Lecture 18

Transistor Amplifiers (I)

Common-Source Amplifier

Outline

- Amplifier fundamentals
- Common-source amplifier
- Common-source amplifier with current-source supply

Reading Assignment:
Howe and Sodini; Chapter 8, Sections 8.1-8.4

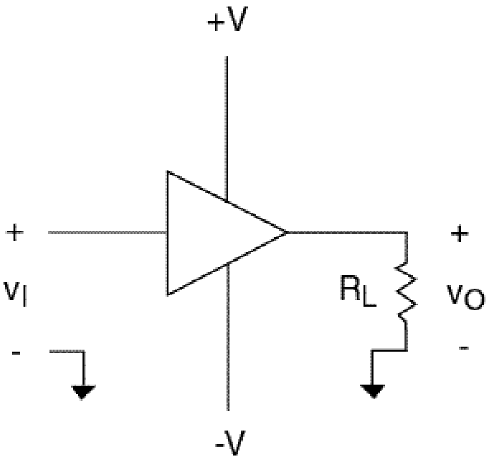
Announcement:
Quiz #2: November 15, 7:30-9:30 PM at Walker.
Calculator Required. Open book.
Quiz Review: Monday, Nov. 13, 7:30-9:30, Rm. 1-390

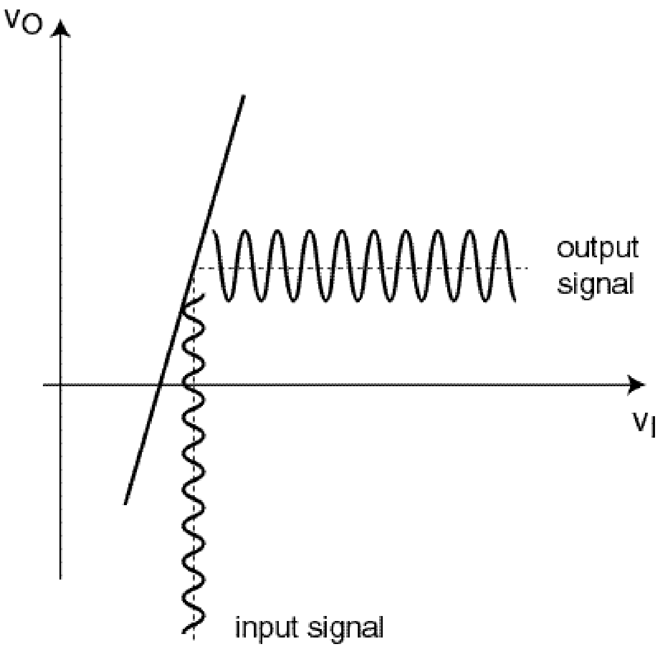
Summary of Key Concepts

- Figures of merit of an amplifier
  - Gain
  - Signal swing
  - Power consumption
  - Frequency response
  - Immunity to process and temperature variations
- Common-source amplifier with resistive supply
  - For high gain, large R_D required
  - Large R_D consumes a lot of Si real estate.
  - Large R_D eventually compromises frequency response
- Performance of common-source amplifier improved using current source supply.
- Computation of two-port network parameters of a voltage amplifier
  - voltage gain, input resistance and output resistance

1. Amplifier fundamentals

Goal of amplifiers: ***signal amplification***

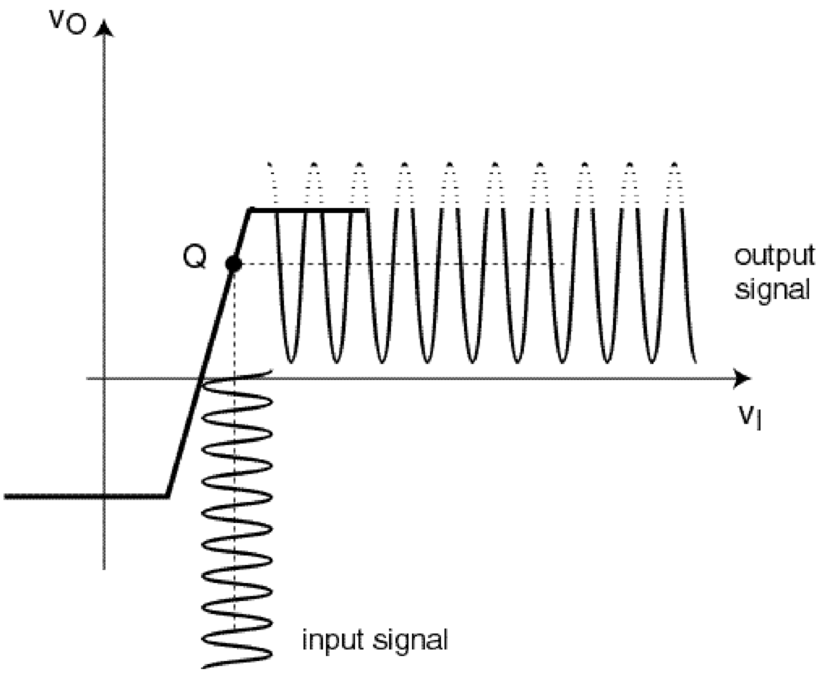




Features of amplifier:

- ***Output signal*** is faithful replica of ***input signal*** but amplified in magnitude.
- Amplifier exhibits ***power gain***:
  - Control of the flow of energy from power supply to output load in response to input signal.
- ***Active device*** is at the heart of amplifier
- Need ***linear transfer characteristics*** for distortion not to be introduced.

“More Realistic” Transfer Characteristics



- Transfer characteristics linear over limited range of voltages: ***amplifier saturation***
- Amplifier saturation limits signal swing.
- Signal swing also depends on choice of ***bias point***, Q (also called ***quiescent point*** or ***operating point***).

Other features desired in amplifiers:

- Low ***power consumption.***
- Wide ***frequency response*** [will discuss in a few days].
- Immunity to process and temperature variations.

2. Common-Source Amplifier:

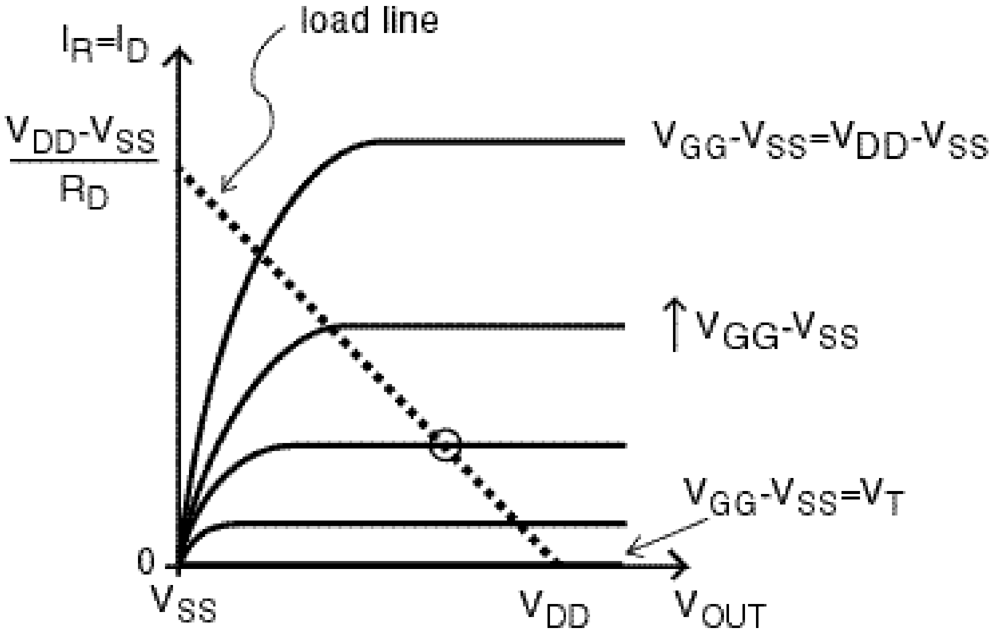
Consider the following circuit:

Consider it first unloaded by R_L. How does it work?

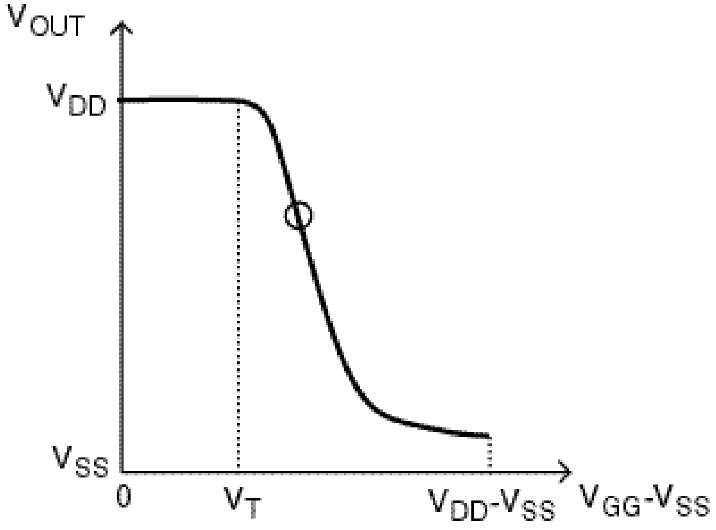
- V_{GG}, R_D and W/L of MOSFET selected to bias transistor in saturation and obtain desired output bias point (i.e. $V_{OUT} = 0$).
- $v_{GS} \uparrow$ $\quad$ $i_D \uparrow$ $\quad$ $i_R \uparrow$ $\quad$ $v_{OUT} \downarrow$
- $A_v = v_{out} / v_s < 0$; output out of phase from input, but if amplifier is well designed, $|A_v| > 1$.

Watch notation: $v_{OUT}(t) = V_{OUT} + v_{out}(t)$

Load line view of amplifier:



Transfer characteristics of amplifier:



Want:

- Bias point calculation;
- Small-signal gain;
- Limits to signal swing
- Frequency response [in a few days]

Bias point: choice of V_{GG}, W/L, and R_D to keep transistor in saturation and to get proper quiescent V_{OUT}.

Assume MOSFET is in saturation:

$$I_D = \frac{W}{2L}\mu_n C_{ox}\left(V_{GG} - V_{SS} - V_T\right)^2$$

$$I_R = \frac{V_{DD} - V_{OUT}}{R_D}$$

If we select $V_{OUT}=0$:

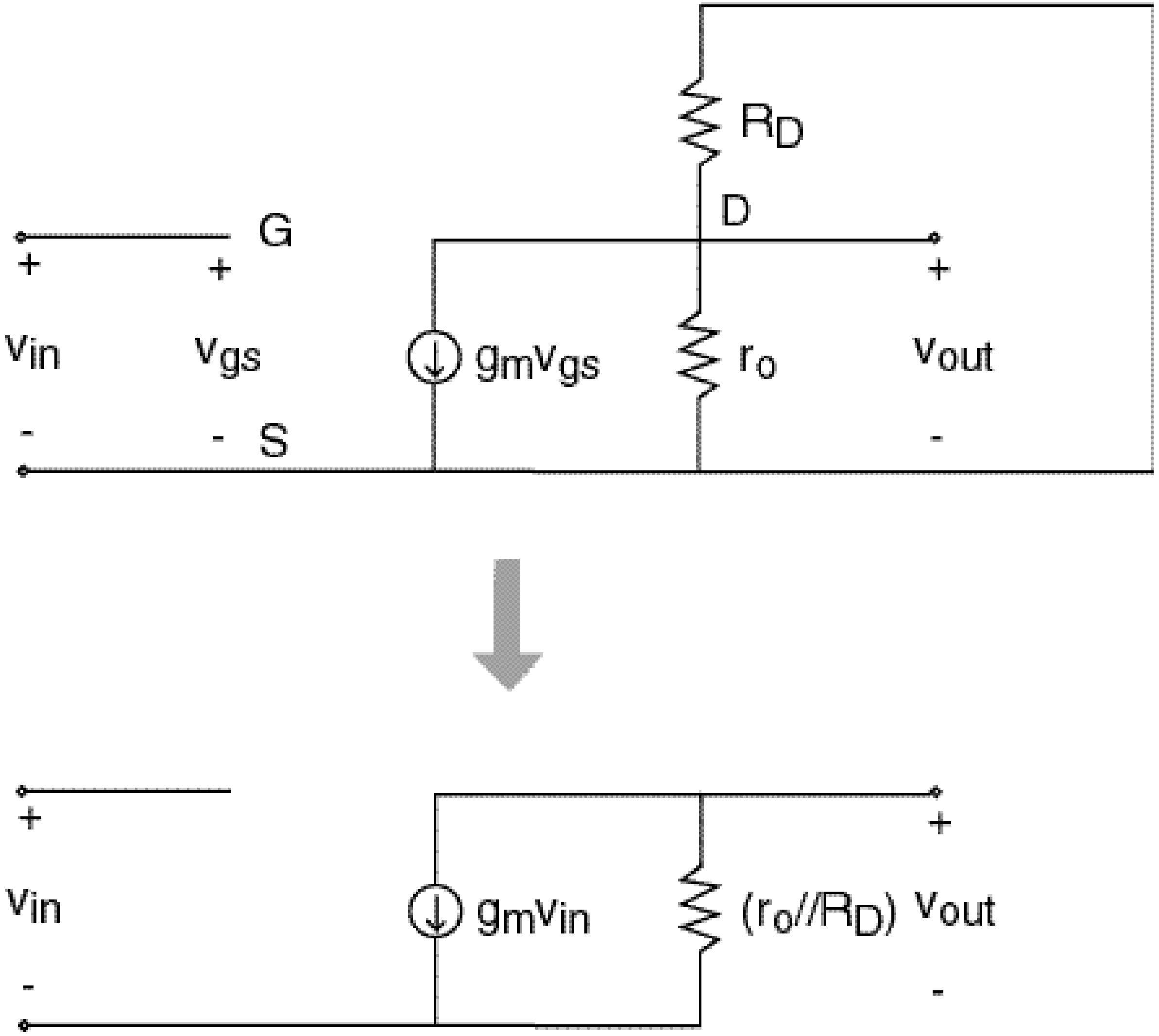
$$I_D = I_R = \frac{W}{2\,L}\mu_n C_{ox}\left(V_{GG} - V_{SS} - V_T\right)^2 = \frac{V_{DD}}{R_D}$$

Then:

$$V_{GG} = \sqrt{\frac{2\,V_{DD}}{R_D \frac{W}{L}\mu_n C_{ox}}} - V_{SS} - V_T$$

Equation that allows us to compute needed V_{GG} given R_D and W/L.

Small-signal voltage gain: draw small-signal equivalent circuit model:

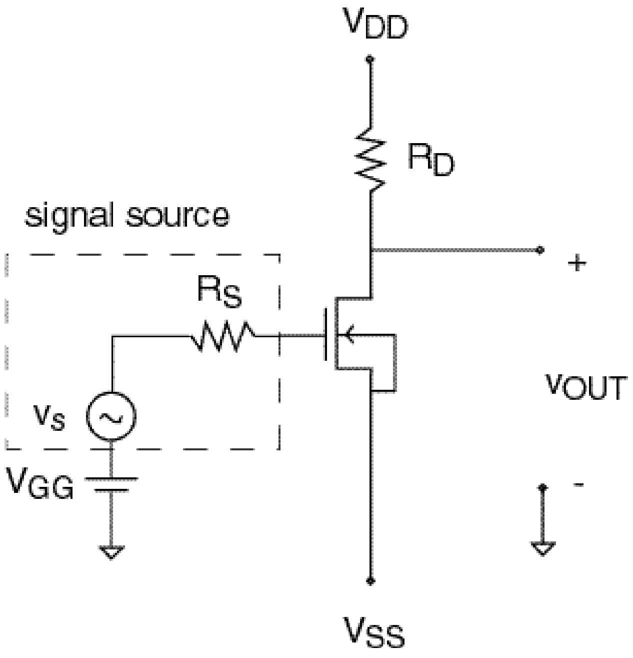


$$v_{out} = -g_m v_{in} \left(r_o // R_D \right)$$

Then unloaded voltage gain:

$$A_{vo} = \frac{v_{out}}{v_{in}} = -g_m \left(r_o // R_D \right)$$

Signal swing:



- Upswing: limited by MOSFET going into cut-off.

$$v_{out,max} = V_{DD}$$

- Downswing: limited by MOSFET leaving saturation.

$$V_{DS,sat} = V_{GS} - V_T$$

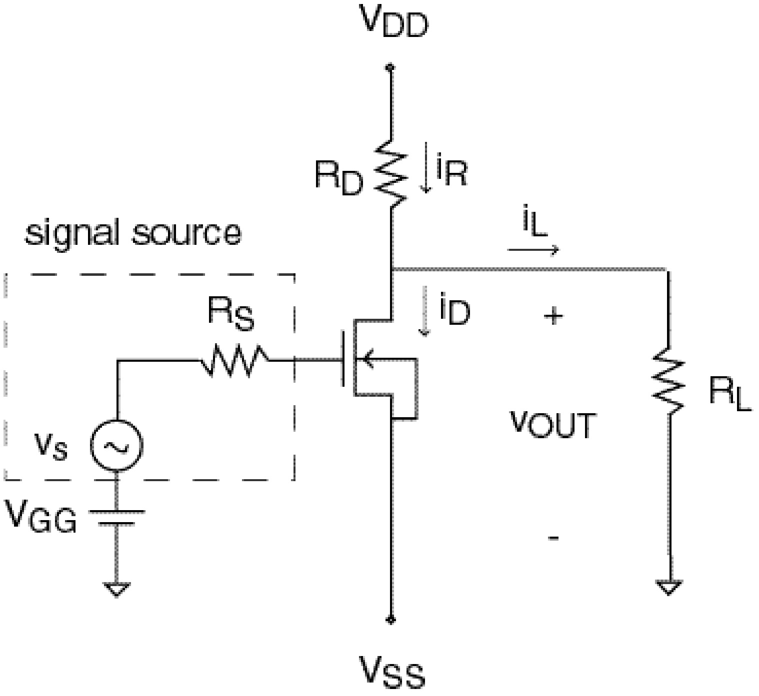
or

$$v_{out,min} - V_{SS} = V_{GG} - V_{SS} - V_T$$

Then:

$$v_{out,min} = V_{GG} - V_T$$

Effect of input/output loading:



- Bias point not affected because selected $V_{OUT}=0$.
- Upswing limited by resistive divider:

$$v_{out,max} = V_{DD}\frac{R_L}{R_L + R_D}$$

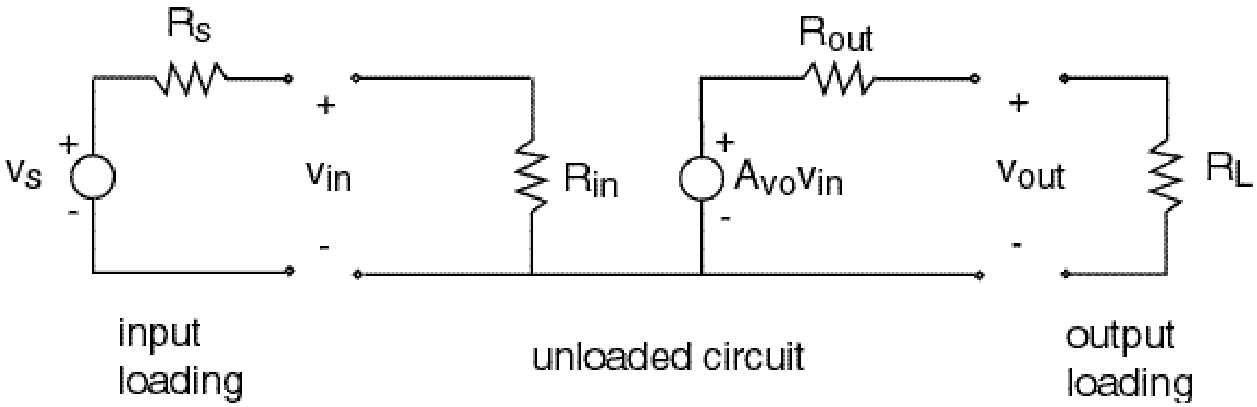
- Downswing not affected by loading
- Voltage gain:
  - Input loading (R_S): no effect because the gate does not draw any current;
  - Output loading (R_L): R_L reduces voltage gain because it draws current.

$$|A_v| = g_m\left(r_o // R_D // R_L\right) < g_m\left(r_o // R_D\right)$$

Generic view of the effect of loading on small-signal operation

Two-port network view of small-signal equivalent circuit model of a voltage amplifier:

R_{in} is ***input resistance***
R_{out} is ***output resistance***
A_{vo} is ***unloaded voltage gain***



Voltage divider at input: $$v_{in} = R_{in} \frac{v_s}{R_{in} + R_s}$$

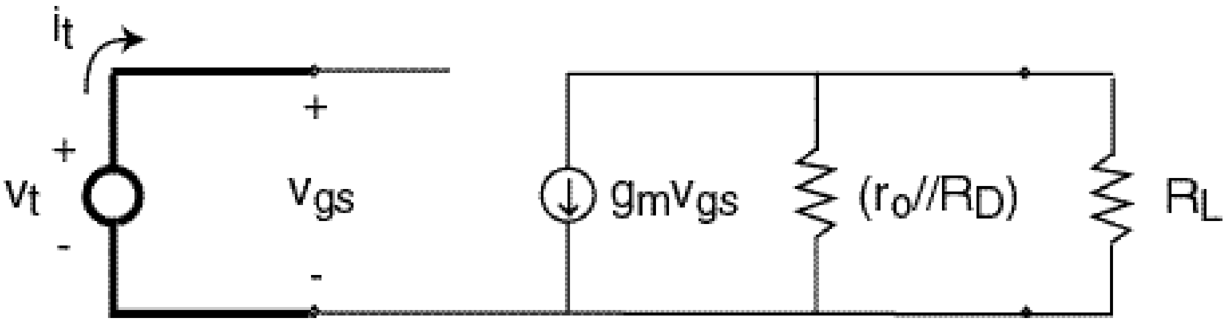
Voltage divider at output: $$v_{out} = R_L \frac{A_{vo} v_{in}}{R_{out} + R_L}$$

Loaded voltage gain: $$\frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in} + R_S} A_{vo} \frac{R_L}{R_L + R_{out}}$$

Input Resistance

- Calculation of input resistance, R_{in}:
  - Load amplifier with R_L
  - Apply test voltage (or current) at input, measure test current (or voltage).

For common-source amplifier:



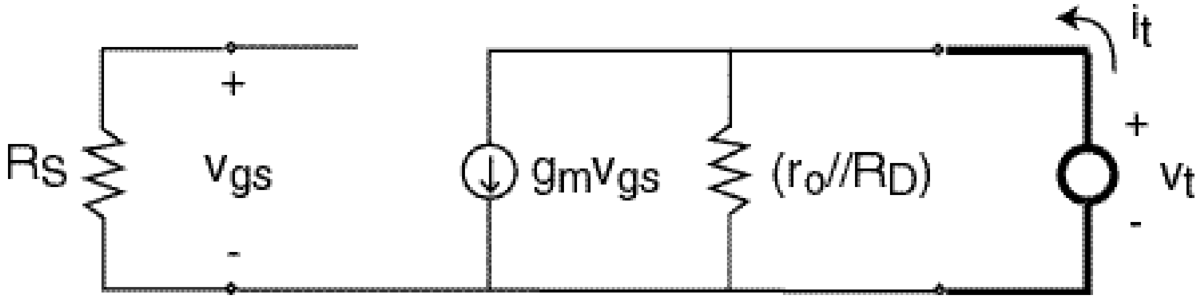
$$i_t = 0 \qquad R_{in} = \frac{v_t}{i_t} = \infty$$

No effect of loading at input.

Output Resistance

- Calculation of output resistance, R_{out}:
  - Load amplifier with R_S
  - Apply test voltage (or current) at output, measure test current (or voltage).

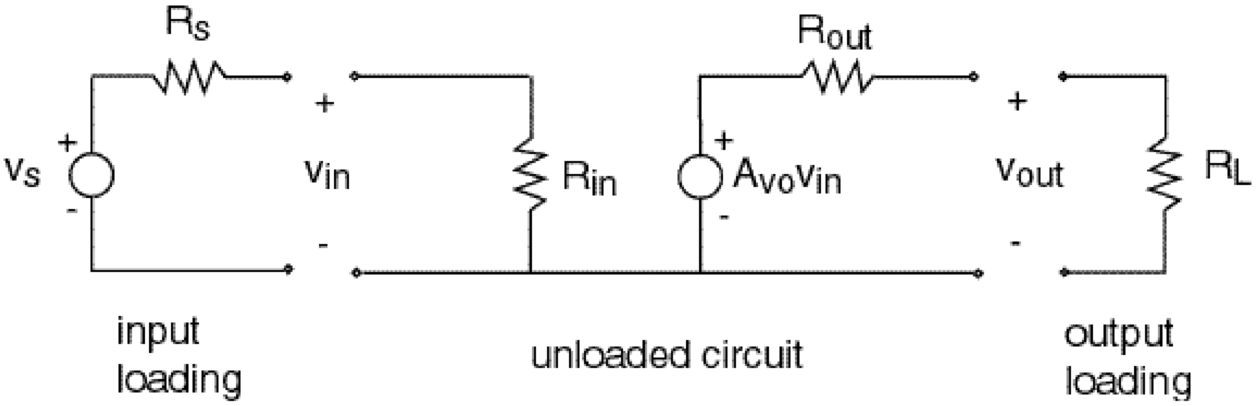
For common-source amplifier:



$$v_{gs} = 0 \qquad g_m v_{gs} = 0 \qquad v_t = i_t \left(r_o // R_D \right)$$

$$R_{out} = \frac{v_t}{i_t} = r_o // R_D$$

Two-port network view of common-source amplifier



$$\frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in} + R_S} A_{vo} \frac{R_L}{R_L + R_{out}} = -g_m \left(r_o \,//\, R_D \right) \frac{R_L}{R_L + r_o \,//\, R_D}$$

Or:

$$\frac{v_{out}}{v_s} = -g_m \left(r_o \,//\, R_D \,//\, R_L \right)$$

Design issues of common-source amplifier (unloaded)

- To maximize gain: want R_D high

$$|A_{vo}| = g_m (r_o \,//\, R_D)$$

- To get high $|A_{vo}|$ $\quad R_D \uparrow \quad I_D = \dfrac{V_{DD}}{R_D} \downarrow$

Rewrite $|A_{vo}|$ in the following way:

$$|A_{vo}| \approx g_m R_D = \sqrt{2 I_D \frac{W}{L} \mu_n C_{ox}} \cdot \frac{V_{DD}}{I_D} \qquad \frac{1}{\sqrt{I_D}}$$

Then:

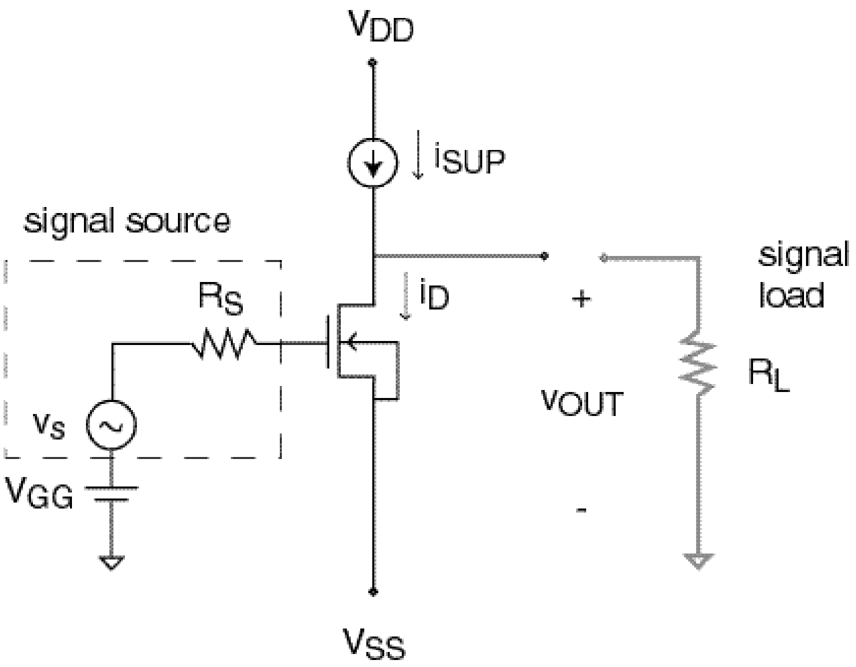
$$R_D \uparrow \qquad I_D \downarrow \qquad g_m \downarrow \qquad |A_{vo}| \uparrow$$

Issues:

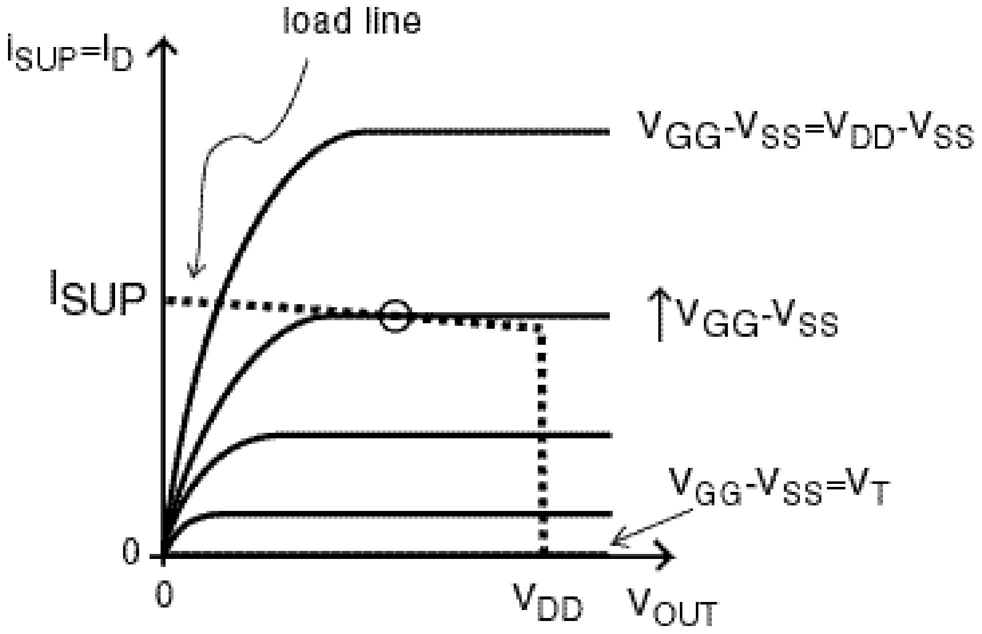
- Large R_D consumes a lot of Si real estate.
- Large R_D eventually compromises frequency response

Solution: CS amplifier with current source supply

3. Common-source amplifier with current-source supply



Loadline view:



3. Common-source amplifier with current-source supply (contd.)

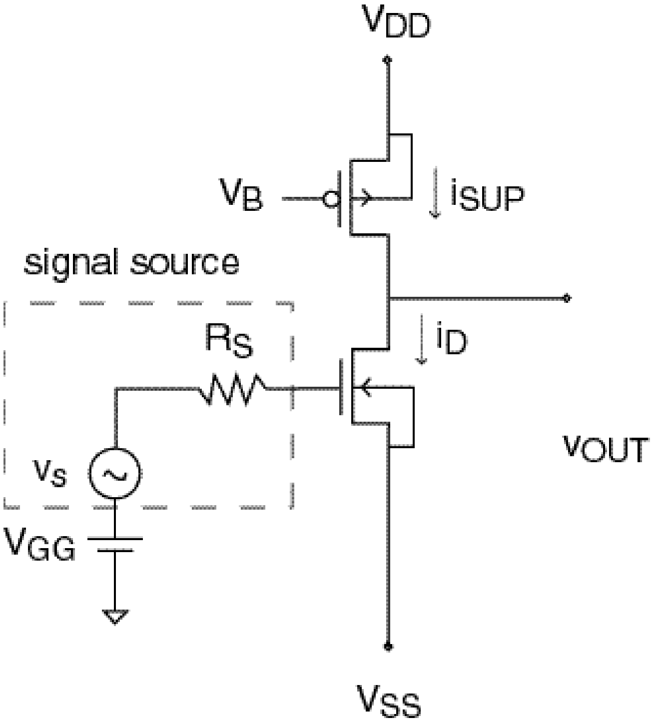
Current source characterized by high output resistance: $r_{out} = r_{oc}$.

Voltage gain:

$$\left|A_{vo}\right| = g_m \left(r_o \,//\, r_{oc}\right)$$

significantly higher than amplifier with resistive supply.

Can implement current source supply by means of p-channel MOSFET:



What did we learn today?

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