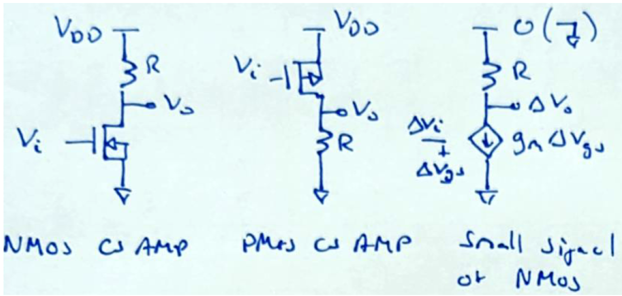
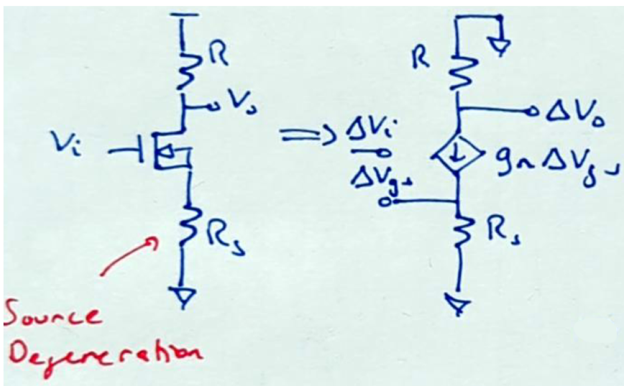
Lecture Notes 15: MOSFET Circuits

Digital circuits, which use MOSFETs as switches, are covered well in other courses. Therefore, this lecture will focus on analog circuits which use the MOSFET as a controlled current source. We have already seen the common-source amplifier (meaning the source is at a fixed potential), which can be made with an NMOS device or with a PMOS device:



Once we draw the small-signal model (and are therefore comfortable solving for only the Δv's and the Δi's), the circuit devolves back into the kinds of circuits we solved in the first part of the course. In this case, $\Delta v_o = -g_m R \Delta v_i$, where we recall that the transconductance of the MOSFET $g_m = \mu_n C_{ox} \frac{W}{L}(V_{gs} - V_{th}$.

The common-source amplifier has a large gain due to g_m, but the gain is not necessarily well controlled. Parameters like μ_n and V_{th} vary with temperature, for example, and the operating point V_{gs} (the constant gate voltage that we then perturb around) could be different. This unpredictable gain is undesirable. One way to provide more reliable (but less) gain is to use **source degeneration**:



The small signal model is only a little more difficult to solve. The main point to keep in mind is that **the source v_s is no longer grounded, so v_{gs} no longer equals v_{in}**. Instead,

$$\Delta i = g_m \Delta v_{gs} = g_m(\Delta v_i - \Delta v_s) = g_m(\Delta v_i - \underbrace{\Delta i R_s)}_{\text{negative feedback}}$$

where we can see negative feedback at play (more current would cause higher v_s which would cause lower v_{gs} which would bring the current back down). Solving yields

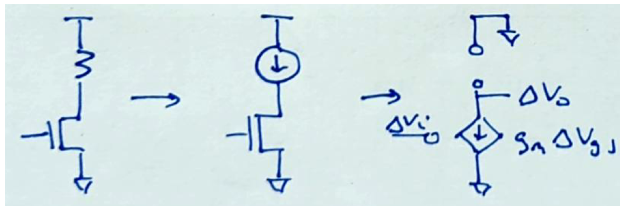
$$\Delta i = \frac{g_m}{1 + g_m R_s} \Delta v_i$$

and therefore

$$\Delta v_o = -\frac{g_m R}{1 + g_m R_s} \Delta v_i \approx -\frac{R}{R_s} \Delta v_i$$

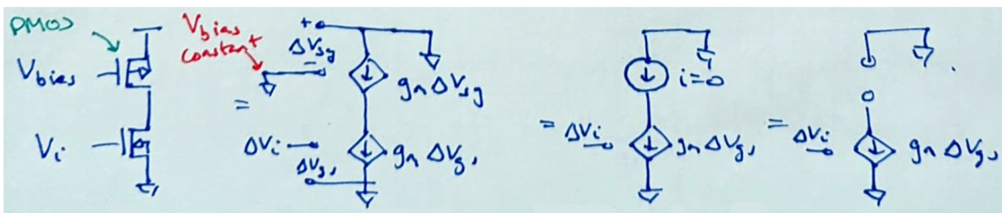
The new gain R/R_s will be less than $g_m R$, but far more constant. Often, $g_m R$ is so large that we're happy to trade some of it away in favor of a more constant gain.

Sometimes we face a different problem – that the gain $g_m R$ is not sufficient. One trick is to "load" the amplifier with a current source rather than a resistor: Here a constant current source brings current to the



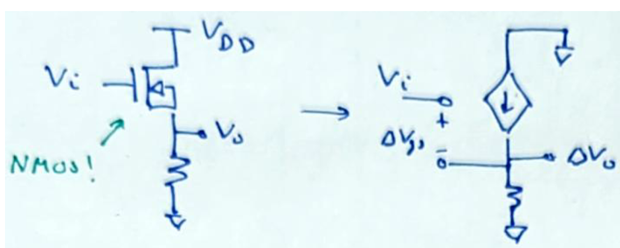
MOSFET rather than a resistor. The constant current source never varies, so its small signal model is $\Delta i = 0$ or an open circuit. In some ways this works just like the original common-source amplifier with $R = \infty$ in small signal. So the circuit equation becomes $\Delta v_o = -\infty \Delta v_i$, or infinite gain.

This is great, but how do we make a current source? $\Rightarrow$ How about a MOSFET! We've used a PMOS for the



current source so that its $v_{sg} = V_{DD} - V_{bias}$ will be constant as long as we apply a constant gate bias. This results in the PMOS having constant current and the near-infinite gain we promised earlier. This circuit is a **common source amplifier with active load**.

Now consider a different circuit entirely: the **common-drain amplifier**. This might look similar to the

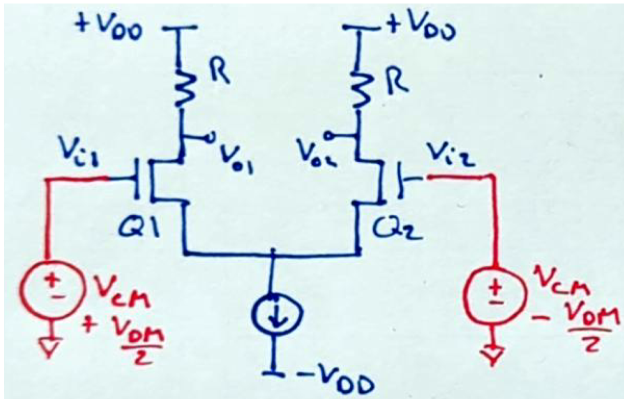


common-source amplifier with a PMOS device, but notice that the device is actually an NMOS. What does this circuit do?

$$\begin{aligned}
\Delta v_o &= R \times g_m \Delta v_{gs} && (10)\\
&= R g_m (\Delta v_i - \underbrace{\Delta v_o)}_{\text{negative feedback}} && (11)\\
&= \frac{g_m R}{1 + g_m R} \Delta v_i && (12)\\
&\approx \Delta v_i && (13)
\end{aligned}$$

This circuit has a gain of ≈ 1 and is often called a **source follower**. But what is the point of such a circuit? Recall when we studied the op-amp buffer – it also had a gain of 1, but it provided infinite input resistance (so it wouldn't significantly load the circuit that generates v_i) and zero output resistance (so it could drive a lot of current through the next circuit after it). This circuit has the same advantages! The MOSFET draws no current from v_i and it can provide substantial current to whatever circuit comes next. (The extra current comes from V_{DD}).

We are even prepared to analyze the initial building blocks of op-amps: the **differential pair**. Now imagine



that the circuit is perfectly balanced. We apply a voltage v_{i1} to the left MOSFET and a voltage v_{i2} to the right MOSFET. Then, it turns out to be easier to perform a change of variables. Let the **common-mode voltage** be defined as the average of the two voltages,

$$v_{cm} = \frac{v_{i1} + v_{i2}}{2}$$

and let the **differential-mode voltage** be defined as the difference between the two voltages (i.e., the difference between either voltage and the average):

$$v_{dm} = v_{i_1} - v_{i2}$$

If we wanted to go backwards, we would say

$$v_{i1} = v_{cm} + \frac{v_{dm}}{2} \tag{14}$$

$$v_{i1} = v_{cm} - \frac{v_{dm}}{2} \tag{15}$$

With only v_{cm} and if the circuit is perfectly balanced, then the operating point current flowing through each device is the current source current I divided by two.

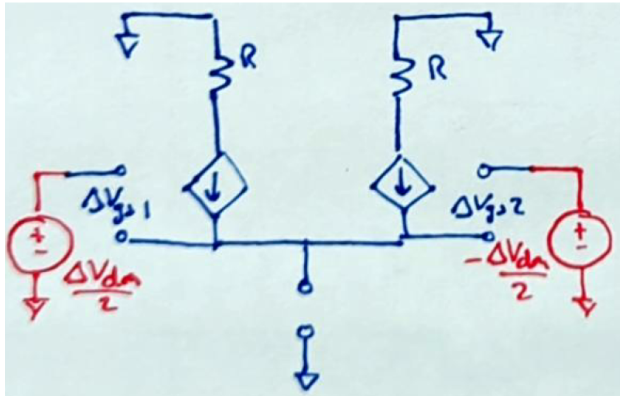
In small signal, we will presume that v_{cm} is never changed but a small *differential* voltage perturbation may be applied between the two inputs. In other words, when v_{i1} goes up a little and v_{i2} goes down by the same amount. This amounts to $\Delta v_{cm} = 0$ and Δv_{dm} being non-zero. In the small signal model, we replace the MOSFETs with their small signal model, V_{DD} becomes ground, $-V_{DD}$ also becomes ground, and the constant current source becomes an open circuit. The two MOSFETs are excited by $+\Delta v_{dm}/2$ and $-\Delta v_{dm}/2$: With this model, we can solve for

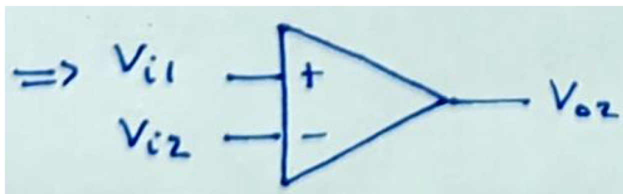
$$\Delta v_{o1} = -R \times g_m \frac{\Delta v_{dm}}{2} \tag{16}$$

$$\Delta v_{o2} = +R \times g_m \frac{\Delta v_{dm}}{2} \tag{17}$$

We now have a rudimentary op amp:

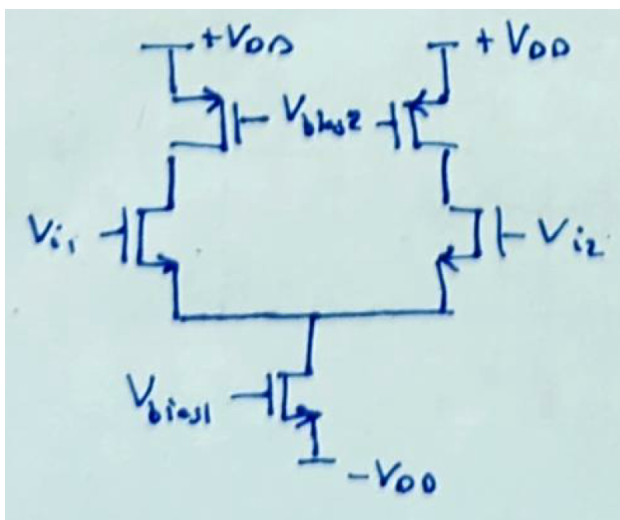
- Output (e.g., Δv_{o2}) is a constant times $v_+ - v_- = v_{dm}$





- No current flows into the positive or negative input terminals

We begin to approach a real op amp by using active loads (PMOS devices) instead of resistors and by implementing the current source as an actual transistor.



Further improvements are needed to achieve anywhere near modern op amp performance, including:

- More gain
- Higher output swing
- Wide common-mode voltage range

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