Lecture 25 - Differential Amplifiers (I)

May 13, 2003

Contents:

1. Introduction
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3. Common-source differential amplifier

Reading assignment:

Howe and Sodini, Ch. 11, §§11.1-11.3

Announcement:

Final exam: May 23, 1:30-4:30 PM, Walker; open book, calculator required; entire subject under examination but emphasis on lectures #18-26.

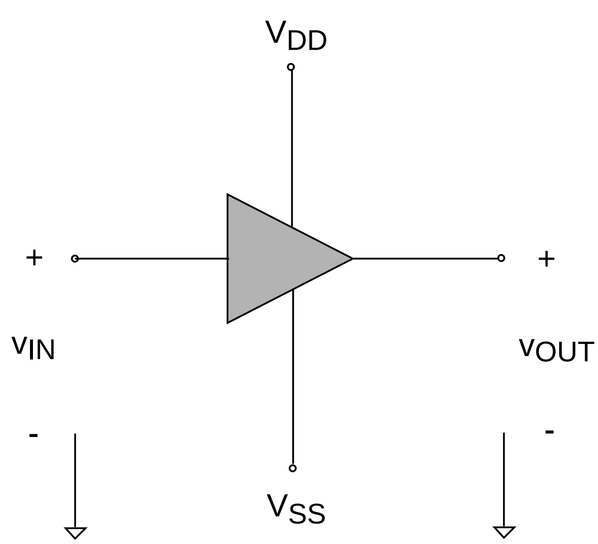
Key questions

- How can one design an amplifier that is insensitive to fluctuations in device parameters and power supply noise?
- What are the key figures of merit of a differential amplifier?
- Is there an efficient way to analyze a differential amplifier?

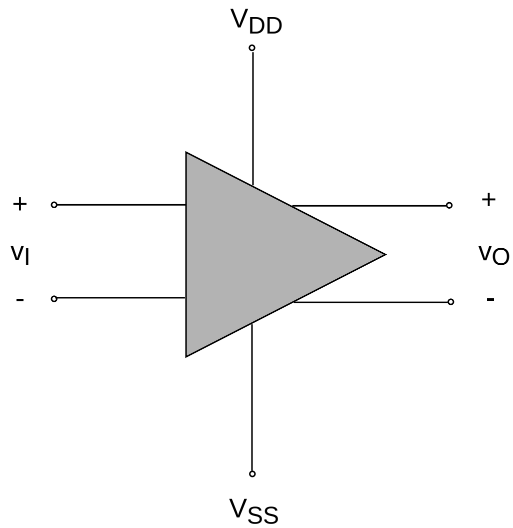
1. Introduction

Three problems in single-transistor amplifier stages:

- Bias and gain sensitive to device parameters (μC_{ox}, V_T); sensitivity can be mitigated but often paying price in performance or cost (gain, power, device area, etc.)
- Vulnerable to *ground and power-supply noise* (in dense IC's there is cross-talk, 60 Hz coupling, substrate noise, etc.)
- Many signal sources exhibit "common-mode" drift that gets amplified.



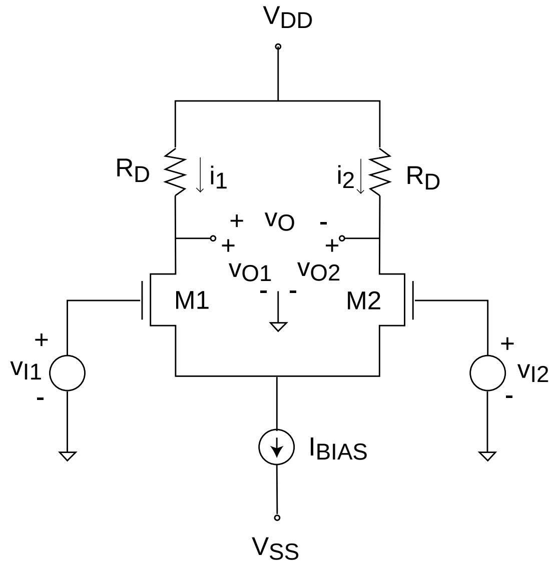
Solution: represent signal by *difference* between two voltages:



Differential amplifier:

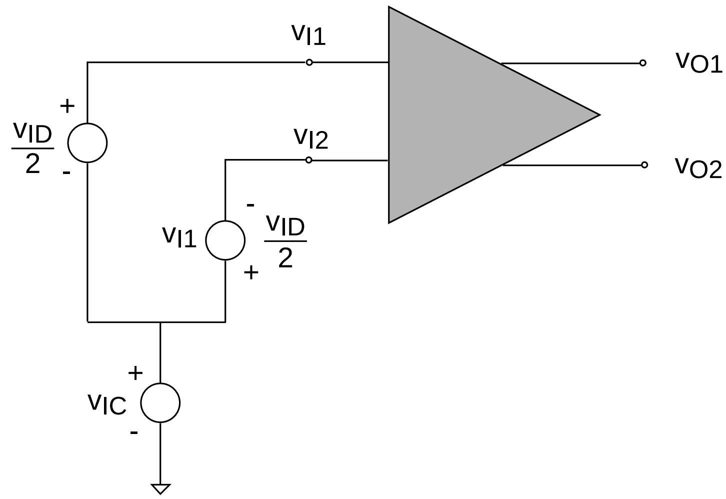
- amplifies <u>difference</u> between two voltages
- rejects components <u>common</u> to both voltages

□ Basic configuration of MOSFET diff. amp.:



- v_O responds to difference of v_I's
  - if $v_{I1} = v_{I2} \Rightarrow$ symmetry $\Rightarrow v_{O1} = v_{O2} \Rightarrow v_O = 0$
  - if $v_{I1} > v_{I2} \Rightarrow$ M1 more *ON* than M2 $\Rightarrow i_1 > i_2$ $\Rightarrow v_{O1} < v_{O2} \Rightarrow v_O < 0$
- v_O insensitive to common mode:
  - if both v_{O1} and v_{O2} move in sync, symmetry preserved $\Rightarrow v_O$ unchanged
  - if ground, V_{DD}, or V_{SS} have noise, symmetry preserved $\Rightarrow v_O$ unchanged
  - if V_T or μC_{ox} change, symmetry preserved $\Rightarrow v_O$ unchanged
- need precise device matching

□ *Differential-mode* and *common-mode* signals:



Distinguish between common mode and differential mode:

$$v_{I1} = v_{IC} + \frac{v_{ID}}{2}, \qquad v_{I2} = v_{IC} - \frac{v_{ID}}{2}$$

Then:

$$v_{ID} = v_{I1} - v_{I2}, \qquad v_{IC} = \frac{v_{I1} + v_{I2}}{2}$$

Similarly at output:

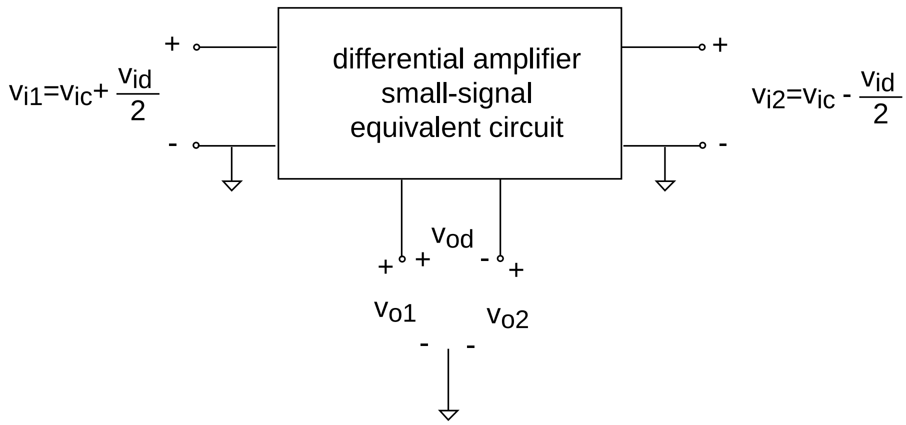
$$v_{O1} = v_{OC} + \frac{v_{OD}}{2}, \qquad v_{O2} = v_{OC} - \frac{v_{OD}}{2}$$

Then:

$$v_{OD} = v_{O1} - v_{O2} \qquad v_{OC} = \frac{v_{O1} + v_{O2}}{2}$$

2. Incremental analysis of differential amplifier

Consider generic differential amplifier:



Figures of merit of interest:

Differential-mode voltage gain (want high):

$$a_{dm} = \frac{v_{od}}{v_{id}}$$

Common-mode voltage gain (want small):

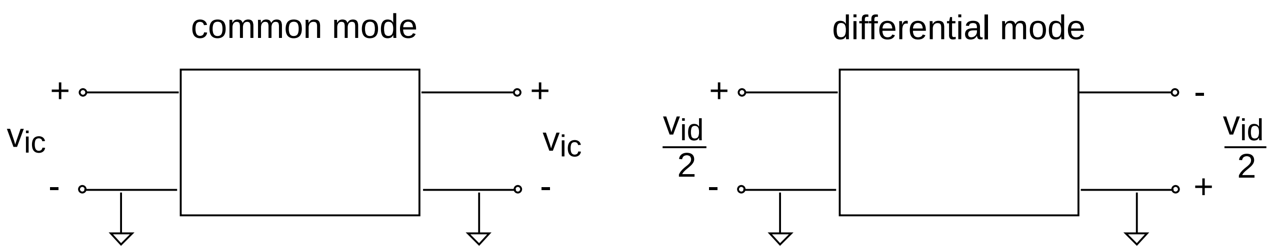
$$a_{dc} = \frac{v_{oc}}{v_{ic}}$$

Common-mode rejection ratio (want very high):

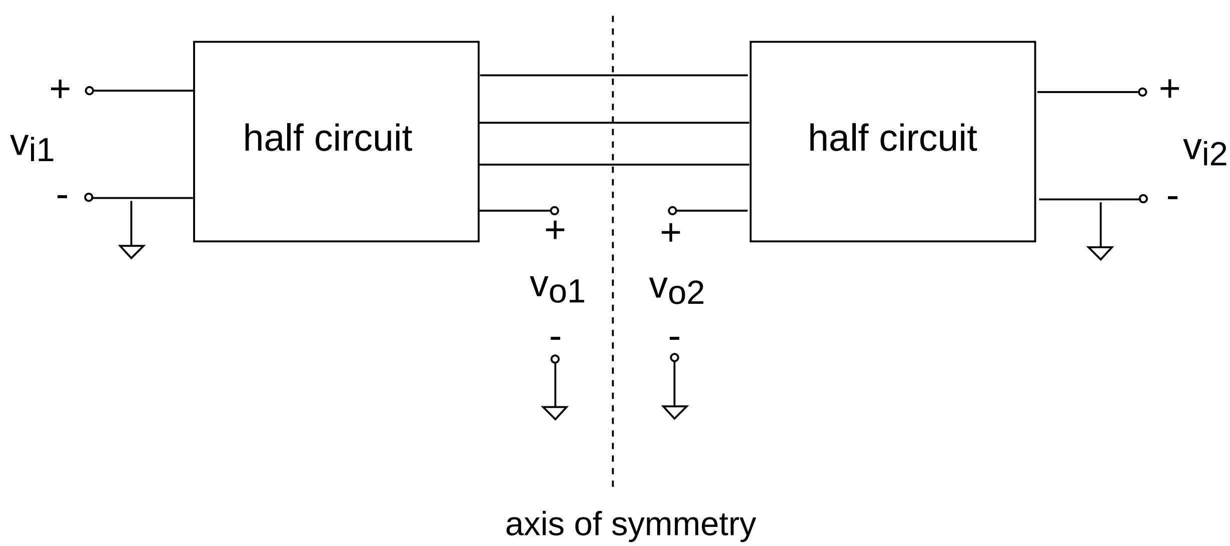
$$CMRR = \frac{a_{dm}}{a_{cm}}$$

Two steps to simplify solution of problem:

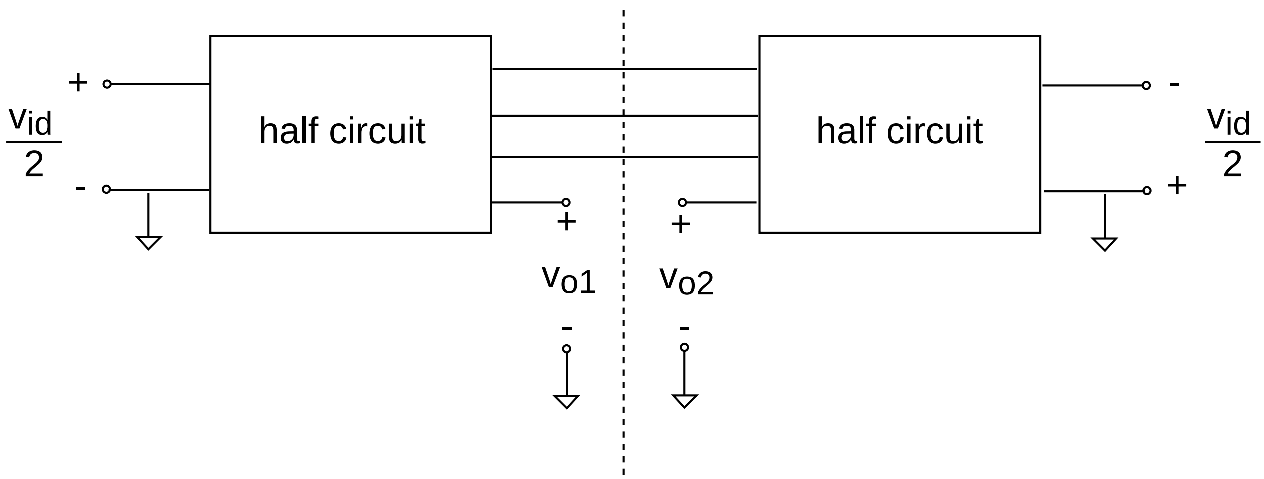
1. Use superposition and break into two problems:



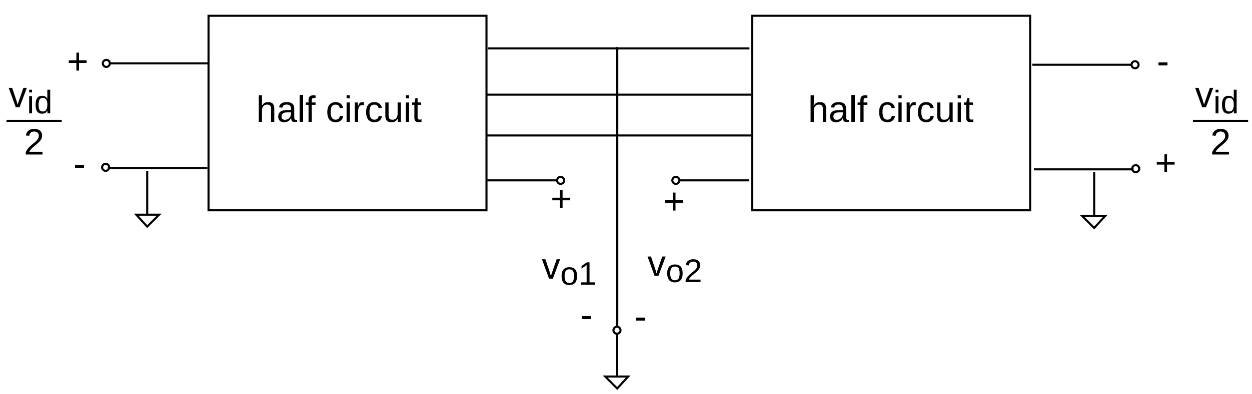
2. Exploit symmetry: break circuit into two "half circuits"



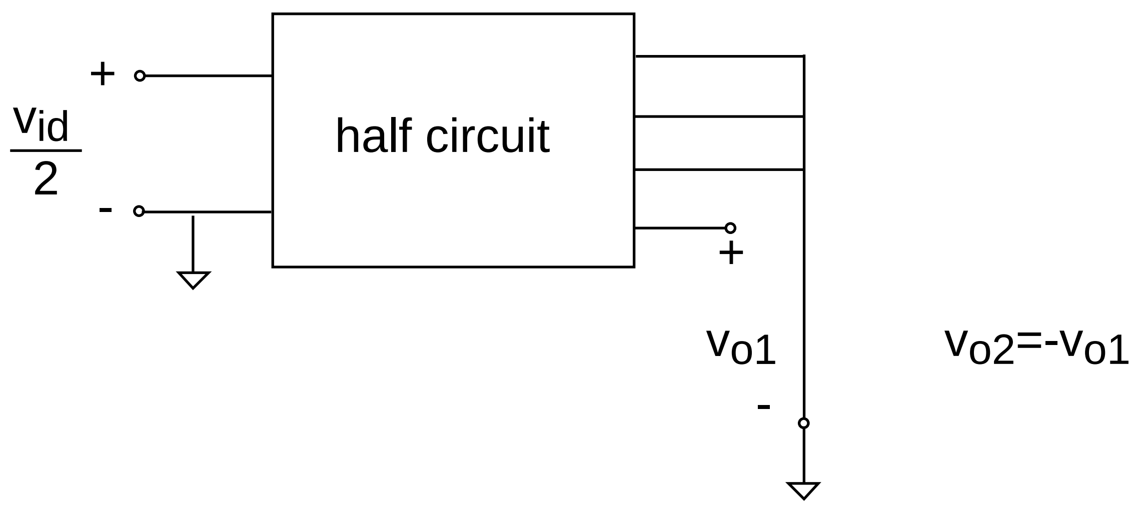
a) Differential-mode analysis:



No voltage relative to ground along axis of symmetry $\Rightarrow$ circuit identical to:



Need only solve:



Differential-mode voltage gain:

$$a_{dm} = \frac{v_{od}}{v_{id}} = \frac{v_{o1} - v_{o2}}{v_{i1} - v_{i2}}$$

In differential mode:

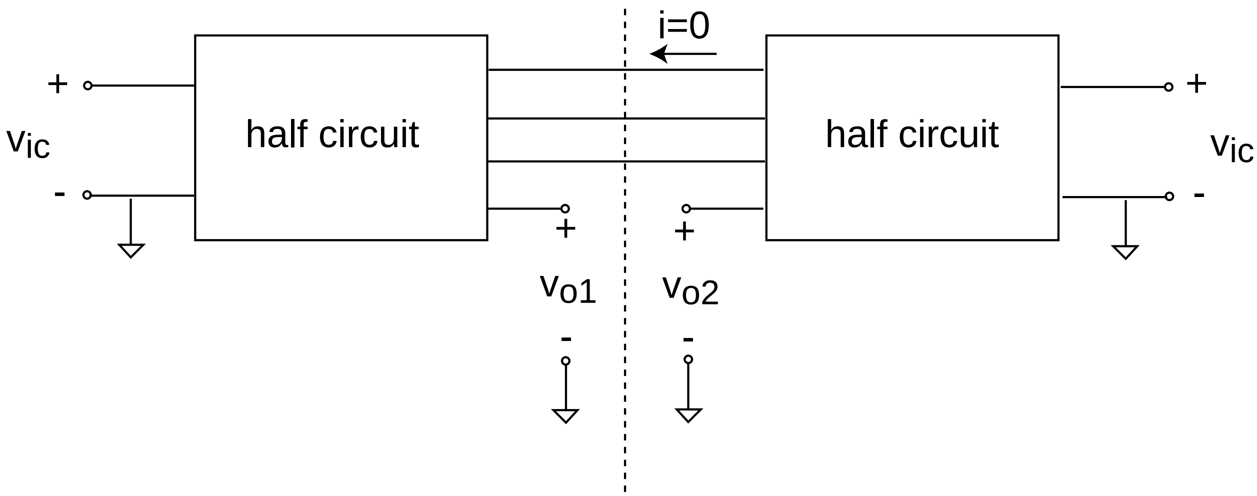
$$v_{i1} = -v_{i2} = \frac{v_{id}}{2}$$

$$v_{o1} = -v_{o2}$$

Then:

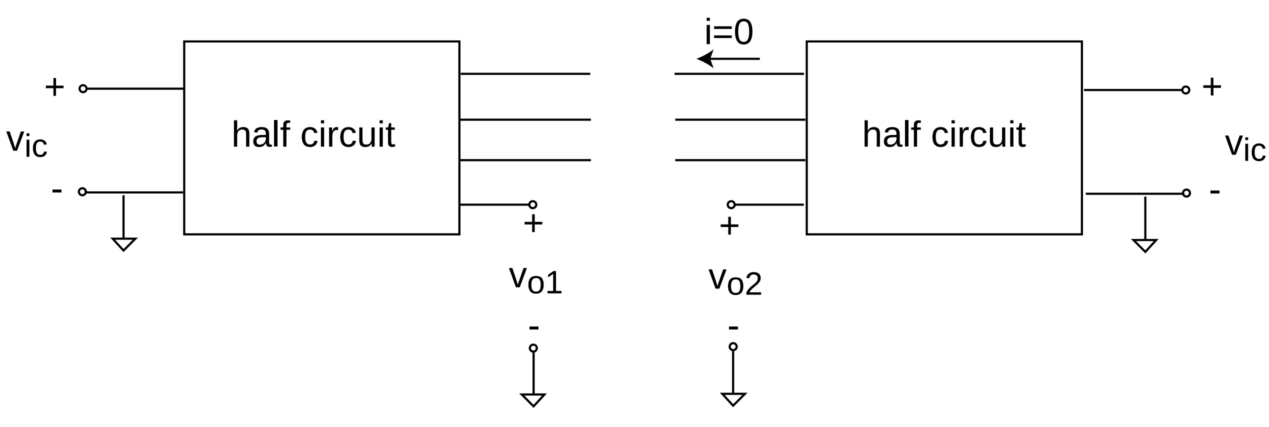
$$a_{dm} = \frac{2v_{o1}}{v_{id}} = \frac{v_{o1}}{\frac{v_{id}}{2}}$$

b) Common-mode analysis:

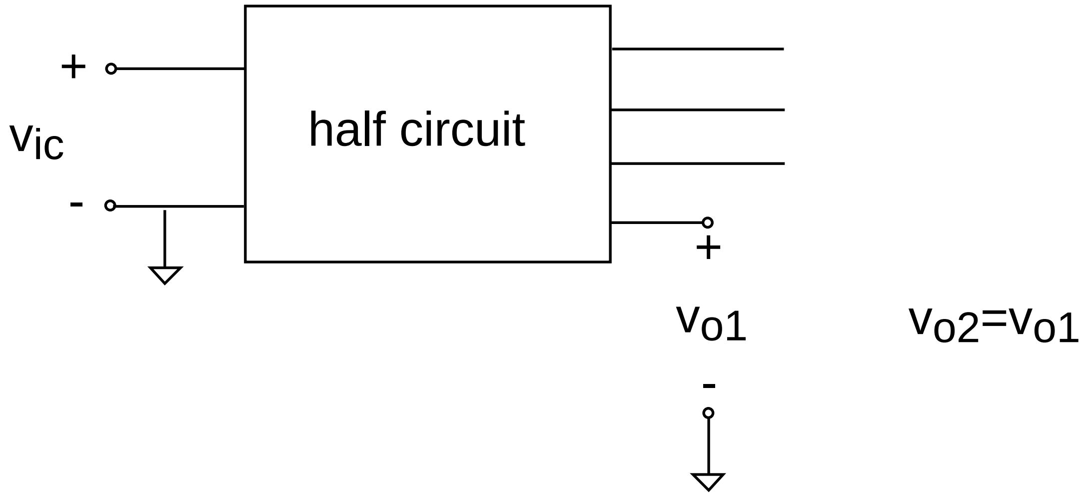


no current across

No current across wires connecting two half circuits $\Rightarrow$ circuit identical to:



Need only solve:



Common-mode voltage gain:

$$a_{cm} = \frac{v_{oc}}{v_{ic}} = \frac{\frac{v_{o1}+v_{o2}}{2}}{v_{ic}}$$

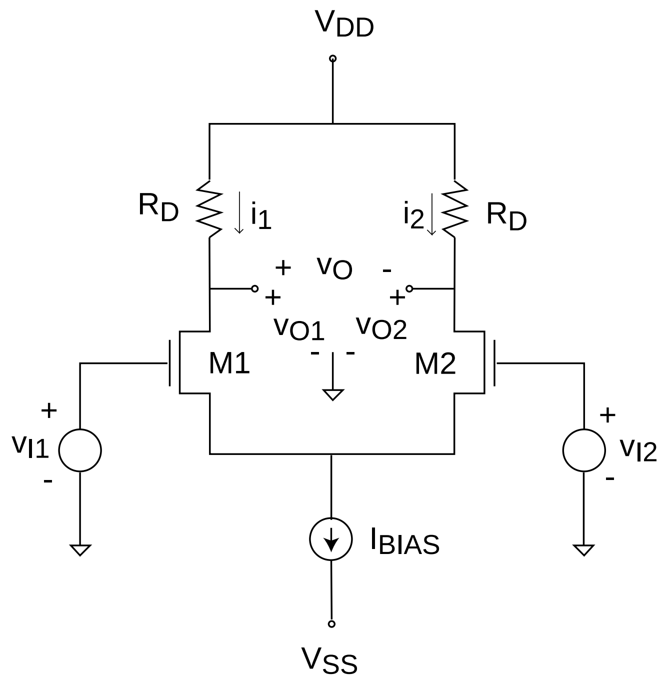
In common mode,

$$v_{o1} = v_{o2}$$

Then:

$$a_{cm} = \frac{v_{o1}}{v_{ic}}$$

3. Common-source differential amplifier (*source-coupled pair*)



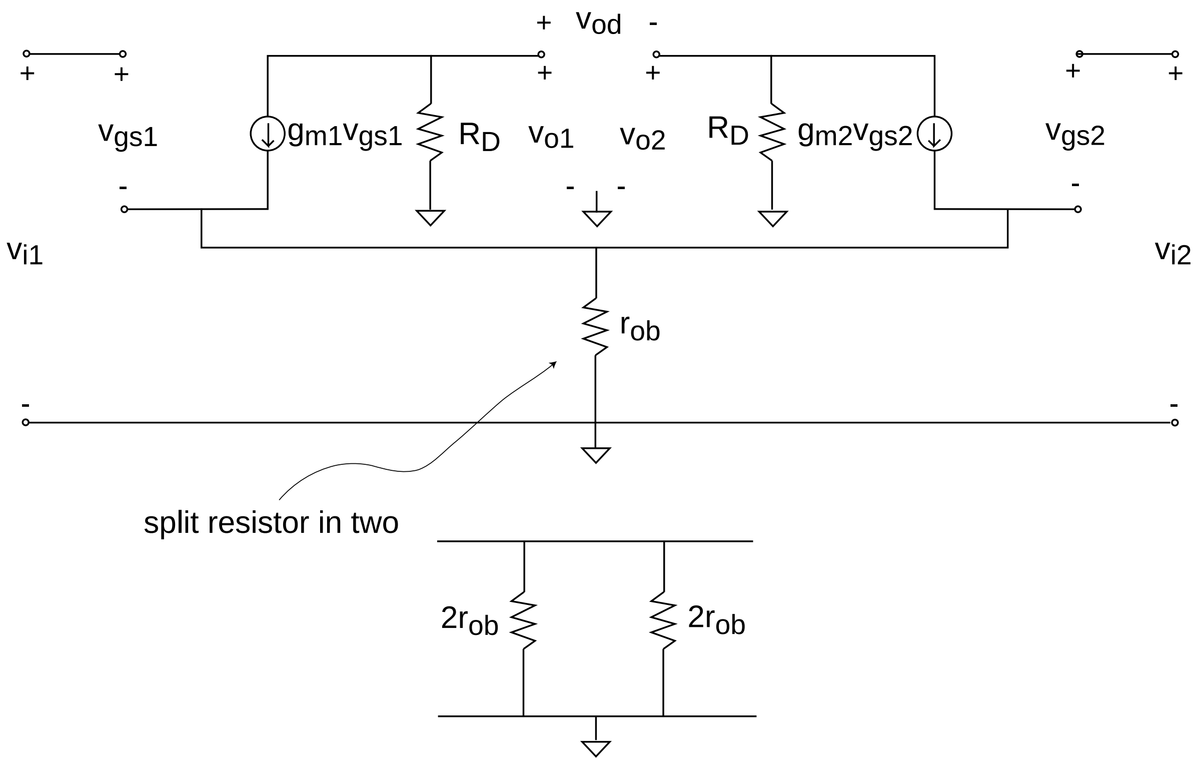
□ Biasing issues: must keep MOSFET's in saturation

• Upper limit to V_{I1} and V_{I2}: M1 and M2 driven into linear regime:

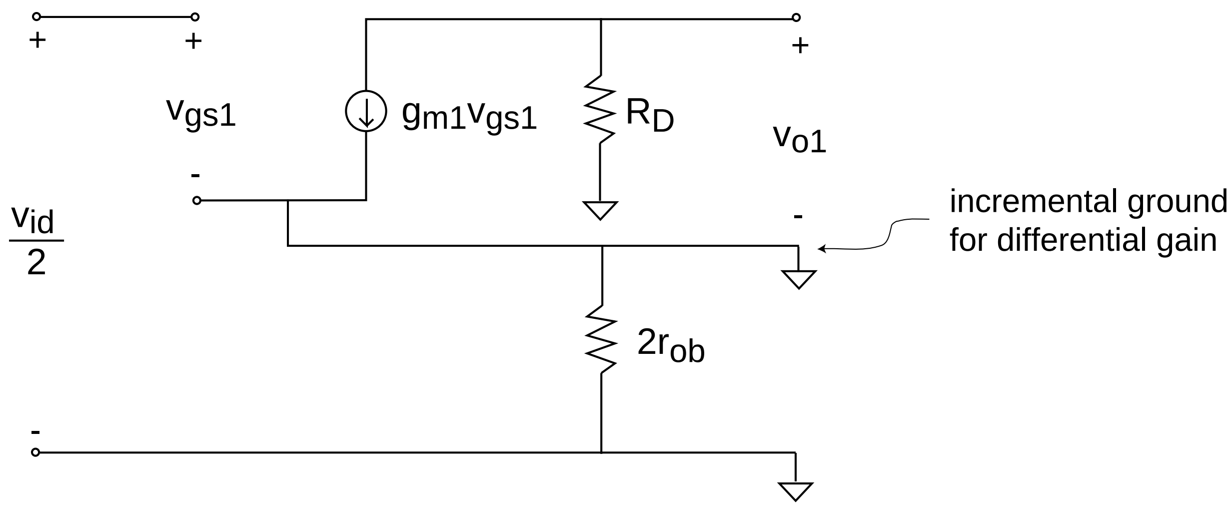
$$V_{IC,max} = V_{O1} + V_T = V_T + V_{DD} - R_D \frac{I_{BIAS}}{2}$$

• Lower limit to V_{I1} and V_{I2}: set by circuit that implements I_{BIAS}

□ Small-signal equivalent circuit model:



- Differential-mode half circuit:

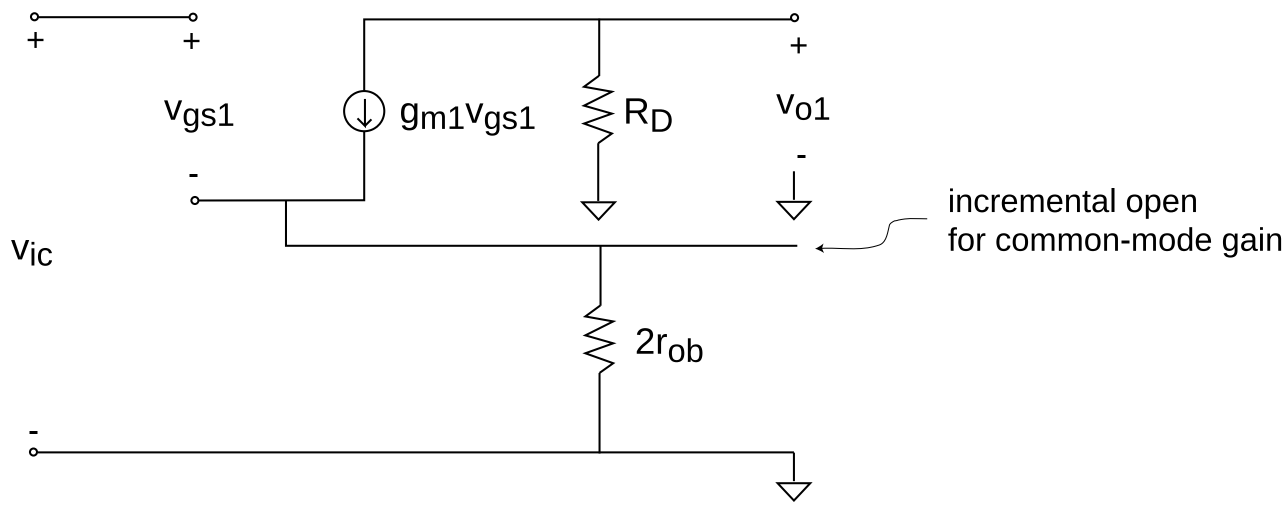


$$v_{o1} = -g_{m1} R_D \frac{v_{id}}{2}$$

Then differential-mode gain:

$$a_{dm} = \frac{v_{o1}}{\frac{v_{id}}{2}} = -g_{m1} R_D$$

• Common-mode half circuit:



$$v_{o1} = -\frac{g_{m1}R_D}{1 + 2g_{m1}r_{ob}}v_{ic}$$

Then common-mode gain:

$$a_{cm} = \frac{v_{o1}}{v_{ic}} = -\frac{g_{m1}R_D}{1 + 2g_{m1}r_{ob}}$$

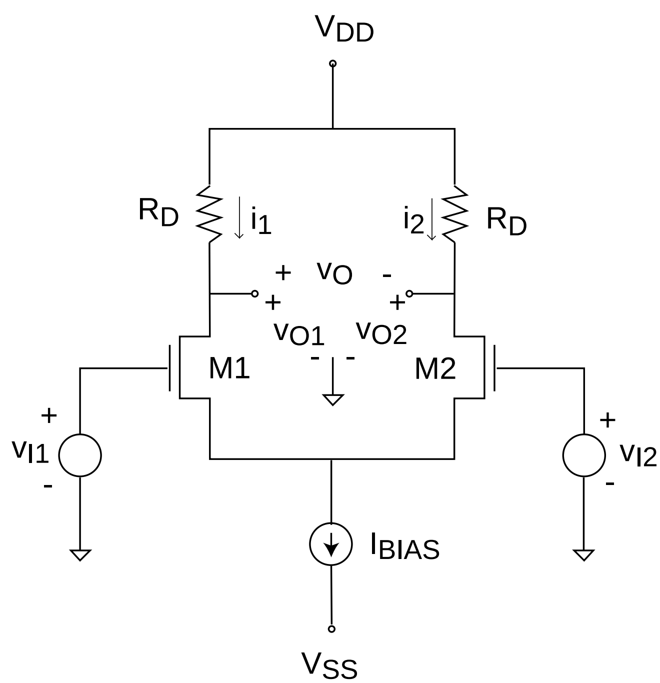
Common-mode rejection ratio:

$$CMRR = \frac{a_{dm}}{a_{cm}} = \frac{-g_{m1}R_D}{-\frac{g_{m1}R_D}{1+2g_{m1}r_{ob}}} = 1 + 2g_{m1}r_{ob}$$

To get good $CMRR$, need good current source.

Key for common-mode rejection:

$\Rightarrow r_{ob}$ must be as high as possible



The higher r_{ob}, the smaller the change in I_{BIAS} in response to a common-mode signal $\Rightarrow$ the smaller the change in v_{01} and v_{o2}.

Key conclusions

- In differential amplifiers signal represented by *difference* between two voltages.
- Differential amplifier: amplifies difference between two voltages but rejects "common mode" ⇒ noise immunity.
- Using "half-circuit" technique, small-signal operation of differential amplifiers is analized by breaking problem into two simpler ones: differential-mode problem and common-mode problem.
- *Common-mode rejection ratio*: important figure of merit of differential amplifiers.
- Differential amplifiers require good device matching.