Lecture 25

Multistage Amplifiers (II)

DC VOLTAGE AND CURRENT SOURCES

Outline

1. DC Voltage Sources
2. DC Current Sources and Sinks
3. Introduction to Differential Amplifiers

Reading Assignment:
Howe and Sodini, Chapter 9, Sections 9-3-9.4

Summary of Key Concepts

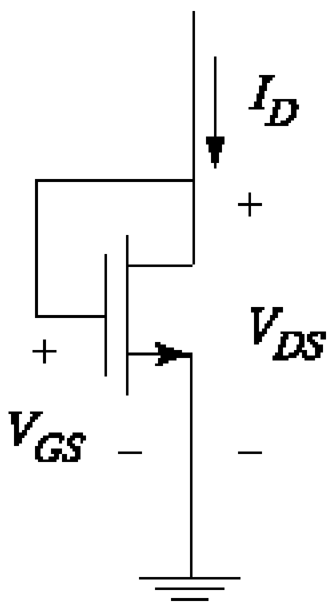
- ***Voltage source*** easily synthesized from ***current source*** using MOSFET in diode configuration
- ***Current source*** easily synthesized from ***current source*** using **current mirror** circuit.
- Multiple current sources and sinks with different magnitudes can be synthesized from a single current source.
- Voltage and current sources rely on the availability of well “matched” transistors in IC technology.
- In differential amplifiers, signals are represented by ***difference*** between two voltages

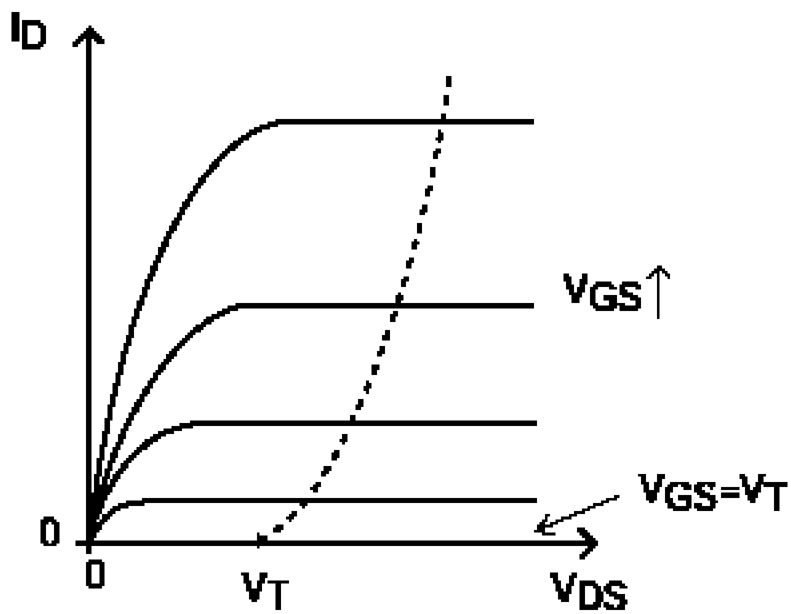
1. DC Voltage Sources

Characteristics of DC Voltage Sources :

- A well controlled output voltage
- Output voltage does not depend on current drawn from source ⇒ ***Low Thevenin Resistance***

Consider a MOSFET connected in "diode configuration"





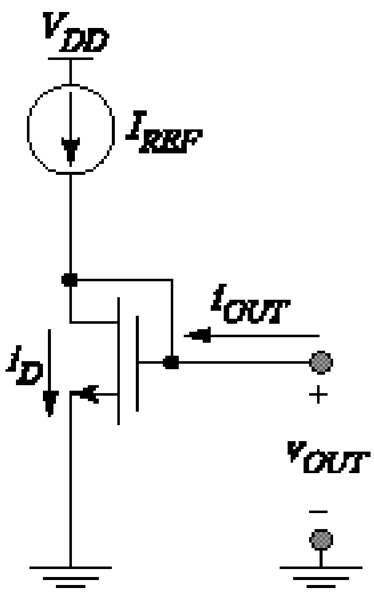
I-V characteristics:

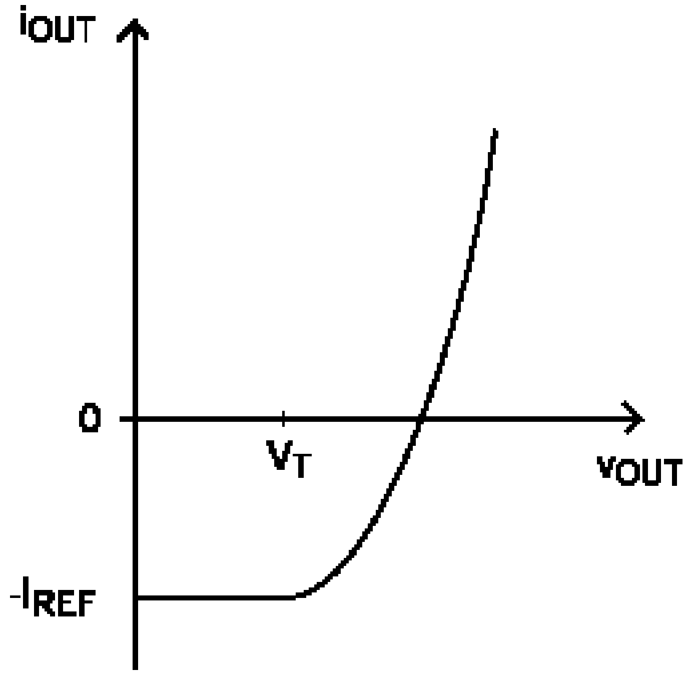
$$\mathbf{I_D} = \frac{\mathbf{W}}{2\mathbf{L}}\mu_n\mathbf{C_{ox}}\left(\mathbf{V_{GS}} - \mathbf{V_{Tn}}\right)^2 = \frac{\mathbf{W}}{2\mathbf{L}}\mu_n\mathbf{C_{ox}}\left(\mathbf{V_{DS}} - \mathbf{V_{Tn}}\right)^2$$

Beyond the threshold voltage, the MOSFET looks like a "diode" with quadratic I-V characteristics

How does one synthesize a voltage source with this?

Assume a current source is available





$V_{GS} = V_{DS}$ takes a value needed to sink current

$$\mathbf{I_D = I_{REF} + i_{OUT} = \frac{W}{2L}\mu_n C_{ox}\left(v_{OUT} - V_{Tn}\right)^2}$$

Then:

$$\mathbf{i_{OUT} = \frac{W}{2L}\mu_n C_{ox}\left(v_{OUT} - V_{Tn}\right)^2 - I_{REF}}$$

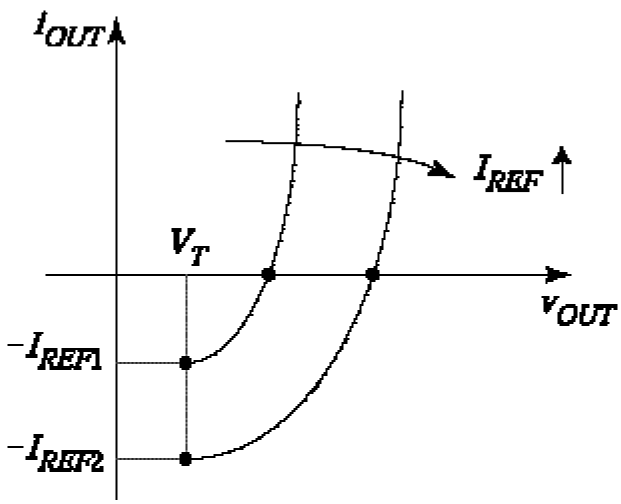
Solving for v_{OUT}:

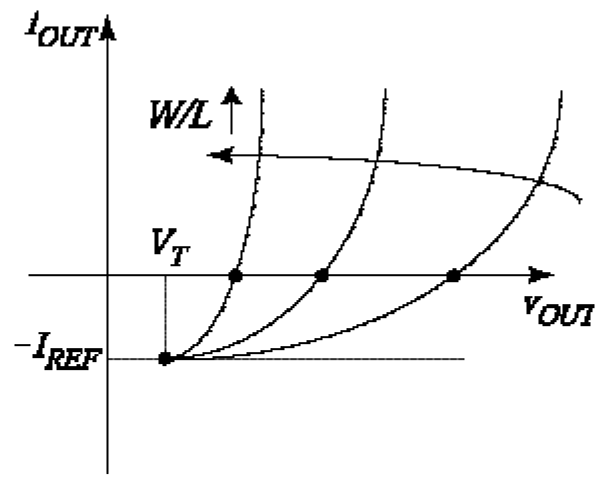
$$\mathbf{v_{OUT} = V_{Tn} + \sqrt{\frac{I_{REF} + i_{OUT}}{\frac{W}{2L}\mu_n C_{ox}}}}$$

Synthesizing Voltage Sources (contd.)

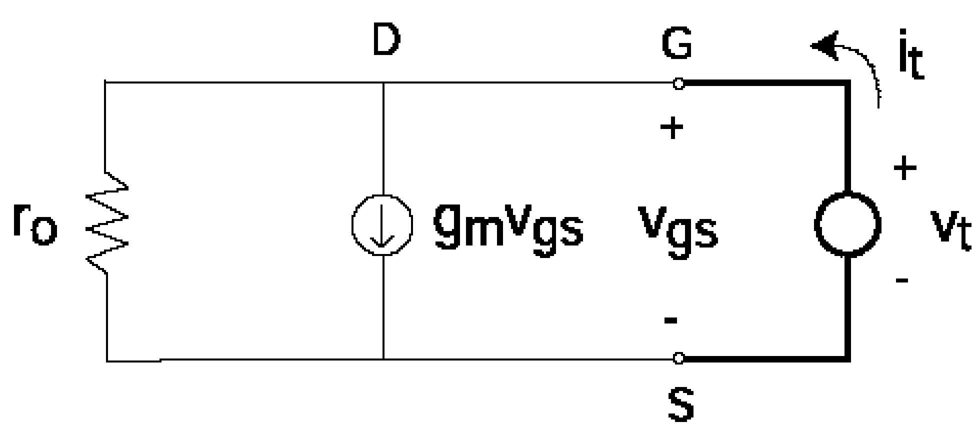
v_{OUT} is a function of I_{REF} and W/L of MOSFET:

- $I_{REF} \uparrow \Rightarrow v_{OUT} \uparrow$
- $W/L \uparrow \Rightarrow v_{OUT} \downarrow$





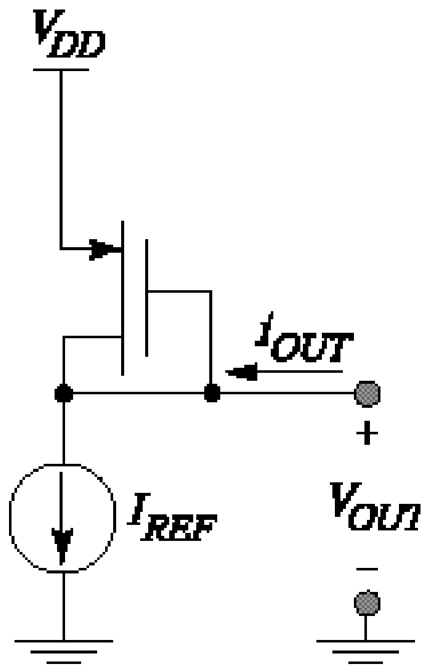
Small Signal Equivalent Circuit Model:



$$\mathbf{R_{out}} = \frac{1}{\mathbf{g_m}} \parallel \mathbf{r_o} \approx \frac{1}{\mathbf{g_m}}$$

R_{out} is small (good!)

PMOS voltage source



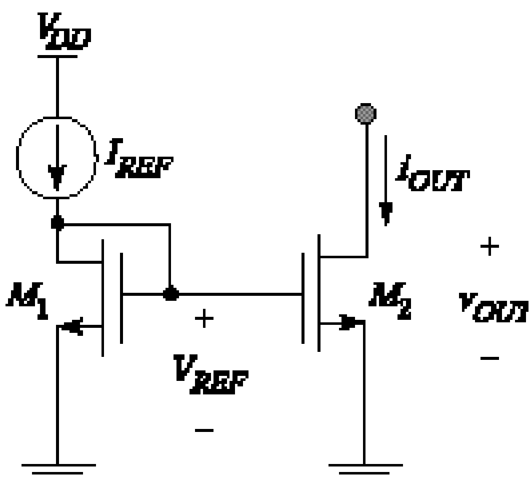
Same operation and characteristics as NMOS voltage source. PMOS needs to be larger to attain the same R_{out}.

3. DC Current Sources and Sinks

Characteristics of Current Sources

- A well controlled output current
- Supplied current does not depend on output voltage
  ⇒ ***High Thevenin Resistance***

Connect a voltage source to the gate of another MOSFET:



$$\mathbf{I_{OUT}} \approx \frac{1}{2}\left(\frac{\mathbf{W}}{\mathbf{L}}\right)_2 \mu_n \mathbf{C_{ox}}\left(\mathbf{V_{REF}} - \mathbf{V_{Tn}}\right)^2$$

$$\mathbf{I_{REF}} \approx \frac{1}{2}\left(\frac{\mathbf{W}}{\mathbf{L}}\right)_1 \mu_n \mathbf{C_{ox}}\left(\mathbf{V_{REF}} - \mathbf{V_{Tn}}\right)^2$$

Then:

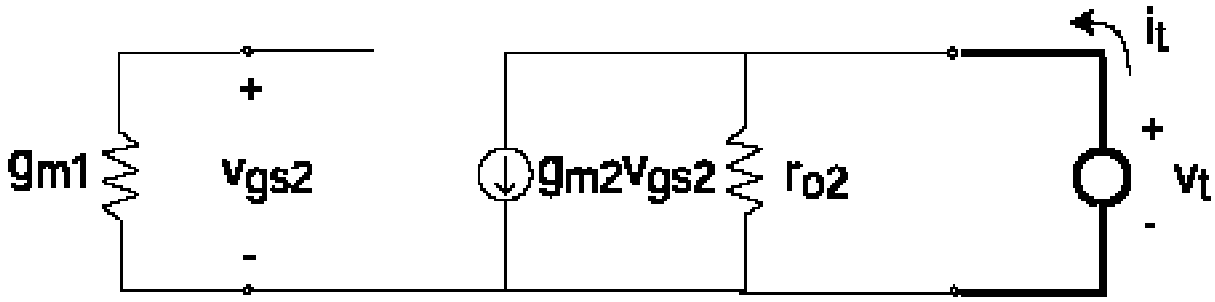
$$\mathbf{I_{OUT}} = \mathbf{I_{REF}} \frac{\left(\frac{\mathbf{W}}{\mathbf{L}}\right)_2}{\left(\frac{\mathbf{W}}{\mathbf{L}}\right)_1}$$

I_{OUT} scales with I_{REF} by W/L ratios of two MOSFETs
⇒ ***Current Mirror Circuit***

Well "matched" transistors important.

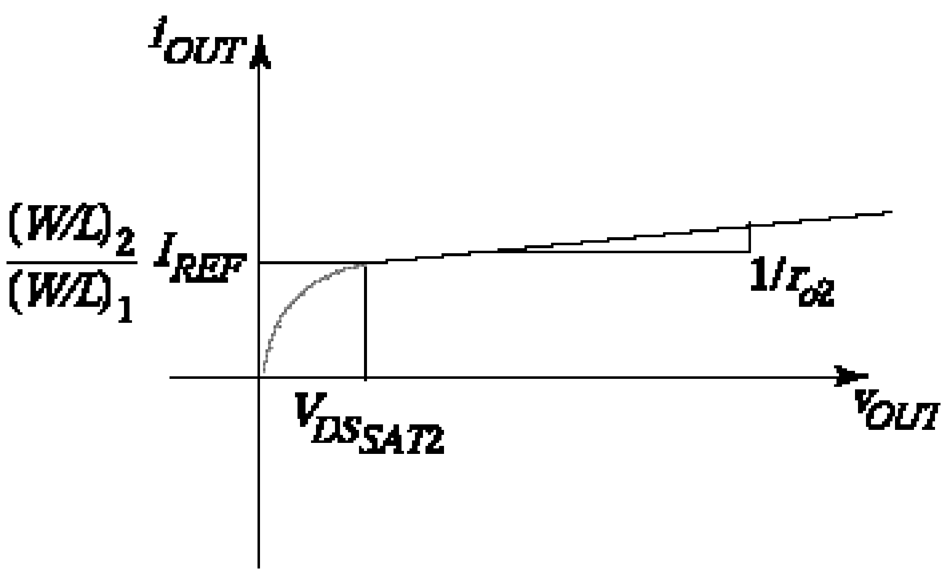
DC Current Sources and Sinks (contd.)

Small Signal Equivalent Circuit Model:



$$\mathbf{R}_{\mathbf{out}\,2} = \mathbf{r}_{\mathbf{o}\,2}$$

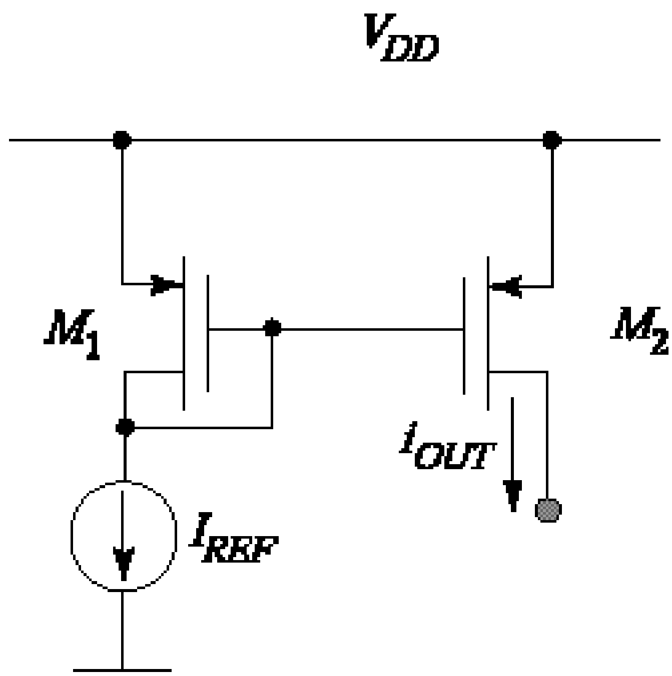
I-V characteristics of NMOS current source:



PMOS Current Source

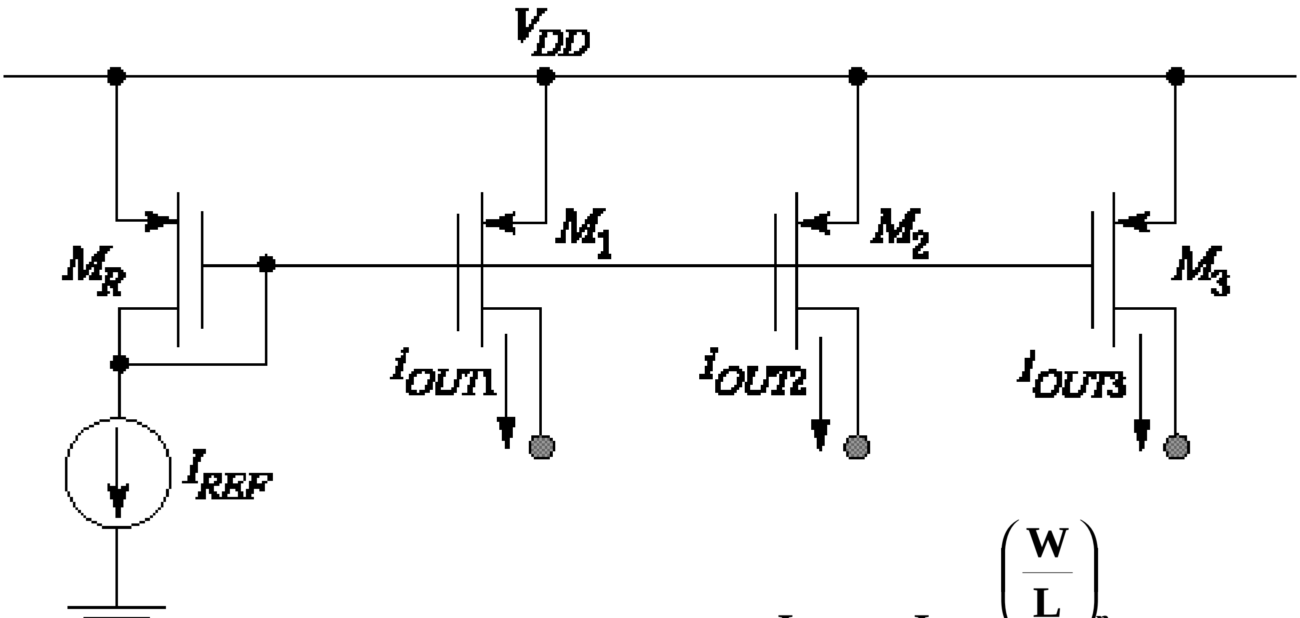
- NMOS current source sinks current to ground
- PMOS current source sources current from positive supply

PMOS Current Mirror:



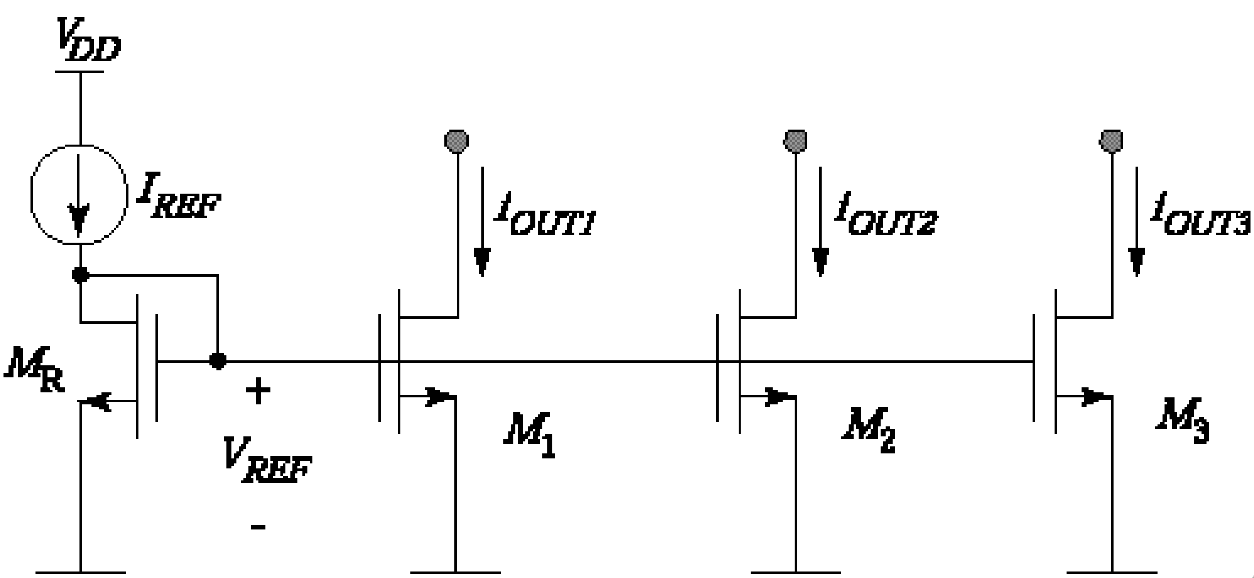
3. Multiple Current Sources

Since there is no DC gate current in MOSFET, we can tie up multiple current mirrors to single current source:



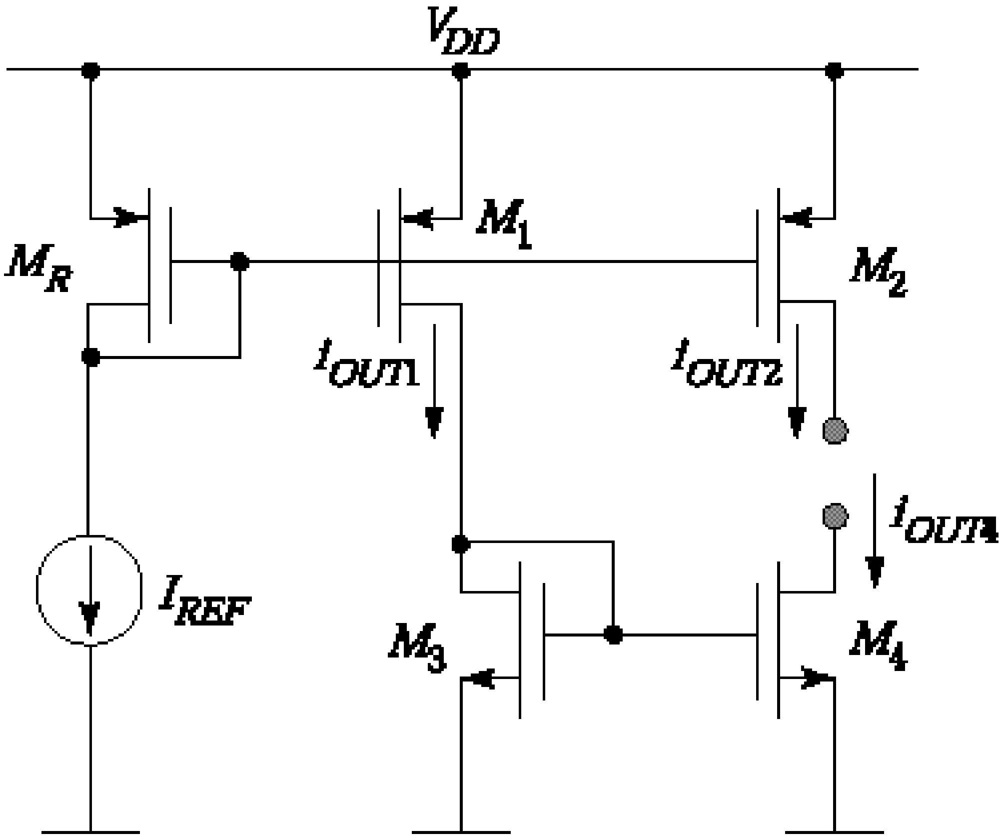
$$I_{OUTn} = I_{REF} \frac{\left(\frac{W}{L}\right)_n}{\left(\frac{W}{L}\right)_R}$$

Similar idea with NMOS current sinks:



Multiple Current Sources and Sinks

Often, in a given circuit, we need current sources and sinks. We can build them all out of a single current source.

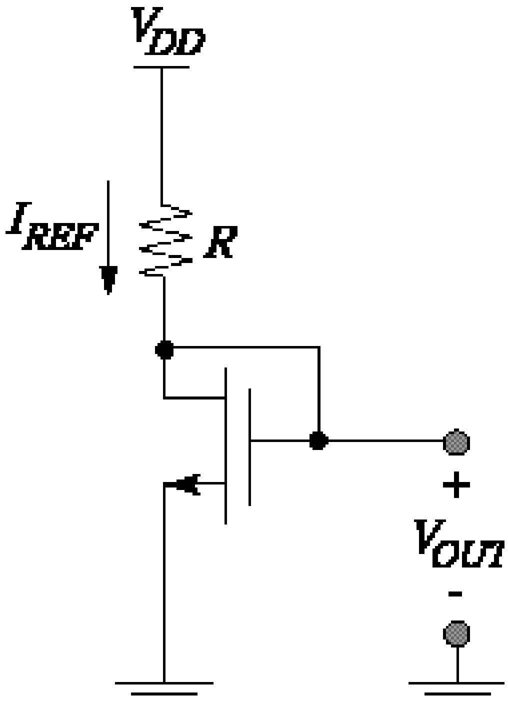


$$I_{OUT1} = I_{REF}\frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_R} \qquad I_{OUT2} = I_{REF}\frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_R}$$

$$I_{OUT4} = I_{OUT1}\frac{\left(\frac{W}{L}\right)_4}{\left(\frac{W}{L}\right)_3} = I_{REF}\frac{\left(\frac{W}{L}\right)_4\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_3\left(\frac{W}{L}\right)_R}$$

Generating I_{REF}

Simple circuit:



$$I_{REF} = \frac{V_{DD} - V_{OUT}}{R}$$

$$V_{OUT} = V_{Tn} + \sqrt{\frac{I_{REF}}{\frac{W}{2L}\mu_n C_{ox}}}$$

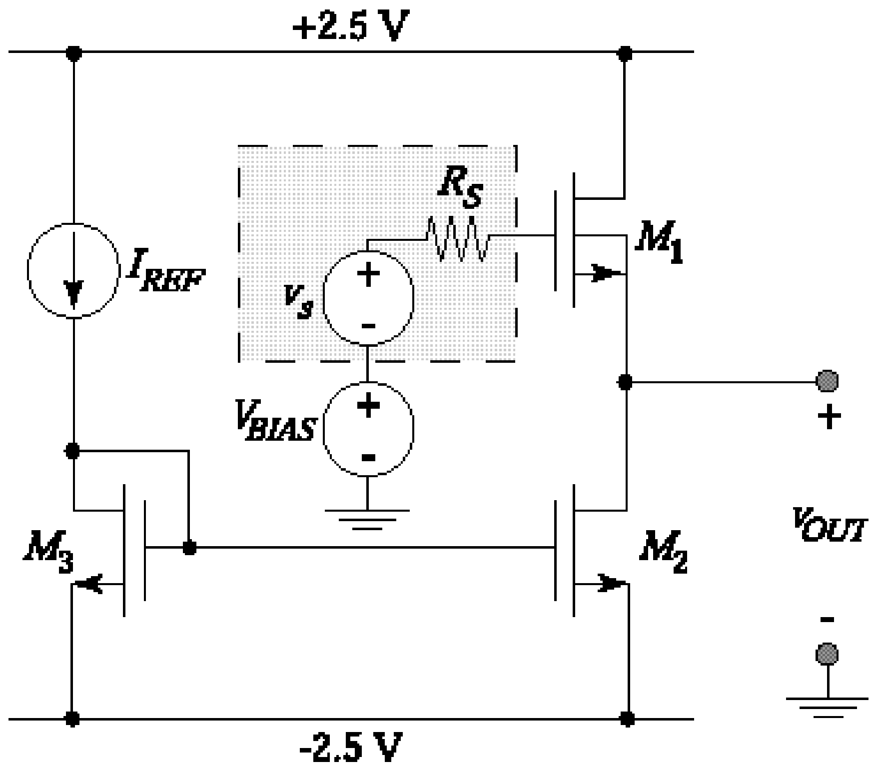
For large W/L: $$I_{REF} \approx \frac{V_{DD} - V_{Tn}}{R}$$

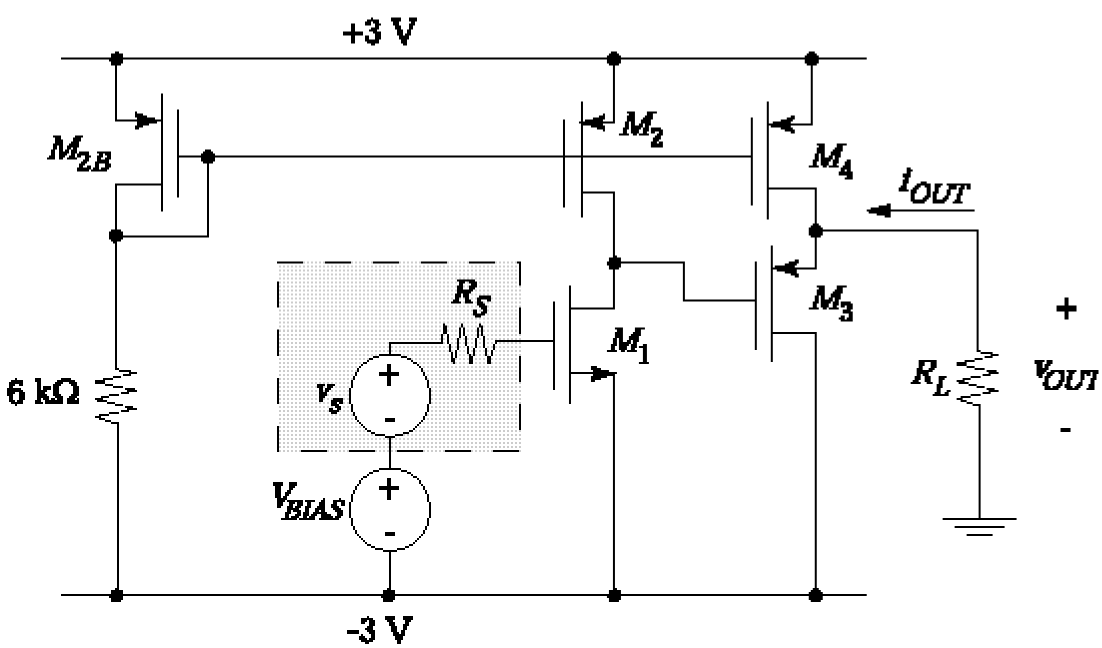
- Advantages
  - I_{REF} set by value of resistor
- Disadvantages
  - V_{DD} also affects I_{REF}.
  - V_{Tn} and R are functions of temperature $\Rightarrow I_{REF}(T)$.

In the real world, more sophisticated circuits are used to generate I_{REF} that are V_{DD} and T independent.

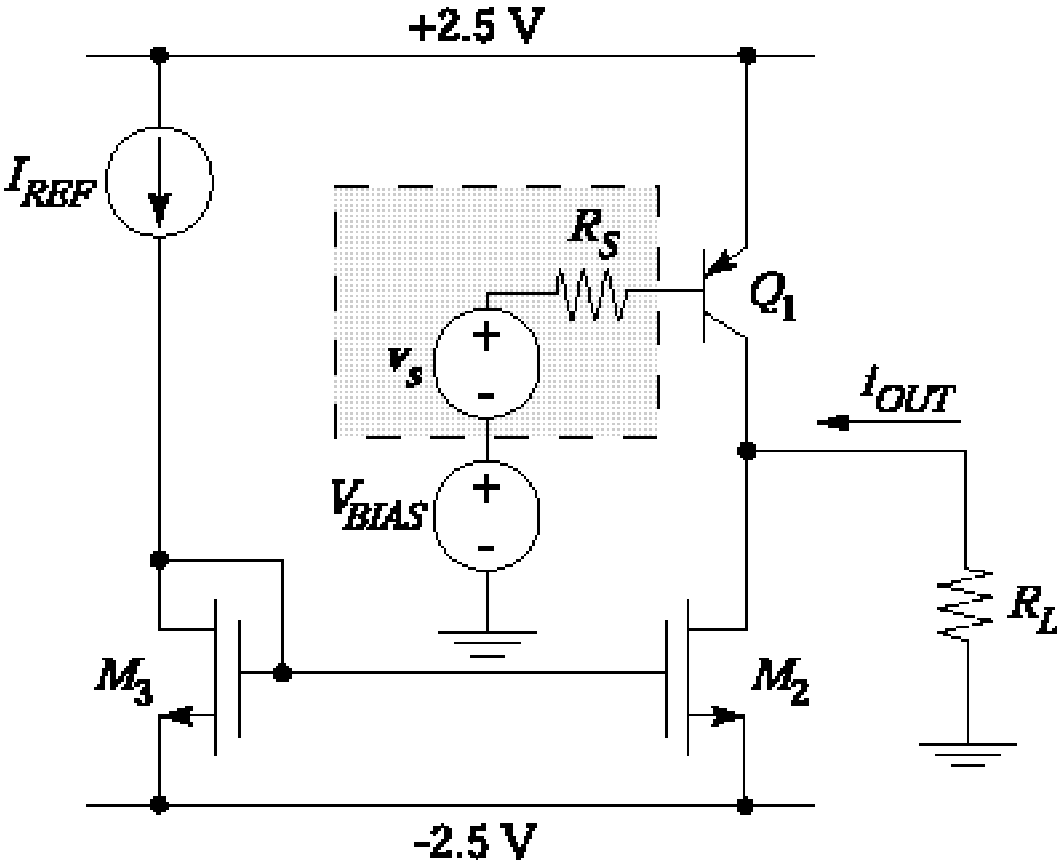
Can now understand more complex circuits?

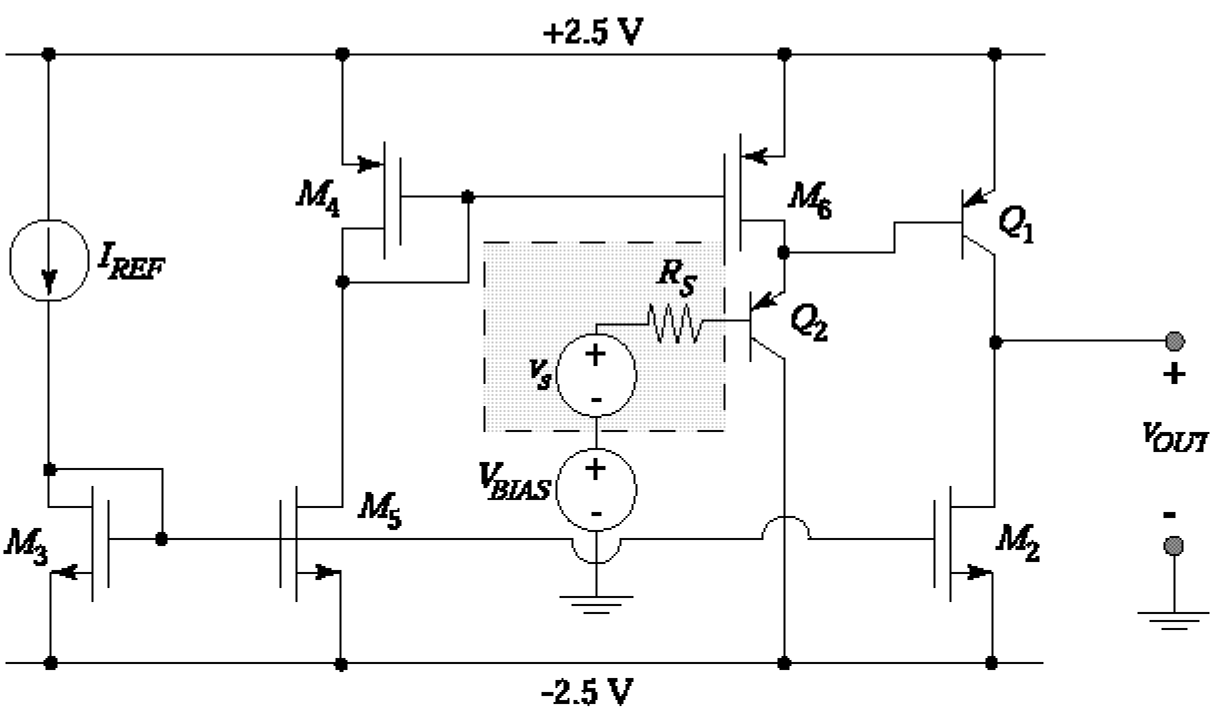
Examples:





Can now understand more complex circuits?

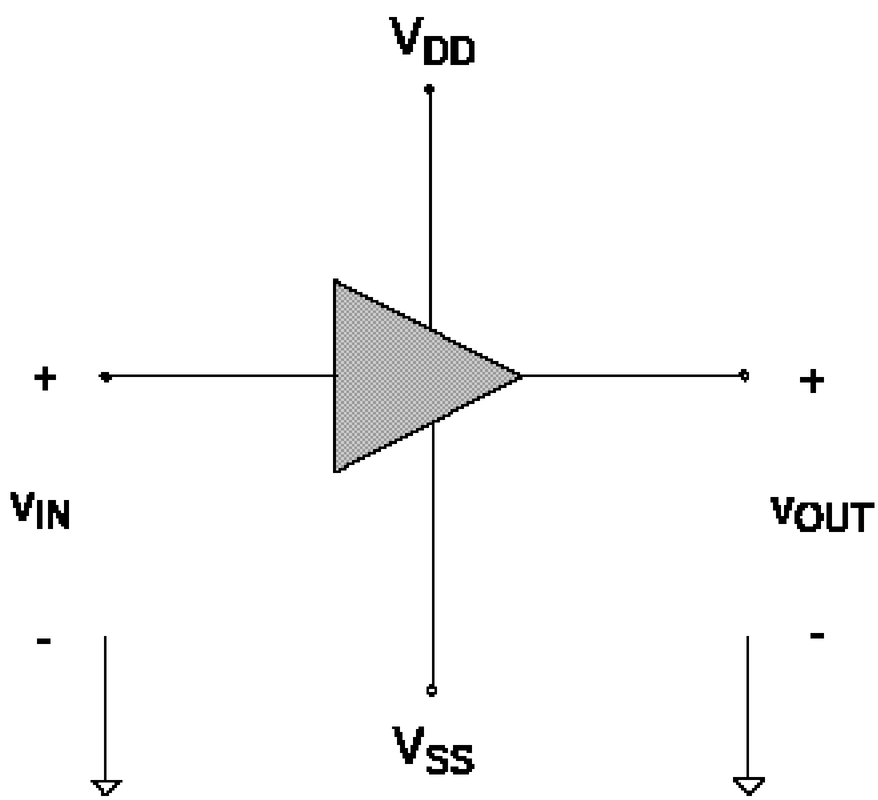




3. Introduction to Differential Amplifiers

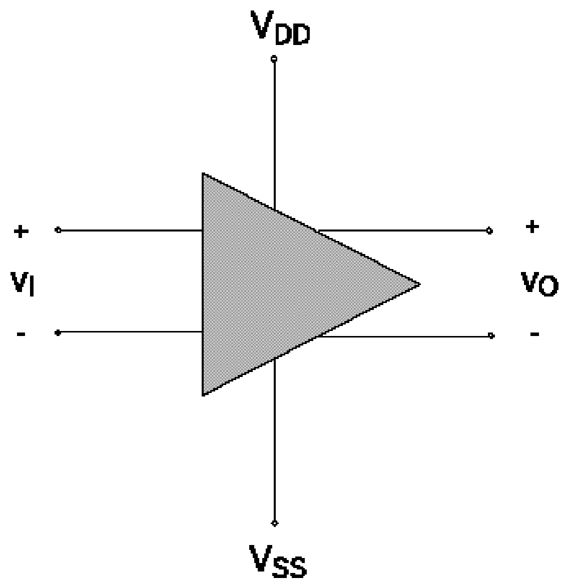
Two problems found in single-transistor amplifier stages are:

- Bias and gain sensitivity to device parameters (μC_{ox}, V_T)
  - Sensitivity can be mitigated but often at a price in terms of performance or cost (gain, power, device area, etc.)
- Vulnerability to ground and power supply noise
  - In dense IC's there is cross-talk, 60 Hz coupling, substrate noise, etc.



Introduction (contd.)

Solution : represent relevant signal by the difference between two voltages

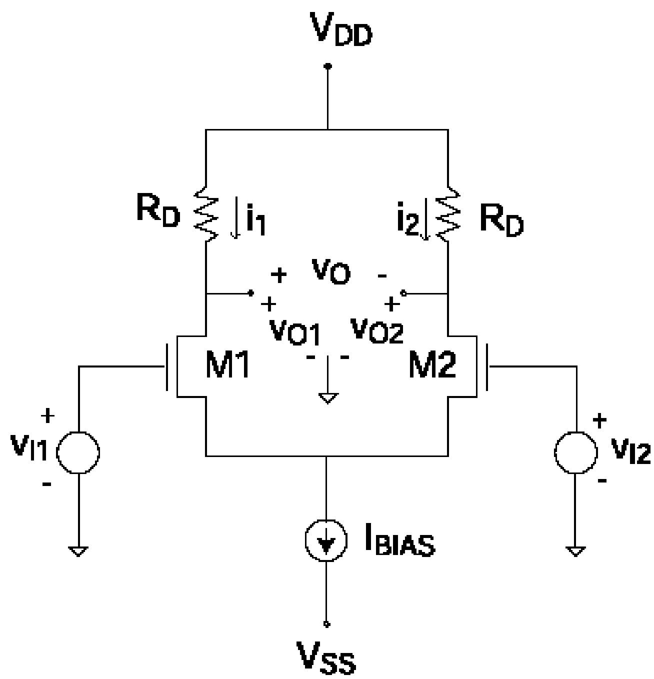


Differential Amplifier:

- Amplifies **difference** between two voltages
- Rejects components **common** to both voltages

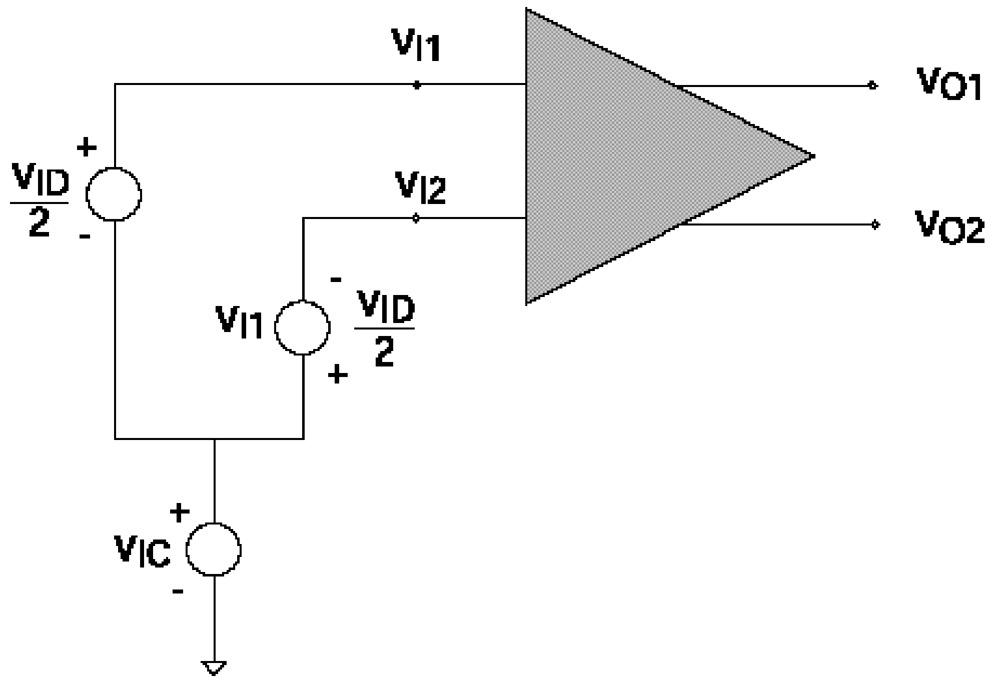
MOSFET Differential Amplifier

Basic Configuration



- v_O responds to difference between 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 conducts more than M2 $\Rightarrow i_1 > i_2$ $\Rightarrow v_{O1} < v_{O2} \Rightarrow v_O < 0$
- v_O insensitive to common mode signals:
  - If both v_{O1} and v_{O2} move in sync, symmetry is 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:

$$\mathbf{v}_{I1} = \mathbf{v}_{IC} + \frac{\mathbf{v}_{ID}}{2}, \qquad \mathbf{v}_{I2} = \mathbf{v}_{IC} - \frac{\mathbf{v}_{ID}}{2}$$

Then:

$$\mathbf{v}_{ID} = \mathbf{v}_{I1} - \mathbf{v}_{I2}, \qquad \mathbf{v}_{IC} = \frac{\mathbf{v}_{I1} + \mathbf{v}_{I2}}{2}$$

Similarly at the output:

$$\mathbf{v}_{O1} = \mathbf{v}_{OC} + \frac{\mathbf{v}_{OD}}{2}, \qquad \mathbf{v}_{O2} = \mathbf{v}_{OC} - \frac{\mathbf{v}_{OD}}{2}$$

Then:

$$\mathbf{v}_{OD} = \mathbf{v}_{O1} - \mathbf{v}_{O2}, \qquad \mathbf{v}_{OC} = \frac{\mathbf{v}_{O1} + \mathbf{v}_{O2}}{2}$$

What did we learn today?

Summary of Key Concepts

- ***Voltage source*** easily synthesized from ***current source*** using MOSFET in diode configuration
- ***Current source*** easily synthesized from ***current source*** using **current mirror** circuit.
- Multiple current sources and sinks with different magnitudes can be synthesized from a single current source.
- Voltage and current sources rely on the availability of well "matched" transistors in IC technology.
- In differential amplifiers, signals are represented by ***difference*** between two voltages