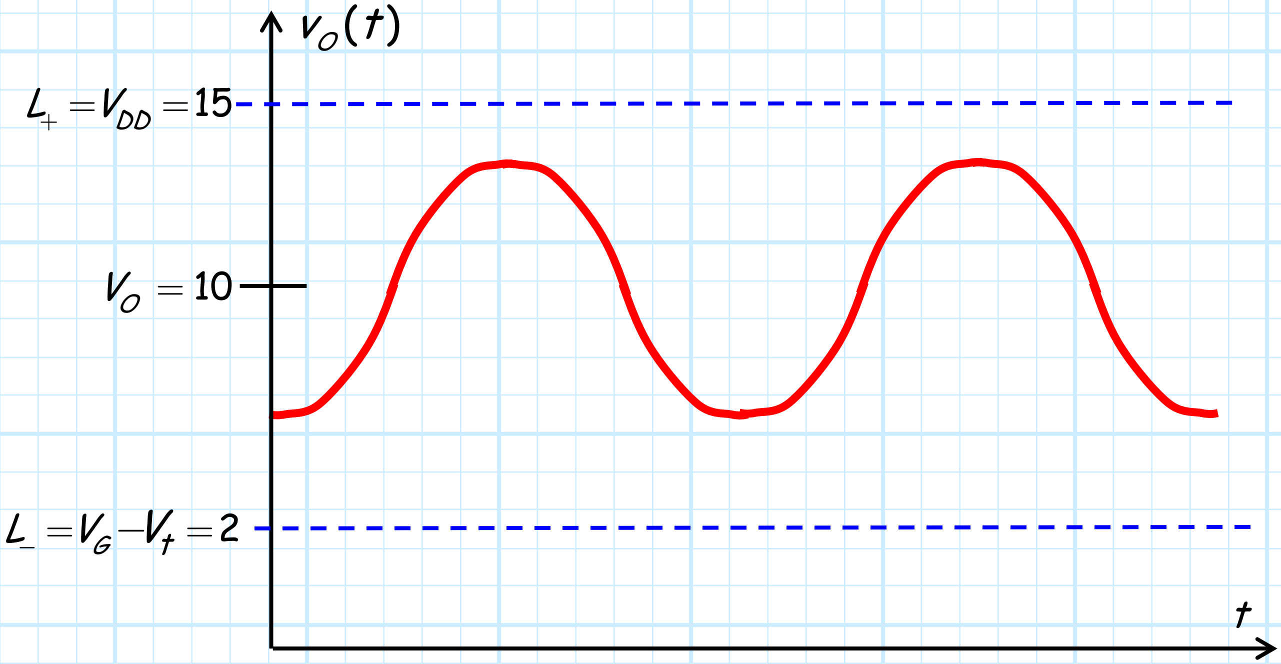
1) If $V_i > 1.6$ V, the MOSFET will at times enter **triode**, and **distortion** will occur!

2) If $V_i > 1.0$ V, the MOSFET will at times enter **cutoff**, and **even more** distortion will occur!

To demonstrate this, let's consider **three** examples:

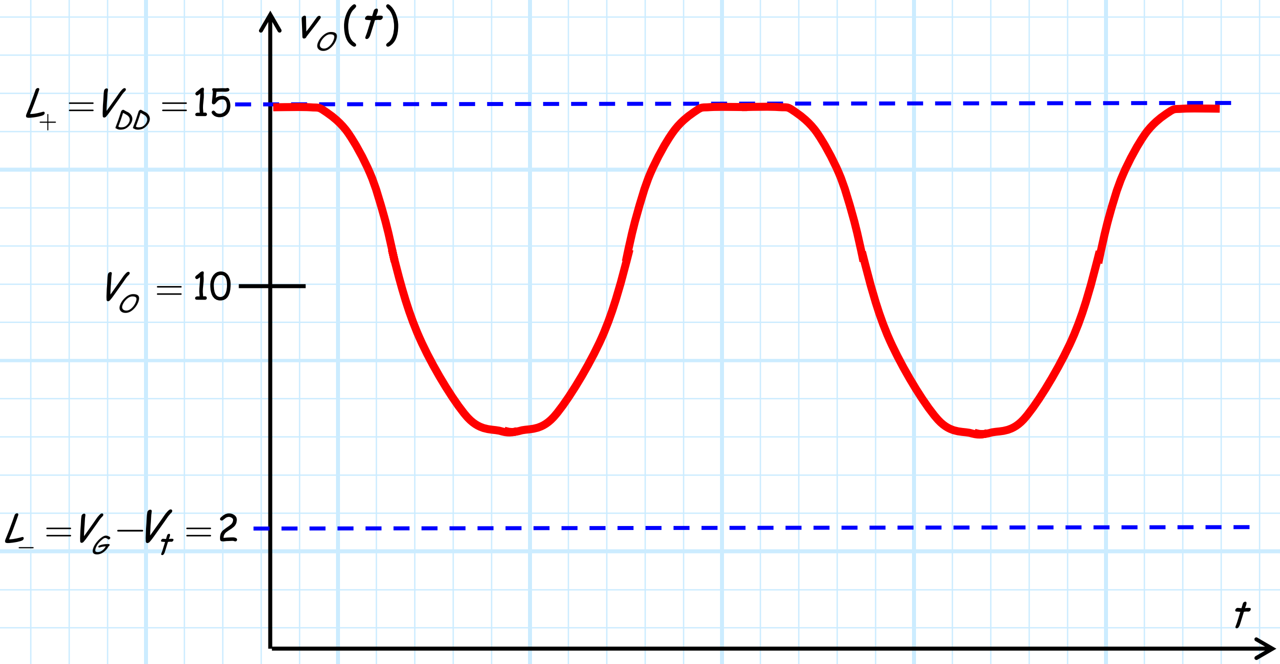
1. $V_i < 1.0$ V

The output signal in this case remains between $V_{DD} = 15.0$ and $V_G - V_t = 2.0$ V for **all** time t. Therefore, the output signal is **not distorted**.



2. 1.6 V $> V_i >$ 1.0 V

The output signal in this case remains greater than $L_- = V_G - V_t = 2$ for all time t. However, the small-signal output is now large enough so that the total output voltage at times tries to **exceed** $L_+ = V_{DD} = 15$. For these times, the MOSFET will enter **cutoff**, and the output signal will be **distorted**.



3. $V_i > 1.6\ V$

In this case, the small-signal input signal is sufficiently **large** so that the total output will attempt to exceed **both** limits (i.e., $V_{DD} = 15.0\text{V}$ and $V_G - V_t = 2.0\text{V}$). Therefore, there are periods of time when the MOSFE will be in **cutoff**, and periods when the MOSFET will be in **saturation**.