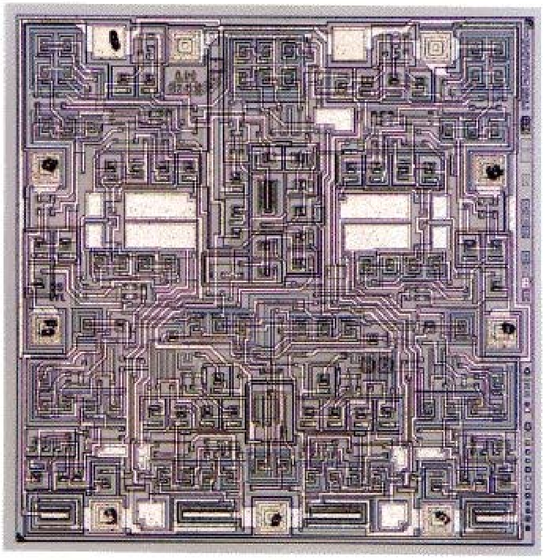
6.5 The Common Source Amp with Active Loads

Reading Assignment: *pp. 582-587*

Amplifiers are frequently made as **integrated circuits** (e.g., op-amps).



Although both BJTs and MOSFET integrated circuit amplifiers are implemented as ICs, we find that MOSFETs amplifiers are almost **exclusively** implemented as integrated circuits (i.e., **rarely** are MOSFET amps made of “discrete” components).

Making integrated circuit amplifiers has many positives, but a few negatives:

Positives:

The amplifier circuit can be quite **complex**, yet still **small and inexpensive**. Thus, **current sources** are "no big deal".

Negatives:

We **cannot** make large capacitors (i.e., **COUS**), so that DC blocking capacitors are not possible—this makes **bias solutions more complex**, particularly for multi-stage amplifiers.

Additionally, it if difficult to make **resistors** in integrated circuits. Instead, we use "resistors" constructed from transistors—so-called "**active loads**".

HO: Enhancement loads

HO: The Common Source Amp with an Active Load

The **sensitivity** problem of the previous circuit can be solved using a **current source** as a "load"

HO: The Common Source Amp with a Current Source

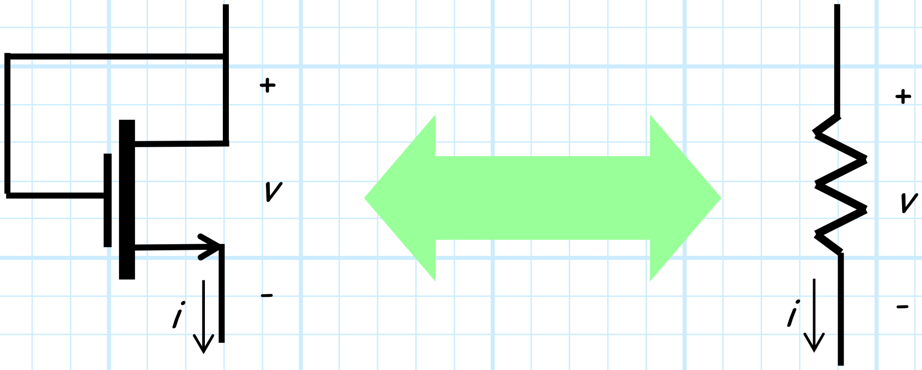
Enhancement Loads

Resistors take up far too much **space** on integrated circuit substrates.

Therefore, we need to make a **resistor** out of a **transistor**!

Q: *How can we do that!? After all, a resistor is a **two** terminal device, whereas a transistor is a **three** terminal device.*

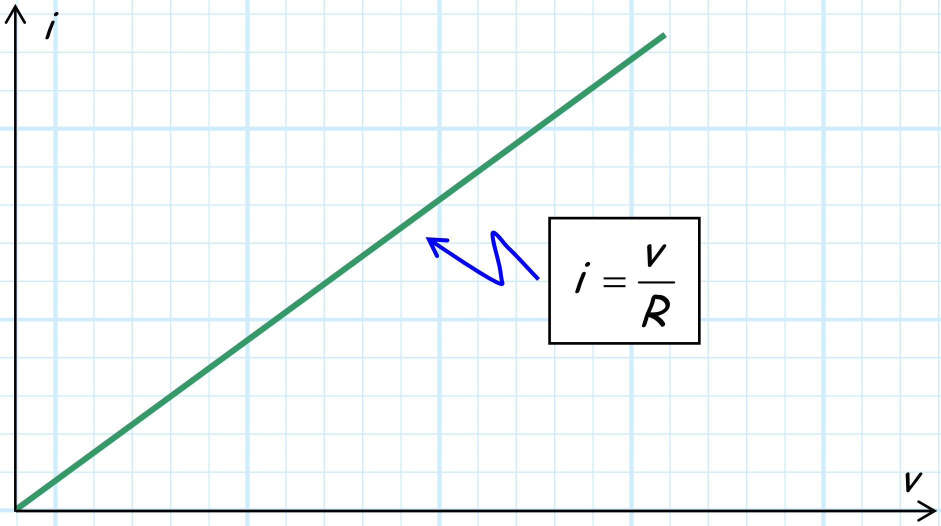
A: We can make a two terminal device from a MOSFET by **connecting** the gate and the drain!



Enhancement Load *Resistor Load*

Q: *How does this "**enhancement load**" resemble a resistor?*

A: Consider the *i-v* curve for a **resistor**:



Now consider the same curve for an **enhancement load**.

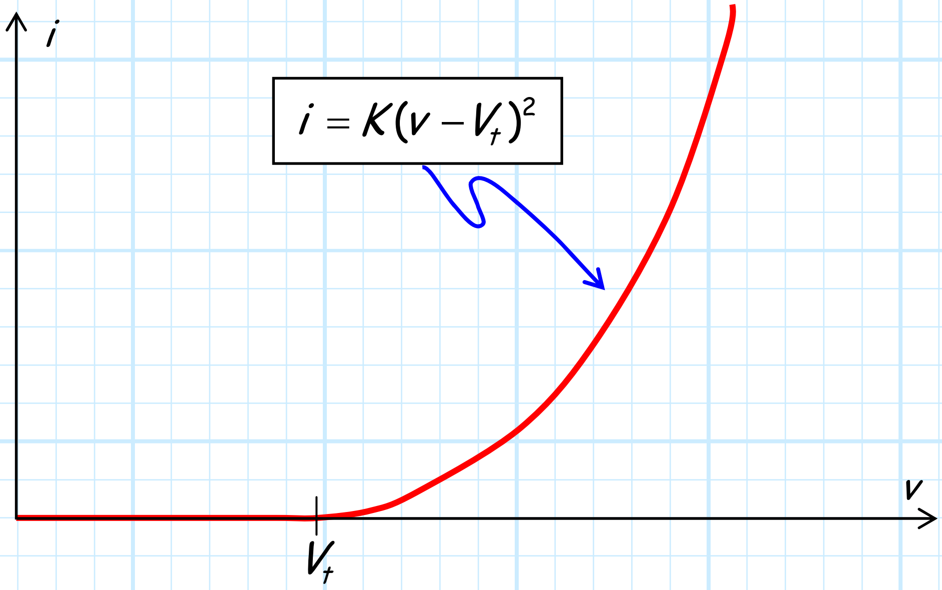
Since the gate is tied to the drain, we find $v_G = v_D$, and thus $v_{GS} = v_{DS}$. As a result, we find that $v_{DS} > v_{GS} - V_t$ **always**.

Therefore, we find that if $v_{GS} > V_t$, the MOSFET will be in **saturation** ($i_D = K(v_{GS} - V_t)^2$), whereas if $v_{GS} < V_t$, the MOSFET is in **cutoff** ($i_D = 0$).

Since for enhancement load $i = i_D$ and $v = v_{GS}$, we can describe the enhancement load as:

$$i = \begin{cases} 0 & \text{for } v < V_t \\ K(v - V_t)^2 & \text{for } v > V_t \end{cases}$$

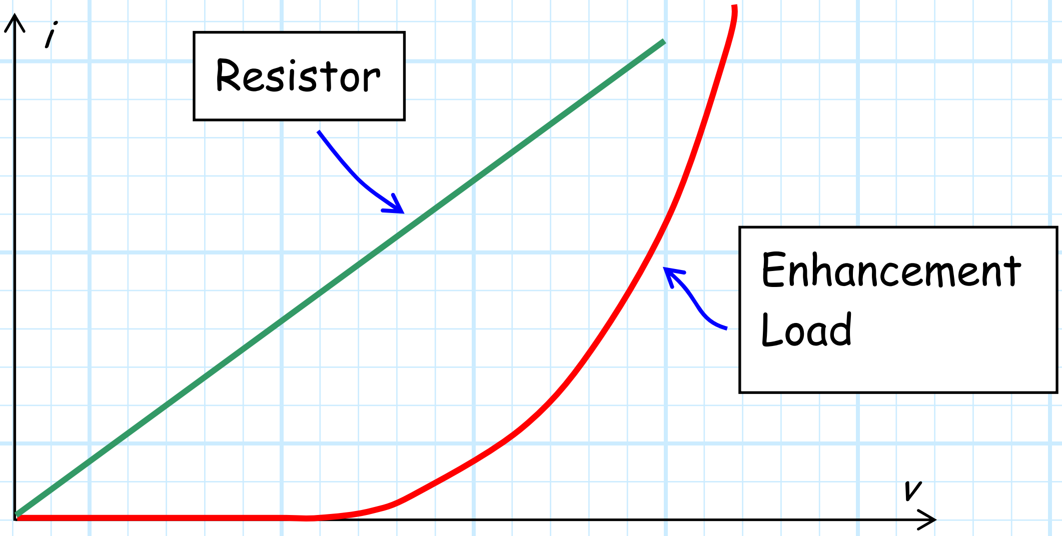
Plotting this equation:



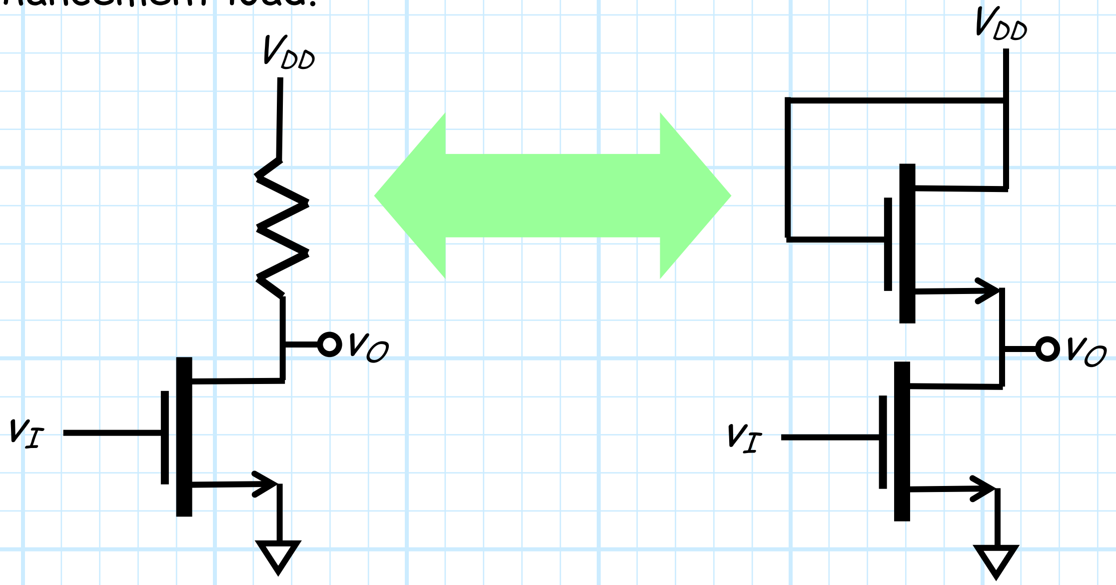
So, resistors and enhancement loads are far from **exactly** the same, but:

1) They **both** have $i = 0$ when $v = 0$.

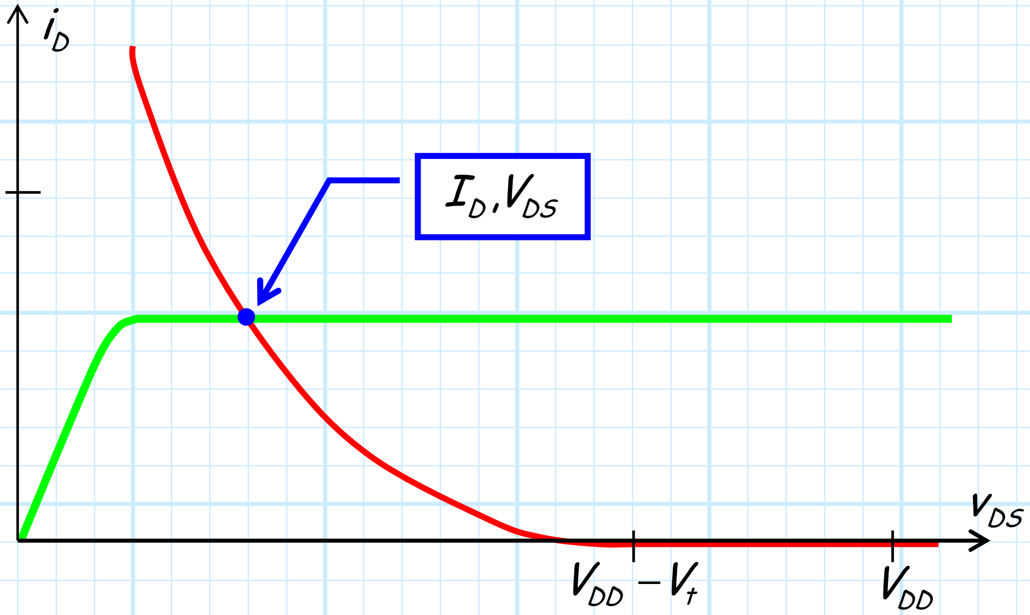
2) They **both** have increasing current i with increasing voltage v.



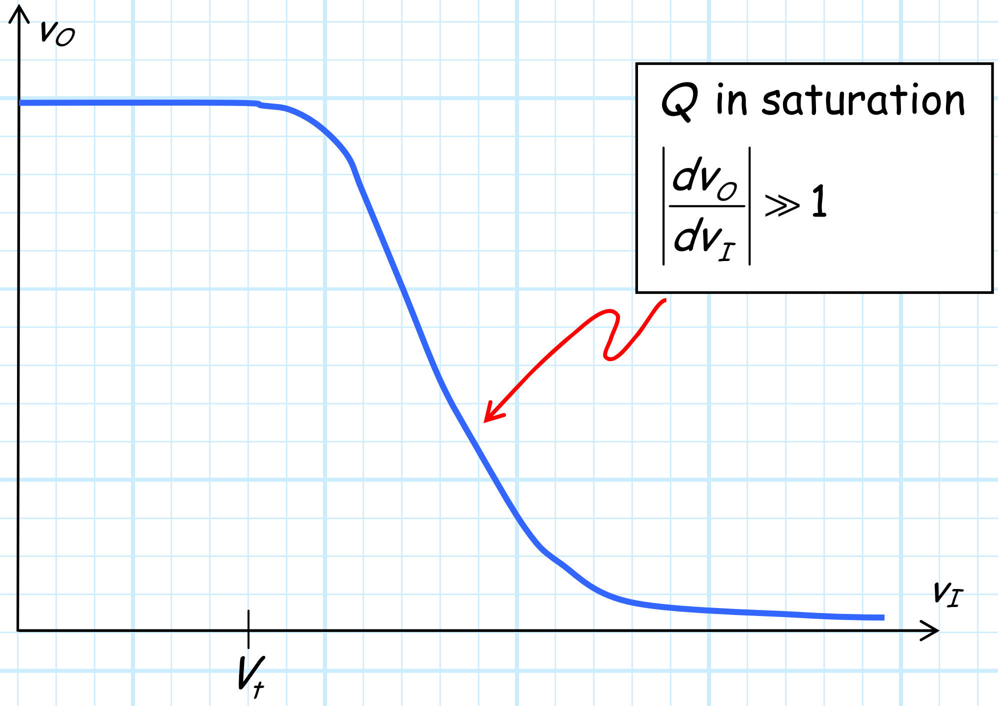
Therefore, we can build a **common source** amplifier with either a resistor, or in the case of an **integrated circuit**, an enhancement load.



For the enhancement load amplifier, the **load line** is replaced with a **load curve** ($v = V_{DD} - v_{DS}$)!



And the **transfer function** of this circuit is:



Q: *What is the **small signal** behavior of an enhancement load?*

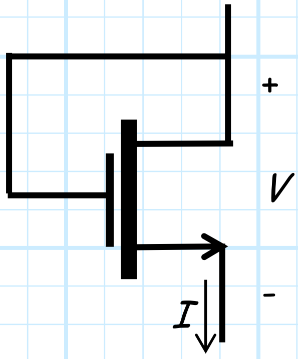
A: The enhancement load is made of a MOSFET device, and we **understand** the small-signal behavior for a MOSFET!

Step 1 - DC Analysis

_If $V > V_t$, then $I = K\left(V - V_t\right)^2$

or:

$$V = \sqrt{\frac{I}{K}} + V_t$$



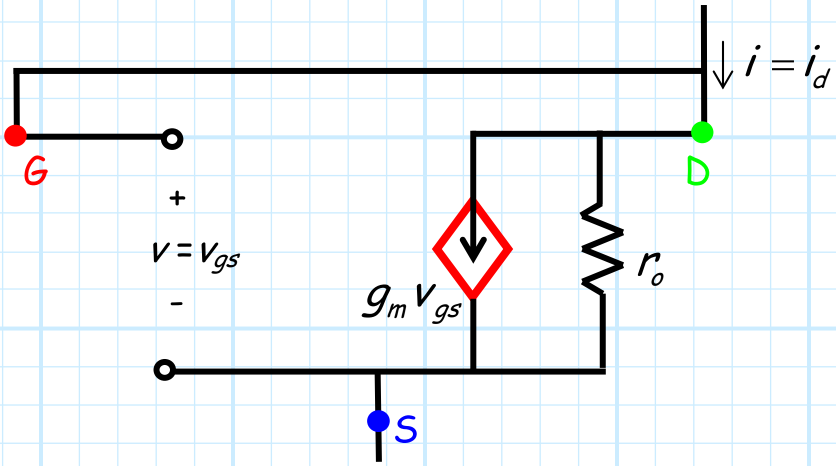
Step 2 – Determine g_m and r_o

$$g_m = 2K\left(V_{GS} - V_t\right) = 2K\left(V - V_t\right)$$

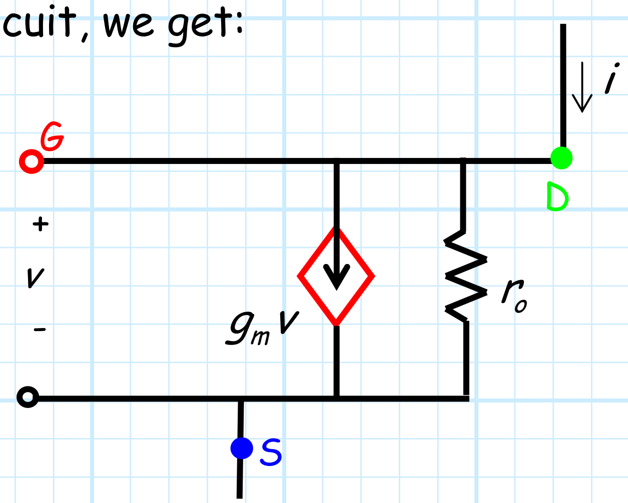
$$r_o = \frac{1}{\lambda I_D} = \frac{1}{\lambda I} = \frac{1}{\lambda K\left(V - V_t\right)^2}$$

Step 3 – Determine the small-signal circuit

Inserting the MOSFET **small-signal model**, we get:



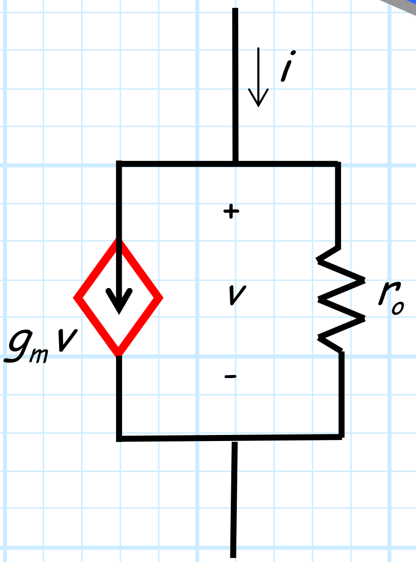
Redrawing this circuit, we get:



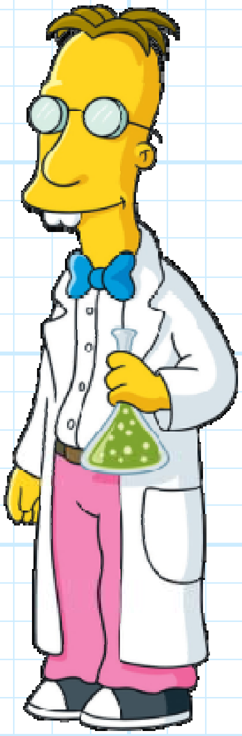
Or, simplifying further, we have the small-signal equivalent circuit for an enhancement load:

*It is imperative that **you** understand that the circuit to my right is the **small-signal equivalent circuit** for an enhancement load.*

*Please replace all **enhancement loads** with this small-signal model whenever you are attempting to find the **small-signal circuit** of any MOSFET amplifier.*

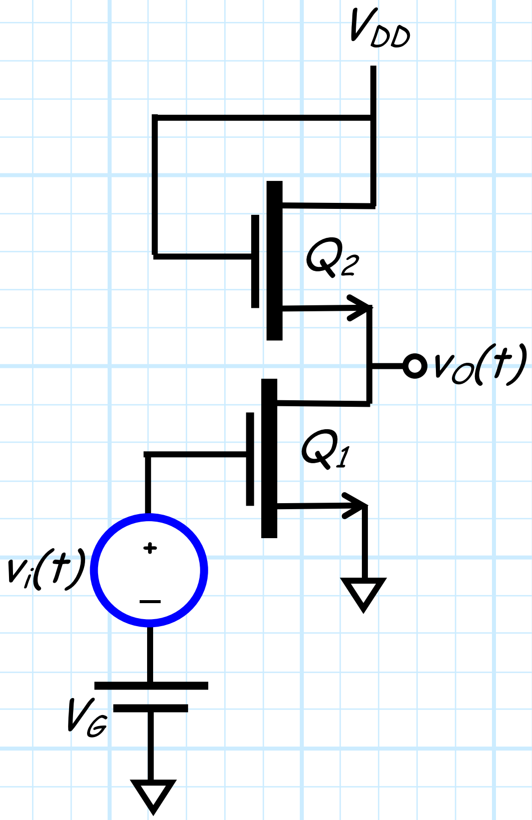


Enhancement Load Small-Signal Model



The Common Source Amp with Enhancement Load

Consider this **NMOS amplifier** using an **enhancement load**.



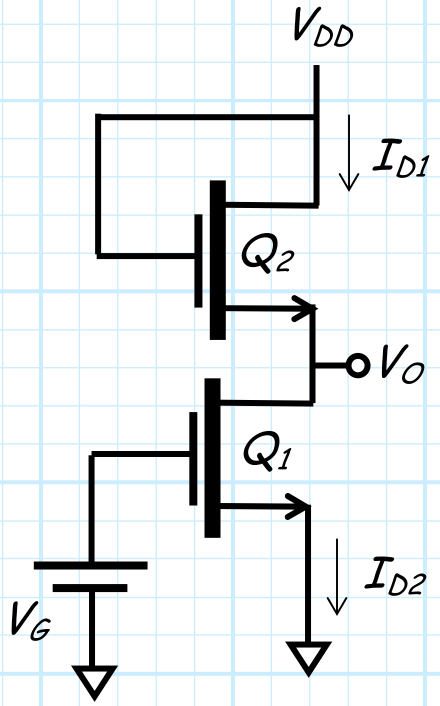
- Note **no** resistors or capacitors are present!
- This is a **common source** amplifier.
- I_D stability **could** be a problem

Q: *What is the small-signal open-circuit voltage gain, input resistance, and output resistance of this amplifier?*

A: The values that we will determine when we follow precisely the same steps as before!!

Step 1 – *DC Analysis*

The DC circuit of this amplifier is:



Note that:

$$I_{D1} = I_{D2} \doteq I_D$$

and that:

$$V_{GS1} = V_G - 0 = V_G$$

and also that:

$$V_{DS2} = V_{GS2}$$

and finally that:

$$V_{DS1} = V_{DD} - V_{DS2}$$

Let's of course **ASSUME** that both Q_1 and Q_2 are in saturation. Therefore we **ENFORCE**:

$$\begin{aligned} I_{D1} &= K_1 \left(V_{GS1} - V_{t1}\right)^2 \\ &= K_1 \left(V_G - V_{t1}\right)^2 \end{aligned}$$

Note that there are no unknowns in the previous equation. The drain current is explicitly determined from K_1 , V_G, and V_{t1}!

Continuing with the **ANALYSIS**, we can find the drain current through the enhancement load (I_{D2}), since it is equal to the current through Q_1:

$$I_{D2} = I_{D1} = K_1 \left(V_G - V_{t1}\right)^2$$

Yet we also know that V_{GS2} must be related to this drain current as:

$$I_{D2} = K_2 \left(V_{GS2} - V_{t2}\right)^2$$

and therefore combining the above equations:

$$\begin{gathered} I_{D1} = I_{D2} \\ K_1 \left(V_G - V_{t1}\right)^2 = K_2 \left(V_{GS2} - V_{t2}\right)^2 \end{gathered}$$

Note this last equation has only one unknown (V_{GS2}) ! Rearranging, we find that:

$$V_{GS2} = \sqrt{\frac{K_1}{K_2}} \left(V_G - V_{t1}\right) + V_{t2}$$

Since $V_{DS2} = V_{GS2}$ and $V_{DS1} = V_{DD} - V_{DS2}$, we can likewise state that:

$$V_{DS2} = \sqrt{\frac{K_1}{K_2}} \left(V_G - V_{t1}\right) + V_{t2}$$

and:

$$V_{DS1} = V_{DD} - V_{t2} - \sqrt{\frac{K_1}{K_2}} \left(V_G - V_{t1}\right)$$

Now, we must **CHECK** to see if our assumption is correct.

The saturation assumption will be correct if:

$$\begin{aligned} V_{DS1} &> V_{GS1} - V_{t1} \\ &> V_G - V_{t1} \end{aligned}$$

and:

$$V_{GS1} > V_{t1} \quad \therefore \quad \text{if} \quad V_G > V_{t1}$$

Step 2 – *Calculate small-signal parameters*

We require the small-signal parameters for each of the transistors Q_1 and Q_2. Therefore:

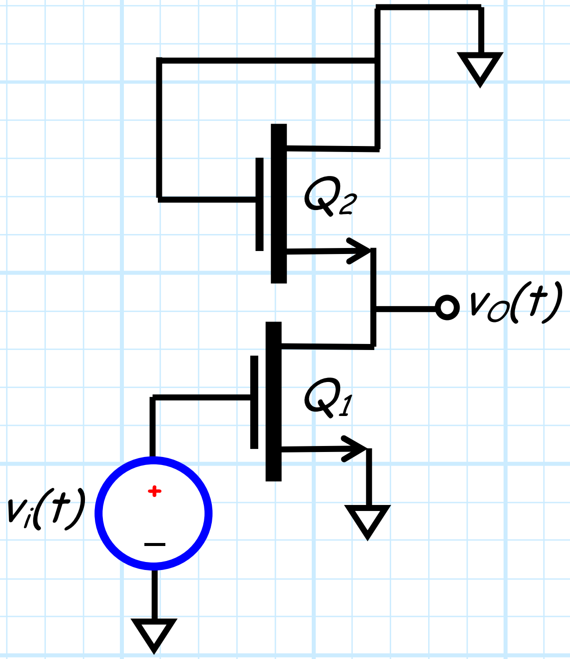
$$g_{m1} = 2K_1 \left(V_G - V_{t1} \right) \qquad \text{and} \qquad g_{m2} = 2K_1 \left(V_{GS2} - V_{t2} \right)$$

and:

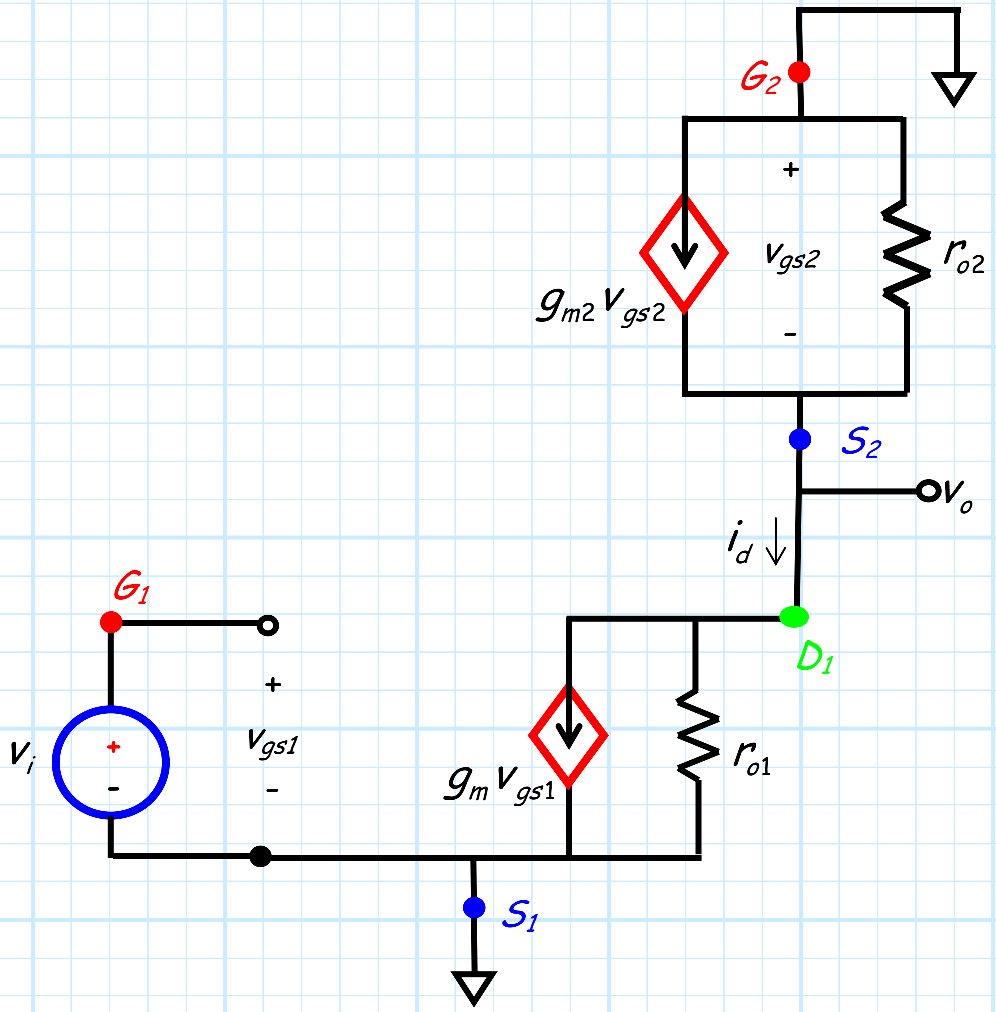
$$r_{o1} = \frac{1}{\lambda_1 \, I_D} \qquad \text{and} \qquad r_{o2} = \frac{1}{\lambda_2 \, I_D}$$

Step 3 – *Determine the small-signal circuit*

First, let's turn off the DC sources:

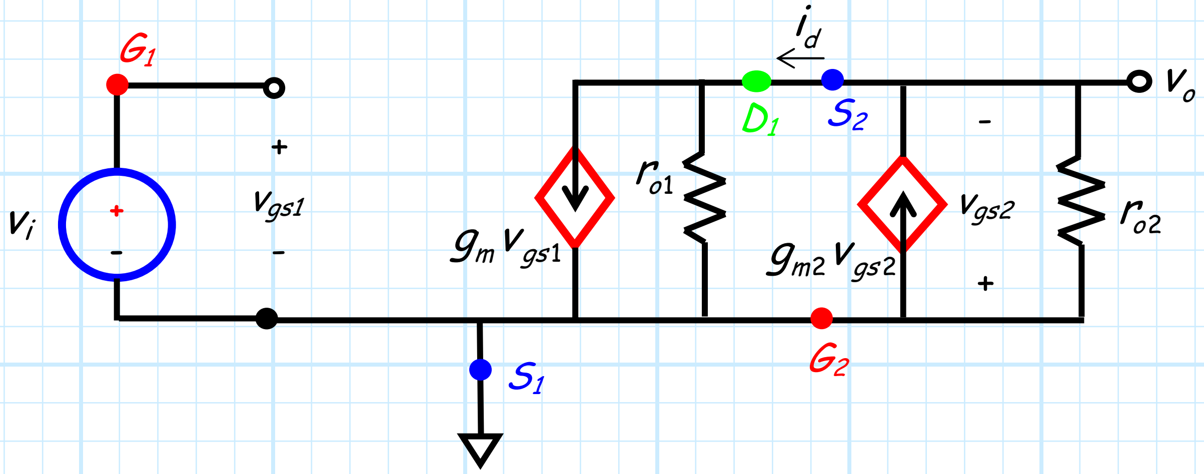


We now replace **MOSFET** Q_1 with its equivalent small-signal model, **and** replace the **enhancement load** with its equivalent small-signal model.

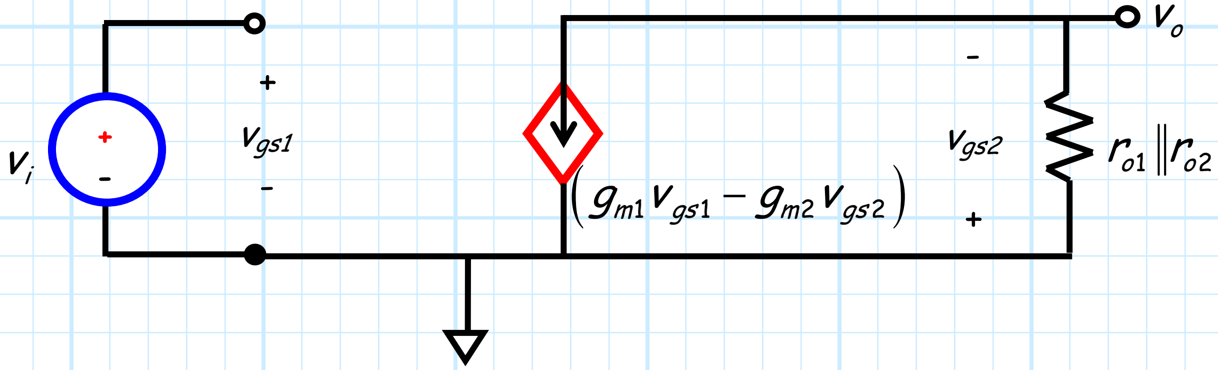


Note S_1 and G_2 are at **small-signal ground**!

Therefore, we can rewrite this circuit as:



Simplifying further, we find:



Therefore, we find that:

$$v_{gs1} = v_i$$

and that:

$$v_{gs2} = -v_o$$

as well as that:

$$\begin{aligned} v_o &= -\left(g_{m1}v_{gs1} - g_{m2}v_{gs2}\right)\left(r_{o1} \| r_{o2}\right) \\ &= -\left(g_{m1}v_i + g_{m2}v_o\right)\left(r_{o1} \| r_{o2}\right) \end{aligned}$$

Rearranging, we find:

$$A_{vo} = \frac{v_o}{v_i} = \frac{-\left(r_{o1} \| r_{o2}\right)g_{m1}}{1 + \left(r_{o1} \| r_{o2}\right)g_{m2}} \approx \frac{-g_{m1}}{g_{m2}}$$

But recall that:

$$\begin{aligned} g_m &= 2K\left(V_{GS} - V_t\right) \\ &= 2\sqrt{K}\sqrt{I_D} \end{aligned}$$

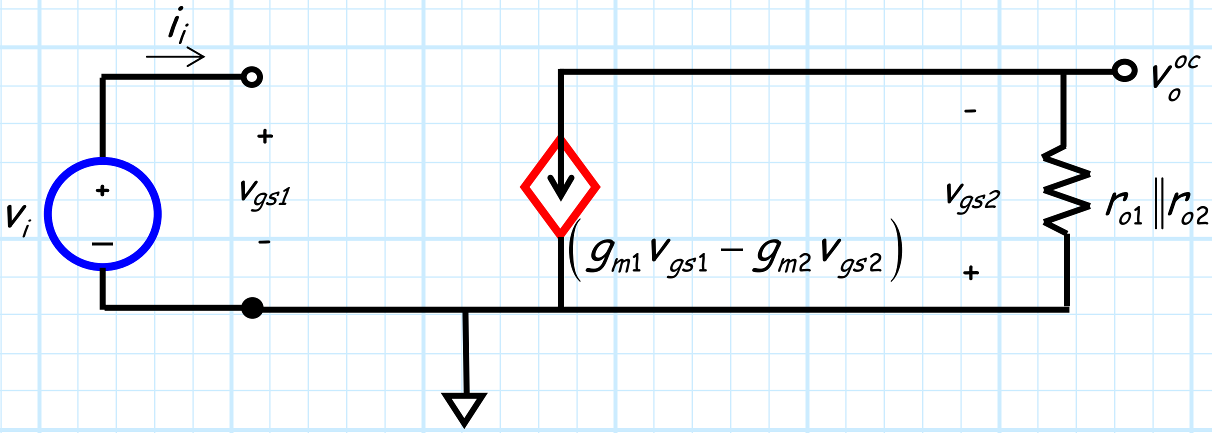
where we have used the fact that $I_D = K\left(V_{GS} - V_t\right)^2$ to determine that $\left(V_{GS} - V_t\right) = \sqrt{I_D / K}$.

Therefore:

$$A_{vo} = \frac{-g_{m1}}{g_{m2}} = \frac{2\sqrt{K_1}\sqrt{I_D}}{2\sqrt{K_2}\sqrt{I_D}} = \sqrt{\frac{K_1}{K_2}} = \frac{\sqrt{\left(W/L\right)_1}}{\sqrt{\left(W/L\right)_2}}$$

In other words, we adjust the MOSFET channel geometry to set the small-signal gain of this amplifier!

Now let's determine the small-signal input and output resistances of this amplifier!

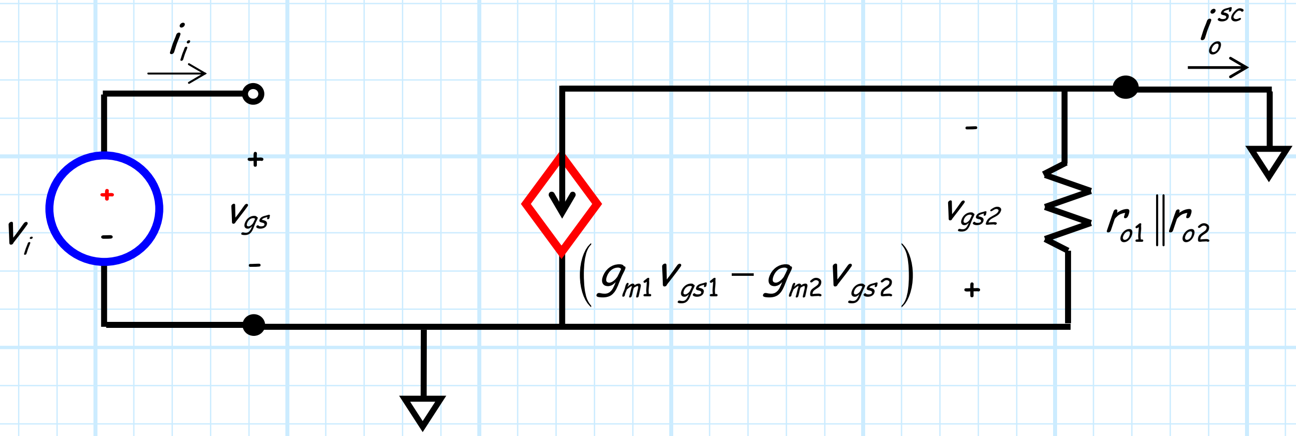


It is evident that since $i_i = i_g = 0$:

$$R_i = \frac{v_i}{i_i} = \infty \qquad \text{(Great!!!)}$$

Now for the output resistance, we know that the open-circuit output voltage is:

$$v_o^{oc} = -\left(g_{m1} v_{gs1} - g_{m2} v_{gs2}\right)\left(r_{o1} \| r_{o2}\right)$$



Likewise, the short-circuit output current i_o^{sc} is:

$$i_{os} = -\left(g_{m1}v_{gs1} - g_{m2}v_{gs2}\right)$$

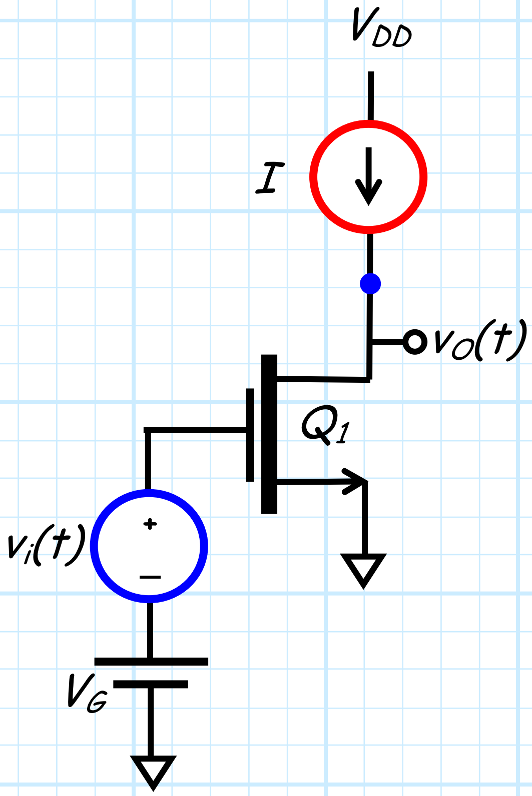
Thus, the small-signal output resistance of this amplifier is equal to:

$$R_o = \frac{v_o^{oc}}{i_o^{sc}} = \frac{-\left(g_{m1}v_{gs1} - g_{m2}v_{gs2}\right)\left(r_{o1}\|r_{o2}\right)}{-\left(g_{m1}v_{gs1} - g_{m2}v_{gs2}\right)} = \left(r_{o1}\|r_{o2}\right) \qquad \textbf{(Doh!!!)}$$

The input resistance and open-circuit voltage gain of this ***common source*** *amplifier are* ***good****, but the* ***output resistance stinks****!!*

Smells like a common emitter amplifier!

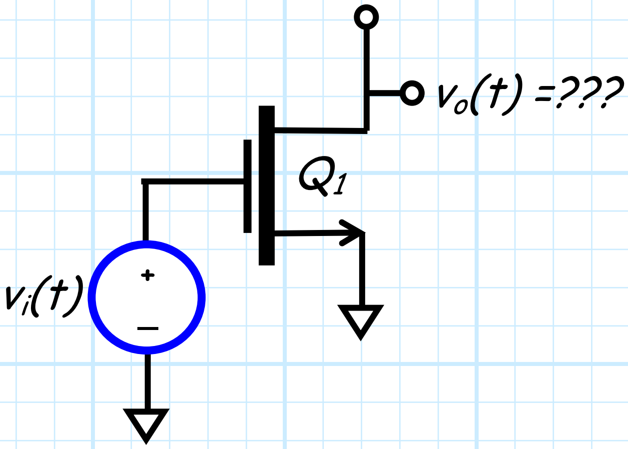
The Common Source Amp with a Current Source



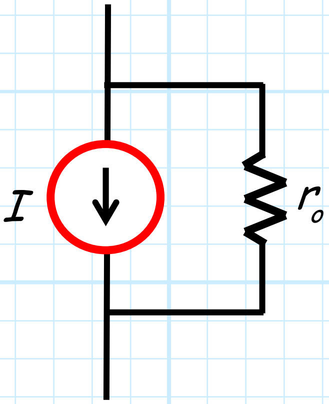
Now consider this NMOS amplifier using a **current source**.

- Note **no** resistors or capacitors are present!
- This is a **common source** amplifier.
- I_D stability **is not a problem!**

Q: *I don't understand! Wouldn't the small-signal circuit be:*



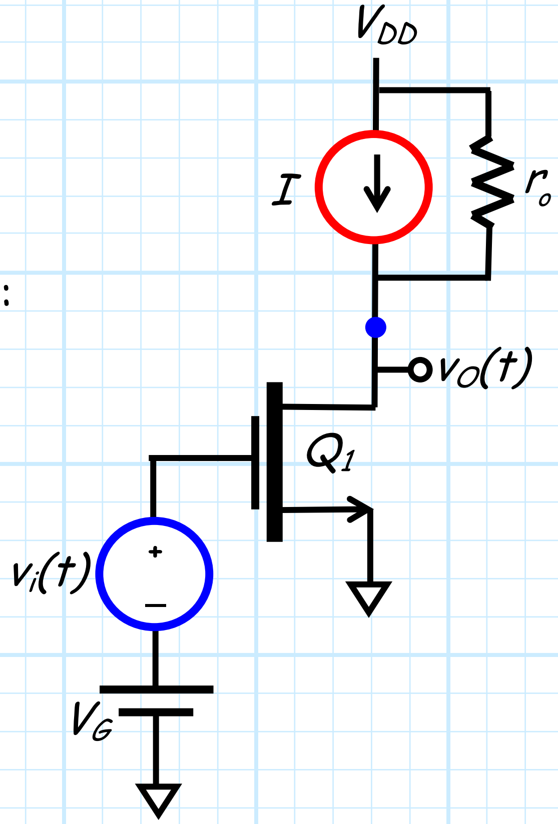
A: Remember, every **real** current source (as with every voltage source) has a **source resistance** r_o. A more **accurate** current source model is therefore:



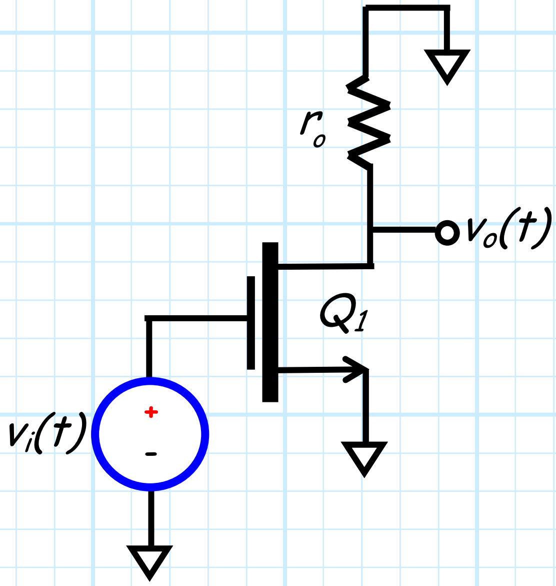
Ideally, $r_o = \infty$. However, for good current sources, this output resistance is large (e.g., $r_o = 100\ K\Omega$). Thus, we mostly **ignore** this value (i.e., approximate it as $r_o = \infty$), but there are some circuits where this resistance makes quite a **difference**.

This is one of those circuits!

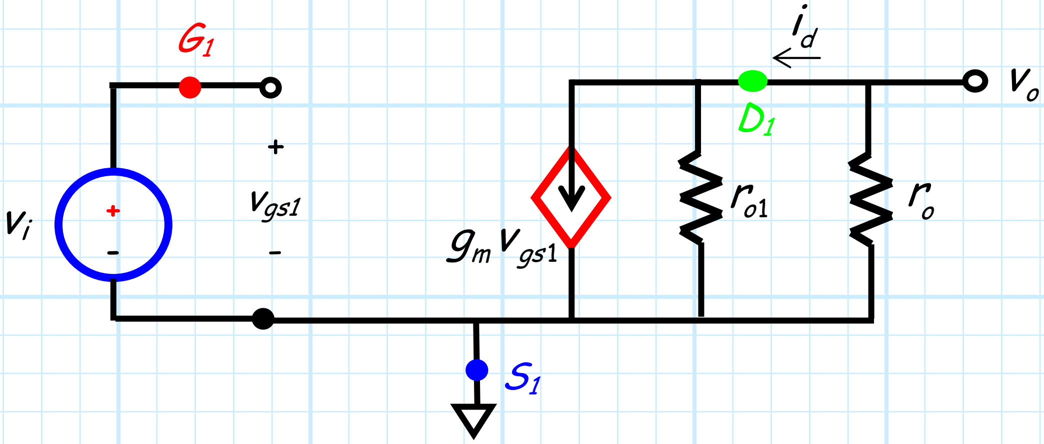
Therefore, a more **accurate** amplifier circuit schematic is:



And so the **small-signal circuit** becomes the familiar:

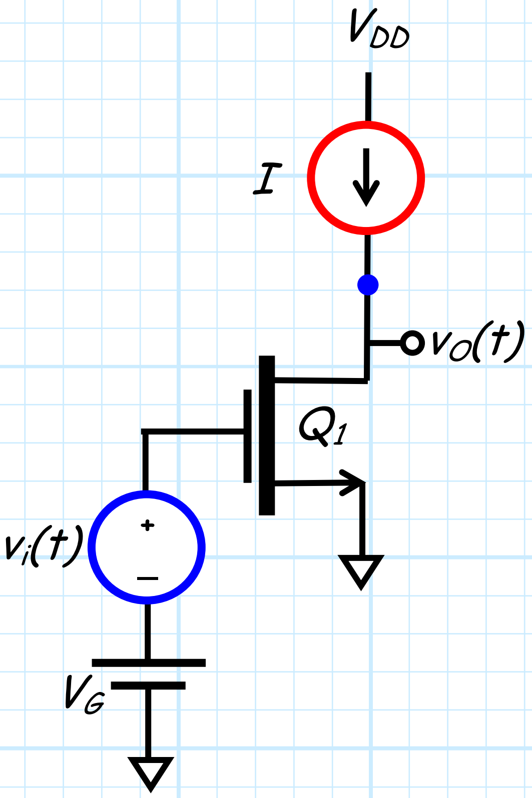


Therefore, with the hybrid-pi model:

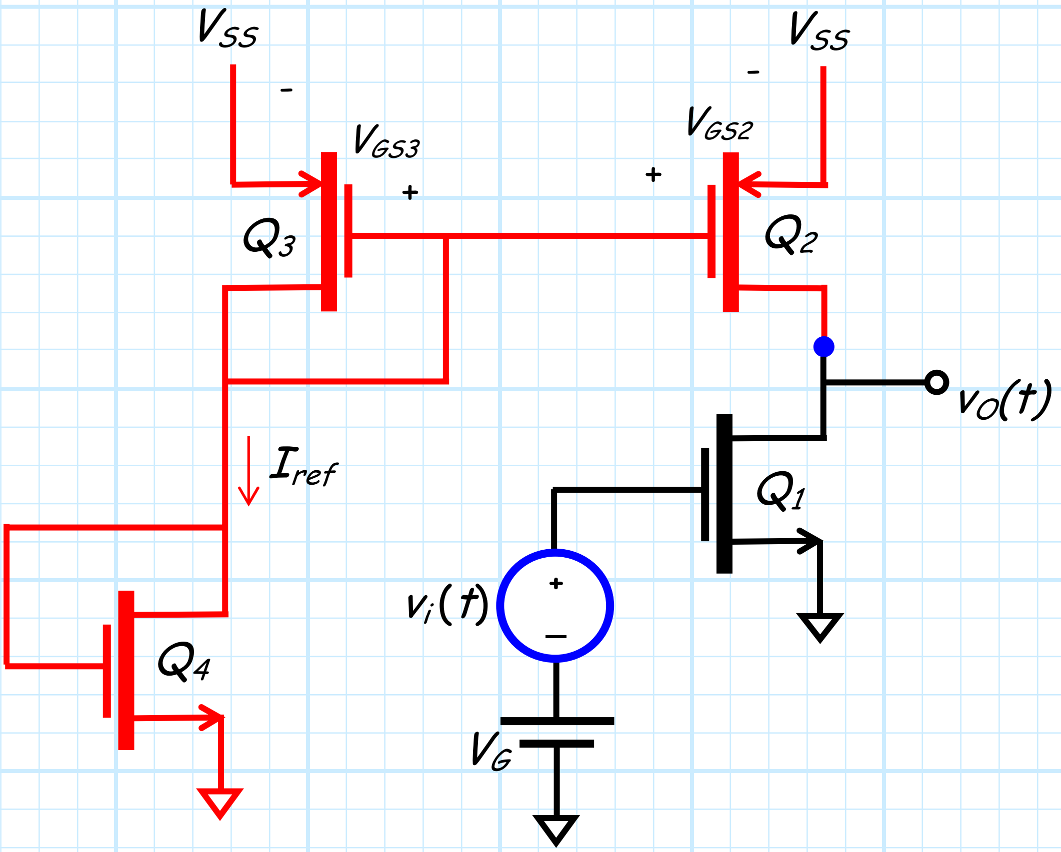


Q: *But, we implement a current source using a **current mirror**. What is the **output resistance** r_o of a current mirror?*

A: Implementing a **PMOS** current mirror, we find that our amplifier circuit:



is specifically:



Q: *Yikes! Where did all those **transistors** come from? What is it that they **do**?*

A: Transistors Q_2, Q_3, and Q_4 form the **current mirror** that acts as the **current source**. Note that transistor Q_4 is an **enhancement load**—it acts as the **resistor** in the current mirror circuit.

Note this amplifier circuit is **entirely** made of NMOS and PMOS **transistors**—we can "easily" implement this amplifier as an **integrated circuit**!

Q: *So again, what **is** the source resistance r_o of this current source?*

A: Let's determine the **small-signal circuit** for this integrated circuit amplifier and find out!

Q: *But there are **four** (count em') transistors in this circuit, determining the small-signal circuit must **take forever**!*

A: Actually **no**.

The important thing to realize when analyzing **this** circuit is that the gate-to-source voltage for transistors Q_2, Q_3, and Q_4 are **DC values**!

Q: *??*

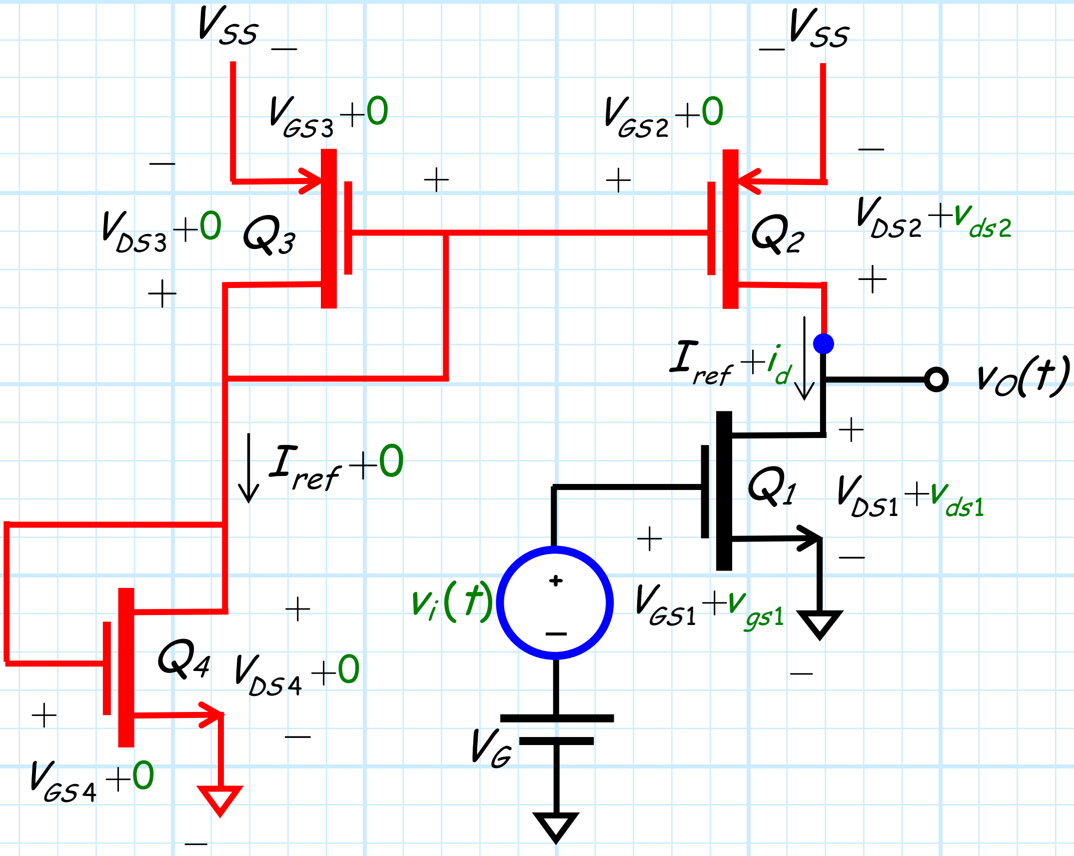
A: In other words, the small signal voltages v_{gs} for each transistor are equal to **zero**:

$$v_{gs2} = v_{gs3} = v_{gs4} = 0$$

Q: *But doesn't the small-signal source $v_i(t)$* ***create*** *small-signal voltages and currents* ***throughout*** *the amplifier?*

A: For **some** of the circuit yes, but for **most** of the circuit no!

Note that for transistor ***Q_1*** there will be small-signal voltages $v_{gs1}(t)$ and $v_{ds1}(t)$, along with $i_{d1}(t)$. Likewise for transistor ***Q_2***, a small-signal voltage $v_{ds2}(t)$ and current $i_{d2}(t)$ will occur.



But, for the remainder of the voltages and currents in this circuit (e.g., V_{DS4}, V_{GS2}, I_{D3}), the small-signal component is zero!

Q: *But wait!* ***How*** *can there be a small-signal* ***drain current*** *$i_{d2}(t)$ through transistor Q_2,* ***without*** *a corresponding small-signal* ***gate-to-source voltage*** *$v_{gs2}(t)$?*

A: Transistor Q_2, is **the** important device in this analysis.

Note its gate-to-source voltage is a **DC value** (no small-signal component!), yet there **must** be (by KCL) a **small-signal** drain current $i_{d2}(t)$!

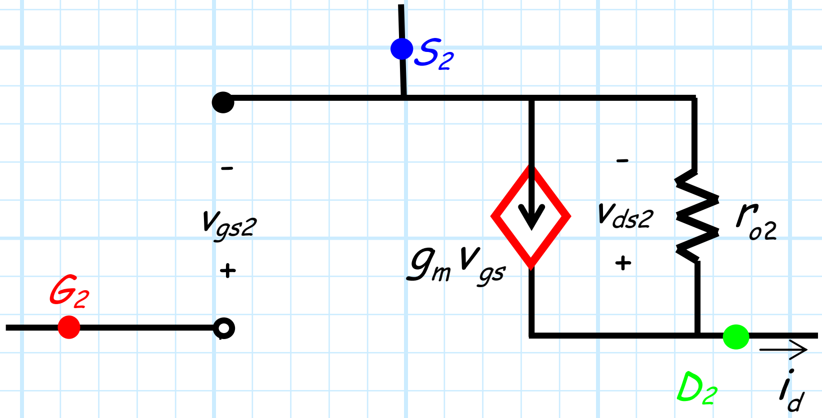
This is a case where we **must** consider the **MOSFET output resistance** r_{o2}. The small-signal drain current for a **PMOS** device is:

$$i_{d2} = g_{m2}\, v_{gs2} - \frac{v_{ds2}}{r_{o2}}$$

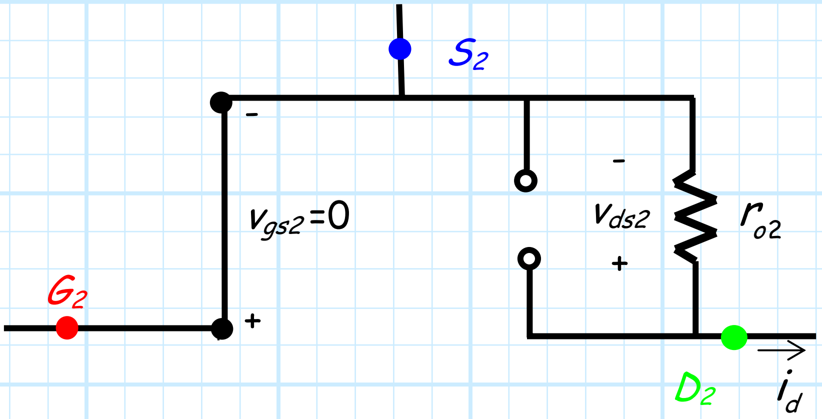
Since $v_{gs2}=0$, this equation **simplifies** to:

$$i_{d2} = -\frac{v_{ds2}}{r_{o2}}$$

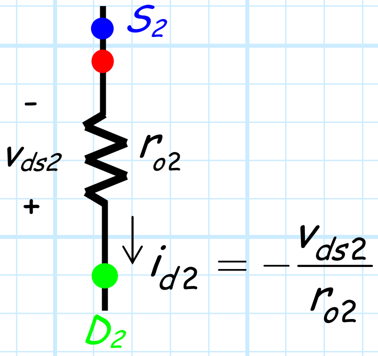
Equivalently, the **small-signal PMOS model** is:



Thus for $v_{gs2}=0$, the small-signal model becomes:

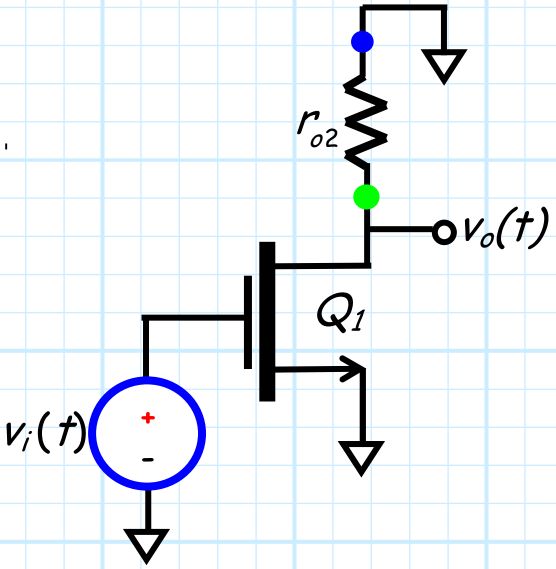


Or, simplifying further:

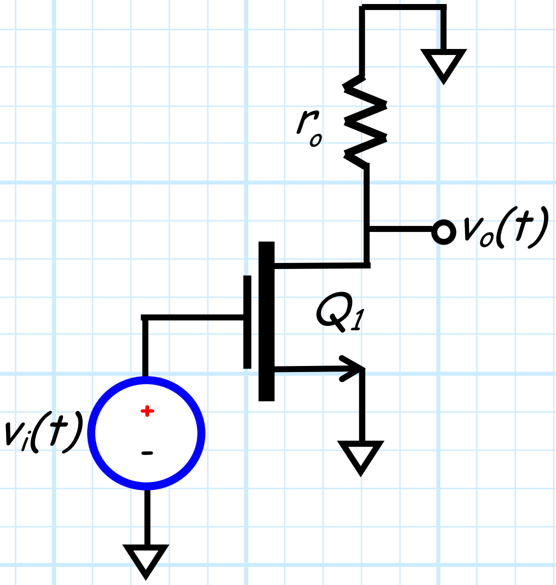


$$i_{d2} = -\frac{v_{ds2}}{r_{o2}}$$

Thus, the small-signal model of the entire current mirror is simply the output resistance of the MOSFET ***Q*$_2$** !



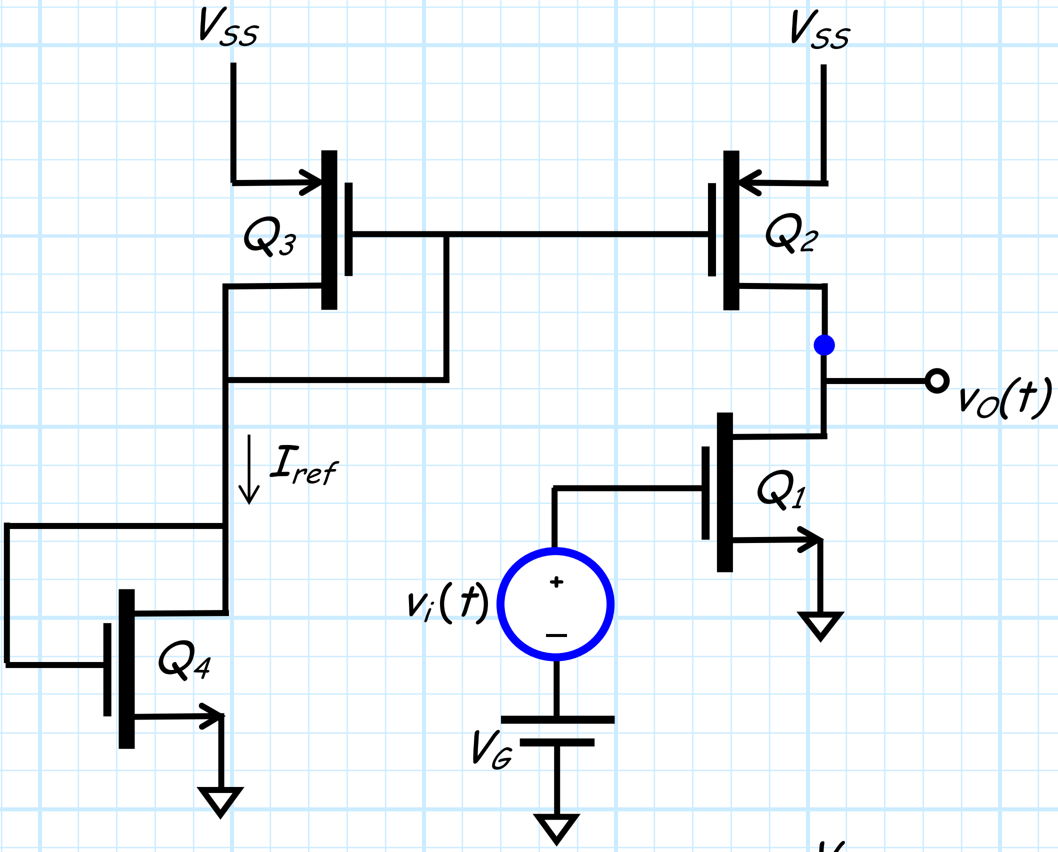
Comparing this to the earlier analysis--with a current source of output resistance r_o:



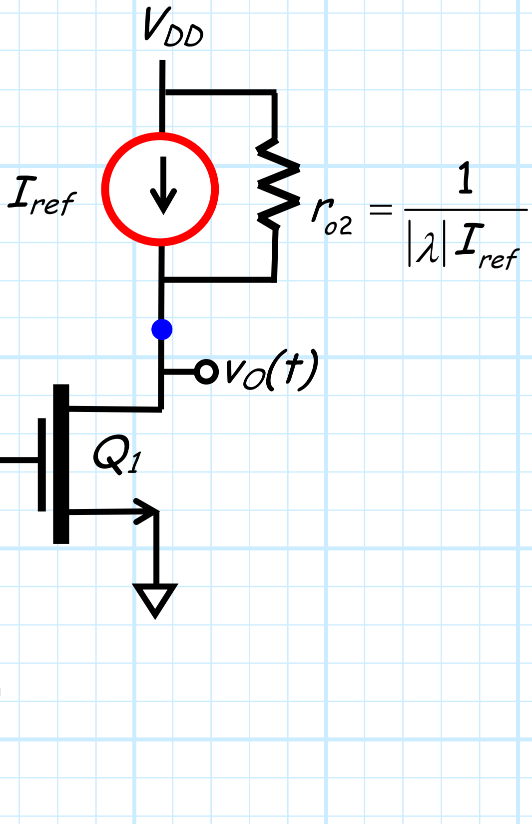
It is evident that the output resistance of the current mirror is simply equal to the output resistance of MOSFET Q_2 !!!!

$$r_o = r_{o2}$$

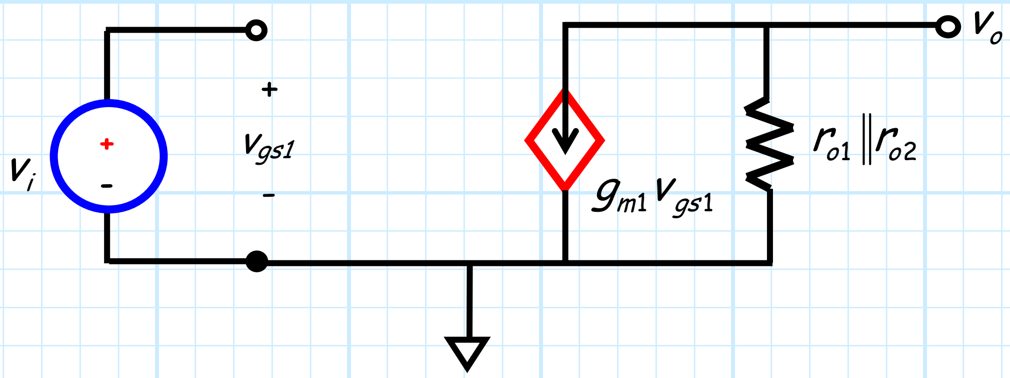
And so **this** circuit:



is equivalent to **this** circuit:



The resulting small-signal circuit of this amp is:



And so the **open-circuit voltage gain** is:

$$A_{vo} = -g_{m1}\left(r_{o1} \| r_{o2}\right) = 2\sqrt{K_1}\sqrt{I_{ref}}\left(r_{o1} \| r_{o2}\right)$$

Note **this** result is **far different** (i.e., larger) than the result when using the **enhancement load** for R_D:

$$A_{vo} = -\sqrt{\frac{K_1}{K_2}}$$

However, we find that the **output** and **input** resistances of this amplifier are the **same** as with the enhancement load:

$$R_i = \infty \qquad\qquad R_o = r_{o1} \| r_{o2}$$