EE204FZ
Lecture 7
FET Amplifiers

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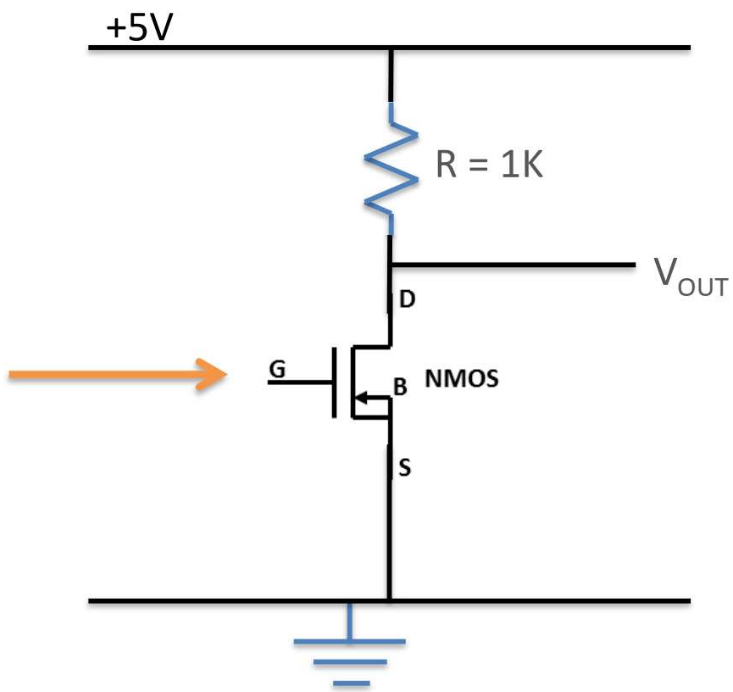
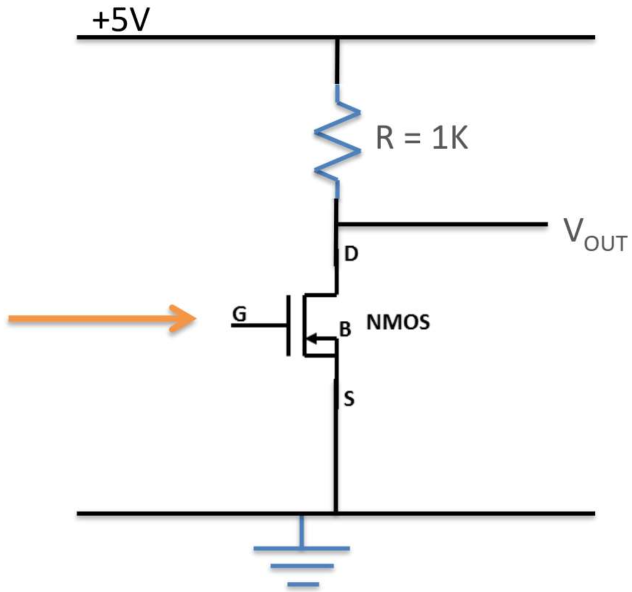
Amplification



$$I_{D(sat)} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_T)^2$$

- Let's imagine that the ideal MOSFET is in saturation, V_{DS} has very little effect on current flows, but V_{GS} sets the current.
  - What happens to I_D if one increases V_{GS}?
  - What happens then to V_{OUT}?

Amplification



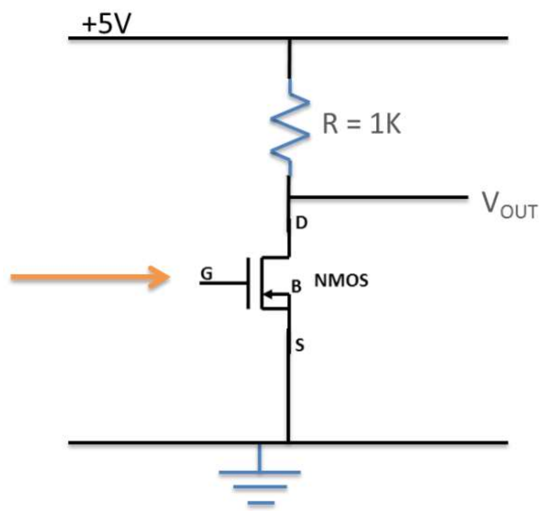
Assume that

- $\mu_n C_{ox} = 50 \times 10^{-6}\ \mathrm{A/V^2}$;
- $W/L = 100$;
- $V_T = 1$ V.

$$I_{D(sat)} = (0.0025)\,(V_{GS} - 1)^2$$

- Let's imagine now that one has $V_{GS} = 2$ V, so $I_{D(sat)} = 2.5$ mA.
  - What voltage is V_{OUT} at?
- If V_{GS} goes up 1% to 2.02 V,
  - What is I_D?
  - What value is V_{OUT}?

Amplification

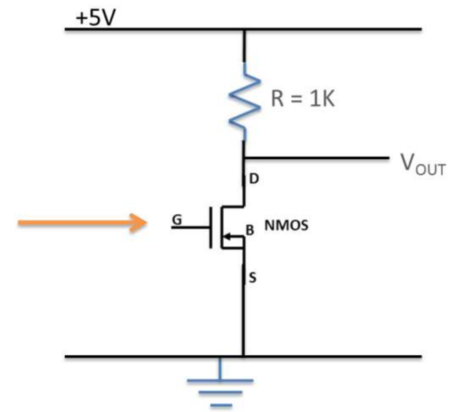


$$I_{\mathrm{D(sat)}} = (0.0025)\,(V_{\mathrm{GS}} - 1)^2$$
$$\Delta I_{\mathrm{D(sat)}} \approx (0.0025)(2)(V_{\mathrm{GS}} - 1)\Delta V_{\mathrm{GS}}$$
$$\Delta V_{\mathrm{out}} \approx -(2.5)(2)(V_{\mathrm{GS}} - 1)\Delta V_{\mathrm{GS}}$$
$$\frac{\Delta V_{\mathrm{out}}}{\Delta V_{\mathrm{GS}}} \approx -(2.5)(2) = -5$$
$$A \approx -5$$

- This is a bit of a hack, with assumptions everywhere, but basically we get an amplification of the change in the gate signal.
- More correctly, this needs to be worked out a bit more carefully.
- NOTE: Gain is usually given the symbol of *A* for Amplification.

Equations Are for Fun!

$$V_{\mathrm{out}} = 5 - RI_{\mathrm{D(Sat)}}$$
$$= 5 - R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2$$



Consider a small change in V_{GS}, now calculate the new V_{out}:

$$V_{\mathrm{out(new)}} = 5 - R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} + \Delta V_{\mathrm{GS}} - V_{\mathrm{T}})^2$$

Let's find the change in V_{out} before doing all the multiplications, etc.

$$\Delta V_{\mathrm{out}} = V_{\mathrm{out(new)}} - V_{\mathrm{out}}$$
$$= \left[5 - R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} + \Delta V_{\mathrm{GS}} - V_{\mathrm{T}})^2\right] - \left[5 - R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2\right]$$
$$= \left[-R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} + \Delta V_{\mathrm{GS}} - V_{\mathrm{T}})^2\right] - [-R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2]$$

Equations Don't Need to be Remembered!

$$\Delta V_{\mathrm{out}} = \left[-R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}}+\Delta V_{\mathrm{GS}}-V_{\mathrm{T}})^2\right] - \left[-R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}}-V_{\mathrm{T}})^2\right]$$

$$= -R\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}[(V_{\mathrm{GS}}+\Delta V_{\mathrm{GS}}-V_{\mathrm{T}})^2 - (V_{\mathrm{GS}}-V_{\mathrm{T}})^2]$$

Now the messy expansion. But let's just look at that bit:

$$(V_{\mathrm{GS}}+\Delta V_{\mathrm{GS}}-V_{\mathrm{T}})^2$$

$$= (V_{\mathrm{GS}})^2 + (\Delta V_{\mathrm{GS}})^2 + (V_{\mathrm{T}})^2 + 2\Delta V_{\mathrm{GS}}V_{\mathrm{GS}} - 2V_{\mathrm{GS}}V_{\mathrm{T}} - 2\Delta V_{\mathrm{GS}}V_{\mathrm{T}}$$

$$(V_{\mathrm{GS}}+\Delta V_{\mathrm{GS}}-V_{\mathrm{T}})^2 - (V_{\mathrm{GS}}-V_{\mathrm{T}})^2$$

$$= [(V_{\mathrm{GS}})^2 + (\Delta V_{\mathrm{GS}})^2 + (V_{\mathrm{T}})^2 + 2\Delta V_{\mathrm{GS}}V_{\mathrm{GS}} - 2V_{\mathrm{GS}}V_{\mathrm{T}} - 2\Delta V_{\mathrm{GS}}V_{\mathrm{T}}]$$

$$-[(V_{\mathrm{GS}})^2 - 2V_{\mathrm{GS}}V_{\mathrm{T}} + (V_{\mathrm{T}})^2]$$

Amplification

Let's start doing cancellation:

$$
\begin{aligned}
&(V_{\mathrm{GS}} + \Delta V_{\mathrm{GS}} - V_{\mathrm{T}})^2 - (V_{\mathrm{GS}} - V_{\mathrm{T}})^2 \\
&\qquad = [(\cancel{V_{\mathrm{GS}}})^2 + (\Delta V_{\mathrm{GS}})^2 + (\cancel{V_{\mathrm{T}}})^2 + 2\Delta V_{\mathrm{GS}} V_{\mathrm{GS}} - 2\cancel{V_{\mathrm{GS}}} V_{\mathrm{T}} - 2\Delta V_{\mathrm{GS}} V_{\mathrm{T}}] \\
&\qquad - [(\cancel{V_{\mathrm{GS}}})^2 - 2\cancel{V_{\mathrm{GS}}} V_{\mathrm{T}} + (\cancel{V_{\mathrm{T}}})^2] \\
&\qquad = 2\Delta V_{\mathrm{GS}} V_{\mathrm{GS}} - 2\Delta V_{\mathrm{GS}} V_{\mathrm{T}} + (\Delta V_{\mathrm{GS}})^2
\end{aligned}
$$

Going all the way back, we get:

$$\Delta V_{\mathrm{out}} = (-R)\frac{1}{2}\mu_{\mathrm{n}} C_{\mathrm{ox}} \frac{W}{L}\,[2\Delta V_{\mathrm{GS}} V_{\mathrm{GS}} - 2\Delta V_{\mathrm{GS}} V_{\mathrm{T}} + (\Delta V_{\mathrm{GS}})^2]$$

The change in V_{out} is solely dependent on V_{GS}. Interesting.

Amplification

- Now for amplification:

$$\frac{\Delta V_{\mathrm{out}}}{\Delta V_{\mathrm{GS}}} = (-R)\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}\left(2V_{\mathrm{GS}} - 2V_{\mathrm{T}} + \Delta V_{\mathrm{GS}}\right)$$

$$\approx (-R)\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}2(V_{\mathrm{GS}} - V_{\mathrm{T}})$$

Assume ΔV_{GS} is small.

- The amplification can be expressed as:

$$A \approx (-R)\,\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{pinch-off}})$$

$V_{\mathrm{pinch-of}} = V_{\mathrm{GS}} - V_{\mathrm{T}}$

- After all that, we can conclude:
  - The amplification is negative, which means if the input signal goes up, the output goes down;
  - If in saturation, the gain is determined by the V_{GS} voltage only, and the value of resistance R.

Amplification

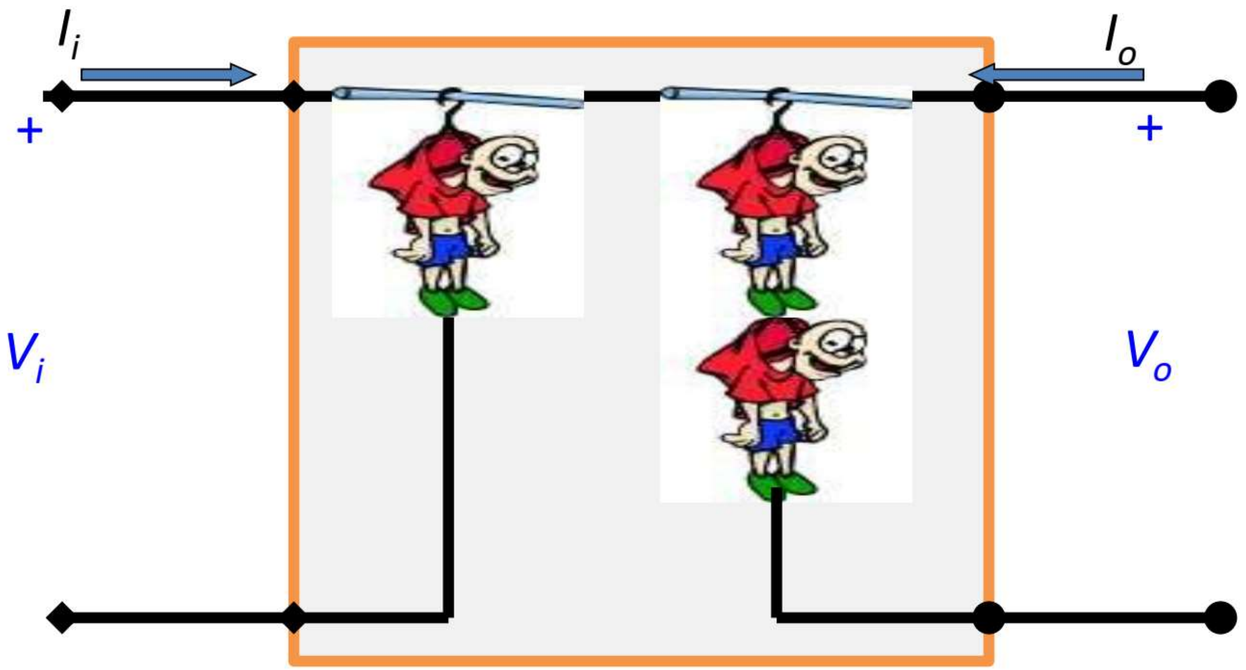
- And the biggest lesson of all is:

  5 pages of maths later, I work out the equations for just one transistor and one resistor. How the *cough* *cough* do I manage something with more than that? Never mind thousands and millions of transistors.

The Trick

- What we need to do is to simplify our circuit as much as possible. To do that we split any circuit into two parts and deal with them one at a time.
  - The large signal (big voltages);
  - The small signals.
- Sometimes we only need to look at the big voltage swings, sometimes we need to focus on the small signals.
- For the small signals, we have a trick called "two-port networks", or black-box design.

Examples of a Black-Box



- It doesn't matter what is really inside the box, just that we can define ratios between input and output voltages, and input and output currents.

Two-Port Systems

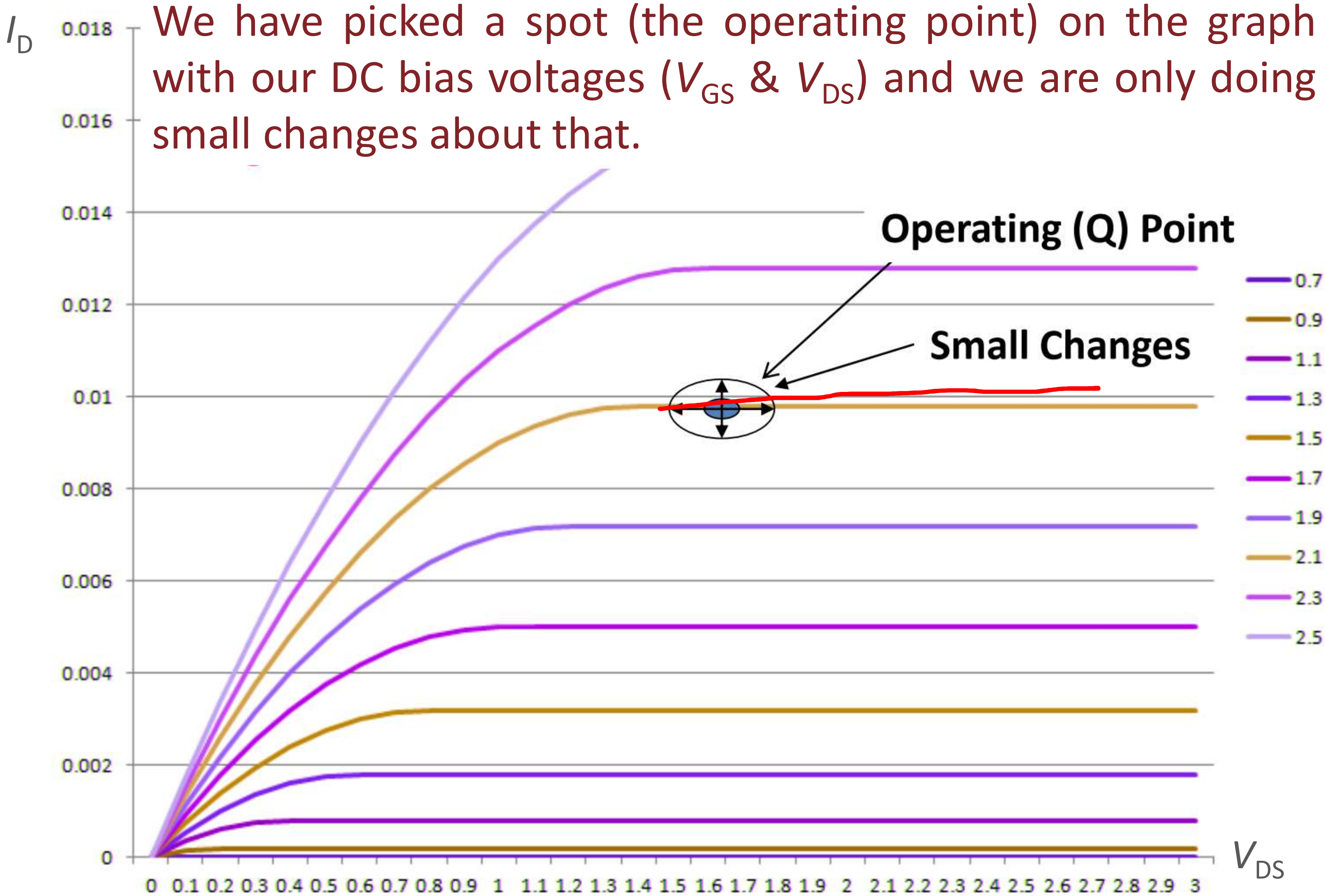
- There are many two-port "electrical" models that can be used to describe the transistor.
- Your choice of model often depends on the application that you need, large signal, small signal, whether you are looking for input or output impedance.
- For small signal the most common models are
  - H-parameter *
  - Hybrid-π *
  - T Equivalent Circuit
  - r_e Model
- For large signal
  - Ebers-Moll *
  - Charge Control Approach

Two-Port Systems

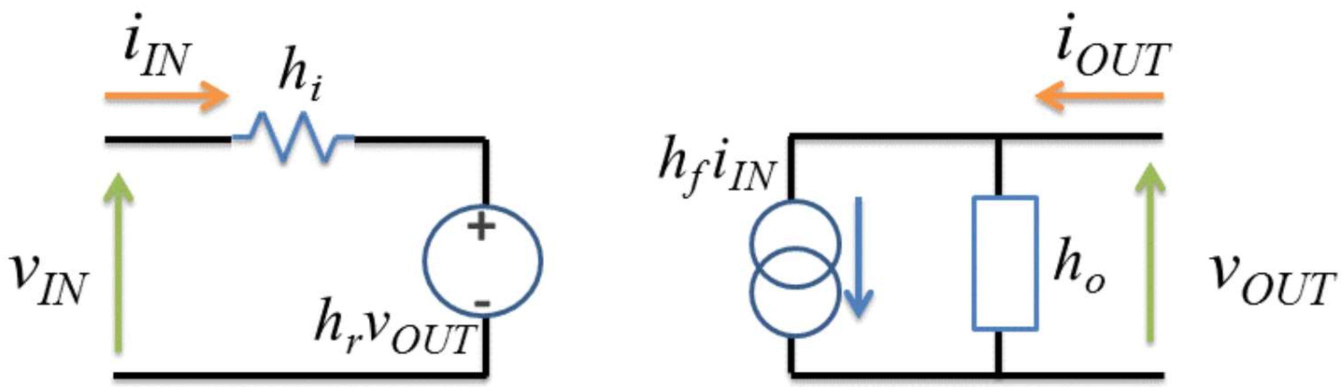
- In this course we are only concerned about SMALL SIGNALS.
- The key thing to remember is that amplification is normally small signals (often very very small) trying to get bigger.
- We are only going to look at 2 models which are related to each other:
  - H-parameter
  - Hybrid-π

Small Signal Analysis

We have picked a spot (the operating point) on the graph with our DC bias voltages (V_{GS} & V_{DS}) and we are only doing small changes about that.



H-Parameter Model



where

$$v_{\mathrm{IN}} = h_i(i_{\mathrm{IN}}) + h_r(v_{\mathrm{OUT}})$$
$$i_{\mathrm{OUT}} = h_f(i_{\mathrm{IN}}) + h_o(v_{\mathrm{OUT}})$$

Note:

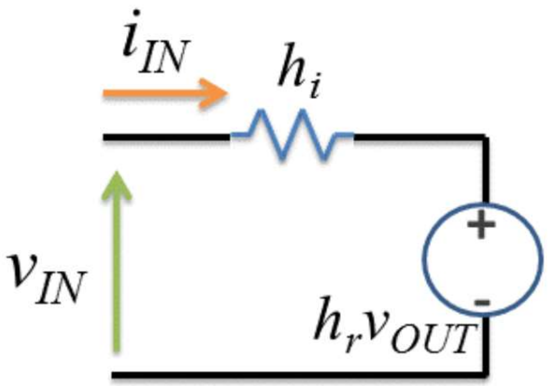
- Capital letters refer to large signals and DC;
- Small letters refer to small signals.

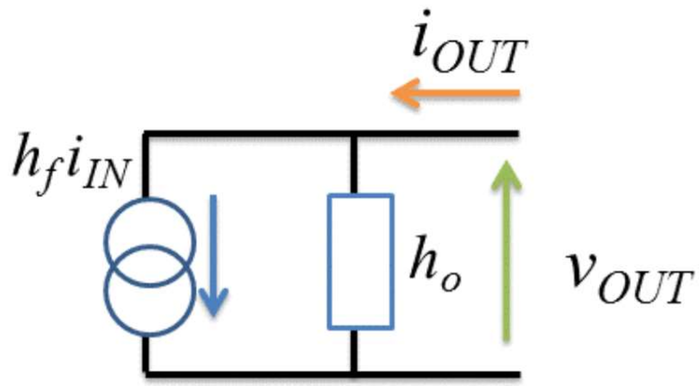
Reading the Expression

$$v_{\text{IN}} = h_i(i_{\text{IN}}) + h_r(v_{\text{OUT}})$$
$$i_{\text{OUT}} = h_f(i_{\text{IN}}) + h_o(v_{\text{OUT}})$$

- $h_i = \frac{v_{\text{IN}}}{i_{\text{IN}}}\Big|_{v_{\text{OUT}}=0}$: h_i is the value of v_{IN} divided by i_{IN} when $v_{\text{OUT}} = 0$;
- $h_o = \frac{i_{\text{OUT}}}{v_{\text{OUT}}}\Big|_{i_{\text{IN}}=0}$: h_o is the value of i_{OUT} divided by v_{OUT} when $i_{\text{IN}} = 0$.

Defining the H-Parameters





$$h_i = \frac{v_{\mathrm{IN}}}{i_{\mathrm{IN}}}\Big|_{v_{\mathrm{OUT}}=0}$$

Input Resistance (ohm)

$$h_r = \frac{v_{\mathrm{IN}}}{v_{\mathrm{OUT}}}\Big|_{i_{\mathrm{IN}}=0}$$

Reverse Transfer Voltage Ratio

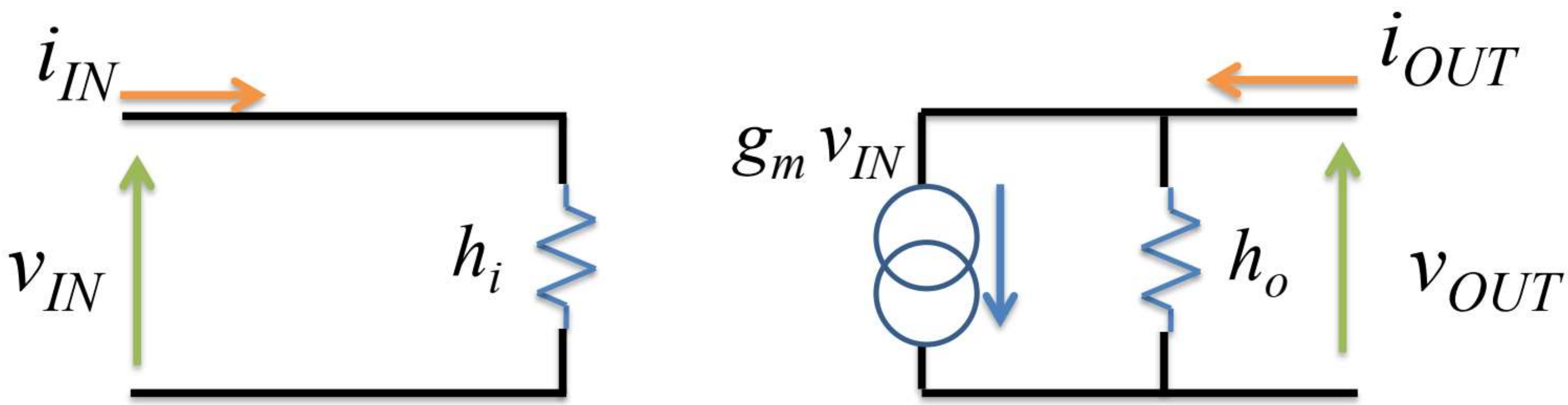
$$h_f = \frac{i_{\mathrm{OUT}}}{i_{\mathrm{IN}}}\Big|_{v_{\mathrm{OUT}}=0}$$

Forward Transfer Current Ratio

$$h_o = \frac{i_{\mathrm{OUT}}}{v_{\mathrm{OUT}}}\Big|_{i_{\mathrm{IN}}=0}$$

Output Conductance or Admittance (1/ohm)

Hybrid- π Parameter Model

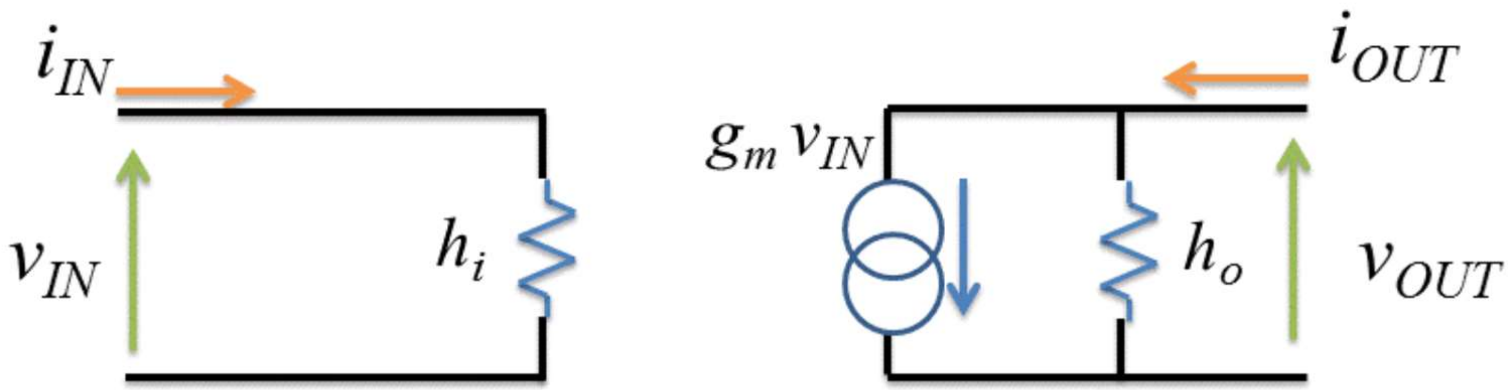


Where

$$i_{\mathrm{OUT}} = g_m(v_{\mathrm{IN}}) + (v_{\mathrm{OUT}})/h_o$$

This is very similar to the h-parameter model except h_o is drawn as a resistor, and the current source is now controlled by v_{IN}.

Defining the Hybrid- π Parameters



$$g_m = \frac{i_{\mathrm{OUT}}}{v_{\mathrm{IN}}}\Big|_{v_{\mathrm{OUT}}=0}$$

Forward Transconductance

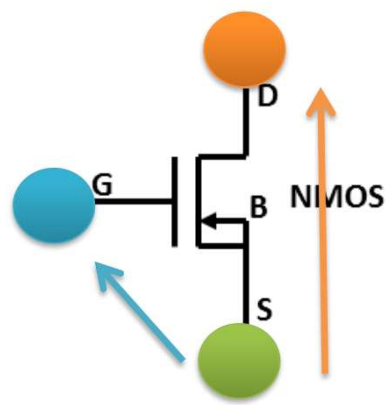
$$h_o = \frac{v_{\mathrm{OUT}}}{i_{\mathrm{OUT}}}\Big|_{v_{\mathrm{IN}}=0}$$

Output Resistance (ohm)

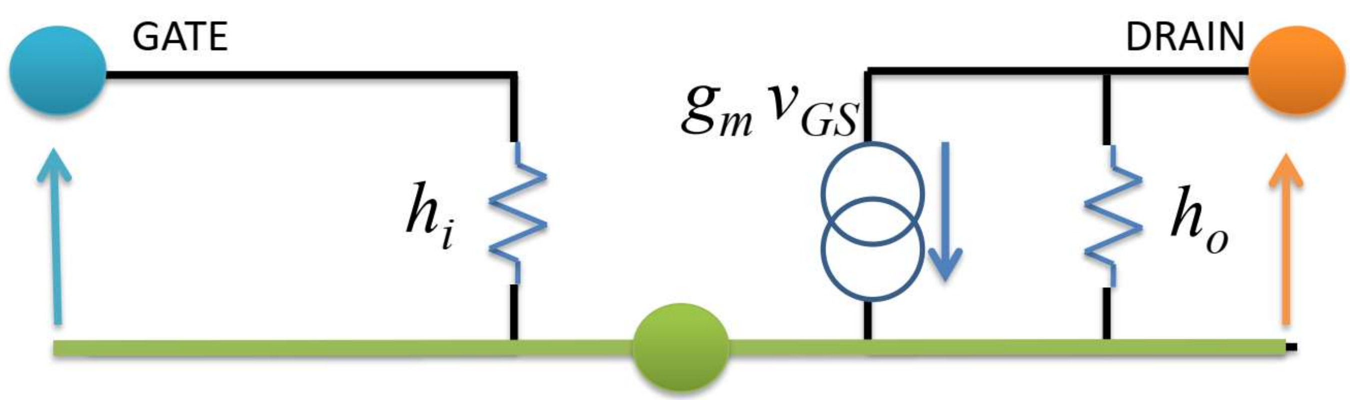
$$h_i = \frac{v_{\mathrm{IN}}}{i_{\mathrm{IN}}}\Big|_{v_{\mathrm{OUT}}=0}$$

Input Resistance (ohm)

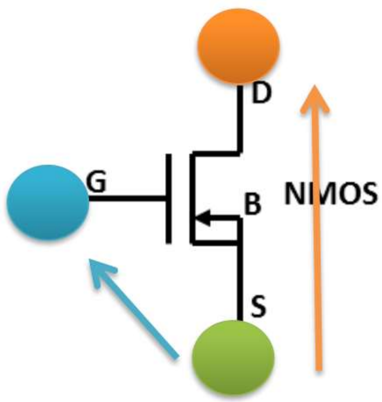
Applying the Hybrid-π Model to a MOSFET



We swap the transistor for the small signal model then carry out our analyses.

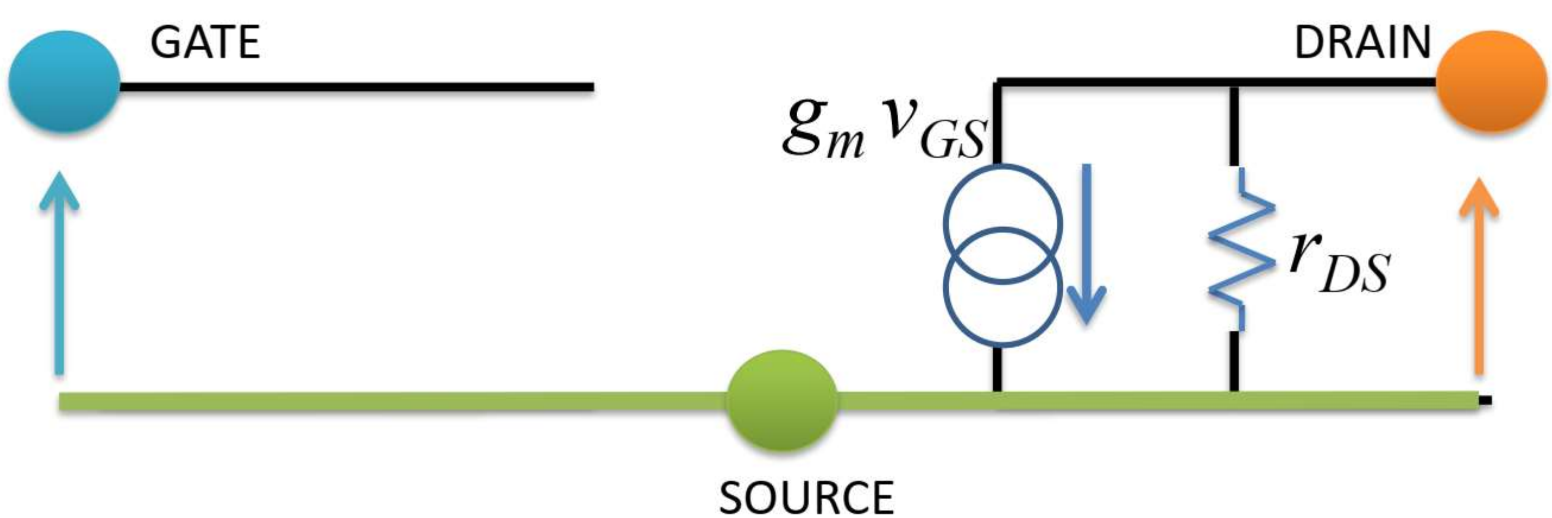


Applying the Hybrid-π Model to a MOSFET

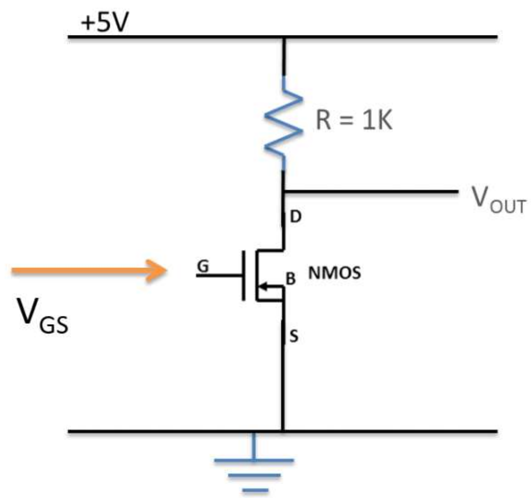


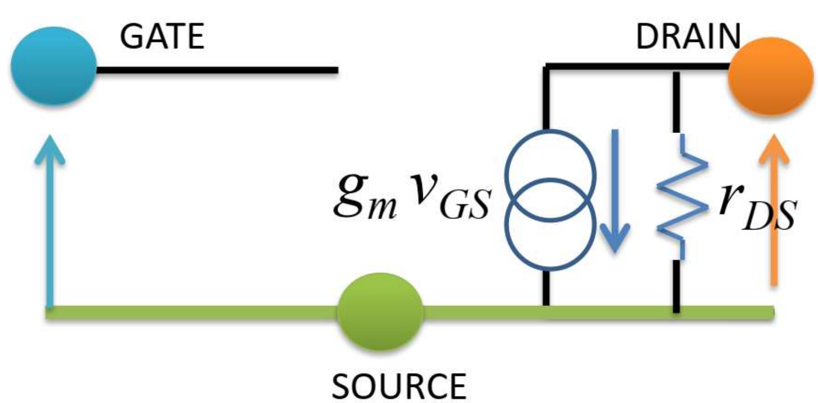
The input resistance of a MOSFET gate is infinite.

The small signal variation of a MOSFET in saturation is given by the slope of the flat-part of the curve, it is called r_{DS} and is either infinite (ideal MOSFETs), or very high (real MOSFETs).

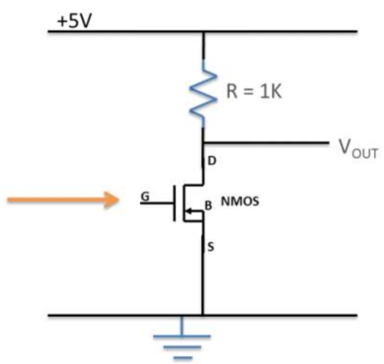


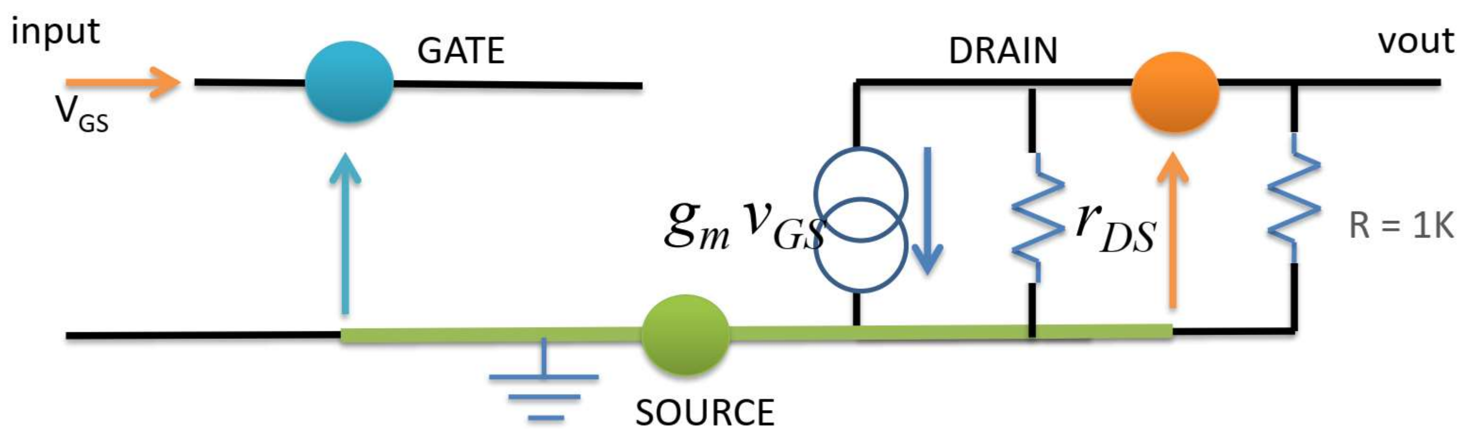
Example: Small Signal Equivalent Circuits





Example: Small Signal Equivalent Circuits





Rules When Constructing Equivalent Small Signal Circuits

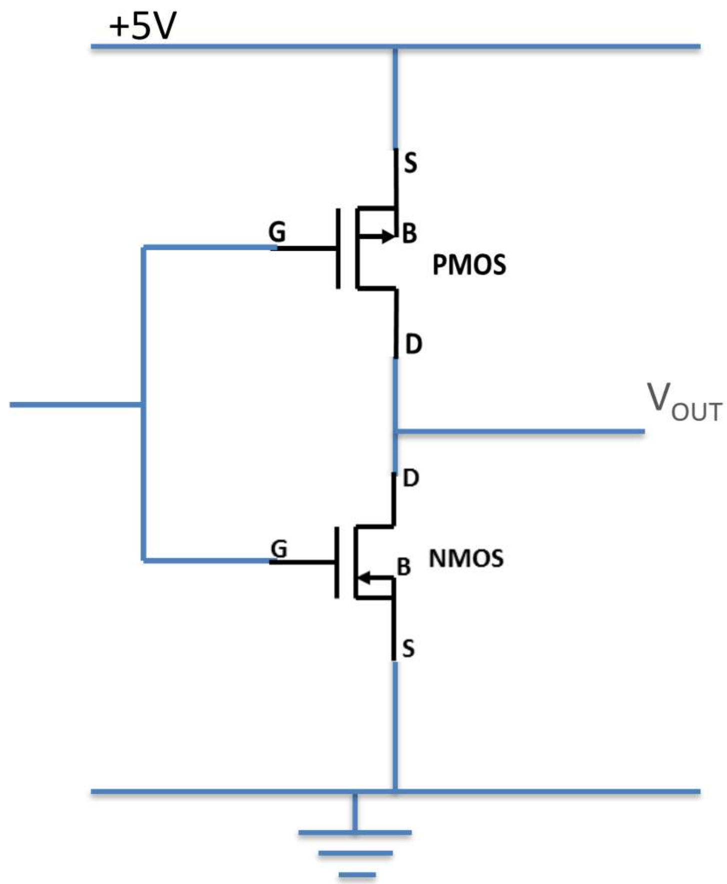
- Start with the transistor model;
- Identify the gate, drain and source;
- All fixed voltages are treated as small-signal grounds. That means the +5 V is also a ground. Think why this is true!!!
- Connect things up, remembering the “new” grounds are all the same place;
- PMOS and NMOS have the same small signal model, perhaps with different values of parameters;
- r_{DS} can often be ignored but it is best to leave it in.

Important Note

- Solving small signal equivalent circuits is much easier than doing a normal transistor analysis;
- However, the results are ONLY ACCURATE for small signals (AC);
- To understand what is happening with your DC signals, you need to carry out a DC analysis of your circuit as well;
- If your AC signals become large, then they'll work sort of like what you expected from the small signal analysis, but they will start experiencing different amplification (usually less) as they move away from your operating point.

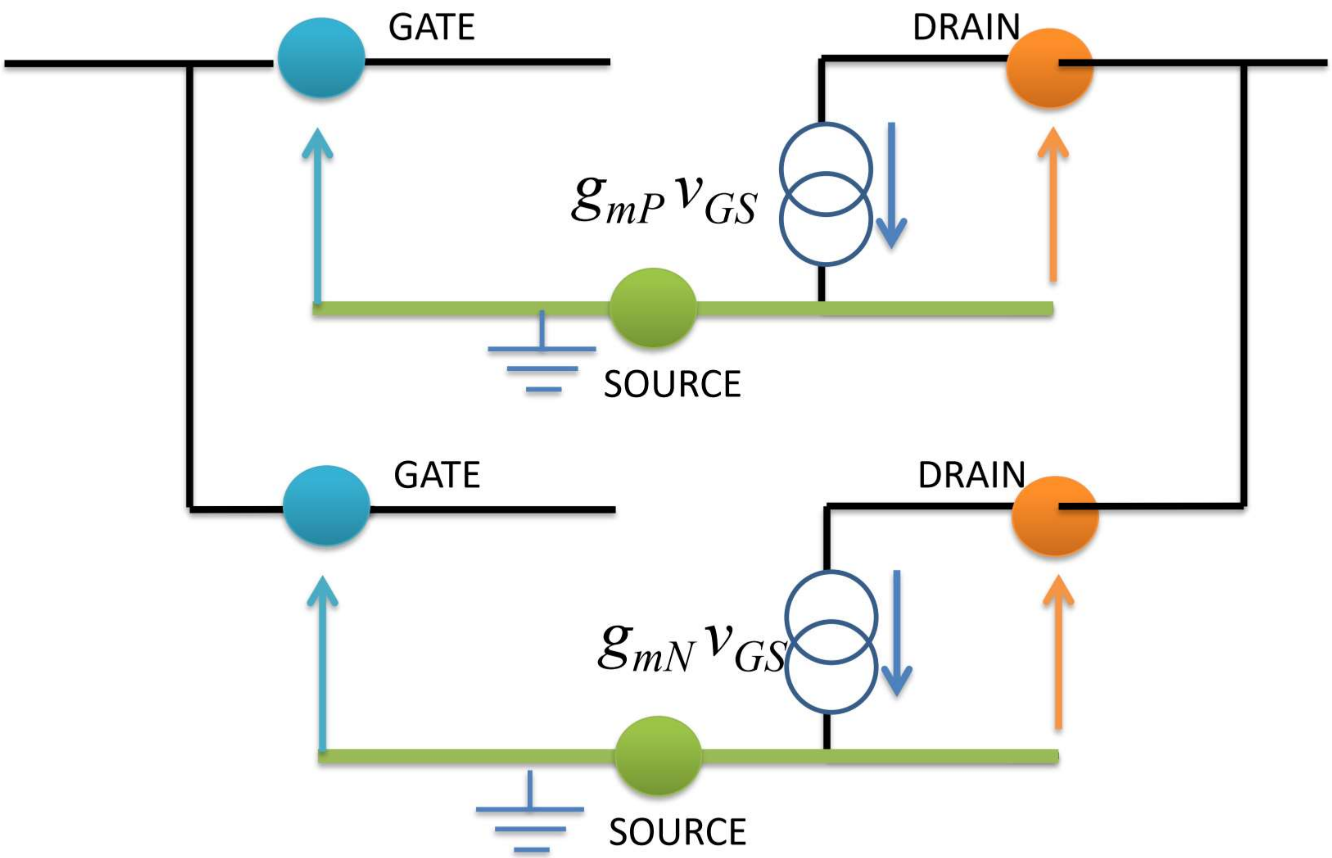
Example: The Invertor

- For fun, draw the small signal equivalent circuit of an inverter.



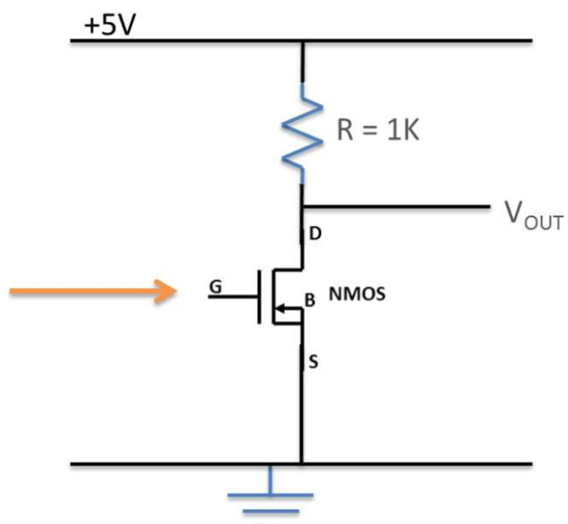
Example: The Invertor

- Only problem is that they are in parallel.



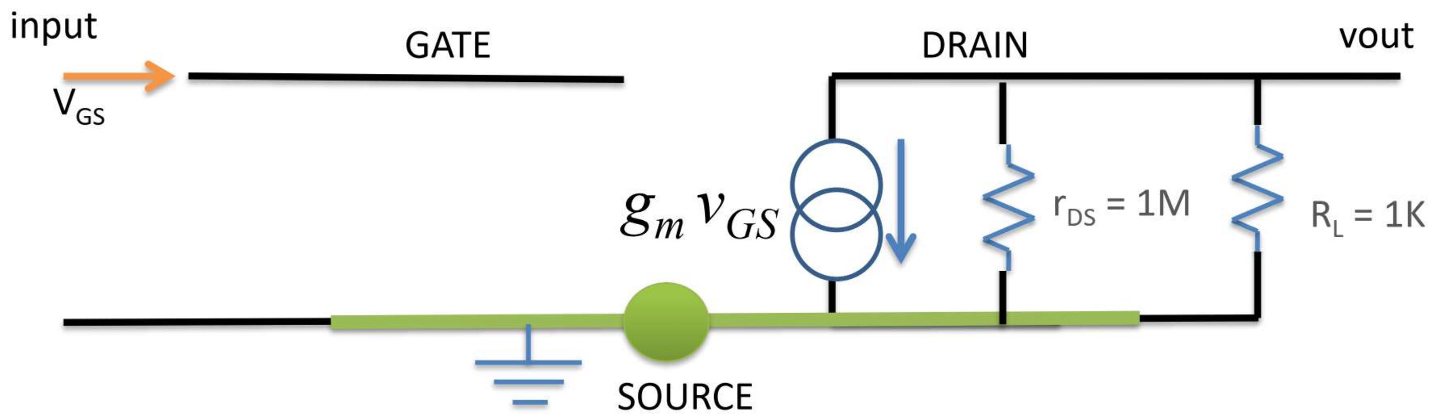
Example: Let's Calculate Gain

- A ZVN3306 n-MOSFET was used with a 1 kohm load resistor. Assuming that we are in saturation and dealing with small signals, calculate the gain a small signal would experience.

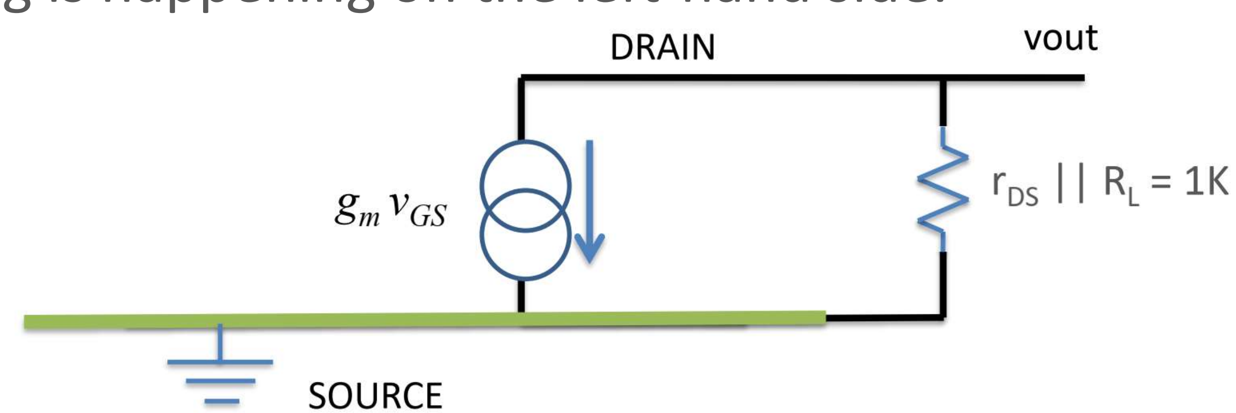


- The datasheet gives the following values:
  - g_m = 0.15 Siemens;
  - r_{DS} > 1 Mohm.

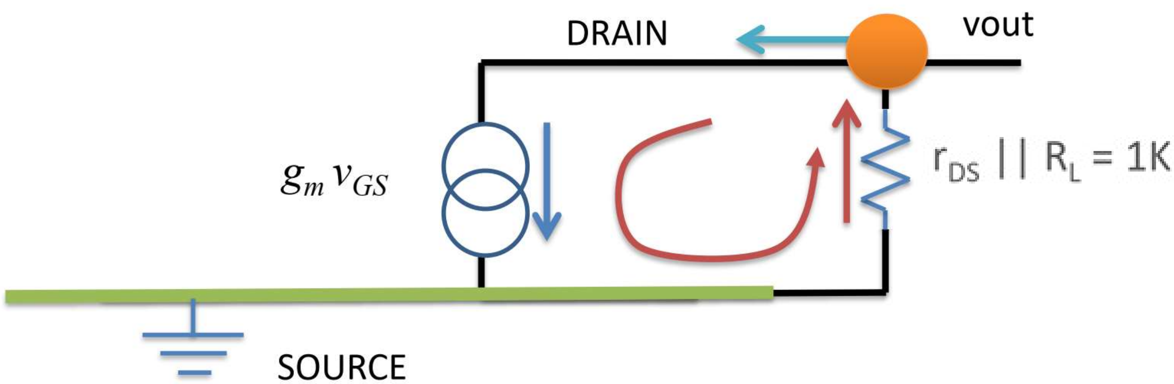
Example: Let's Calculate Gain



- r_{DS} is much much bigger than R_L, so it can be ignored.
- Secondly, we only need to look at the right-hand side as nothing is happening on the left-hand side.



Example: Let's Calculate Gain



- Now there is nothing connected to V_{OUT}, so all the current leaving the ORANGE node must be matched with that entering:

$$I_R = -g_m v_{GS}$$

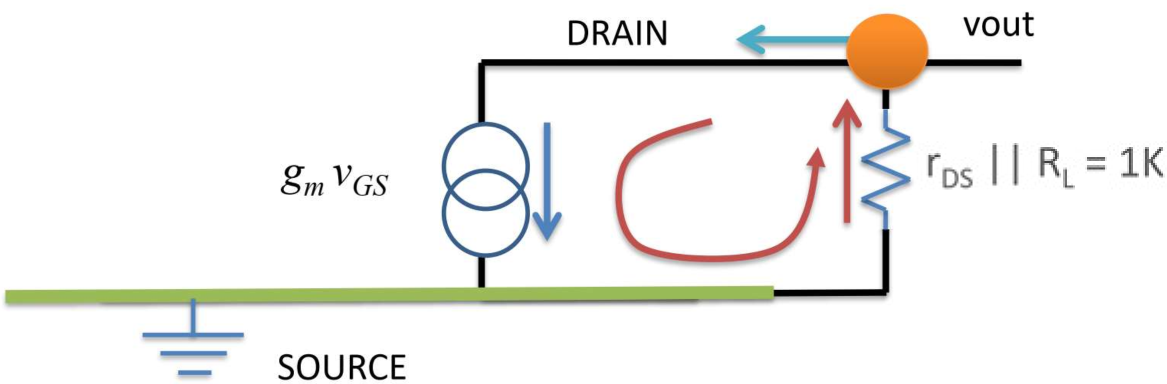
- The output small signal v_{out}:

$$v_{out} = -R_L I_R = -R_L g_m v_{GS}$$

- The gain is therefore:

$$A = \frac{v_{out}}{v_{GS}} = \frac{-R_L g_m v_{GS}}{v_{GS}} = -R_L g_m$$

Example: Let's Calculate Gain



$$A = \frac{v_{\mathrm{out}}}{v_{\mathrm{GS}}} = \frac{-R_{\mathrm{L}} g_{\mathrm{m}} v_{\mathrm{GS}}}{v_{\mathrm{GS}}} = -g_{\mathrm{m}} R_{\mathrm{L}}$$

- Plugging in the numbers we get:

$$A = -(1000)(0.15) = -150$$

- This is a large gain, and if you get too much gain, you might experience clipping.

Clipping: A Small Signal Failure

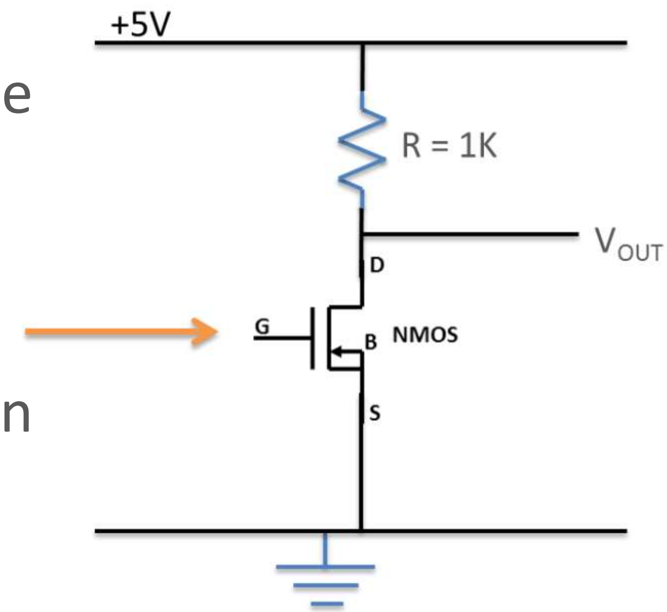
- The DC value of V_{OUT} is given by the DC values for the gate voltage:

$$I_{\mathrm{D(sat)}} = \frac{1}{2}\mu_{\mathrm{n}} C_{\mathrm{ox}} \frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2$$

- The value of V_{OUT} is therefore given by:

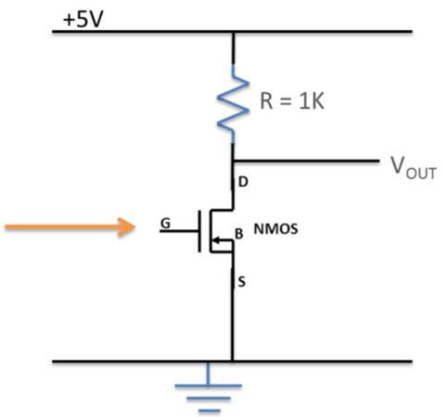
$$V_{\mathrm{OUT}} = 5 - R_{\mathrm{L}} I_{\mathrm{D(sat)}}$$

- What is the biggest and smallest values V_{OUT} can take?

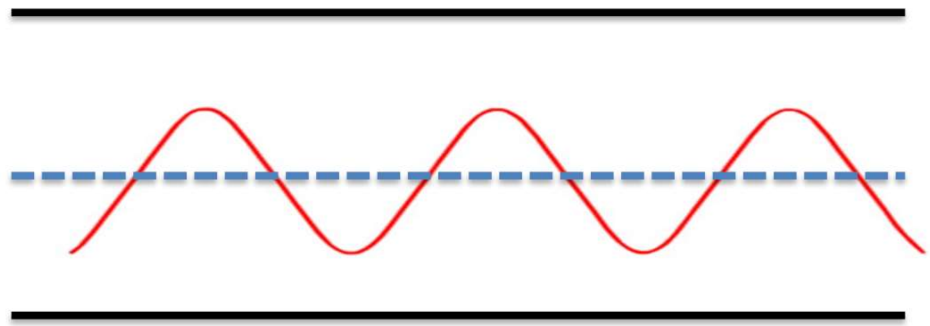


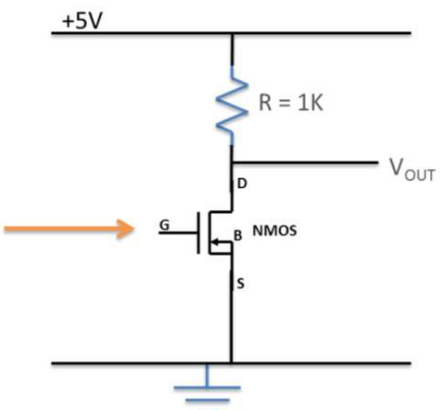
- If we get a signal on the gate that is amplified and the output goes too high, what will happen?

Clipping

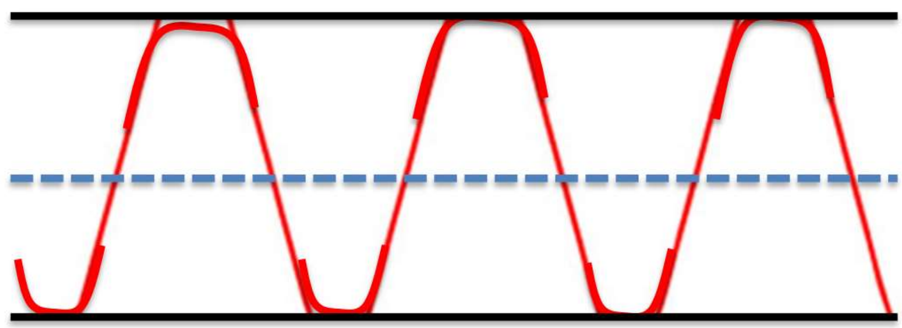


Using a small signal.

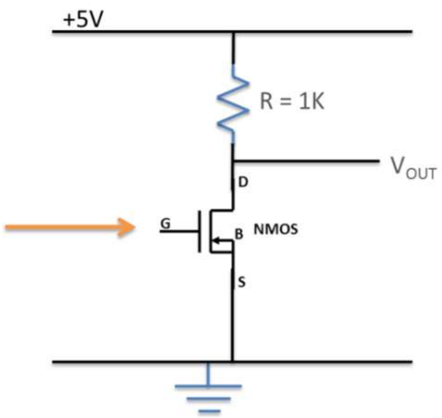




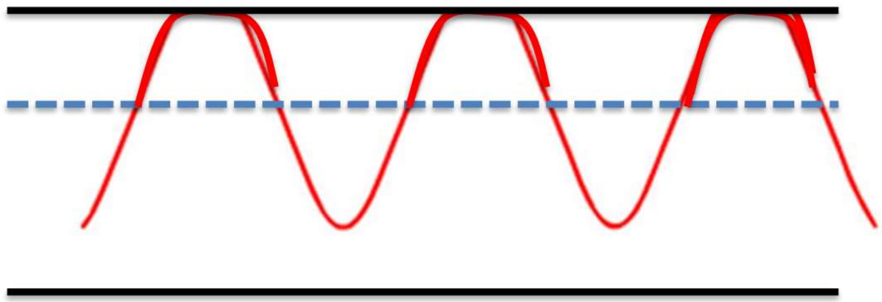
Signal gets clipped at the top and bottom.

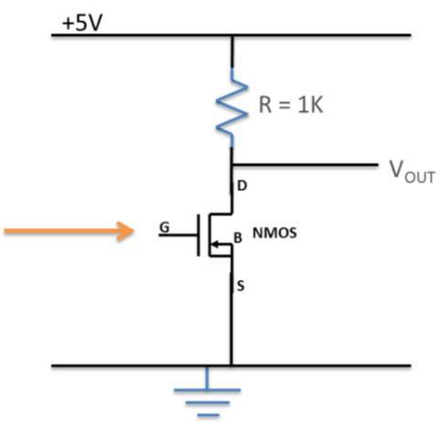


Clipping

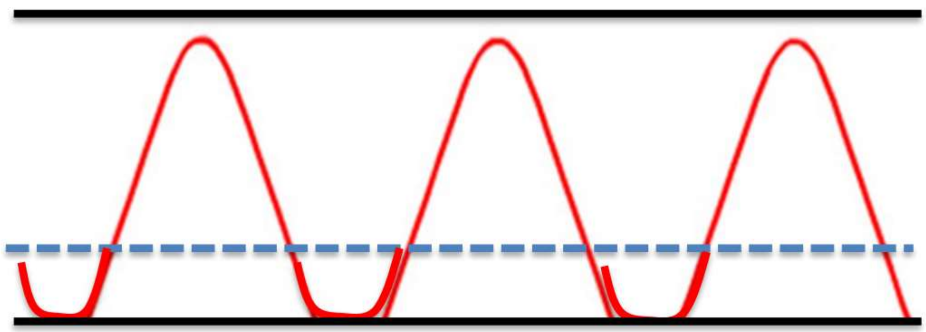


Centre V_{OUT} on the high side, clipping on one side.

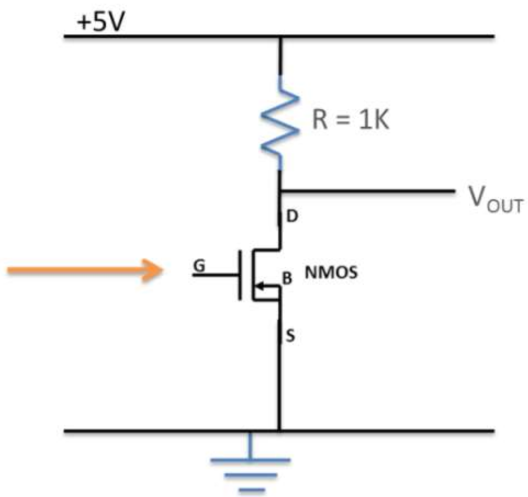


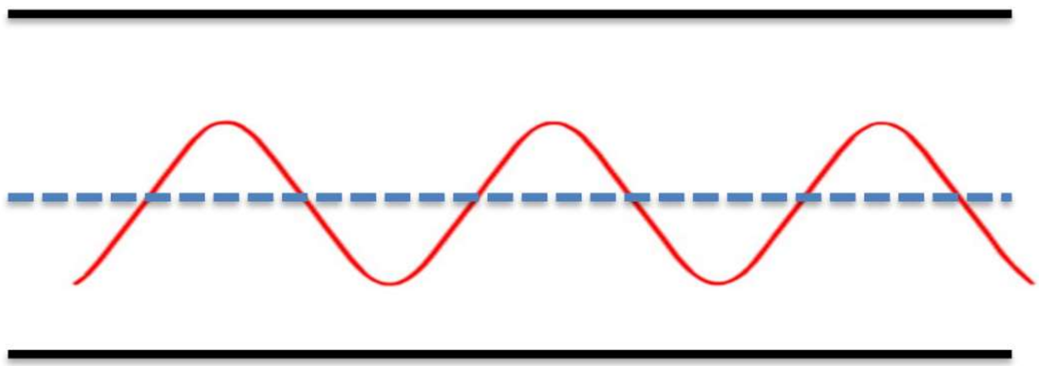


Centre V_{OUT} on the low side, clipping on the other side.



What's a Good "Small Signal"?

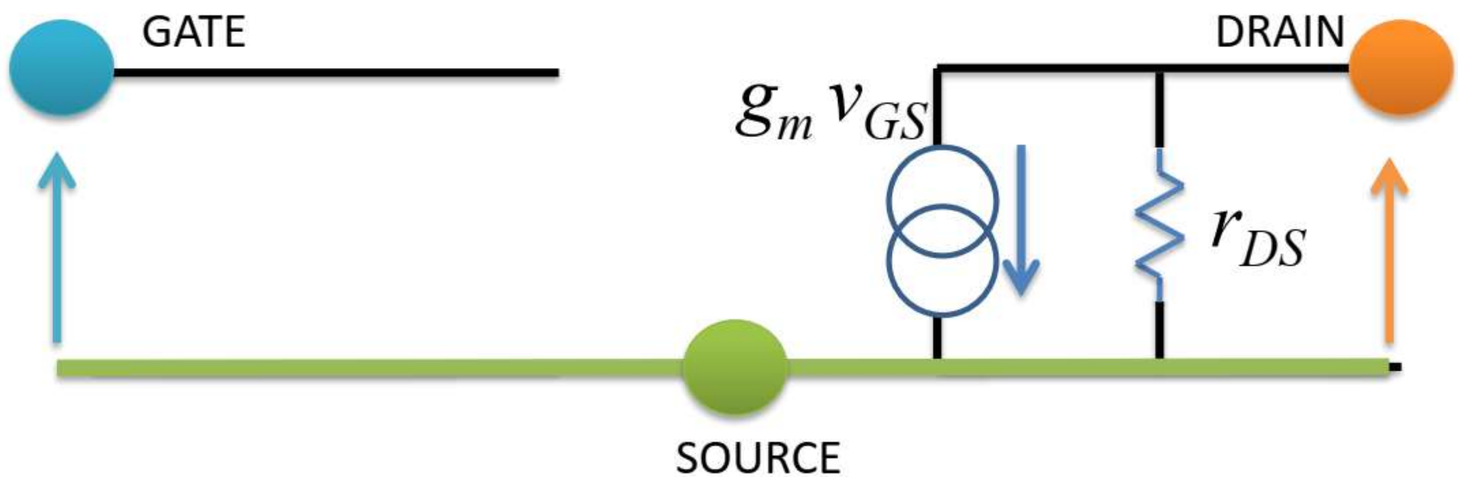




- In an audio microphone application, a small signal is ~10 mV.
- In a mobile phone receiver, a large signal is 10 mV, a small signal is 1 μV.
- In these cases, you can use a gain of 100 and still have small enough for the output signal and no clipping. It all depends on your application.
- You can use special pre-amps or low-noise amps that concentrate on very weak signals and boost them a little, so you can use other circuits that concentrate on producing larger, more powerful outputs… sensitivity *vs.* power.

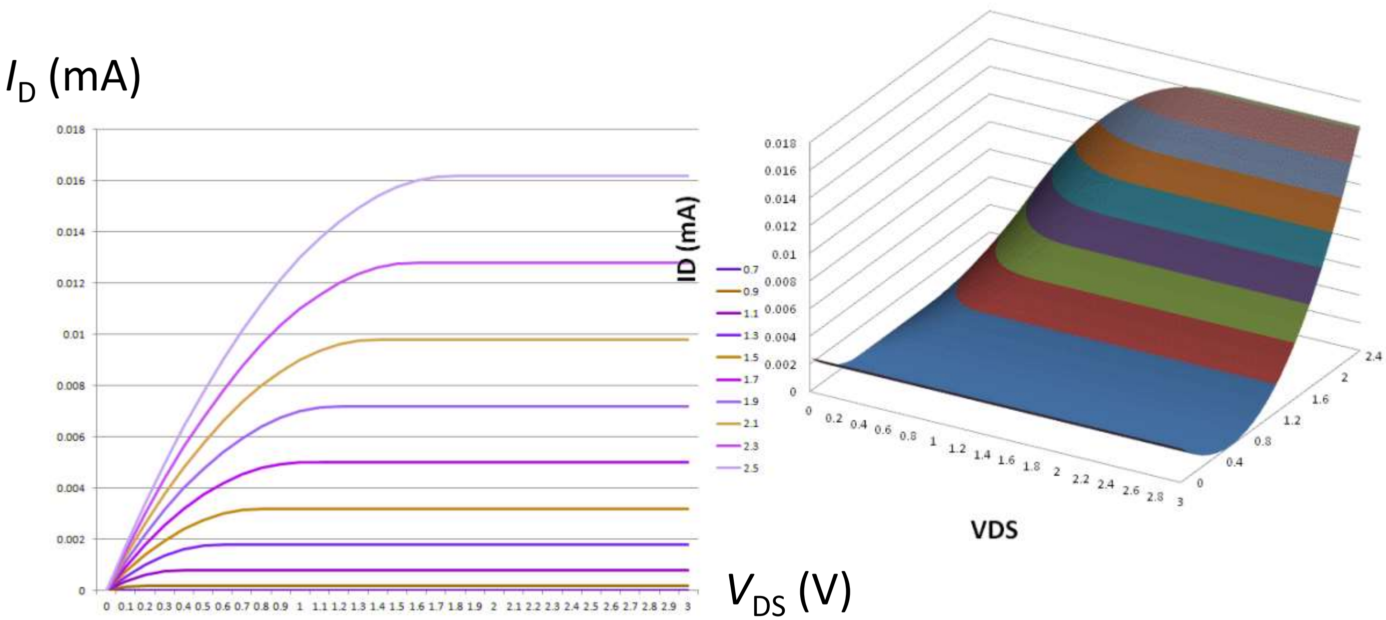
The Importance of Bias

- Biasing is important. It controls
  - When the output will clip;
  - The amplification we can achieve as it controls g_m;
  - It also controls the value of r_{DS}.



What is Really Biasing?

- A lot of it is picking where on the transistor curve we want to be. And that means choosing values of V_{GS}, I_D and V_{DS}.



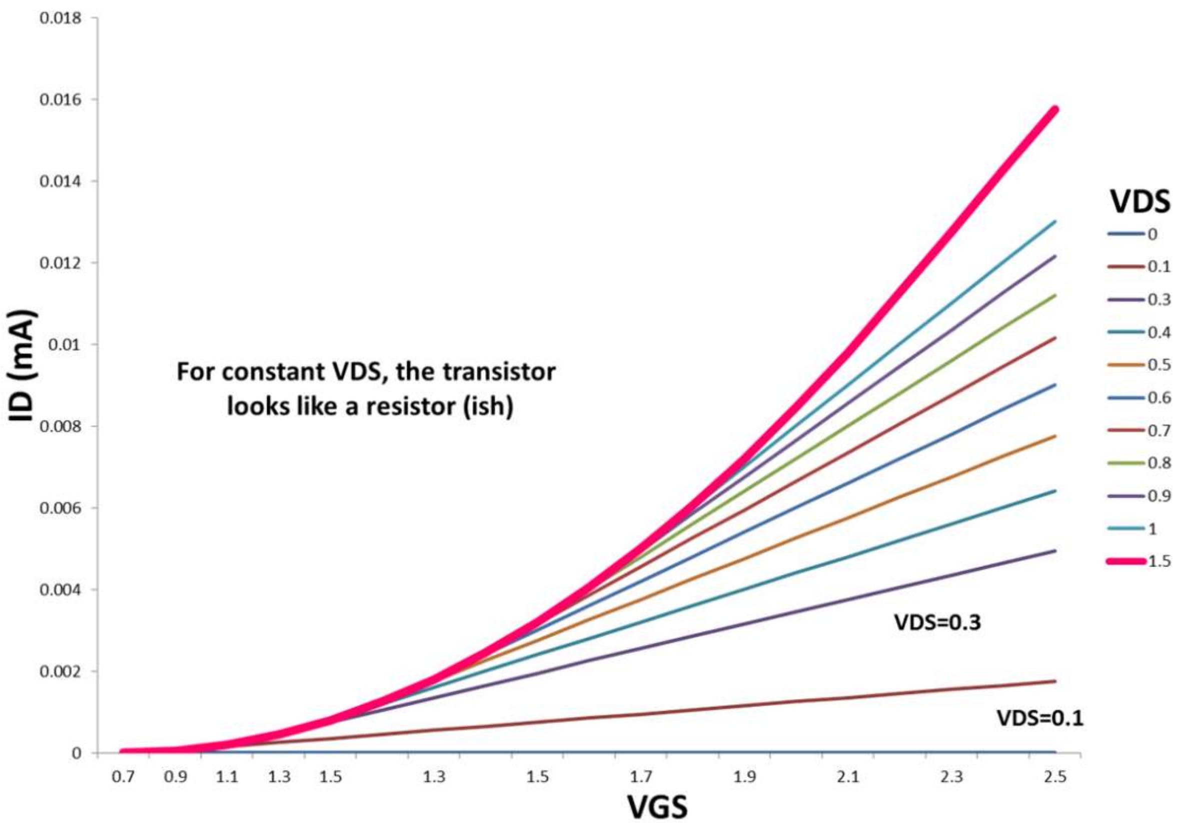
- In the analogy, biasing is picking what part of the mountain I want to walk a few steps back and forth on (saying go 3 km to the east and 500 metres up).

What is Really Biasing?

- Biasing uses DC voltages to control the values of small-signal parameters.
- The next few slides have a bit of maths but the important thing is the relationships between the key small-signal parameters and the DC values:
- $I_{D(\mathrm{sat})} = \frac{1}{2}\mu_{\mathrm{n}} C_{\mathrm{ox}} \frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2$
- $g_m = \mu_{\mathrm{n}} C_{\mathrm{ox}} \frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}}) = \sqrt{2\mu_{\mathrm{n}} C_{\mathrm{ox}} \frac{W}{L} I_{D(\mathrm{sat})}} = k\sqrt{I_{D(\mathrm{sat})}}$
- $r_{\mathrm{DS}} = \frac{1}{\lambda I_{D(\mathrm{sat})}}$

Biasing and g_m

- $g_m = \frac{dI_D}{dV_{GS}}$, g_m is the local slope of the curve when I_D is plotted as a function of V_{GS}.



Biasing and g_m

- For this analysis, we ignore the channel length modulation (since it is a small effect):

$$I_{D(\text{sat})} = \frac{1}{2}\mu_\text{n} C_\text{ox} \frac{W}{L} (V_\text{GS} - V_\text{T})^2$$

- Let's look at the small-signal output:

$$g_m = \frac{dI_{\text{D(sat)}}}{dV_\text{GS}} = \frac{d}{dV_\text{GS}} [\frac{1}{2}\mu_\text{n} C_\text{ox} \frac{W}{L} (V_\text{GS} - V_\text{T})^2]$$

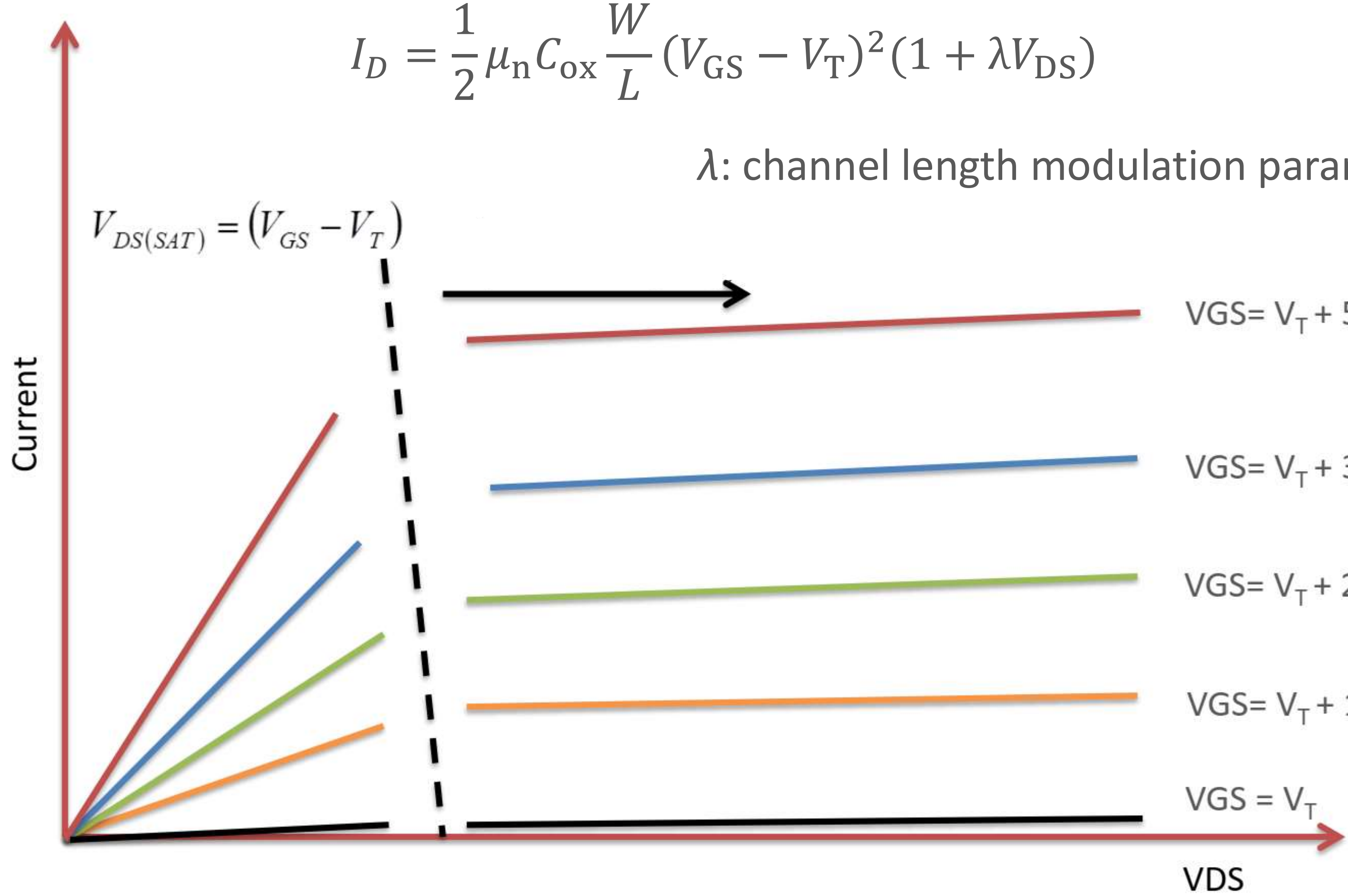
$$= \left(\frac{1}{2}\mu_\text{n} C_\text{ox} \frac{W}{L}\right) 2(V_\text{GS} - V_\text{T}) = \mu_\text{n} C_\text{ox} \frac{W}{L} (V_\text{GS} - V_\text{T})$$

$$= \sqrt{2\mu_\text{n} C_\text{ox} \frac{W}{L} I_{D(\text{sat})}} = k\sqrt{I_{D(\text{sat})}}$$

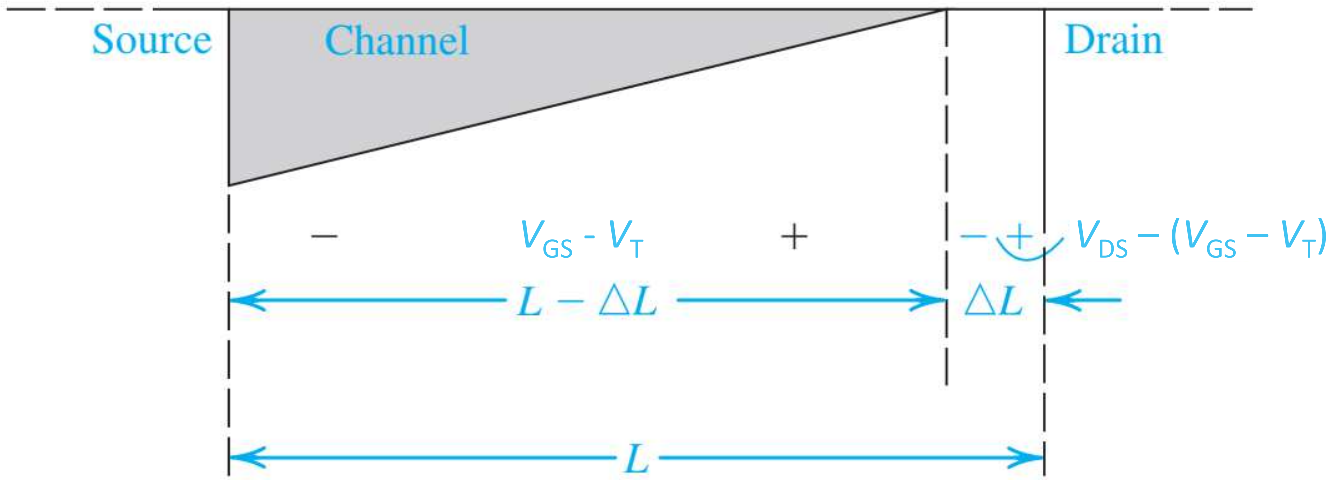
Biasing and r_{DS}

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda V_{DS})$$

λ: channel length modulation parameter



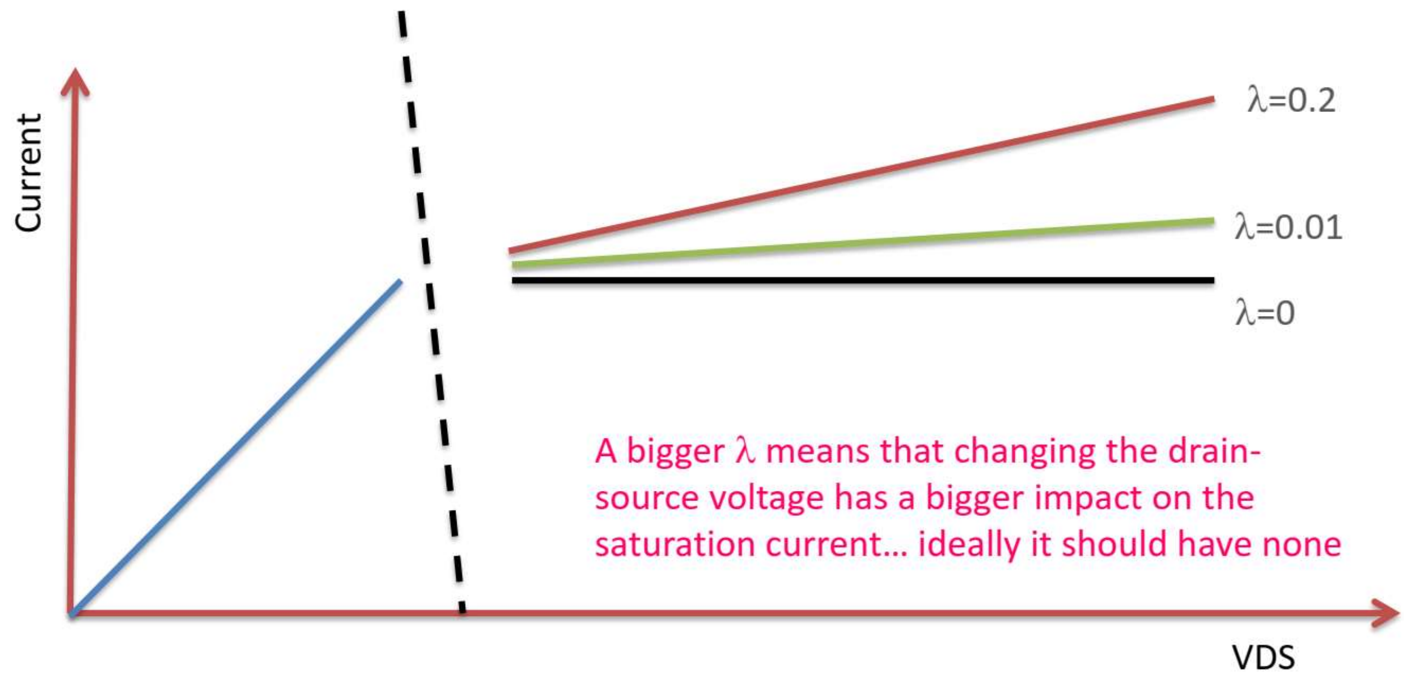
Recall Channel-Length Modulation



- In the saturation region, when V_{DS} further increases, the channel pinch-off point moves slightly away from the drain and towards the source;
- The effective channel length becomes $(L - \Delta L)$;
- The electric potential difference across the channel remains constant at $(V_{GS} - V_T)$. This is sometimes called the "overdrive voltage".

A Few Extra Words on λ

- λ is the "channel length modulation parameter" that indicates how far we are away from an ideal MOSFET device in saturation. It is a constant value that varies for each transistor type manufactured. It gets bigger for small devices, especially in modern processes. For modern devices it could be anywhere from 0.01 to 0.2 depending on device length (longer devices, smaller λ).



Back to r_{DS}

- Let's look at the small-signal output impedance:

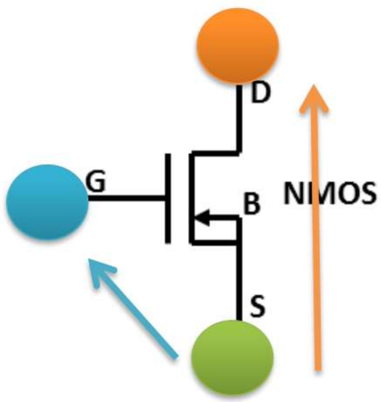
$$\frac{1}{r_{\mathrm{DS}}} = \frac{dI_{\mathrm{D}}}{dV_{\mathrm{DS}}} = \frac{d}{dV_{\mathrm{DS}}}[\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2(1 + \lambda V_{\mathrm{DS}})]$$

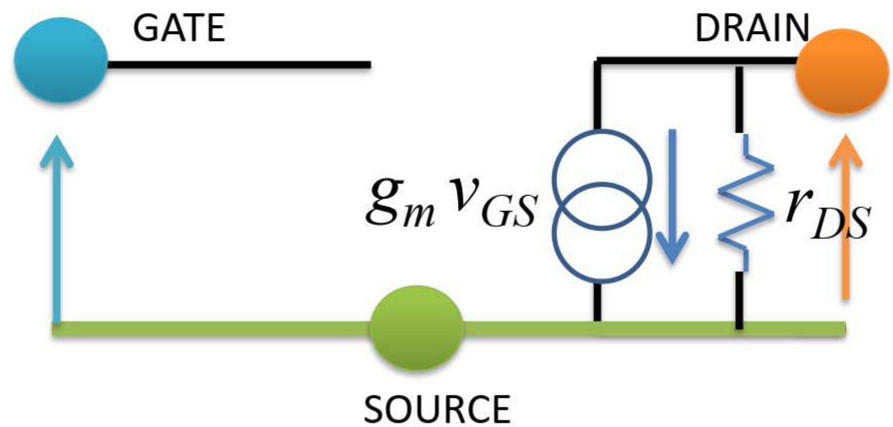
$$\frac{1}{r_{\mathrm{DS}}} = \lambda\frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2 = \lambda I_{D(\mathrm{sat})}$$

$$r_{\mathrm{DS}} = \frac{1}{\lambda I_{D(\mathrm{sat})}}$$

and $I_{D(\mathrm{sat})} = \frac{1}{2}\mu_{\mathrm{n}}C_{\mathrm{ox}}\frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2$.

Summary: Small-Signal Parameters





- $I_{D(\mathrm{sat})} = \frac{1}{2}\mu_{\mathrm{n}} C_{\mathrm{ox}} \frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2$
- $g_m = \mu_{\mathrm{n}} C_{\mathrm{ox}} \frac{W}{L}(V_{\mathrm{GS}} - V_{\mathrm{T}}) = \sqrt{2\mu_{\mathrm{n}} C_{\mathrm{ox}} \frac{W}{L} I_{D(\mathrm{sat})}} = k\sqrt{I_{D(\mathrm{sat})}}$
- $r_{\mathrm{DS}} = \frac{1}{\lambda I_{D(\mathrm{sat})}}$

Back to Biasing

- $I_{D(\text{sat})} = \frac{1}{2}\mu_\text{n} C_\text{ox} \frac{W}{L}(V_\text{GS} - V_\text{T})^2$
- $g_m = \mu_\text{n} C_\text{ox} \frac{W}{L}(V_\text{GS} - V_\text{T}) = \sqrt{2\mu_\text{n} C_\text{ox} \frac{W}{L} I_{D(\text{sat})}} = k\sqrt{I_{D(\text{sat})}}$
- $r_\text{DS} = \frac{1}{\lambda I_{D(\text{sat})}}$
- The reason all of this is interesting is the equation for gain:

$$\text{gain} = A = -g_m R_\text{L}$$

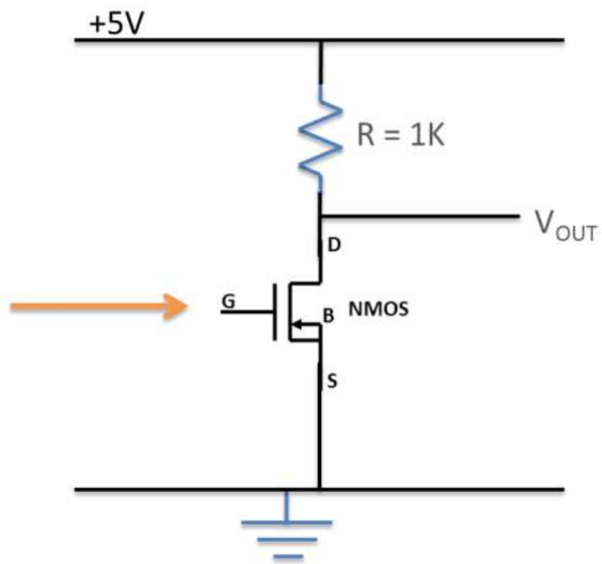
- When in saturation, everything is controlled by the $I_\text{D(sat)}$ current which is controlled only by the DC bias voltage on the gate V_GS. Changing that, we change the current.
- Triode region has different equations but we almost never use it for amplifiers.

The Effect of Varying V_{GS}

- $I_{D(\text{sat})} = \frac{1}{2}\mu_\text{n} C_\text{ox} \frac{W}{L}(V_\text{GS} - V_\text{T})^2$
- $g_m = \mu_\text{n} C_\text{ox} \frac{W}{L}(V_\text{GS} - V_\text{T}) = \sqrt{2\mu_\text{n} C_\text{ox} \frac{W}{L} I_{D(\text{sat})}} = k\sqrt{I_{D(\text{sat})}}$
- $r_\text{DS} = \frac{1}{\lambda I_{D(\text{sat})}}$

- Let's increase V_{GS}:
  - V_{GS}
  - $I_{D(\text{sat})}$
  - $g_m = k\sqrt{I_{D(\text{sat})}}$
  - |gain|=$|A| = g_m R_\text{L}$

What Happens with V_{OUT}?



$$V_{\mathrm{OUT}} = V_{\mathrm{DD}} - R_{\mathrm{L}} I_{\mathrm{D(sat)}} = 5 - R_{\mathrm{L}} I_{\mathrm{D(sat)}}$$

- If we increase V_{GS}:
  - V_{GS} ↑
  - $I_{D(\mathrm{sat})}$ ↑
  - $R_{\mathrm{L}} I_{\mathrm{D(sat)}}$ ↑
  - V_{OUT} ↓

We have to be careful. Too much current will push V_{OUT} down unless we reduce R_{L} at the same time. But we need R_{L} for gain ($A = -g_m R_{\mathrm{L}}$).

Increase Gain While Maintaining V_{OUT}?

- We are playing with the following two equations:

$$V_{\mathrm{OUT}} = 5 - R_{\mathrm{L}} I_{\mathrm{D(sat)}} \text{ and } |\text{gain}| = |A| = g_m R_{\mathrm{L}}$$

- If I_{D} increases, R_{L} must decrease, but if we decrease R_{L} the gain goes down. If we increase R_{L}, then I_{D} must go down. What do we do???
- The key is that the relation between g_m and $I_{\mathrm{D(sat)}}$ is not linear!

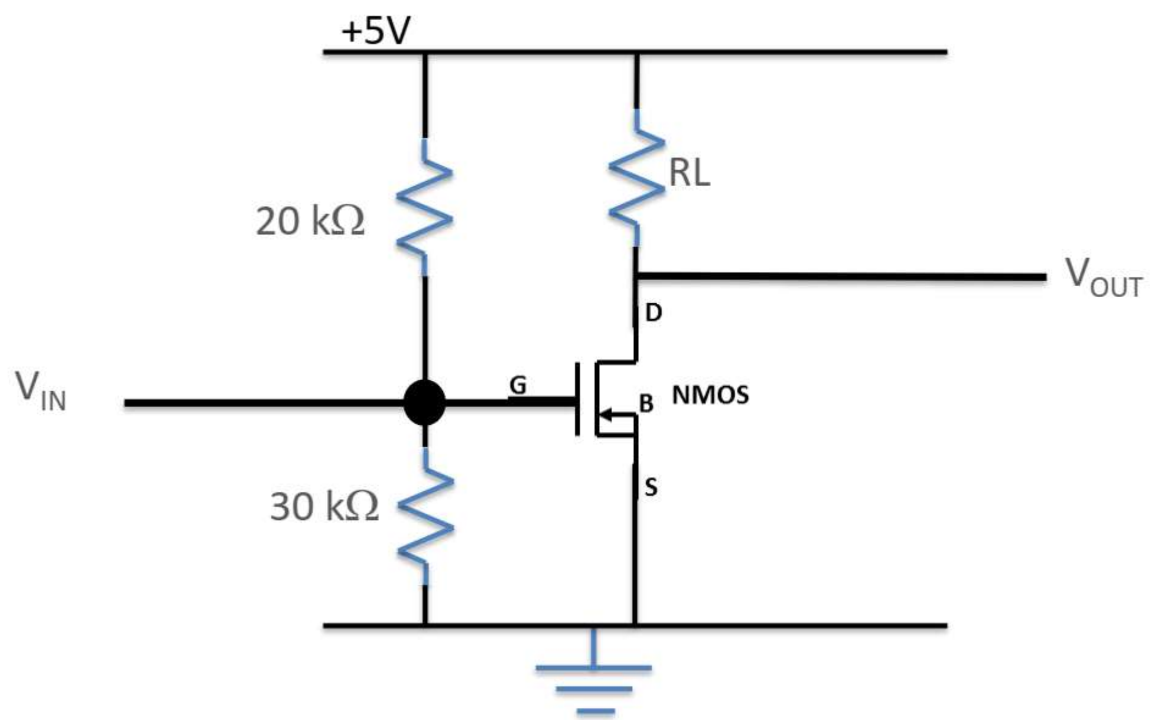
$$V_{\mathrm{OUT}} = 5 - R_{\mathrm{L}} I_{\mathrm{D(sat)}} \text{ and } |\text{gain}| = k\sqrt{I_{D(\mathrm{sat})}}(R_{\mathrm{L}})$$

- What we could do is to decrease I_{D} (for example by a factor of 2), increase R_{L} (by a factor of 2), and gain would then actually go up by a factor of $\sqrt{2}$ without affecting V_{OUT} (no change).

Is Decreasing $I_{D(sat)}$ Bad?

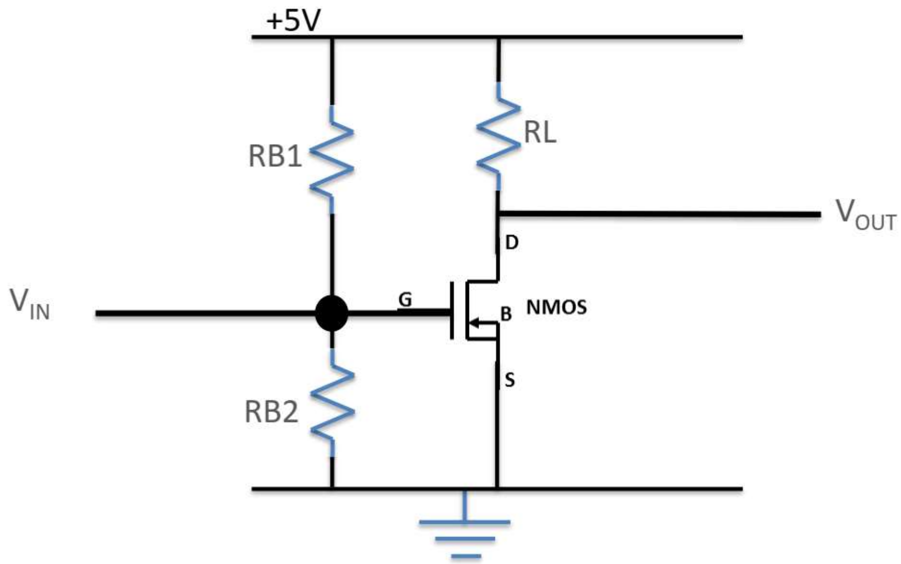
- IT CAN BE!!!!
- There is a limit to how far we can decrease I_D before we get to an unacceptable value of V_{GS} and start turning off the device. V_{GS} must be greater than V_T, we do not want to be close to that boundary as our small signal will be changing V_{GS}. So stay away!!!
- A very low I_D will make it difficult to run the transistor fast (handle high frequency signals) as we have no current to rapidly charge/discharge capacitors connected to the load.
- This is less of an issue for tiny signals but a serious issue for anything you'd want to do in a project.

How Do We Set a Bias Voltage?



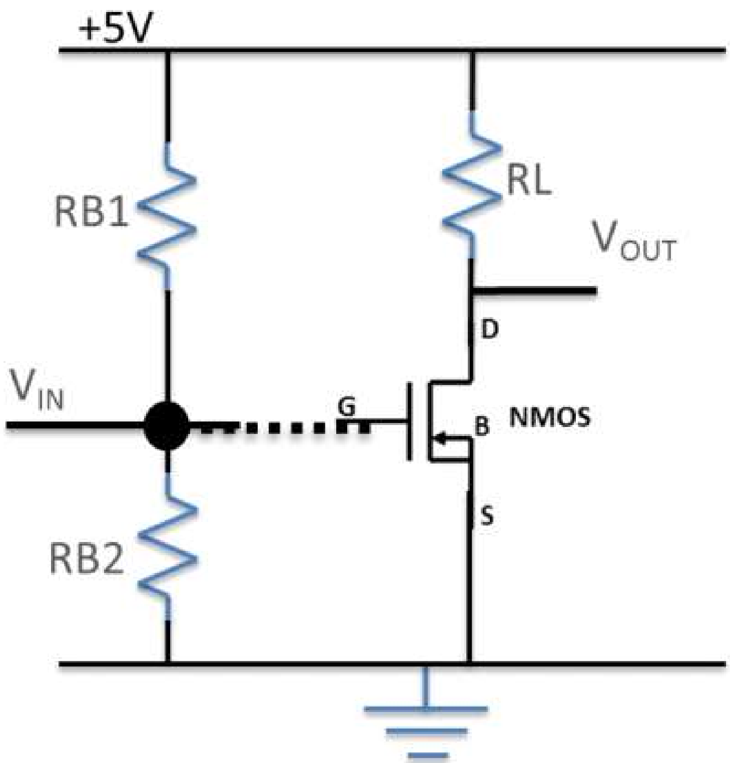
- Remember the voltage-divider biasing scheme? This is a very common biasing circuit for a CMOS device. What voltage is on the gate of the transistor?

Voltage-Divider Biasing



- What current flows into the gate of the CMOS transistor?
- What happens if one connects an input signal that has a
  - low resistance?
  - high resistance?
- What happens if one connects an output that has a
  - low resistance?
  - high resistance?

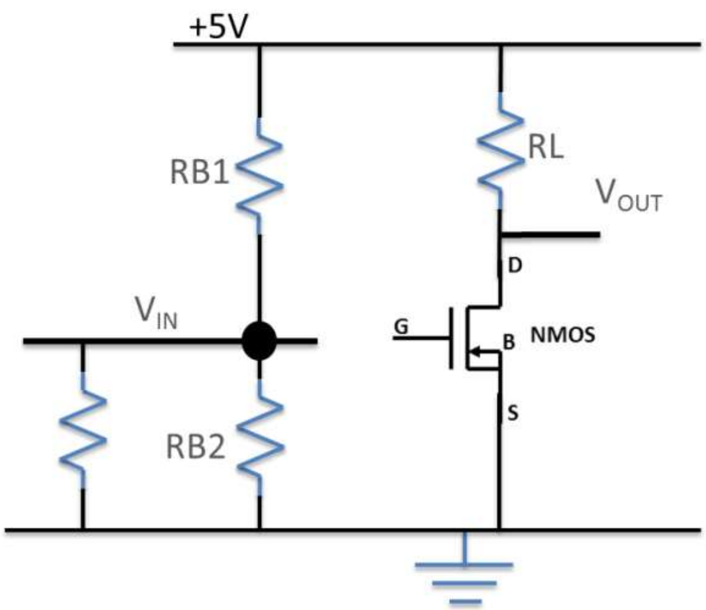
How is V_{GS} Set?

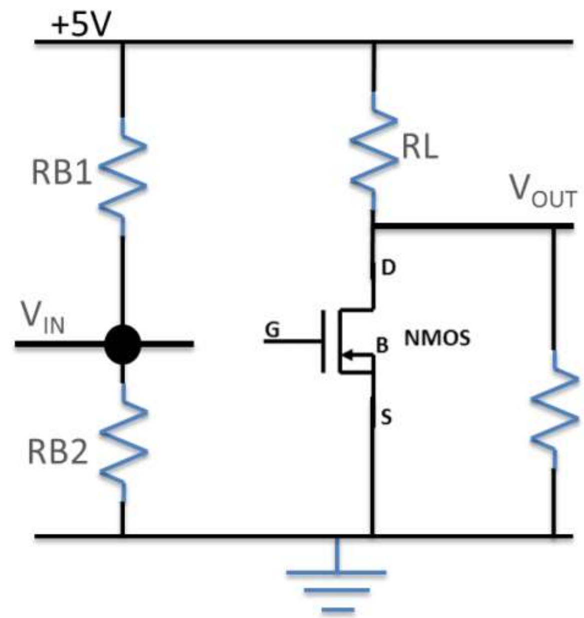


If no current flows, it's effectively a break. The voltage is set by the resistors, not by the transistor.

$$V_{\mathrm{GS}} = \frac{R_{\mathrm{B2}}}{R_{\mathrm{B1}} + R_{\mathrm{B2}}}(5\ \mathrm{V})$$

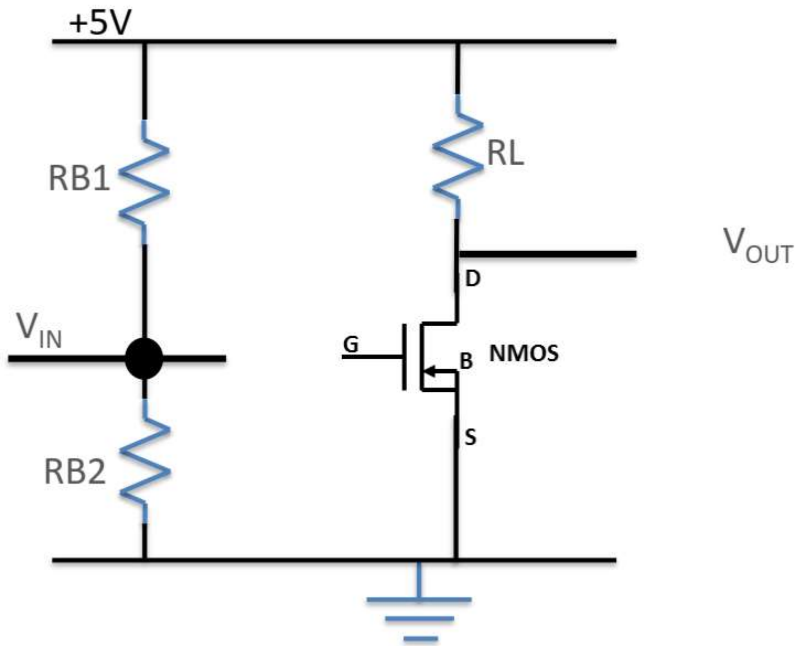
What Happens with Load Resistances?





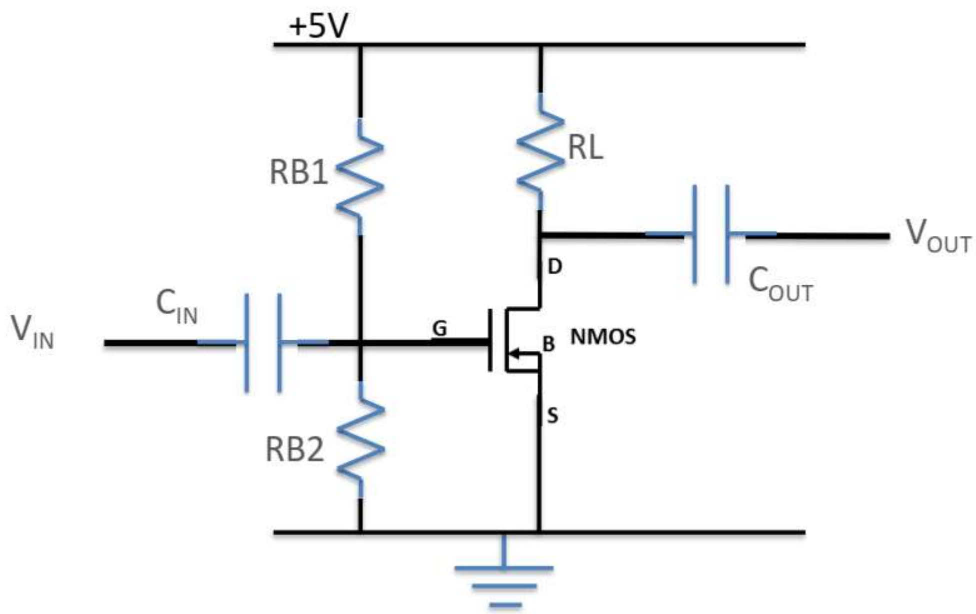
- Connecting resistors to the inputs and the outputs could change our values for V_{OUT} and V_{IN} badly, messing up our transistor. Not desirable.

More on Voltage-Divider Biasing



- Assuming that no current flows back into the V_{in}, how much current do you need to set the voltage on the gate?
- What value should the resistors be?
- Why? (think power efficiency)

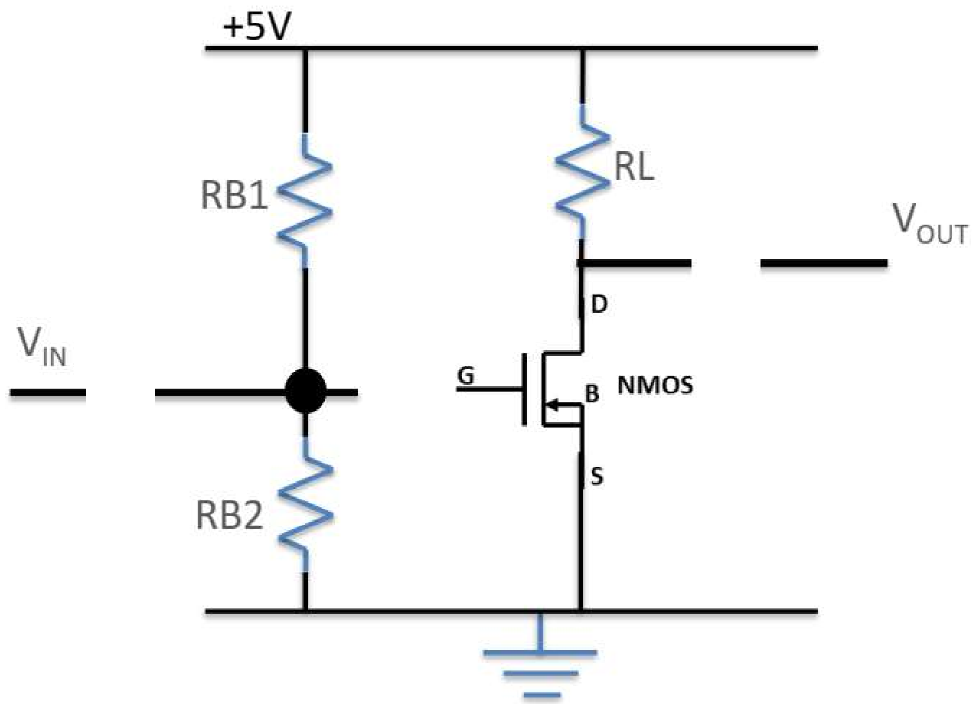
(De-)Coupling Capacitors



If in doubt, throw a big capacitor in, commonly 1 μF or 10 μF used.

- These capacitors can also be used at the input and output.
- Capacitors block DC, so basically you are splitting the DC circuit. Then the internal DC values don't make a difference to what happens before or after. Sometimes this is a good thing, sometimes not.
- How well do they block? It depends on your frequency of operation. Higher frequencies go with smaller capacitors. Impedance of a capacitor is $1/(j\omega C)$.

The DC Part of the Circuit



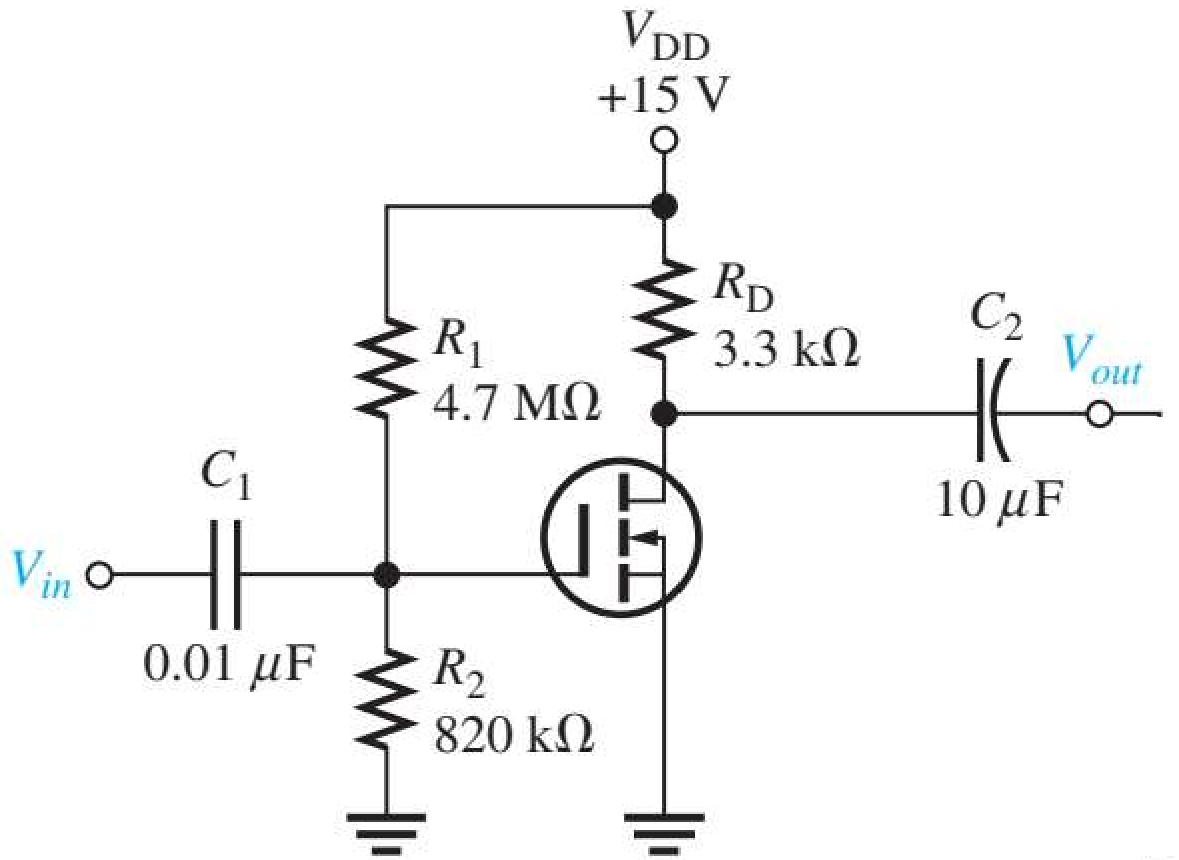
If in doubt, throw a big capacitor in, commonly 1μF or 10 μF used.

- Now it really doesn't matter what you connect to the output or the input. The biasing is isolated and protected!!!

$$V_{\mathrm{GS}} = \frac{R_{\mathrm{B2}}}{R_{\mathrm{B1}} + R_{\mathrm{B2}}} V_{\mathrm{DD}}$$

Recall This Circuit?

- Capacitors can be used to de-couple the DC bias.

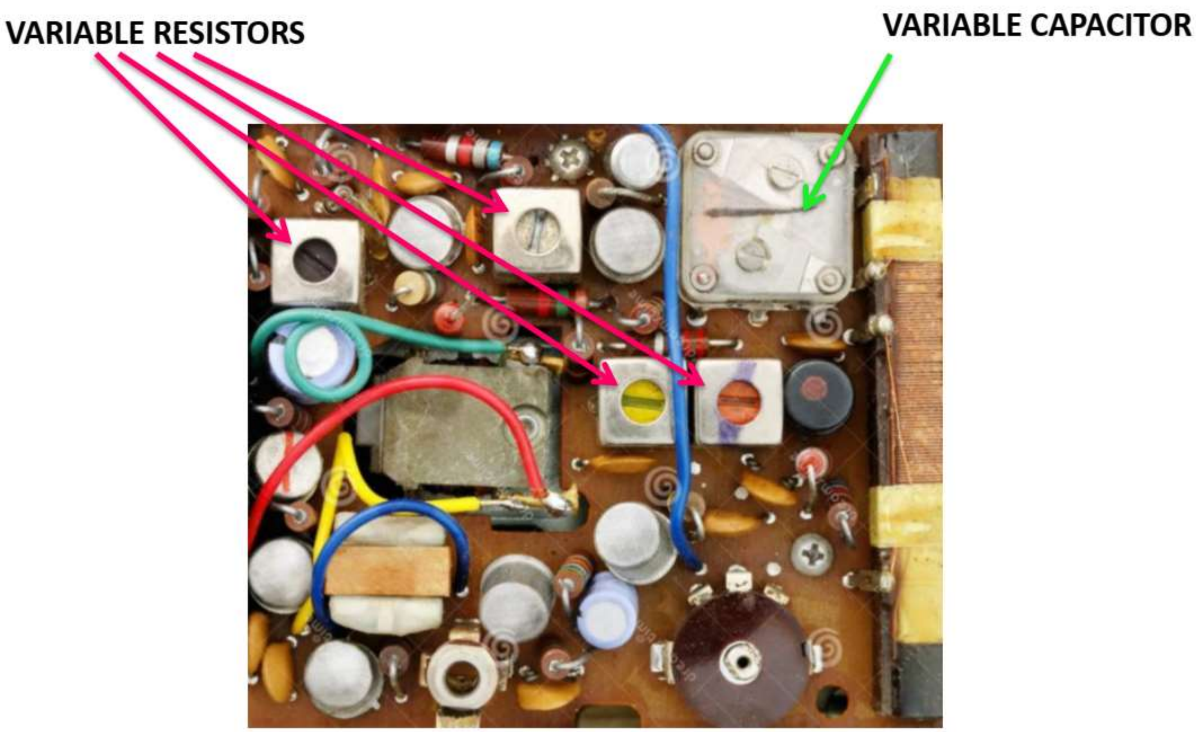


How to Choose a Bias Voltage?

$V_{\mathrm{OUT}} = 5 - R_{\mathrm{L}} I_{\mathrm{D(sat)}}$ and |gain|=$|A| = g_m R_{\mathrm{L}}$

- There are two settings you need to adjust, and they are interlinked. There is no perfect answer.
- A common process goes like this:
  - Start with a reasonable value of I_{D} for your transistor;
  - What value of V_{GS} gives me that current;
  - What value of R_{L} gives me V_{OUT};
  - What is my value of GAIN;
  - If the GAIN is too low, adjust V_{GS} and R_{L} to try to get a good compromise.
- Software design tools can assist you in getting the precise answer but it is always a compromise and that is why it takes an engineer to pick the BEST COMPROMISE. There is no single correct answer.
- That’s why it’s called design.

Use of Trimmers



- An old radio circuit board. With discrete components one doesn’t always get things right the first time, so tweaking used to be an important part of the manufacturing process.

Some Terminology

- You’ll see this mentioned in different places, just so you know…
  - GND Ground;
  - V_{CC} positive voltage for BJT circuits (or older circuits), originally means voltage common collector;
  - V_{DD} positive voltage for CMOS circuits;
  - V_{EE} negative voltage (normally for BJT or op-amp circuits);
  - V_{SS} negative voltage for CMOS circuits (not seen that often). It is usually just the ground in a single-supply circuit.