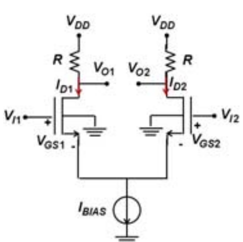
Lecture 17

Differential Amplifiers – II
Advanced Concepts

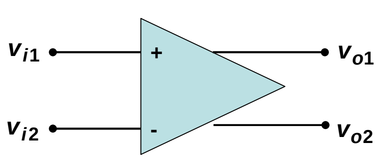
In this lecture you will learn:

- Differential Amplifiers
- Use of Current Mirrors in Differential Amplifiers
- Small Signal and Large Signal Models with Current Mirrors

Differential Amplifier: Double-Ended Output



The FET differential amplifiers considered in the previous handout had a double-ended output



$$v_{o1} = \frac{A_{vd}}{2}(v_{i1} - v_{i2}) + A_{vc}\left(\frac{v_{i1}+v_{i2}}{2}\right)$$

$$= A_{vd}\frac{v_{id}}{2} + A_{vc}v_{ic}$$

$$v_{o2} = -\frac{A_{vd}}{2}(v_{i1} - v_{i2}) + A_{vc}\left(\frac{v_{i1}+v_{i2}}{2}\right)$$

$$= -A_{vd}\frac{v_{id}}{2} + A_{vc}v_{ic}$$

Difference-Mode Output:

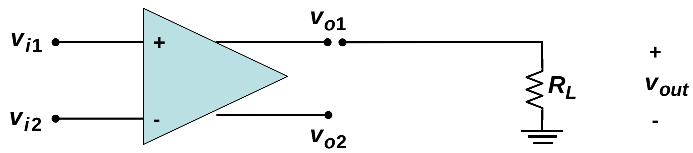
$$v_{od} = v_{o1} - v_{o2} = A_{vd}v_{id}$$

Common-Mode Output:

$$v_{oc} = \frac{v_{o1}+v_{o2}}{2} = A_{vc}v_{ic}$$

Differential Amplifier: Double-Ended Output

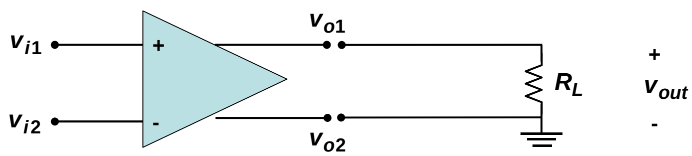
Suppose one tries to connect a load to one of the outputs:



$$v_{out} = v_{o1} = A_{vd}\frac{v_{id}}{2} + A_{vc}v_{ic} \approx A_{vd}\frac{v_{id}}{2}$$

We have lost half of the voltage
We can do better……….

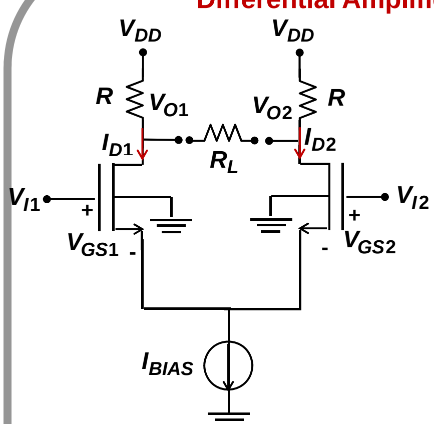
Try another scheme:



$$v_{out} = v_{od} = v_{o1} - v_{o2} = A_{vd}v_{id}$$

We have recovered the full signal but this scheme is not always practical

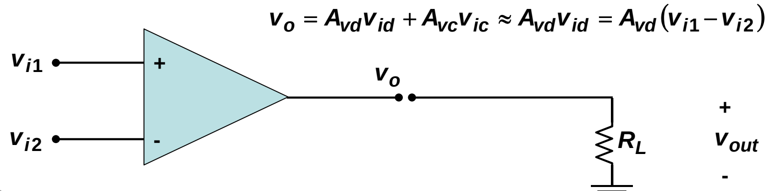
Differential Amplifier: Single-Ended Output



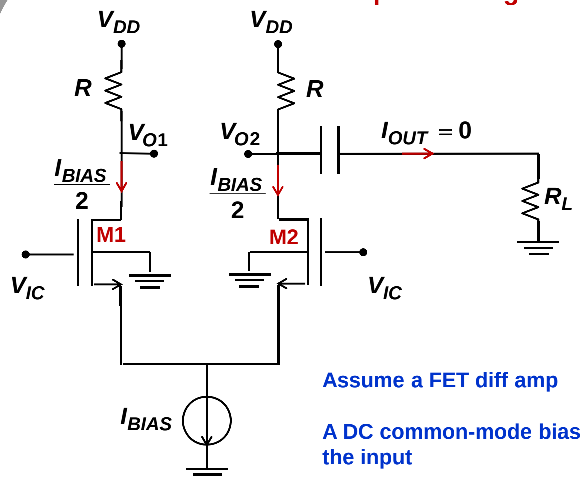
This is an awkward way to connect the load at the output ………!

Most of the time what one would really like to have is a single-ended output (without loosing the factor of 2):

$$v_o = A_{vd}v_{id} + A_{vc}v_{ic} \approx A_{vd}v_{id} = A_{vd}\left(v_{i1} - v_{i2}\right) = v_{out}$$



FET Differential Amplifier: Single-Ended Operation

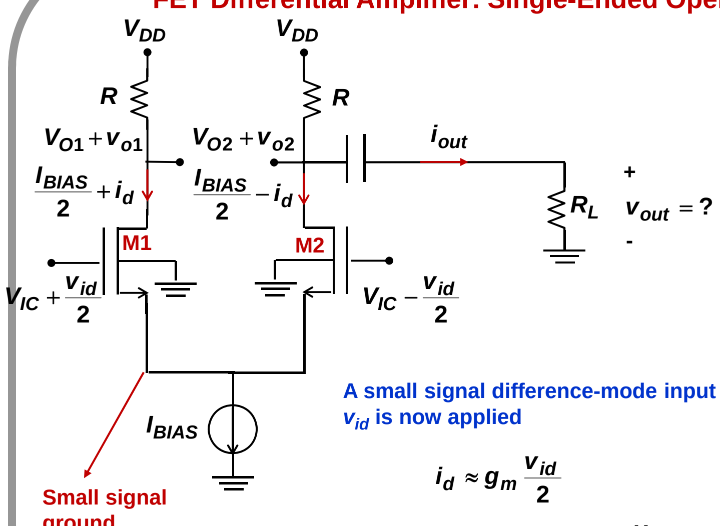


Assume a FET diff amp

A DC common-mode bias V_{IC} is applied at the input

Assume very large r_{o1}, r_{o2}, and R (compared to R_L) for simplicity

FET Differential Amplifier: Single-Ended Operation



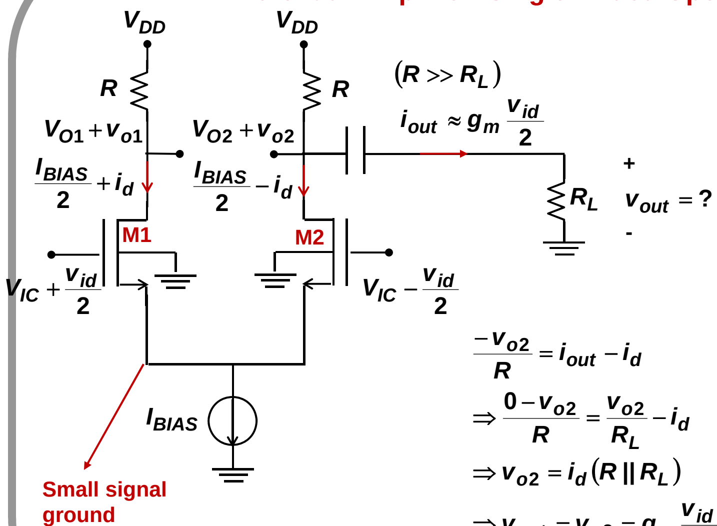
A small signal difference-mode input signal v_{id} is now applied

$$i_d \approx g_m \frac{v_{id}}{2}$$

$$v_{o1} = -i_d R \approx -g_m \frac{v_{id}}{2} R$$

FET Differential Amplifier: Single-Ended Operation

$\boxed{i_d \approx g_m \frac{v_{id}}{2}}$



$$\frac{-v_{o2}}{R} = i_{out} - i_d$$

$$\Rightarrow \frac{0 - v_{o2}}{R} = \frac{v_{o2}}{R_L} - i_d$$

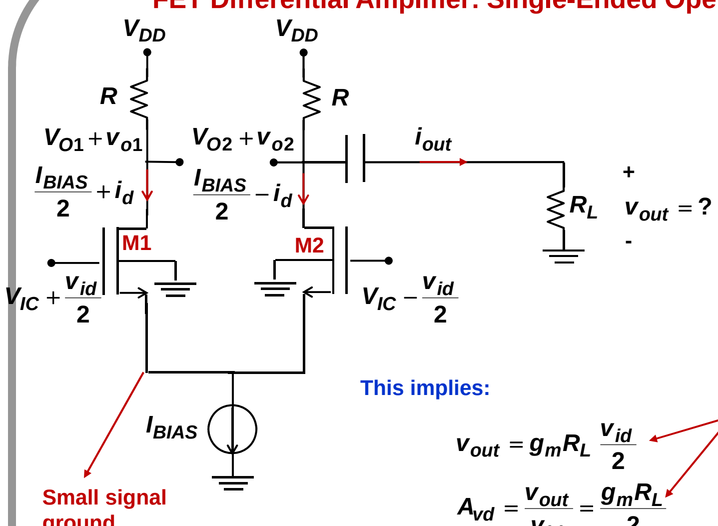
$$\Rightarrow v_{o2} = i_d (R \,||\, R_L)$$

$$\Rightarrow v_{out} = v_{o2} = g_m \frac{v_{id}}{2}(R \,||\, R_L) \approx g_m \frac{v_{id}}{2} R_L$$

$$\Rightarrow i_{out} = \frac{v_{o2}}{R_L} \approx g_m \frac{v_{id}}{2}$$

FET Differential Amplifier: Single-Ended Operation

$\boxed{i_d \approx g_m \frac{v_{id}}{2}}$



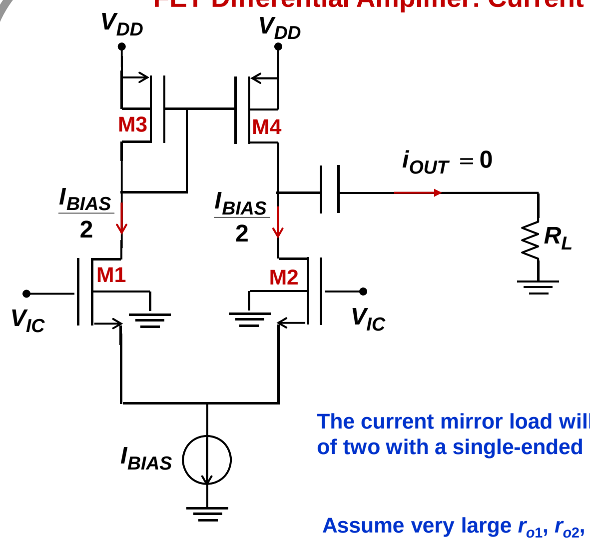
This implies:

$$v_{out} = g_m R_L \frac{v_{id}}{2}$$

$$A_{vd} = \frac{v_{out}}{v_{id}} = \frac{g_m R_L}{2}$$

Note the factor 2
Q: How to fix it?!

FET Differential Amplifier: Current Mirror Load

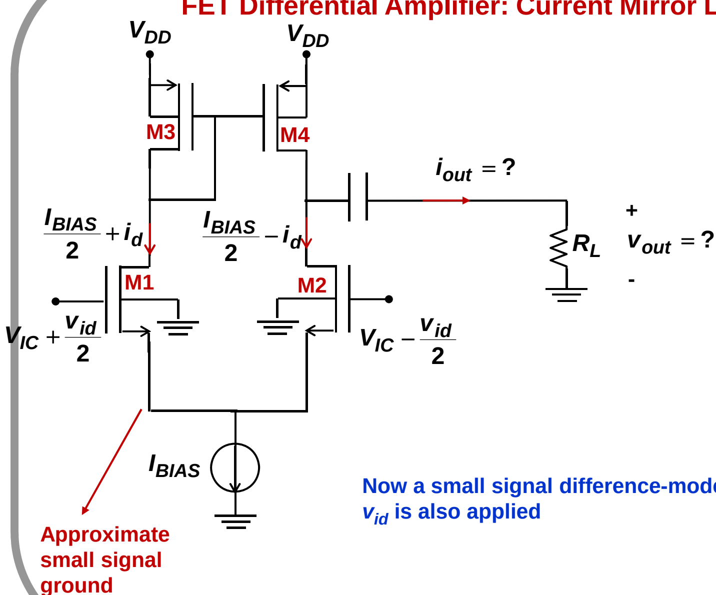


The current mirror load will let us recover the factor of two with a single-ended output!

Assume very large r_{o1}, r_{o2}, r_{o3} and r_{o4} (compared to R_L)

FET Differential Amplifier: Current Mirror Load

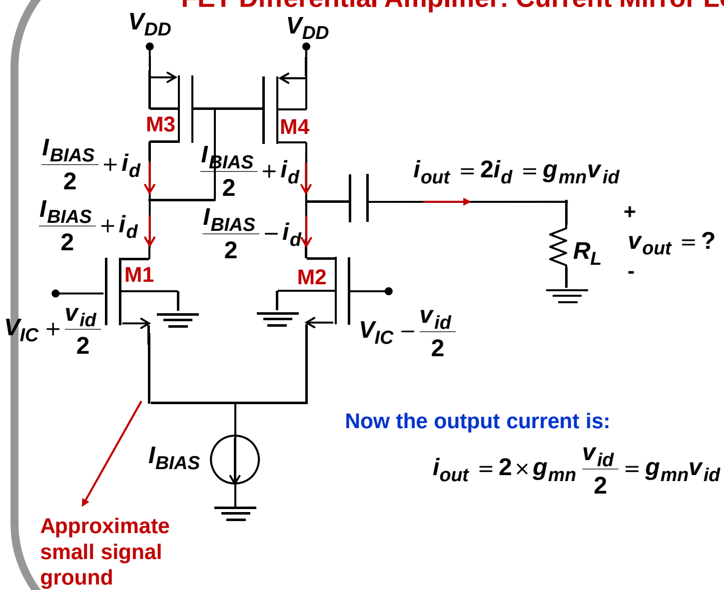
$$\boxed{i_d \approx g_{mn} \frac{v_{id}}{2}}$$



Now a small signal difference-mode input signal v_{id} is also applied

FET Differential Amplifier: Current Mirror Load

$$i_d \approx g_{mn}\frac{v_{id}}{2}$$

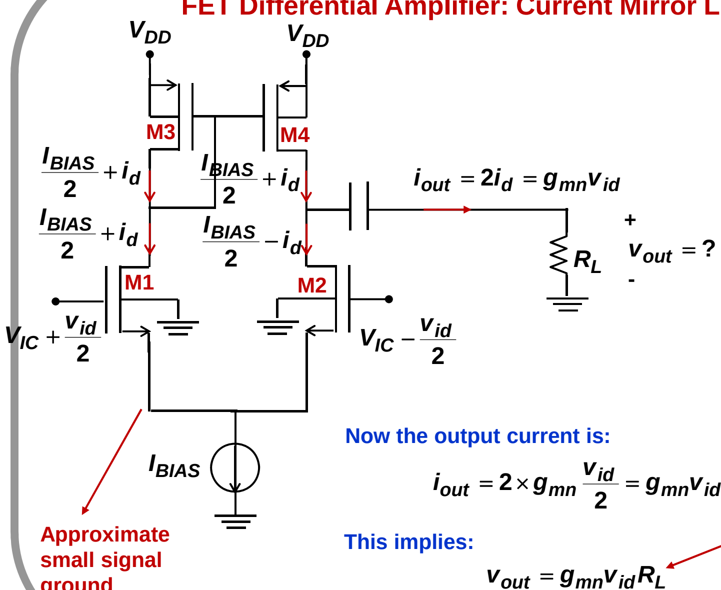


Now the output current is:

$$i_{out} = 2\times g_{mn}\frac{v_{id}}{2} = g_{mn}v_{id}$$

FET Differential Amplifier: Current Mirror Load

$$i_d \approx g_{mn}\frac{v_{id}}{2}$$



Now the output current is:

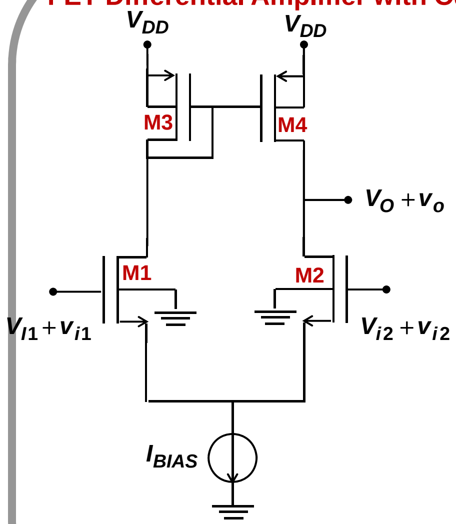
$$i_{out} = 2\times g_{mn}\frac{v_{id}}{2} = g_{mn}v_{id}$$

This implies:

$$v_{out} = g_{mn}v_{id}R_L$$

Note the factor of 2 is gone!

FET Differential Amplifier with Current Mirror: Small Signal Analysis

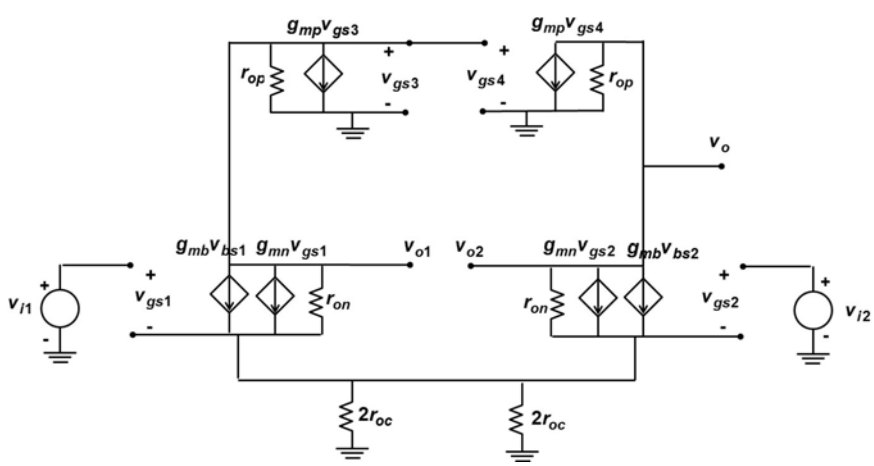


Need to make and analyze a small circuit model and calculate:

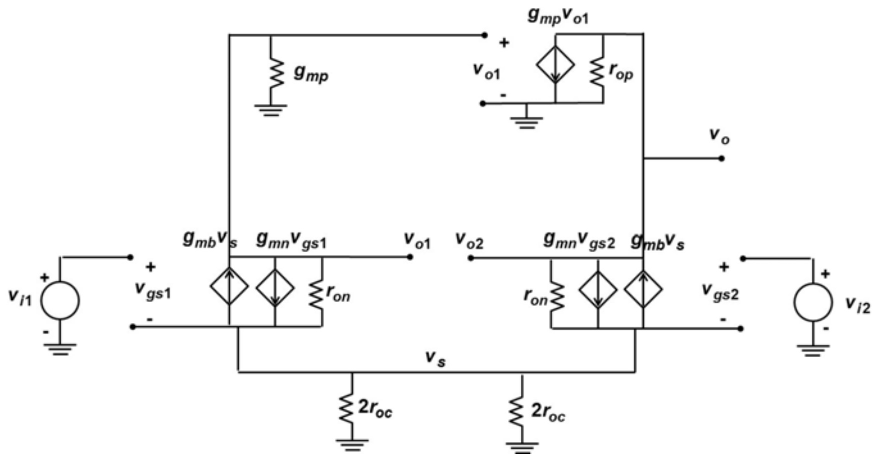
$$A_{vd} = \frac{v_o}{v_{id}}$$ Difference-Mode Gain

$$A_{vc} = \frac{v_o}{v_{ic}}$$ Common-Mode Gain

FET Differential Amplifier with Current Mirror: Small Signal Analysis



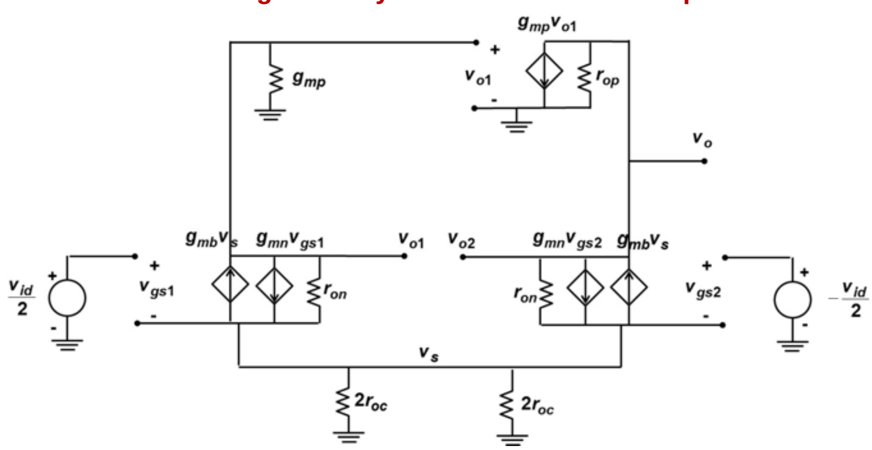
FET Differential Amplifier with Current Mirror: Small Signal Analysis



Small signal circuit model

Note the lack of symmetry!!

Small Signal Analysis: Difference-Mode Input

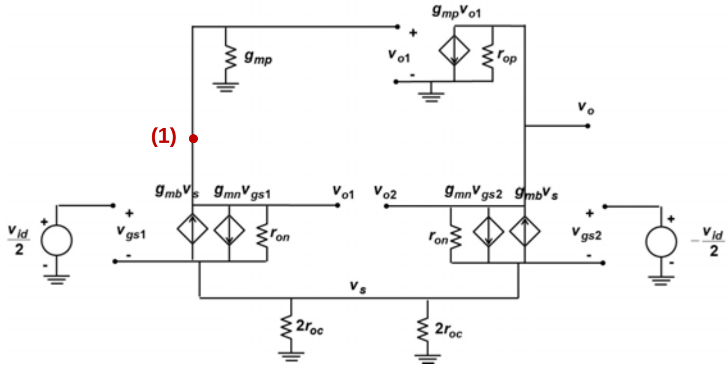


There are three unknown internal voltage variables: v_{o1} v_{o2} v_s

We therefore need three equations

Try KCL at three different nodes…………

Small Signal Analysis: Difference-Mode Input

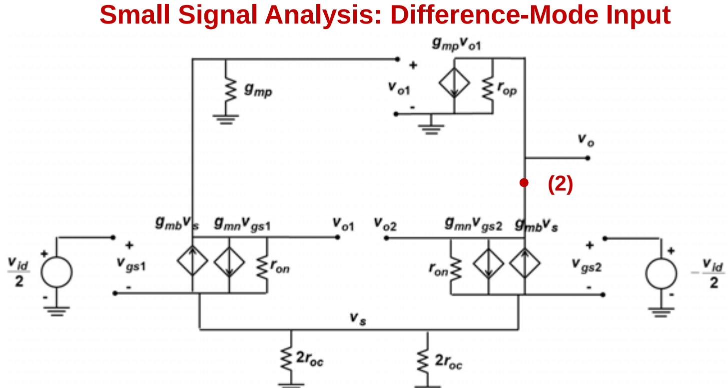


(1) $$g_{mn}\left(\frac{v_{id}}{2}-v_s\right)+g_{on}(v_{o1}-v_s)-g_{mb}v_s+g_{mp}v_{o1}=0$$

$$\Rightarrow g_{mn}\left(\frac{v_{id}}{2}-v_s\right)-(g_{on}+g_{mb})v_s+(\overset{\text{small}}{\cancel{g_{on}}}+g_{mp})v_{o1}=0$$

$$\Rightarrow -(g_{on}+g_{mb})v_s+g_{mp}v_{o1}\approx -g_{mn}\left(\frac{v_{id}}{2}-v_s\right)$$

Small Signal Analysis: Difference-Mode Input



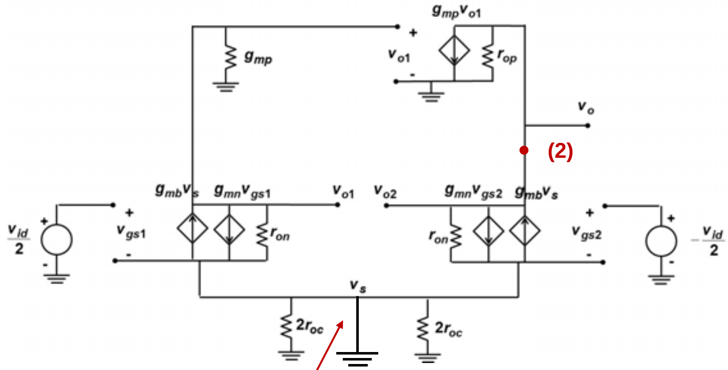
(2) $$g_{mn}\left(-\frac{v_{id}}{2}-v_s\right)+g_{on}(v_{o2}-v_s)-g_{mb}v_s+g_{mp}v_{o1}+g_{op}v_{o2}=0$$

$$\Rightarrow g_{mn}\left(-\frac{v_{id}}{2}-v_s\right)+(g_{on}+g_{op})v_{o2}-(g_{on}+g_{mb})v_s+g_{mp}v_{o1}=0$$

$$\Rightarrow g_{mn}\left(-\frac{v_{id}}{2}-v_s\right)+(g_{on}+g_{op})v_{o2}-g_{mn}\left(\frac{v_{id}}{2}-v_s\right)\approx 0$$

$$\Rightarrow v_o=v_{o2}=\frac{g_{mn}}{g_{on}+g_{op}}v_{id}=g_{mn}(r_{on}\,\|\,r_{op})v_{id} \qquad \Big\{\ A_{vd}=\frac{v_o}{v_{id}}\approx g_{mn}(r_{on}\,\|\,r_{op})$$

Small Signal Analysis: Difference-Mode Input



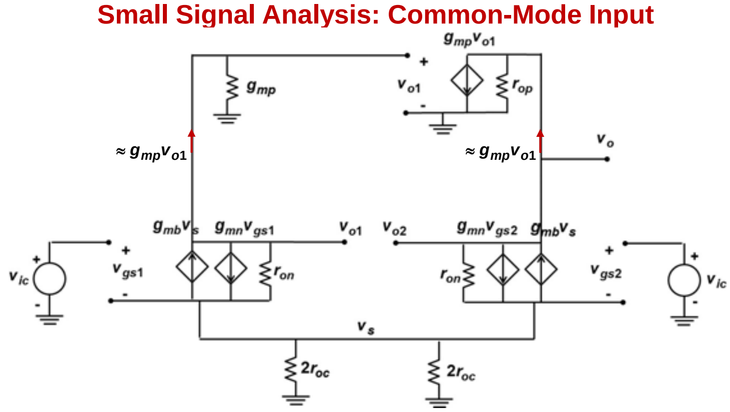
One can also get the correct results by assuming a-priori that the in the difference-mode the voltage v_s is approximately zero (i.e. the node is a small signal ground)

If v_s is assumed to be approximately zero then:

$$v_{o1} \approx -\frac{g_{mn}}{g_{mp}}\frac{v_{id}}{2} \quad \Rightarrow \quad v_{o2} \approx \frac{\left(-g_{mp}v_{o1} + g_{mn}\frac{v_{id}}{2}\right)}{(g_{on}+g_{op})} = \frac{g_{mn}v_{id}}{(g_{on}+g_{op})}$$

$$= g_{mn}(r_{on} \| r_{op})v_{id} = v_o$$

Small Signal Analysis: Common-Mode Input

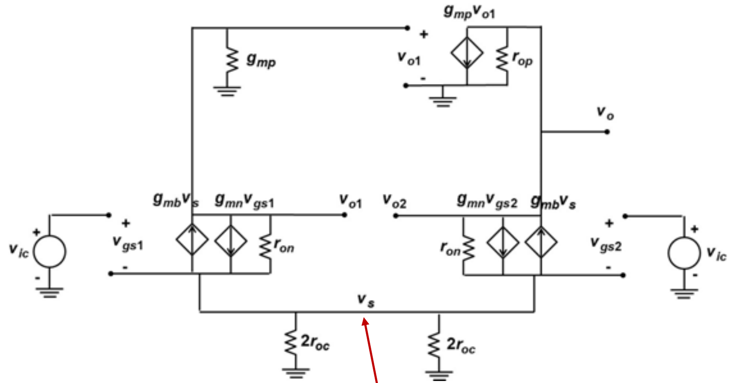


One good way to think about the amplifier in common-mode operation:

If the output resistance of M4 is assumed to be very large, then the current mirror, as the name suggests will ensure that the drain currents of M1 and M2 are identical (both equal to $-g_{mp}v_{o1}$) – as you can see above as well.

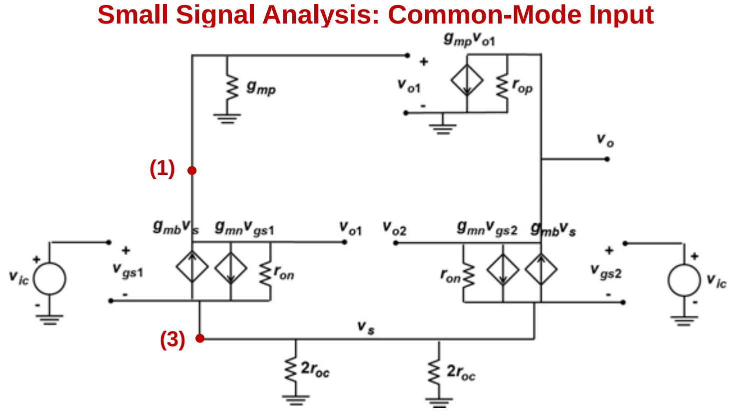
Since the input voltages, v_{ic}, on the two sides are also the same, the circuit (at least the bottom portion) has complete left-right symmetry in common-mode operation

Small Signal Analysis: Common-Mode Input



So one can assume that the in the common-mode, even with the current mirror, <u>no current flows in the bottom most horizontal wire</u> (i.e. it is a small signal open)

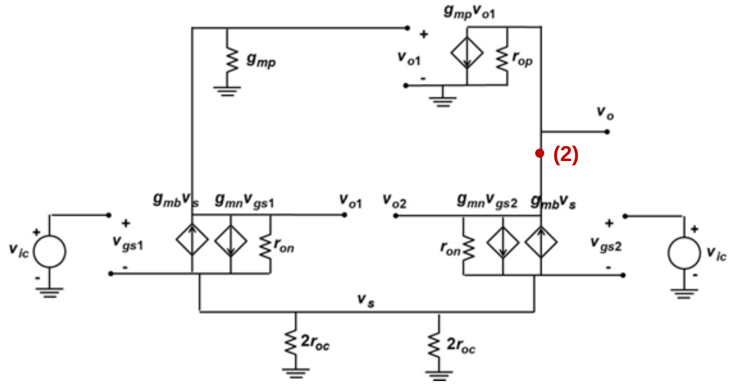
Small Signal Analysis: Common-Mode Input



Doing KCL at (1) and (3) gives:

$$v_{o1} \approx -\frac{\frac{g_{mn}}{g_{mp}} r_{on}}{r_{on} + \frac{1}{g_{mp}} + 2r_{oc} + (g_{mn} + g_{mb}) r_{on} (2r_{oc})} v_{ic}$$

Small Signal Analysis: Common-Mode Input

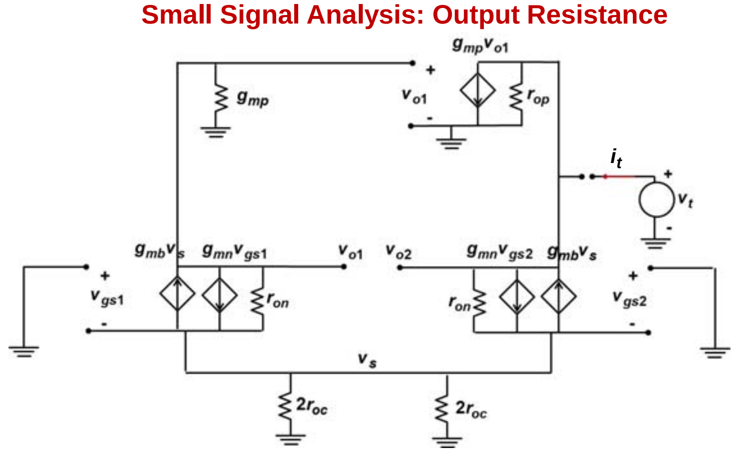


Using the left-right symmetry gives:

$$v_o = v_{o2} \approx v_{o1}$$

$$A_{vc} = \frac{v_o}{v_{ic}} \approx -\frac{\dfrac{g_{mn}}{g_{mp}} r_{on}}{r_{on} + \dfrac{1}{g_{mp}} + 2r_{oc} + (g_{mn} + g_{mb}) r_{on} (2r_{oc})}$$

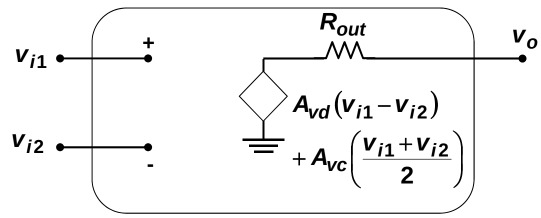
Small Signal Analysis: Output Resistance



$$R_{out} \approx r_{on} \,||\, r_{op}$$

Left for homework

Two-Port Model of a FET Differential Amplifier with Current Mirror



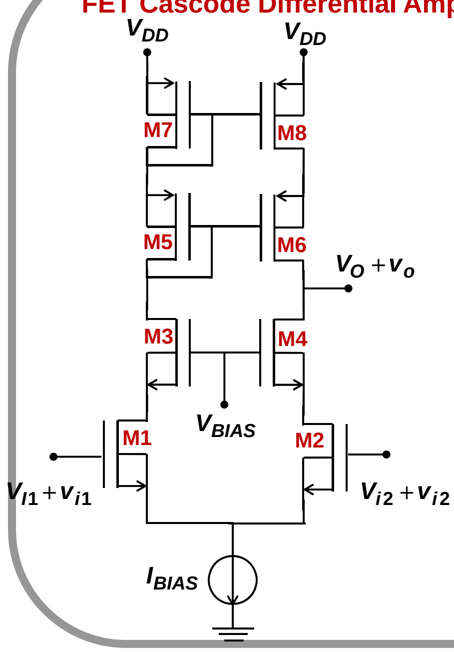
$$A_{vd} \approx g_{mn}(r_{on} \,||\, r_{op})$$

$$A_{vc} = \frac{v_o}{v_{ic}} \approx -\frac{\frac{g_{mn}}{g_{mp}} r_{on}}{r_{on} + \frac{1}{g_{mp}} + 2r_{oc} + (g_{mn} + g_{mb}) r_{on} (2r_{oc})}$$

$$\approx -\frac{\frac{g_{mn}}{g_{mp}}}{1 + \frac{2r_{oc}}{r_{on}} + (g_{mn} + g_{mb})(2r_{oc})}$$

$$R_{out} \approx r_{on} \,||\, r_{op}$$

FET Cascode Differential Amplifier with Cascode Current Mirror



$$R_{out} \approx (g_{mn} r_{on} r_{on}) \,||\, (g_{mp} r_{op} r_{op})$$

$$A_{vd} \approx g_{mn} R_{out}$$

$$A_{vd} \approx g_{mn}\left[(g_{mn} r_{on} r_{on}) \,||\, (g_{mp} r_{op} r_{op})\right]$$