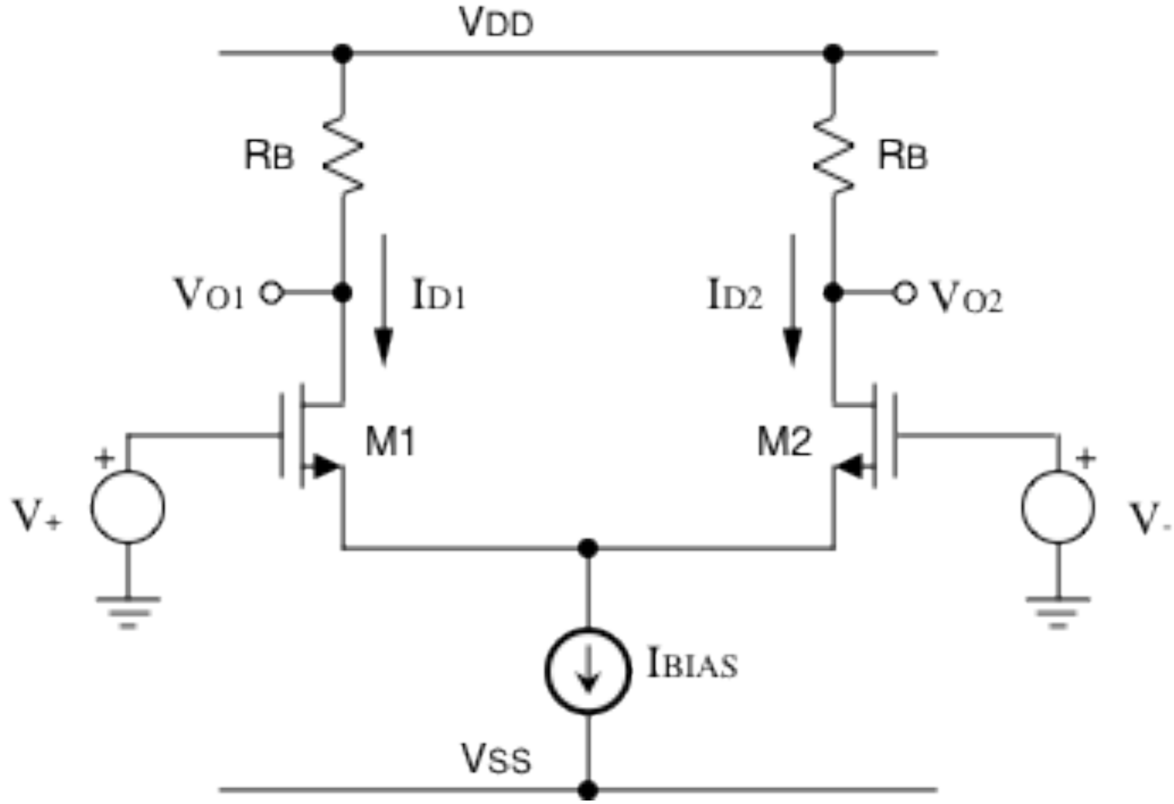
Studio 7 Overview

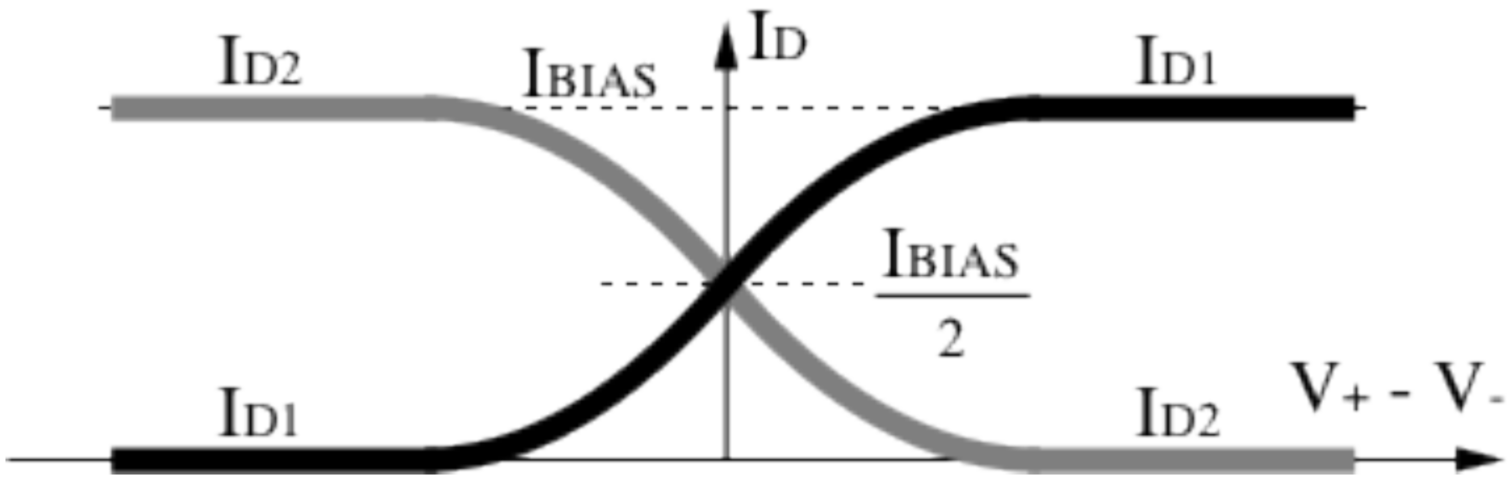
- **Differential Amplifier, Current Mirror Load**
  - **Textbook Razavi 4.1-4.3, 5.3**

Circuit: Differential Amplifier (Resistive Load)



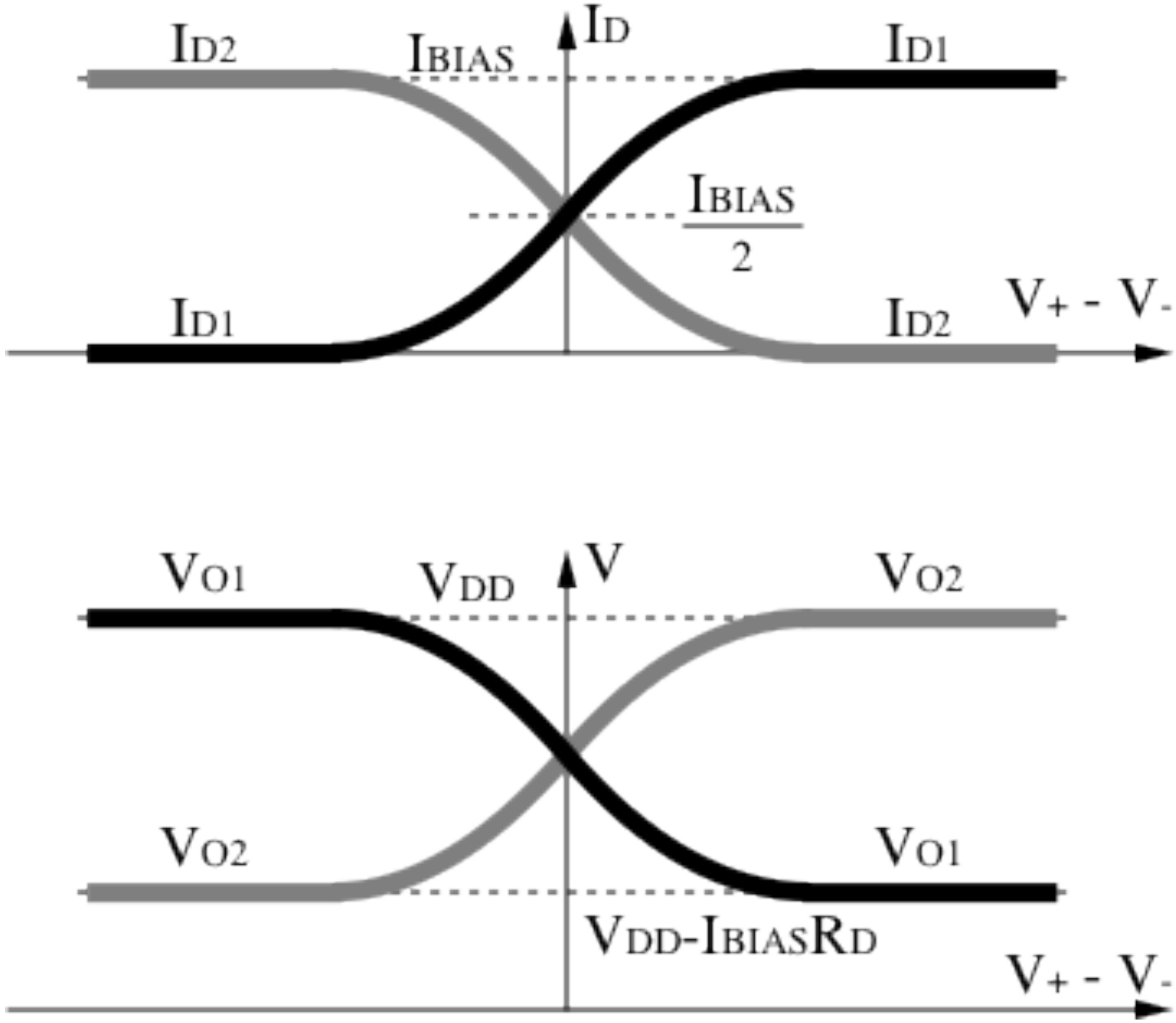
Differential input voltage controls "split" of I_{BIAS} to I_{D1}, I_{D2}

Qualitative V-I Characteristic: "Connect the dots"



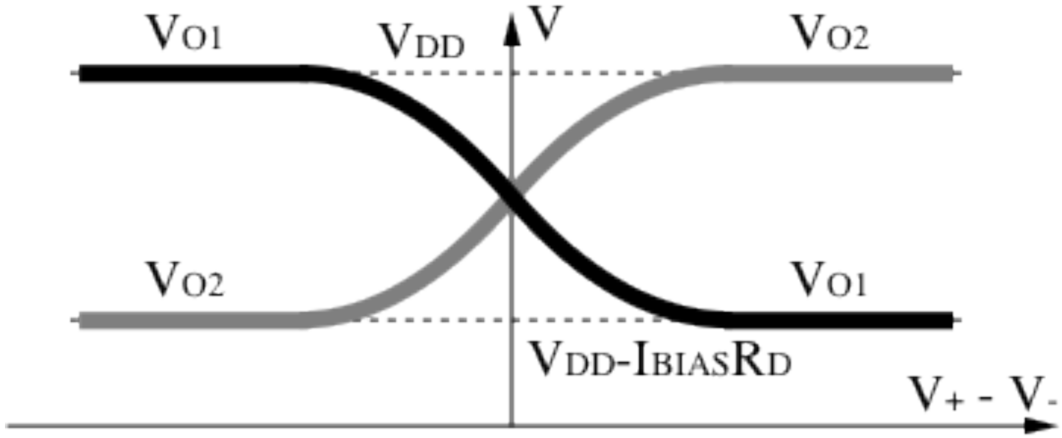
- **General shape for any differential pair: MOSFET, BJT, JFET, ...**
- **Specifics depend on bias, technology, etc.**

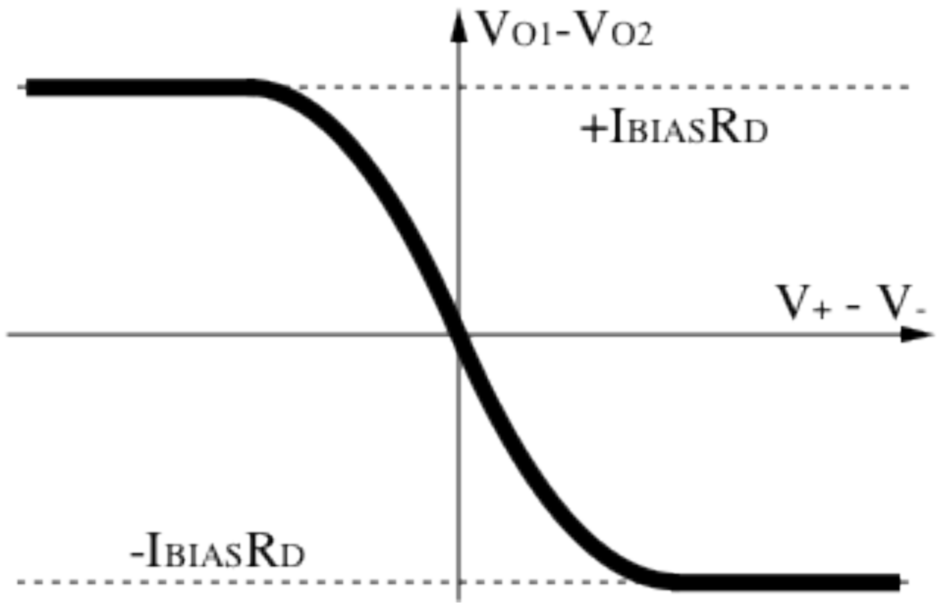
Voltage Output



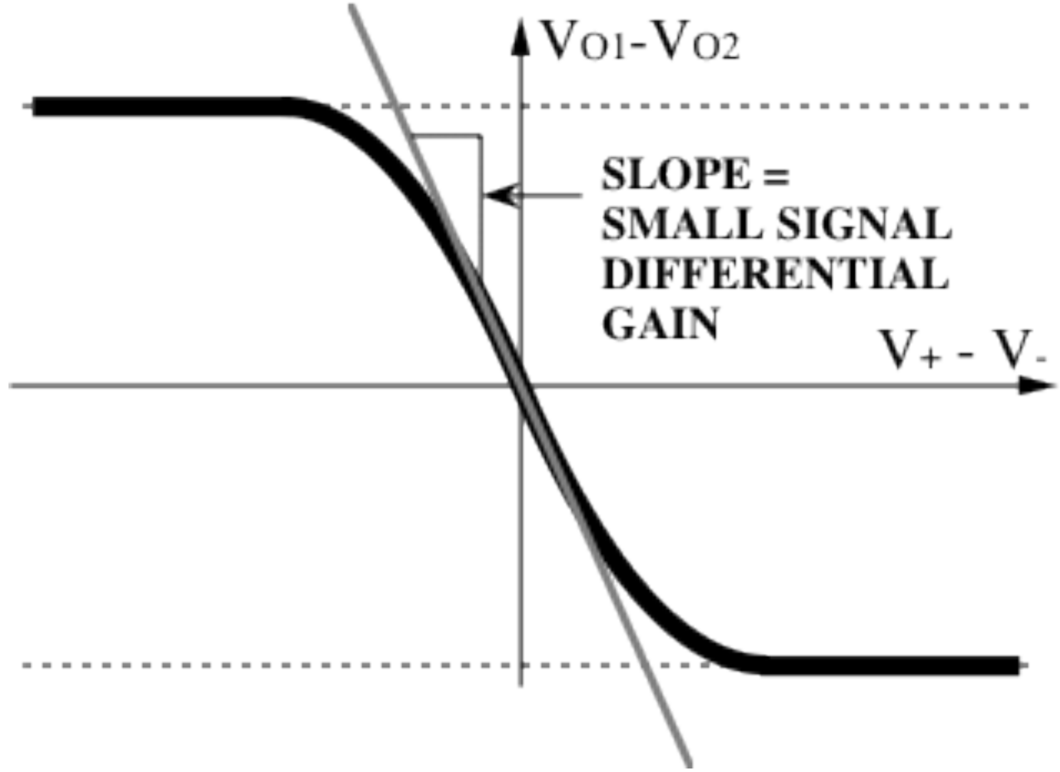
$V_{O1} = V_{DD} - I_{D1}R_D$ $\qquad$ $V_{O2} = V_{DD} - I_{D2}R_D$

Differential Voltage Output: $V_{OD} = V_{O1} - V_{O2}$





Differential Voltage Output



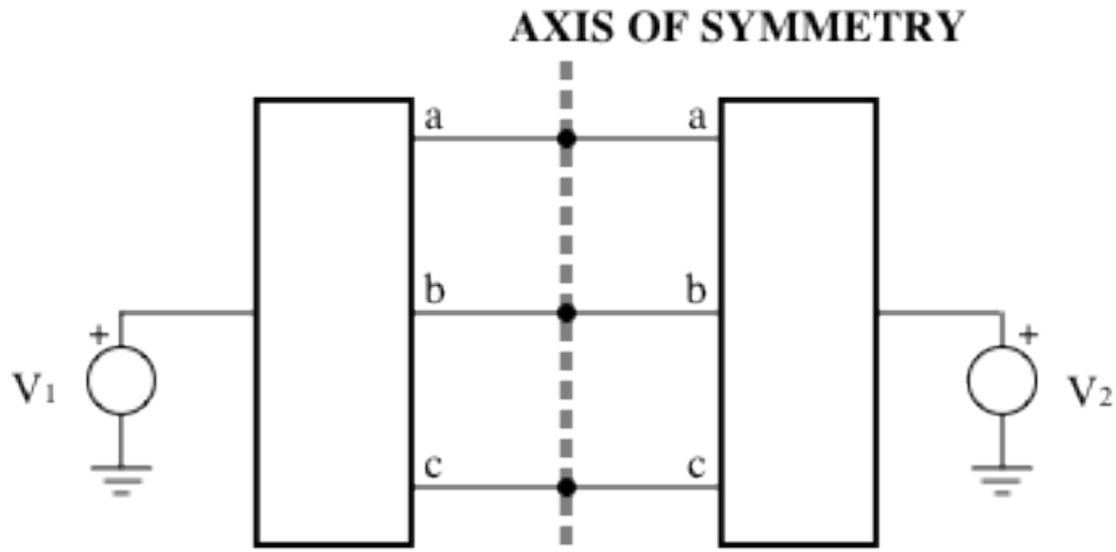
- **Slope of plot at operating point (origin): Small signal differential gain $a_{v(diff)}$**

Differential Gain

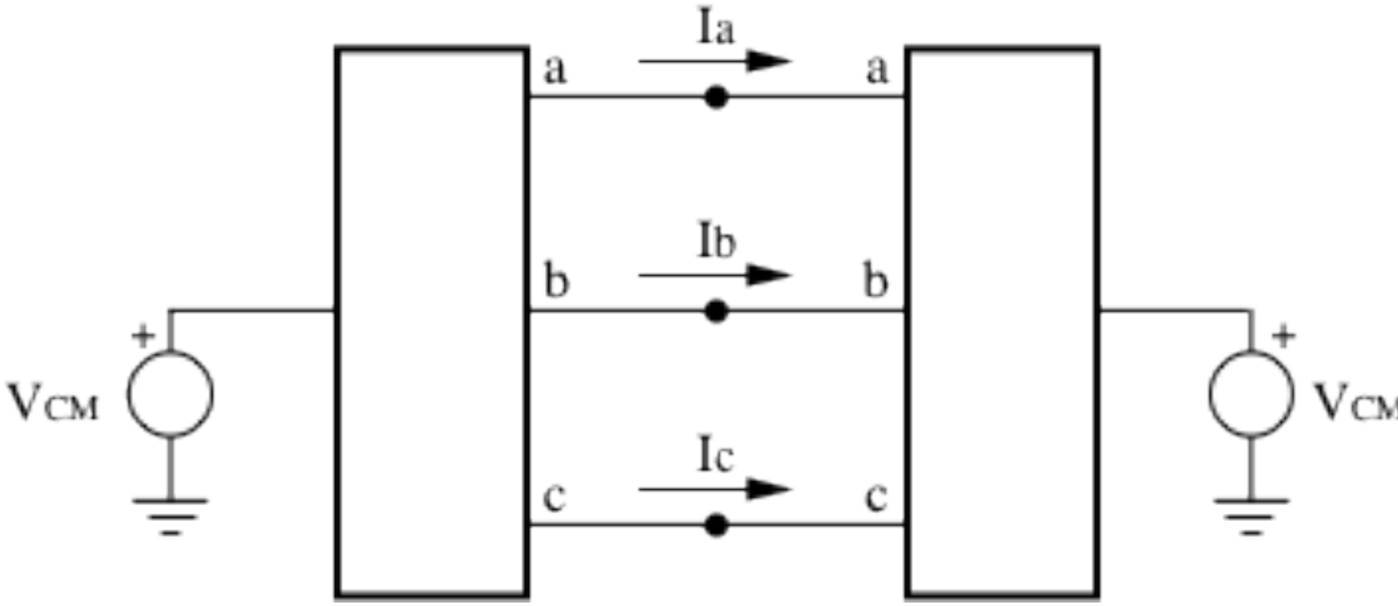
- **Need to improve $\Rightarrow$ need to be quantitative**
- **Analytic tool:**
  Bartlett's Bisection Theorem
- **Applies for symmetrical circuits**
- **Simplifies analysis:**
  Allows splitting of circuit into separate halves

Bartlett's Bisection Theorem

- **Two completely symmetrical circuits a, b, c are connected points of symmetry**

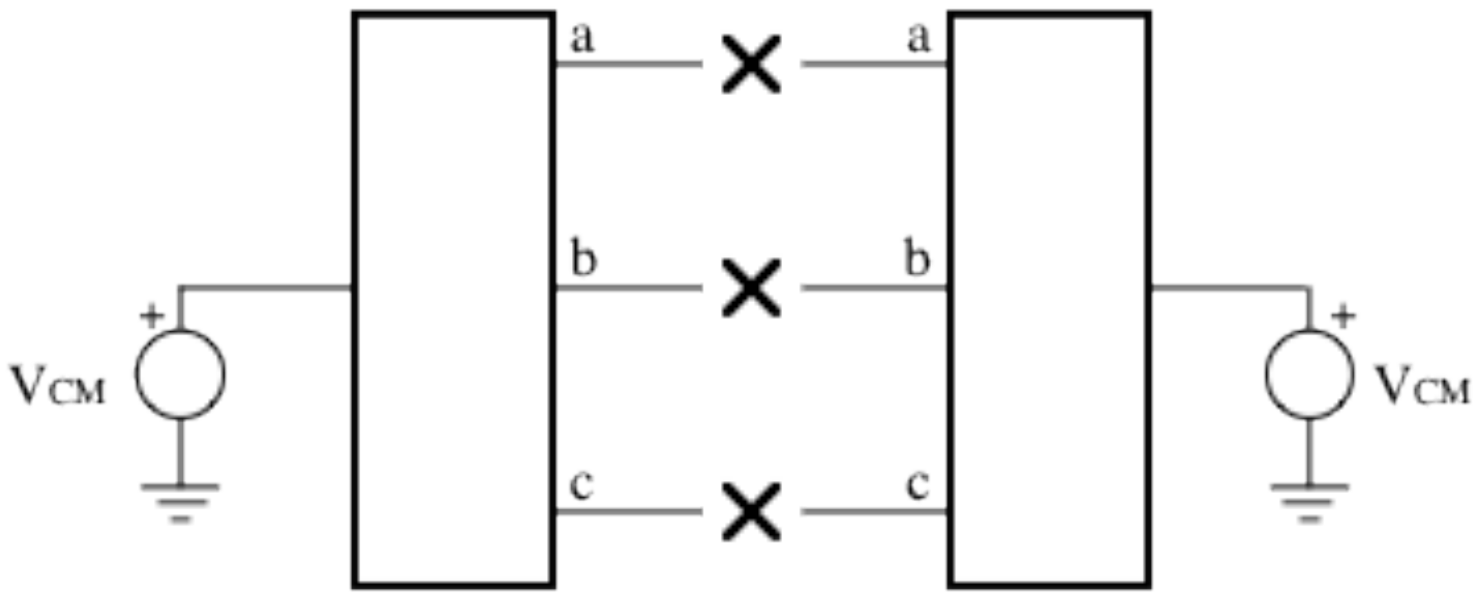


Common mode: Symmetric excitation



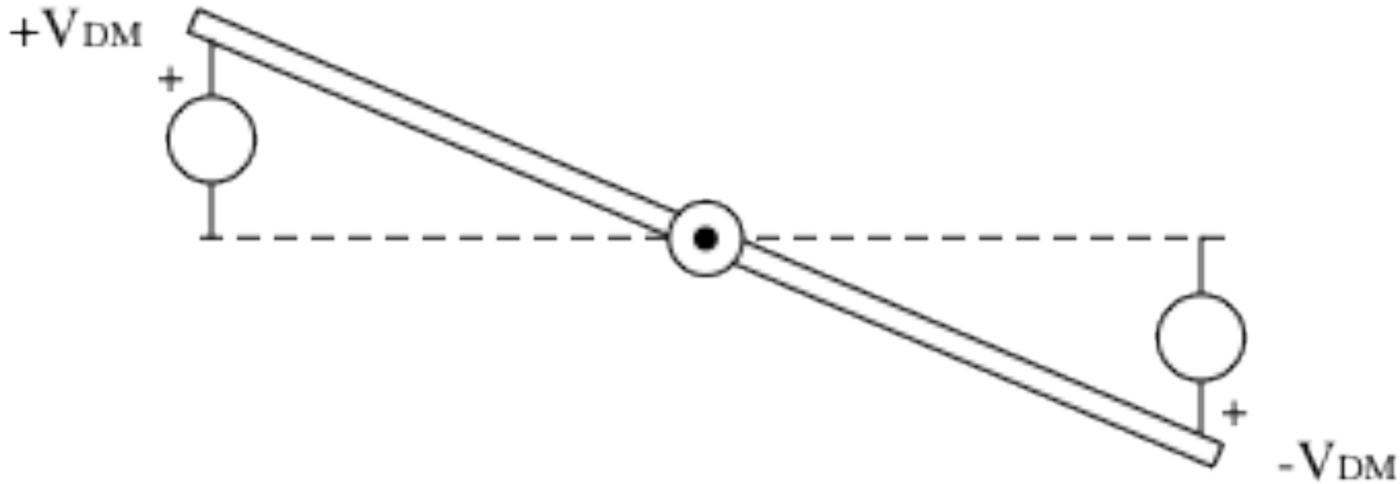
- If $V_1 = V_2 = V_{CM}$ (same input to both circuits)
- No current at connected points of symmetry
- Imagine mirror reversal: $I_a = -I_a \Rightarrow I_a = 0$

Common mode: Symmetric excitation



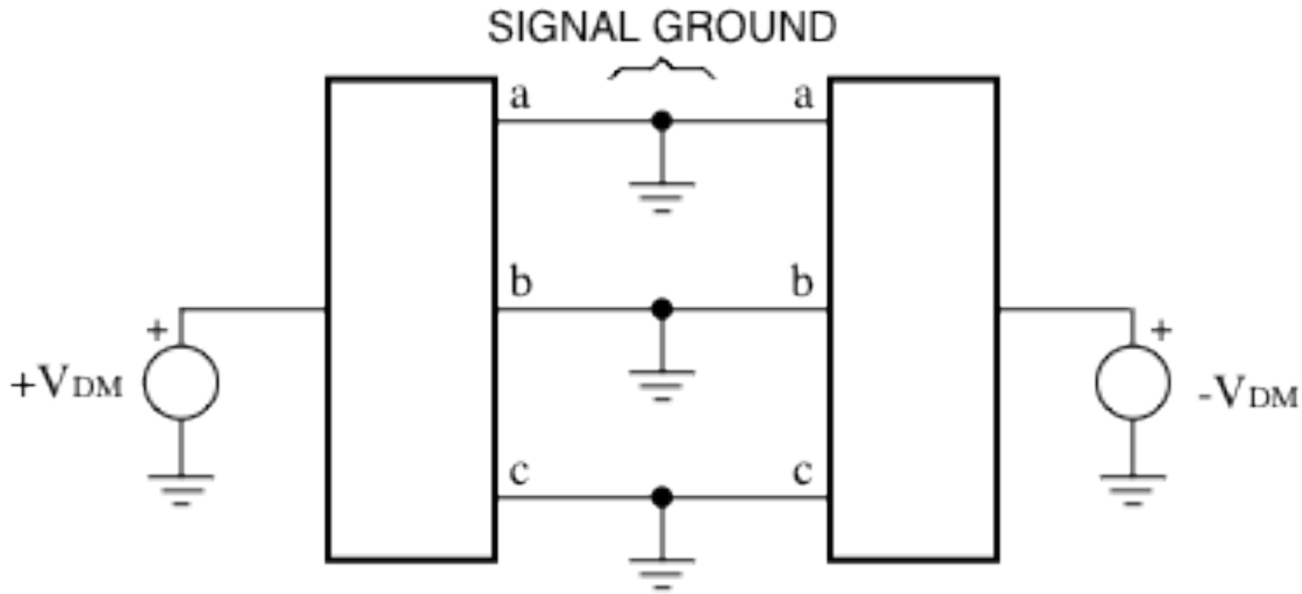
- We can open all leads between connected points of symmetry without affecting circuit operation
- Applies for any circuit (linear or nonlinear)

Differential mode: Antisymmetric excitation



If V_1 = $-V_2$: "See-Saw":
Fixed voltage at connected points of symmetry

Differential mode: Antisymmetric excitation

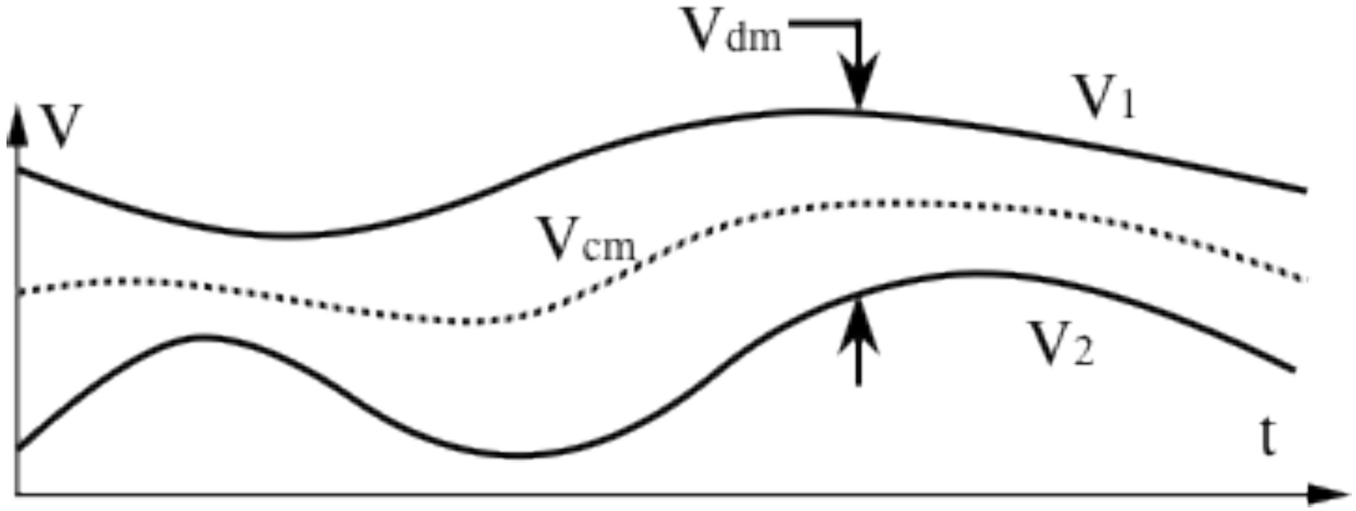


- All leads between connected points of symmetry can be tied to <u>small signal</u> ground without affecting circuit operation
- Requires linearity

Bartlett's Bisection Theorem

- Applies to symmetric circuits
- Common mode (symmetric) excitation
  - Open connected points of symmetry
- Differential (antisymmetric) excitation
  - Connected points of symmetry tied to signal ground
  - Requires linearity

Any two signals!



Can be expressed as sum of common mode, differential mode:

Any two signals!

- **Define:**

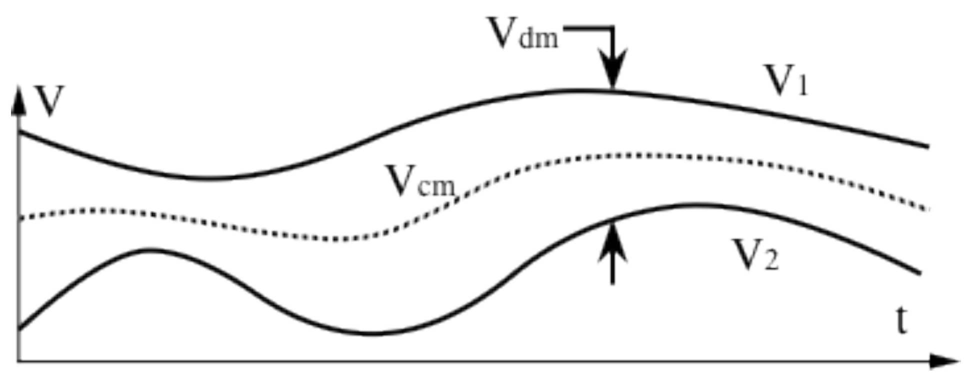
$$V_{CM} = \frac{V_1 + V_2}{2}$$

$$V_{dm} = V_1 - V_2$$

- **Can verify:**

$$V_1 = V_{CM} + \frac{V_{dm}}{2}$$

$$V2 = V_{CM} - \frac{V_{dm}}{2}$$

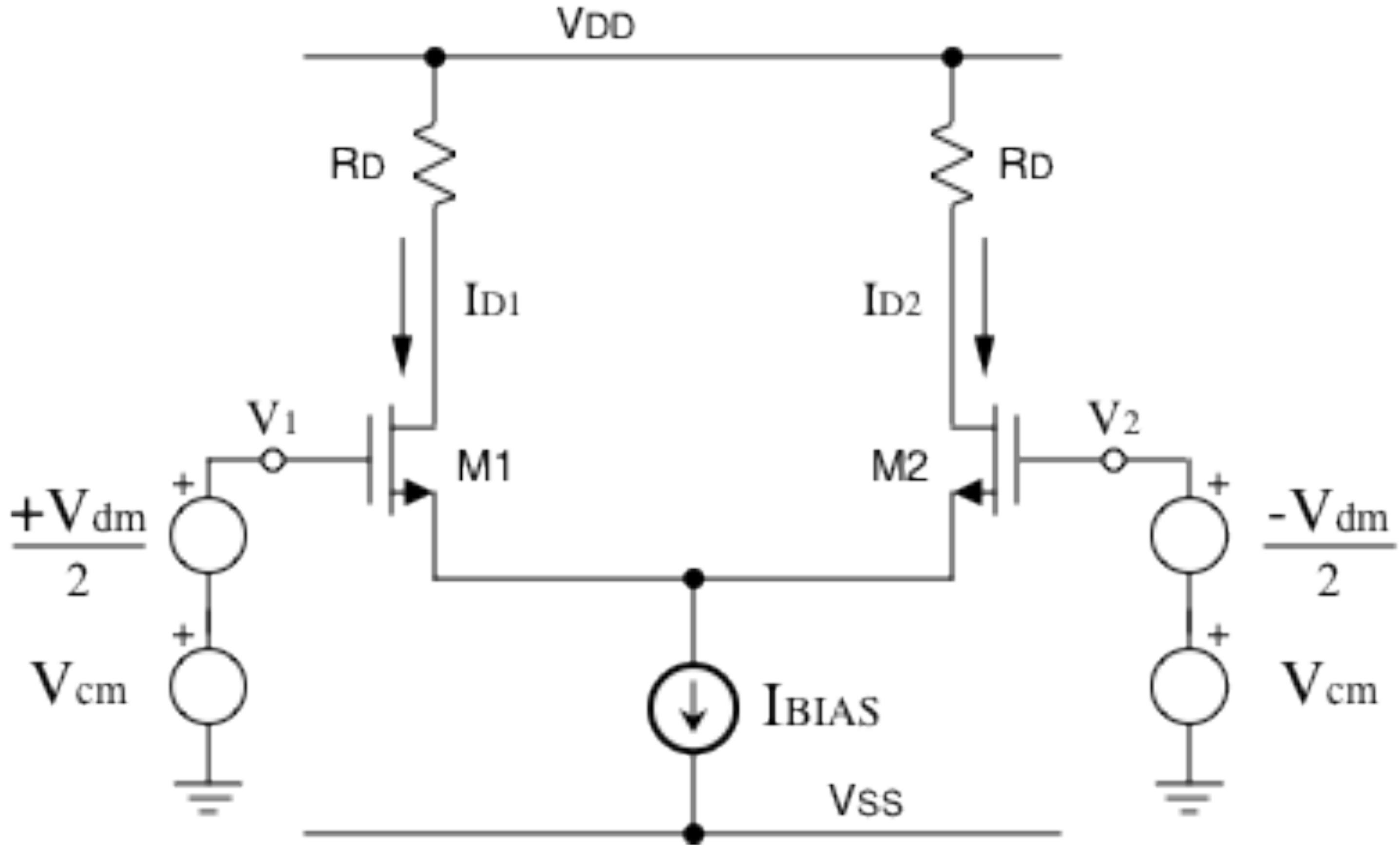


Half circuit analysis technique

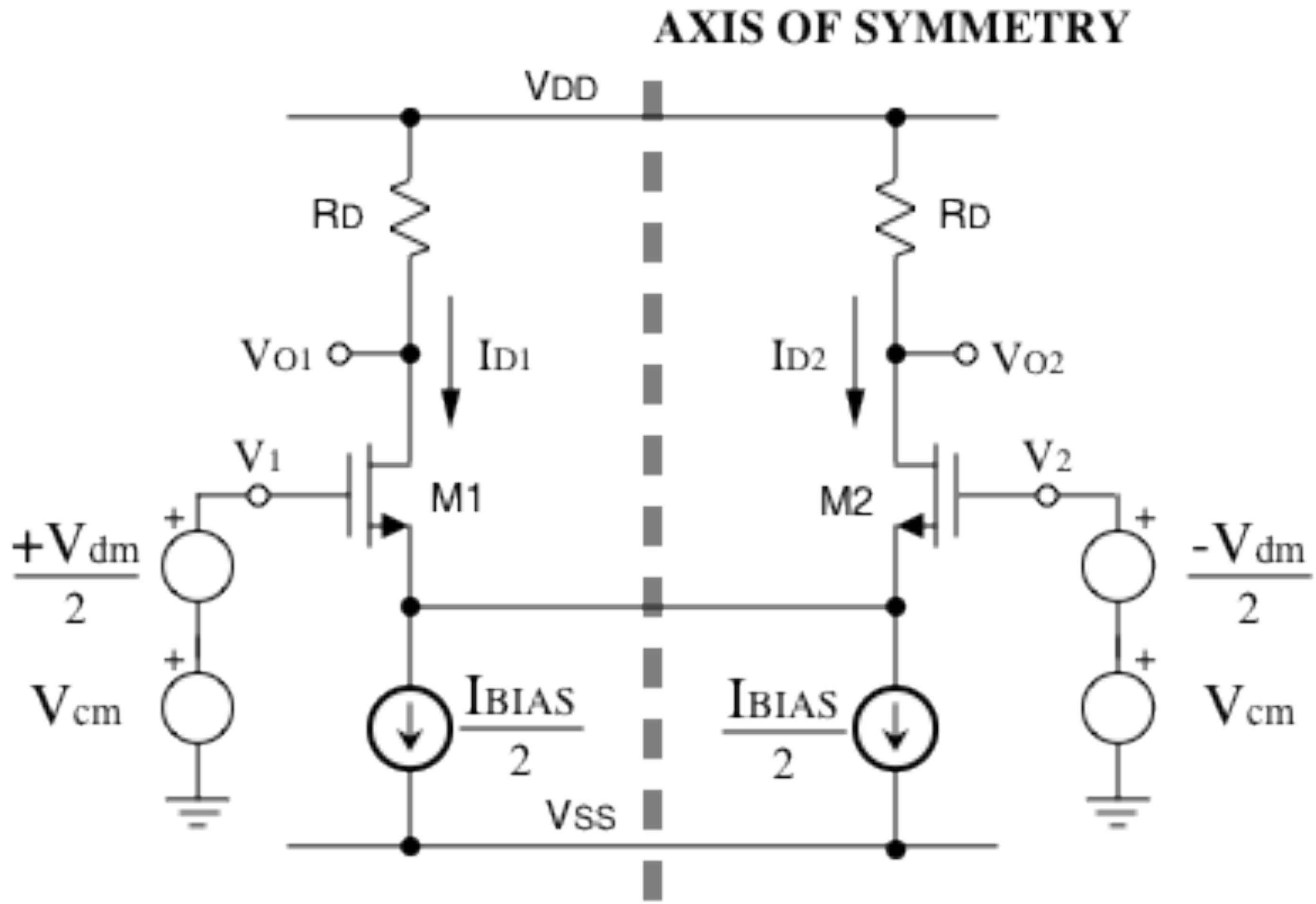
1) Represent inputs in terms of V_{dm}, V_{CM}
2) Redraw circuit to emphasize symmetry
3) Use superposition to find output:
   - DC bias: V_1, $V_2 = 0$ (all inputs suppressed)
   - CM Response: keep v_{CM} , set $v_{dm} = 0$
   - DM response: keep v_{dm} , set $v_{CM} = 0$
   - Add results for total output

- Split circuit using bisection theorem:
  - Analyze each half separately

1) Represent inputs in terms of V_{dm}, V_{cm}



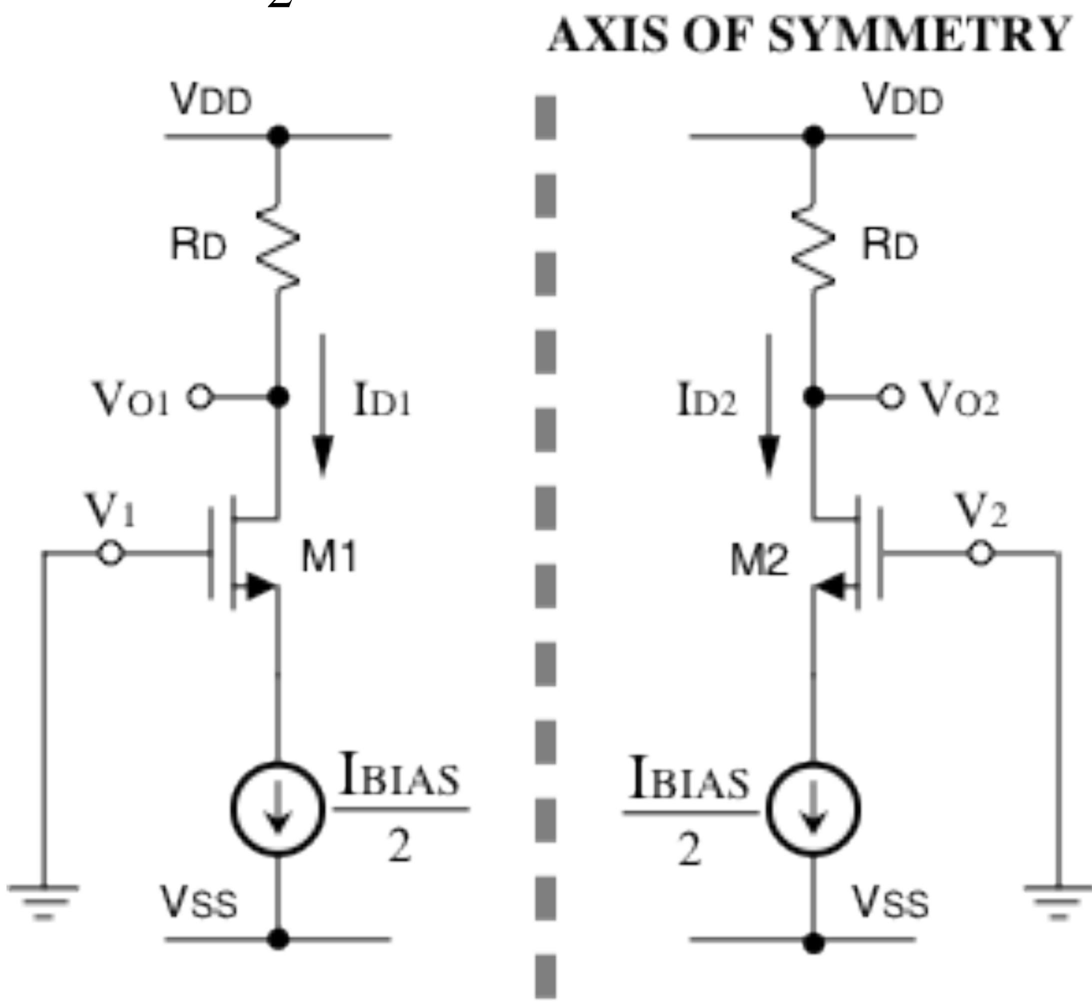
2) Redraw to show symmetry



- I_{BIAS} equivalent: two $I_{BIAS}/2$ in parallel

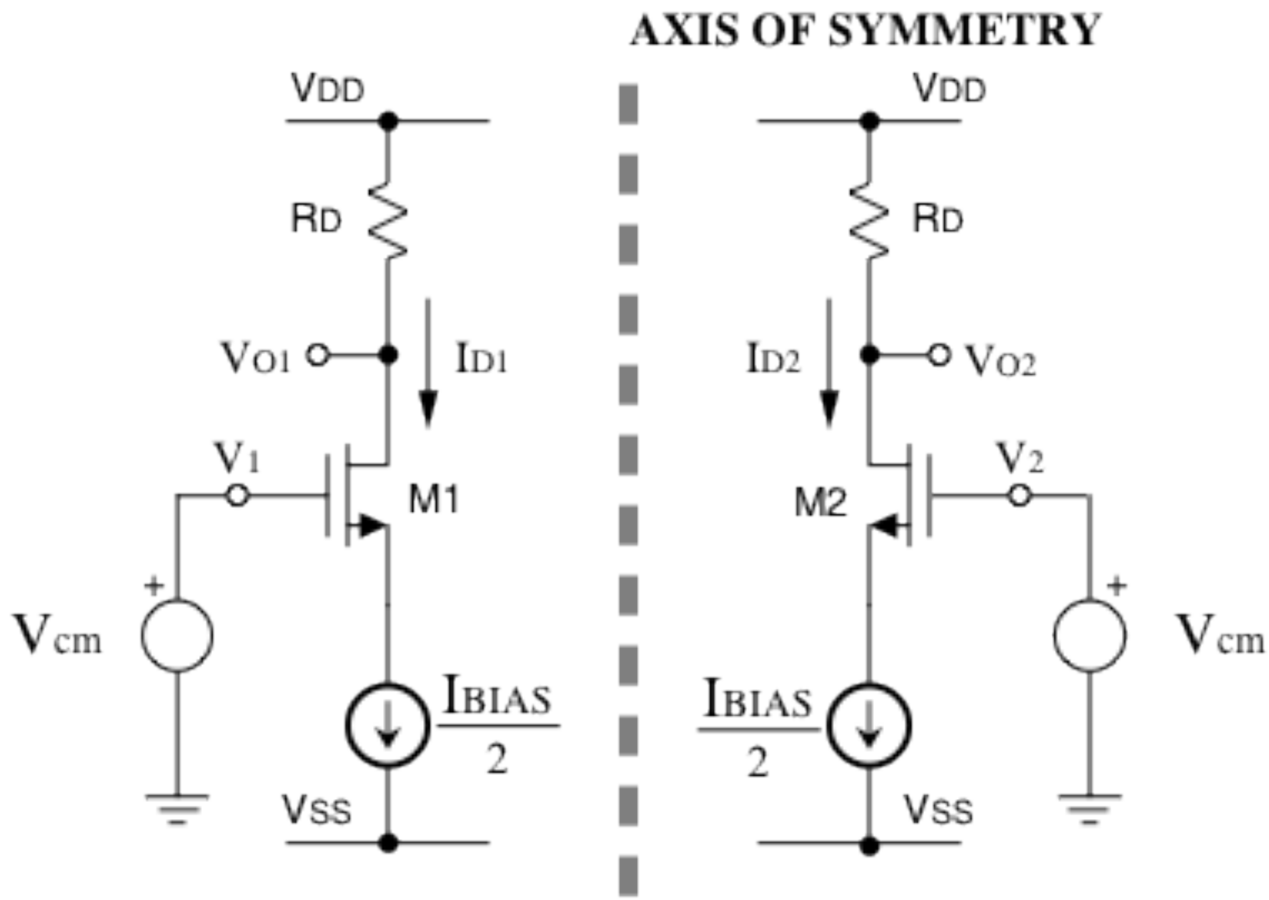
DC bias: $V_1, V_2 = 0$ (all signal inputs suppressed)

$$V_{O1(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D \qquad V_{O2(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D$$



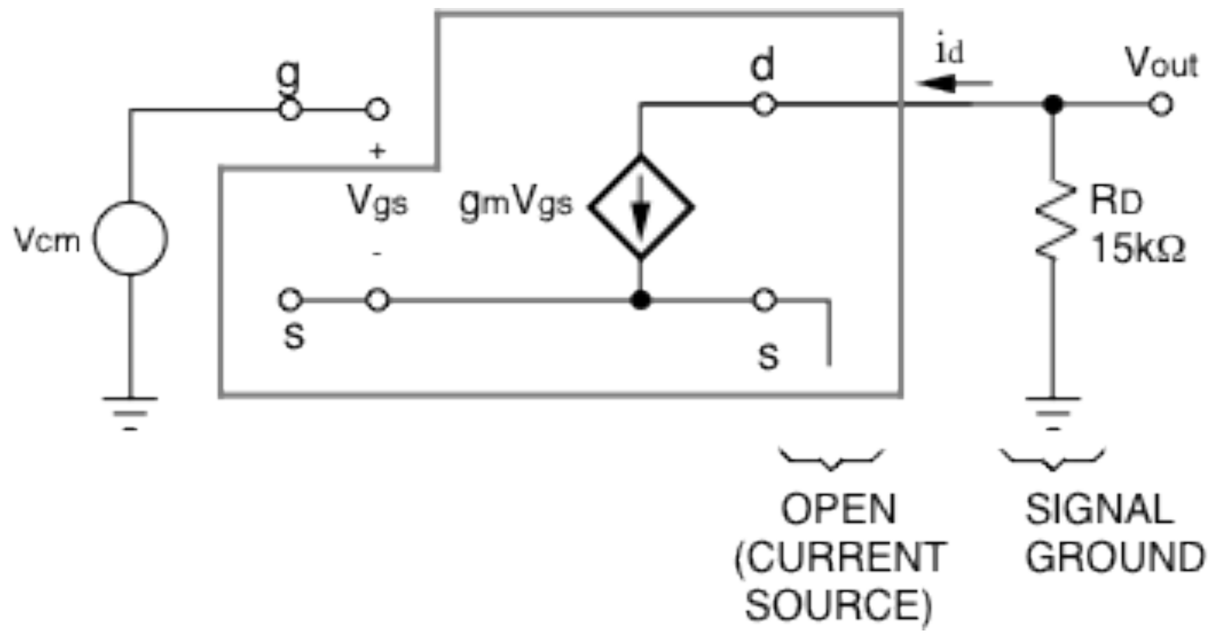
- **Symmetric excitation:**
  open connected points of symmetry

Common Mode Response: $v_{dm} = 0$



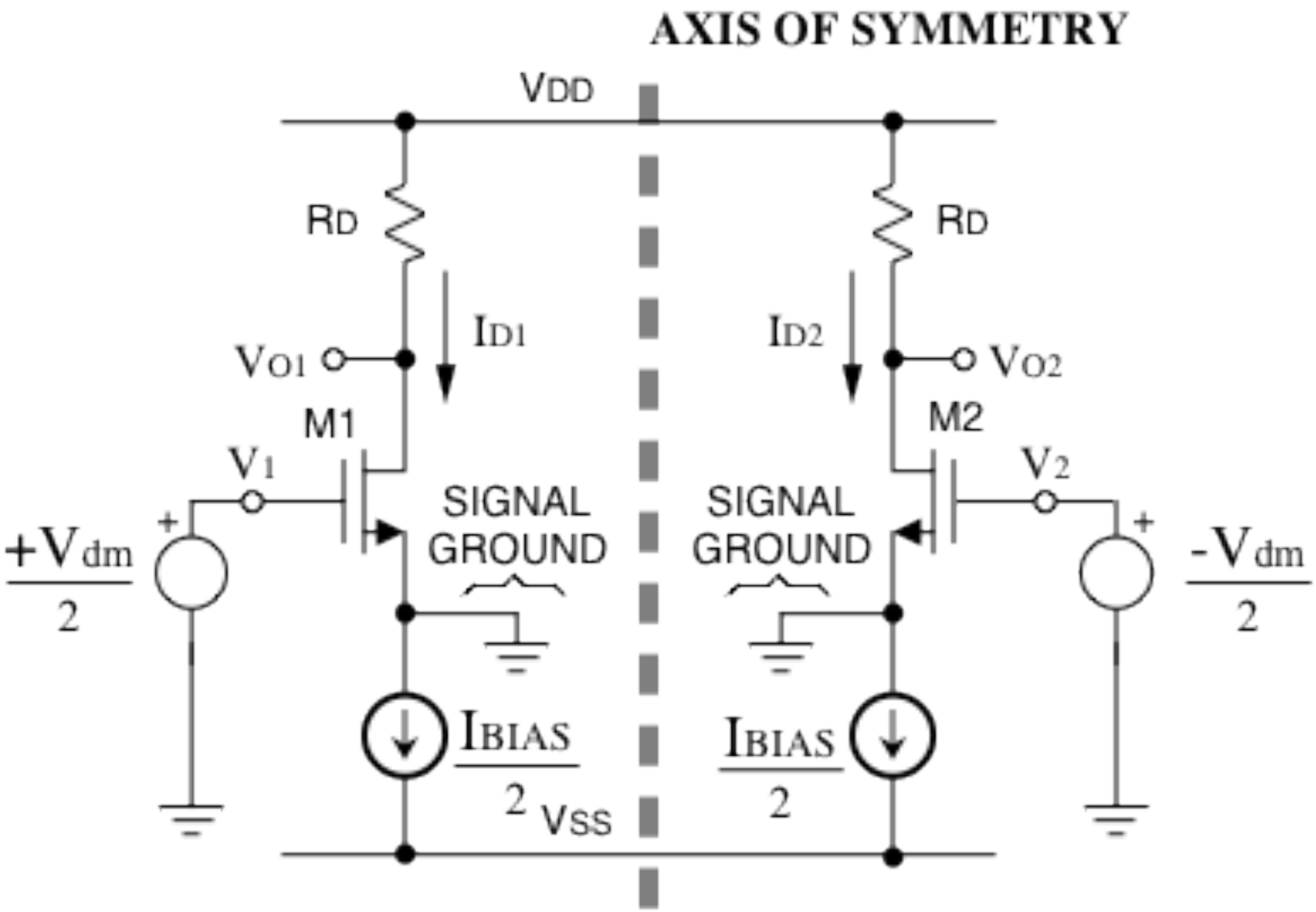
- **Open connected points of symmetry**

Note "supernode": $i_d = 0$



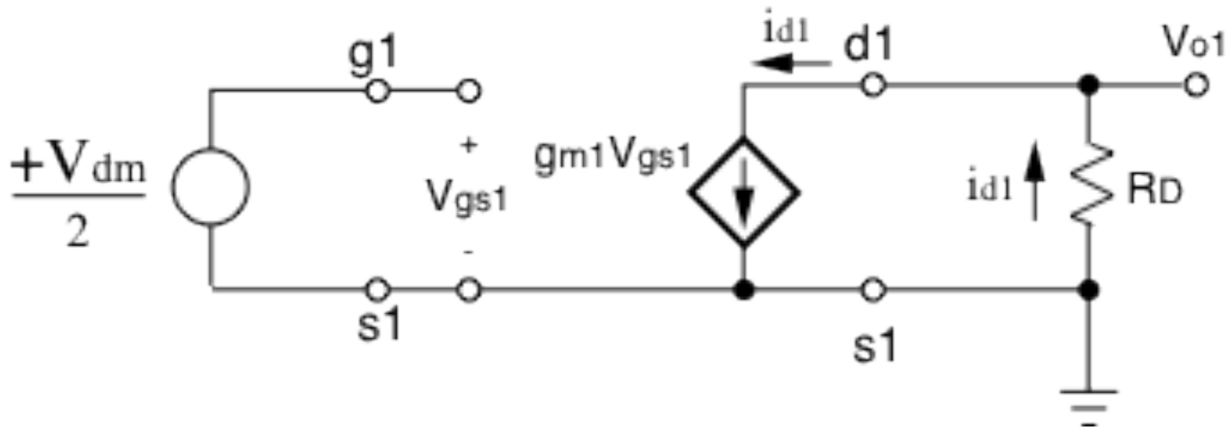
$$V_{o1(cm)} = -i_d R_D = 0 \qquad V_{o2(cm)} = 0$$

Differential mode response: $v_{cm} = 0$



- **Connected points of symmetry to signal ground**

Small signal model of half-circuit



$$\underbrace{V_{o1(dm)}}_{OUTPUT} = -g_m R_D \underbrace{\frac{v_{dm}}{2}}_{INPUT} \qquad \underbrace{V_{o2(dm)}}_{OUTPUT} = -g_m R_D \underbrace{\frac{-v_{dm}}{2}}_{INPUT}$$

- **Common source amplifier!**
- **Note: $g_{m1} = g_{m2} = g_m$**

Summary: Output "parts"

- **DC bias**

$$V_{O1(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D \qquad V_{O2(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D$$

- **Common mode**

$$V_{o1(cm)} = 0 \qquad V_{o2(cm)} = 0$$

- **Differential mode**

$$V_{o1(dm)} = \frac{-g_m R_D}{2} v_{dm} \qquad V_{o2(dm)} = \frac{g_m R_D}{2} v_{dm}$$

Summary: Total output sum of components

$$V_{O1} = \underbrace{V_{DD} - \frac{I_{BIAS}}{2} R_D}_{DCBIAS} + \underbrace{0}_{CM} + \underbrace{\frac{-g_m R_D}{2} v_{dm}}_{\substack{DIFFERENTIAL\\ MODE}}$$

$$V_{O2} = \underbrace{V_{DD} - \frac{I_{BIAS}}{2} R_D}_{DCBIAS} + \underbrace{0}_{CM} + \underbrace{\frac{g_m R_D}{2} v_{dm}}_{\substack{DIFFERENTIAL\\ MODE}}$$

Studio 7 Exercise

- $I_{BIAS} = 250\mu A,\ R_D = 20k\Omega$
- DCbias

$$V_{O1(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D = +5V - \frac{250\,\mu A}{2} 20k\Omega = +2.5V$$

- Small signal: $g_m \approx 400\mu A/V$

$g_{m1}R_D \approx (400\mu A/V)(20k\Omega) = 8$

Differential gain

$$a_{v(diff)} = \frac{\overbrace{V_{o1(dm)} - V_{o2(dm)}}^{\substack{\textit{DIFFERENTIAL} \\ \textit{OUTPUT}}}}{\underbrace{v_{dm}}_{\substack{\textit{DIFFERENTIAL} \\ \textit{INPUT}}}}$$

$$a_{v(diff)} = \frac{-g_m R_D \dfrac{v_{dm}}{2} - g_m R_D \dfrac{v_{dm}}{2}}{v_{dm}}$$

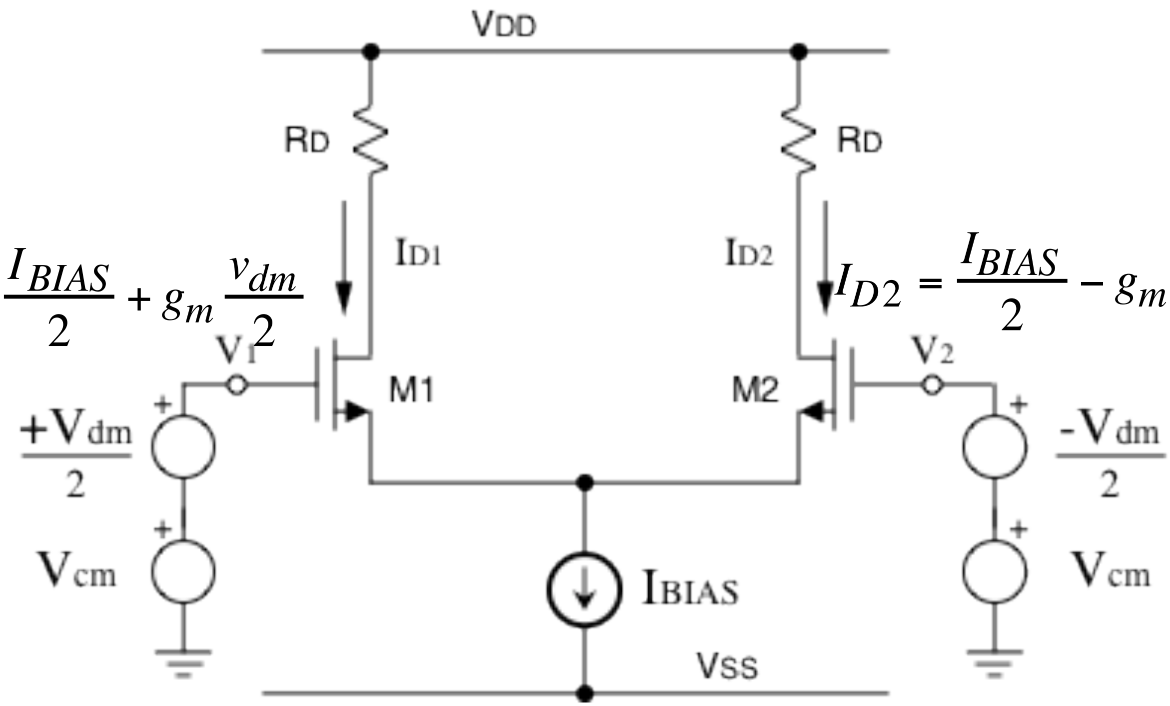
$$\boxed{a_{v(diff)} = -g_m R_D}$$

- **Same as common source amplfier**
- **Still low for resistive load!**

Drain Currents

$$I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2}$$

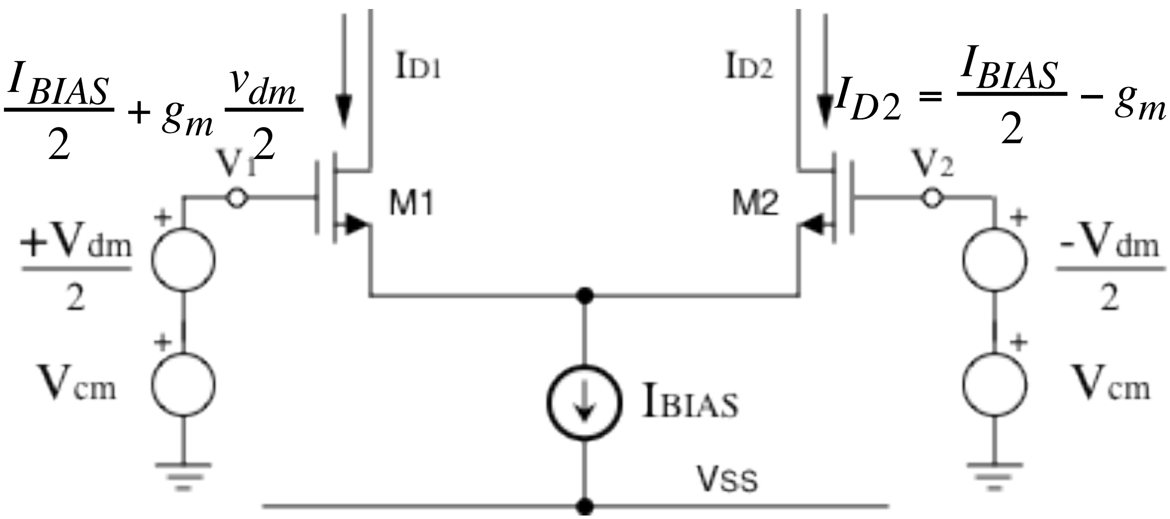
$$I_{D2} = \frac{I_{BIAS}}{2} - g_m \frac{v_{dm}}{2}$$



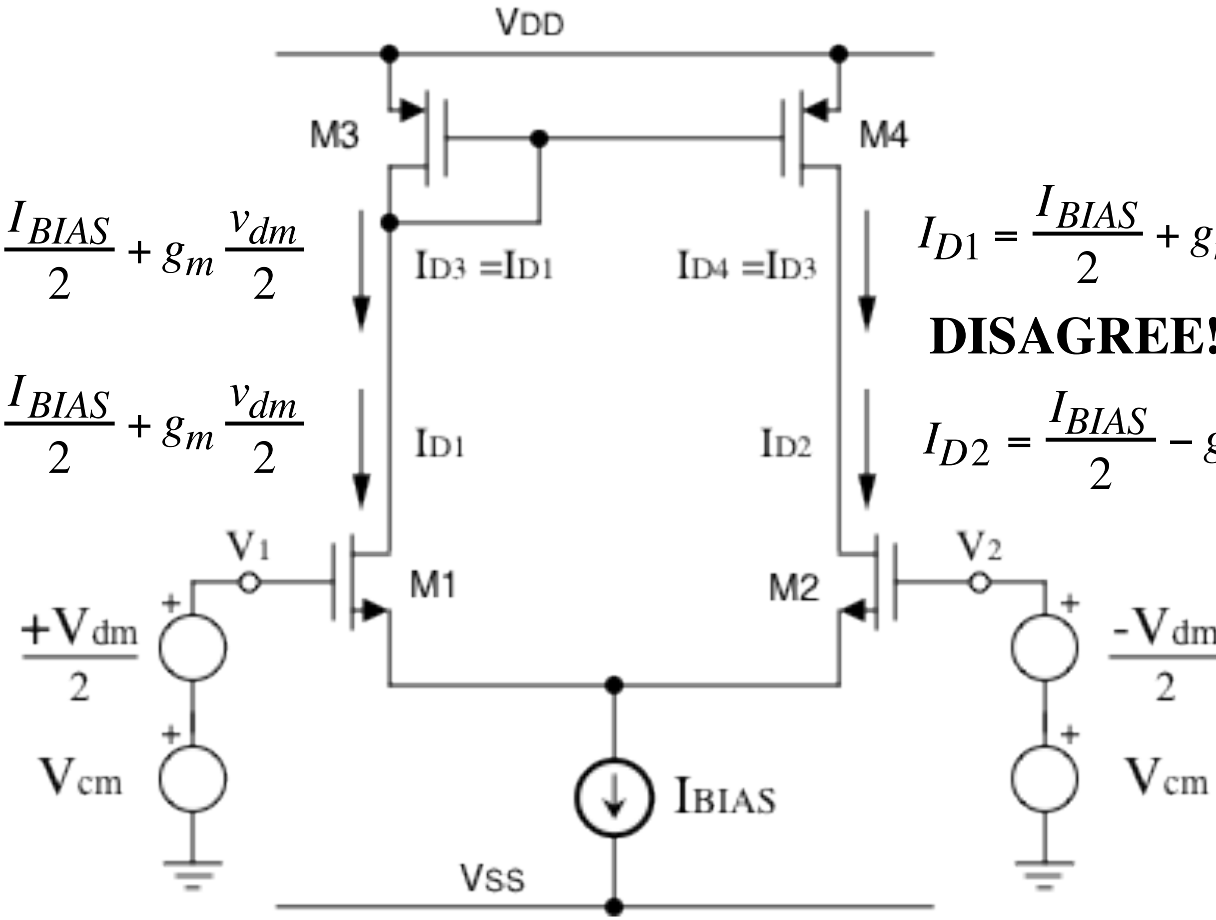
Drain Currents

$$I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2}$$

$$I_{D2} = \frac{I_{BIAS}}{2} - g_m \frac{v_{dm}}{2}$$



Mirror load



$$I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2}$$

$$I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2}$$

$$I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2}$$

DISAGREE!

$$I_{D2} = \frac{I_{BIAS}}{2} - g_m \frac{v_{dm}}{2}$$