

Lecture 19 - Transistor Amplifiers (I)

COMMON-SOURCE AMPLIFIER

November 15, 2005

Contents:

1. Amplifier fundamentals
2. Common-source amplifier
3. Common-source amplifier with current-source supply

Reading assignment:

Howe and Sodini, Ch. 8, §§8.1-8.6

Announcements:

Quiz 2: 11/16, 7:30-9:30 PM,
open book, must bring calculator; lectures #10-18.

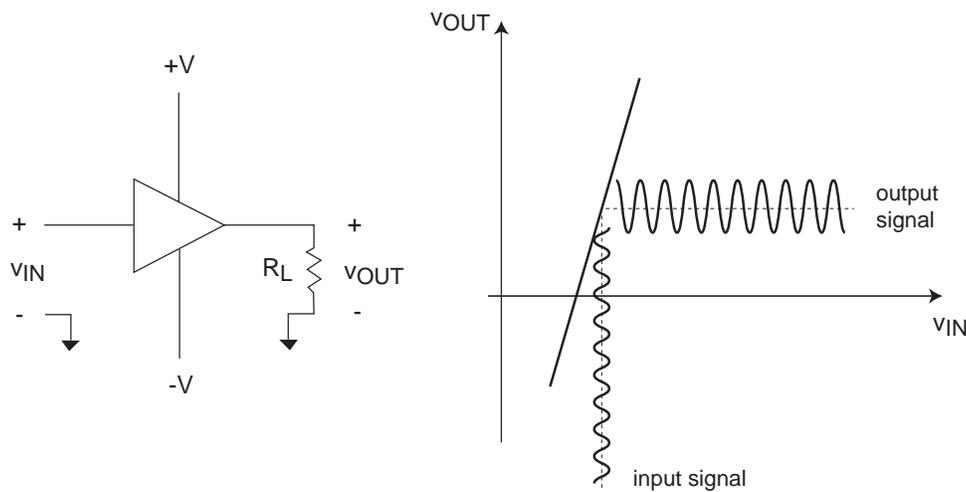
Quiz 2 TA Review Session: 11/15, 7:30-9:30 PM,

Key questions

- What are the key figures of merit of an amplifier?
- How can one make a voltage amplifier with a single MOSFET and a resistor?
- How can this amplifier be improved?

1. Amplifier fundamentals

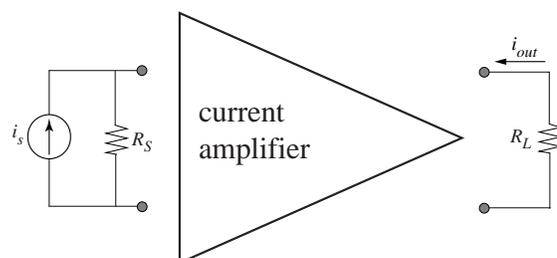
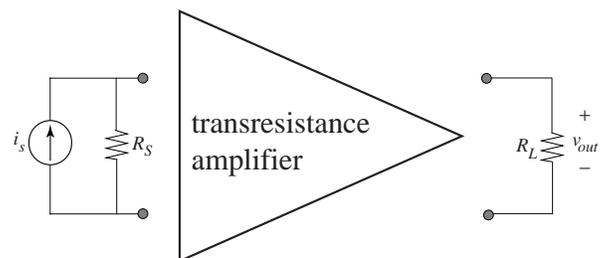
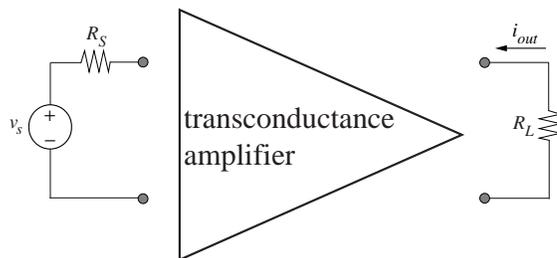
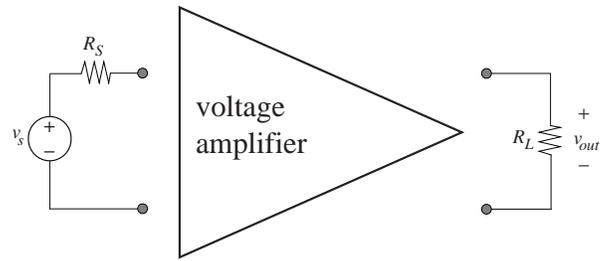
Goal of amplifiers: *signal amplification*.



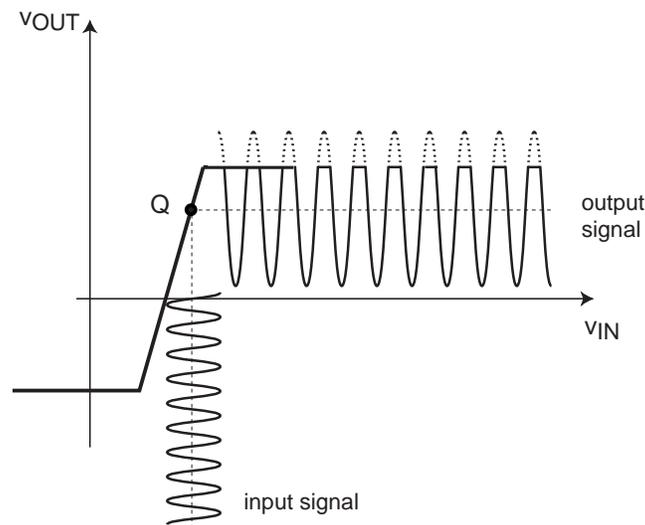
Features of amplifier:

- *Output signal* is faithful replica of *input signal* but amplified in magnitude.
- *Active device* is at the heart of amplifier.
- Need *linear transfer characteristics* for distortion not to be introduced.

Signal could be represented by *current* or *voltage*
⇒ four broad types of amplifiers:



More realistic transfer characteristics:



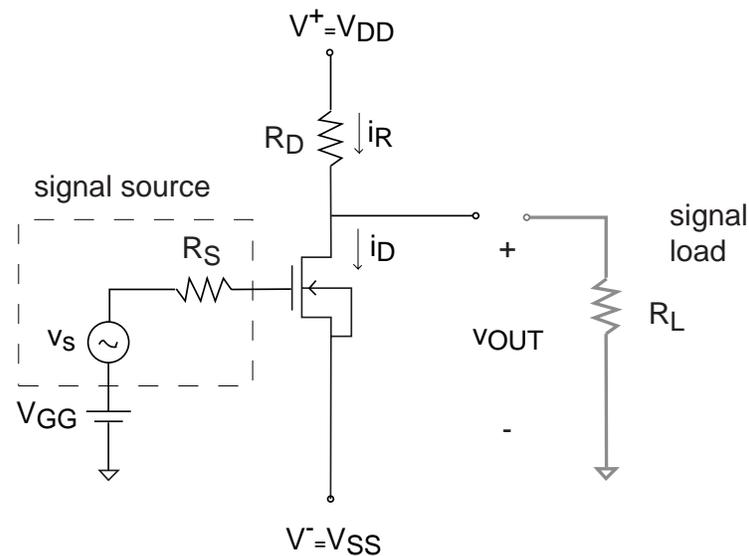
- Transfer characteristics linear over limited range of voltages: *amplifier saturation*.
- Amplifier saturation limits *signal swing*.
- Signal swing also depends on choice of *bias point*, Q (also called *quiescent point* or *operating point*).

Other features desired in amplifiers:

- Low *power consumption*.
- Wide *frequency response* [will discuss in a few days].
- *Robust* to process and temperature variations.
- *Inexpensive*: must minimize use of unusual components, must be small (in Si area)

2. Common-Source Amplifier

Consider the following circuit:

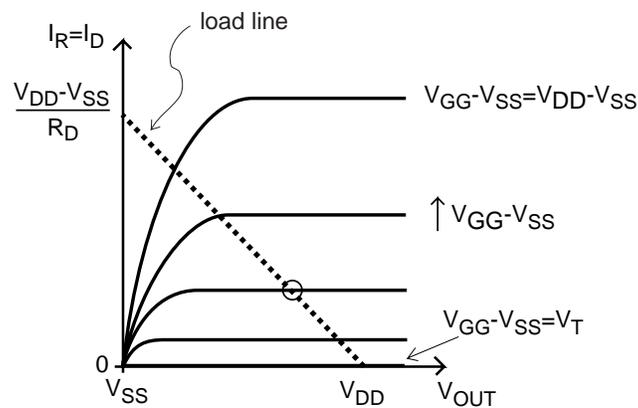


Consider it first unloaded by R_L . How does it work?

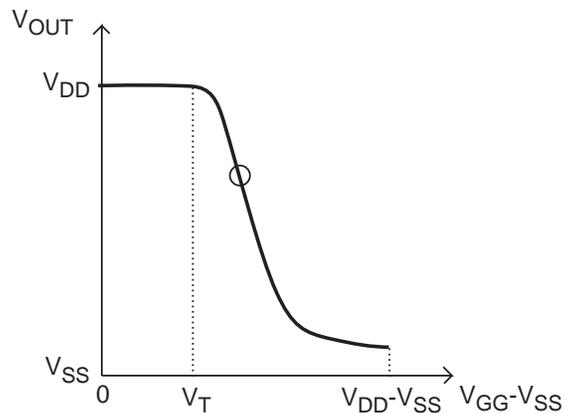
- V_{GG} , R_D and W/L of MOSFET selected to bias transistor in saturation and obtain desired output bias point (*i.e.* $V_{OUT} = 0$).
- $v_{GS} \uparrow \Rightarrow i_D \uparrow \Rightarrow i_R \uparrow \Rightarrow v_{out} \downarrow$
- $A_v = \frac{v_{out}}{v_s} < 0$; output out of phase from input,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

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

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

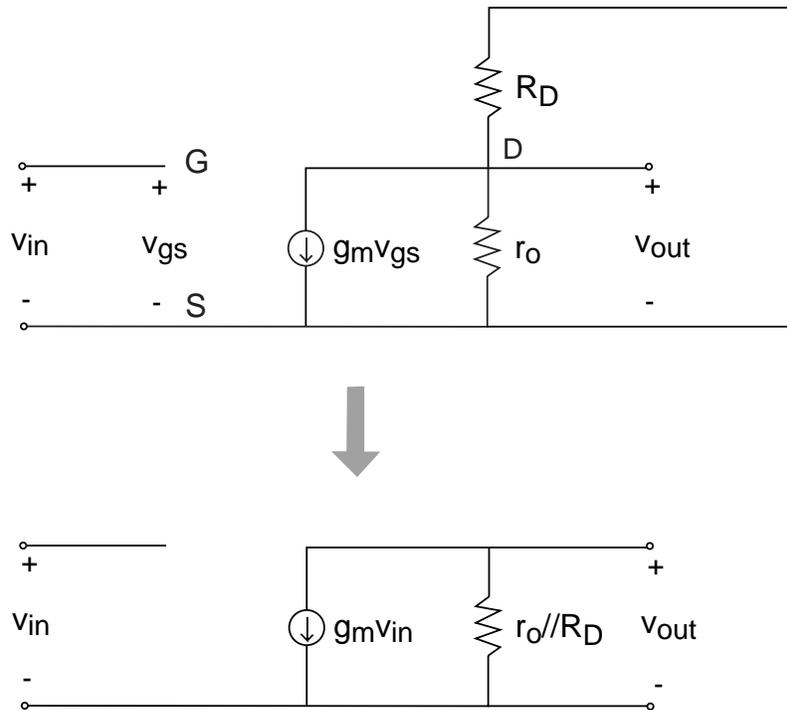
If we select $V_{OUT} = 0$:

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

Then:

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

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

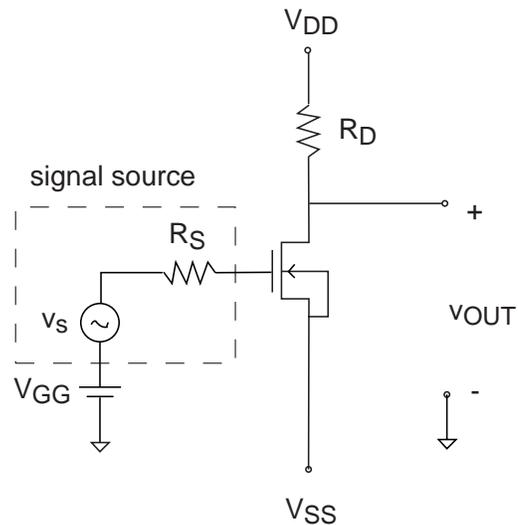


$$v_{out} = -g_m v_{in} (r_o // R_D)$$

Then *unloaded voltage gain*:

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

□ *Signal swing:*



- Upswing: limited by transistor going into cut-off:

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

- Downswing: limited by MOSFET entering linear regime:

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

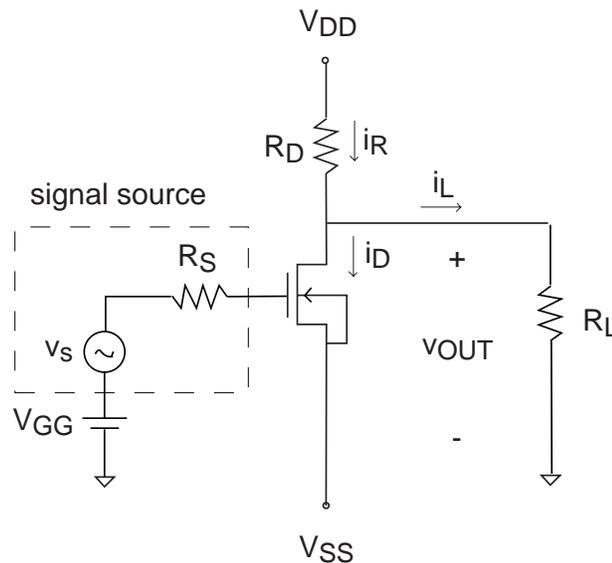
or

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

Then:

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

□ *Effect of input/output loading:*



- Bias point not affected because selected $V_{OUT} = 0$.

- Signal swing:

– 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 gate does not draw current;

– output loading (R_L): R_L detracts from voltage gain because it draws current.

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

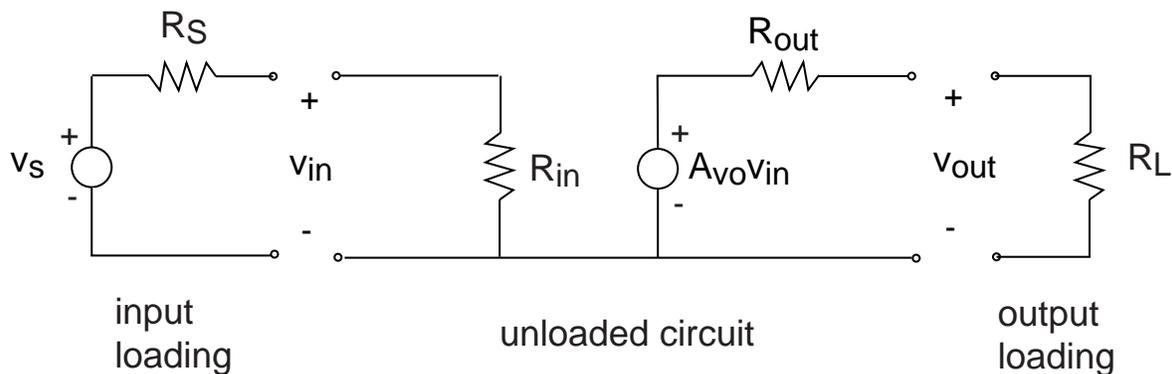
□ Generic view of loading effect on small-signal operation:

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

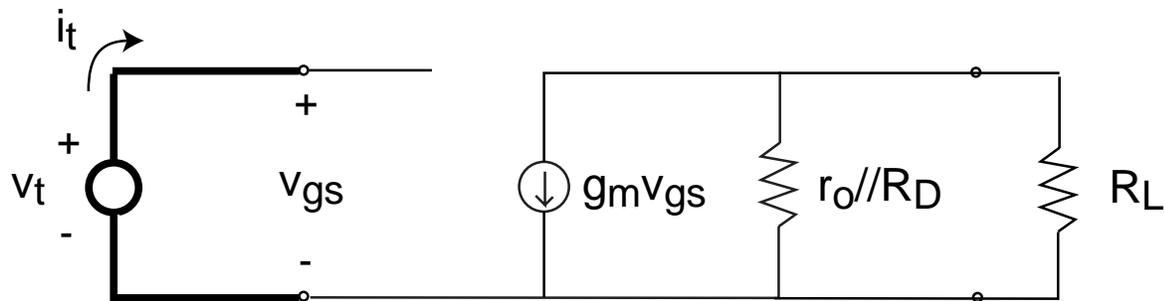
$$v_{out} = R_L \frac{A_{vo} v_{in}}{R_{out} + R_L}$$

Loaded voltage gain:

$$A_v = \frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in} + R_s} A_{vo} \frac{R_L}{R_L + R_{out}}$$

- 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:



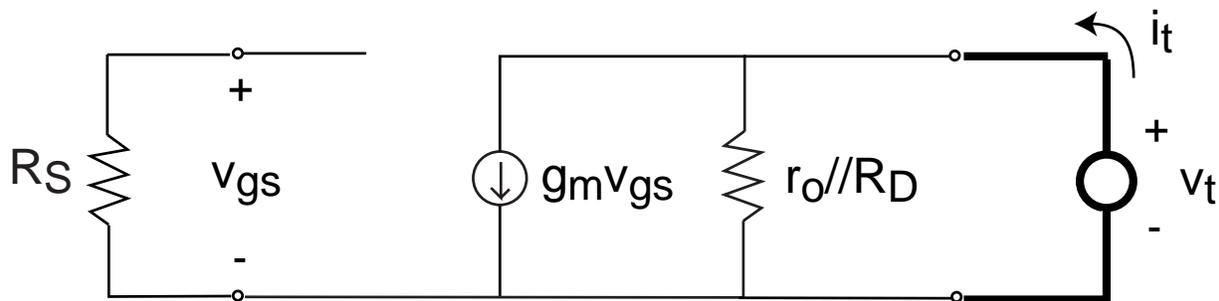
$$i_t = 0 \Rightarrow R_{in} = \frac{v_t}{i_t} = \infty$$

No effect of loading at input.

- Calculation of output resistance, R_{out} :

- load amplifier at input with R_S
- apply test voltage (or current) at output, measure test current (or voltage)

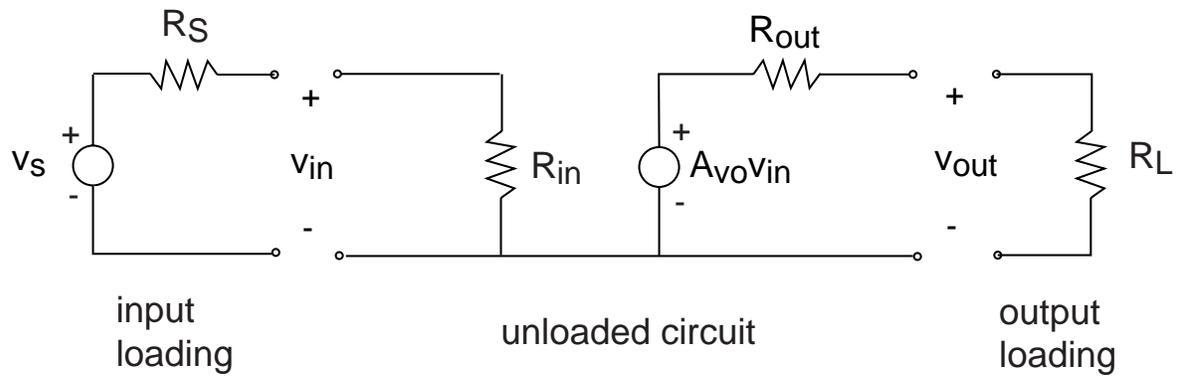
For common-source amplifier:



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

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

Two-port network view of common-source amplifier:



$$\begin{aligned}
 A_v &= \frac{v_{out}}{v_s} \\
 &= \frac{R_{in}}{R_{in} + R_S} A_{vo} \frac{R_L}{R_L + R_{out}} = -g_m (r_o // R_D) \frac{R_L}{R_L + r_o // R_D}
 \end{aligned}$$

Or:

$$A_v = -g_m (r_o // R_D // R_L)$$

□ Design issues of common-source amplifier (unloaded):

Examine bias dependence:

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

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

$$|A_{vo}| \simeq g_m R_D = \sqrt{2 \frac{W}{L} \mu_n C_{ox} I_D} \frac{V_{DD}}{I_D} \propto \frac{V_{DD}}{\sqrt{I_D}}$$

Then, to get high $|A_{vo}|$:

$$\Rightarrow V_{DD} \uparrow$$

$$\Rightarrow I_D \downarrow$$

Both approaches imply $\Rightarrow R_D = \frac{V_{DD}}{I_D} \uparrow$

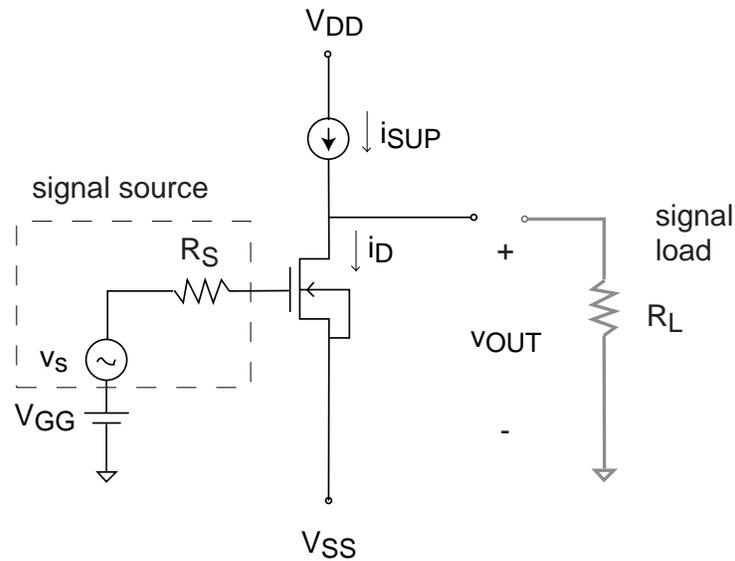
Consequences of high R_D :

- large R_D consumes a lot of Si real state
- large R_D eventually compromises frequency response

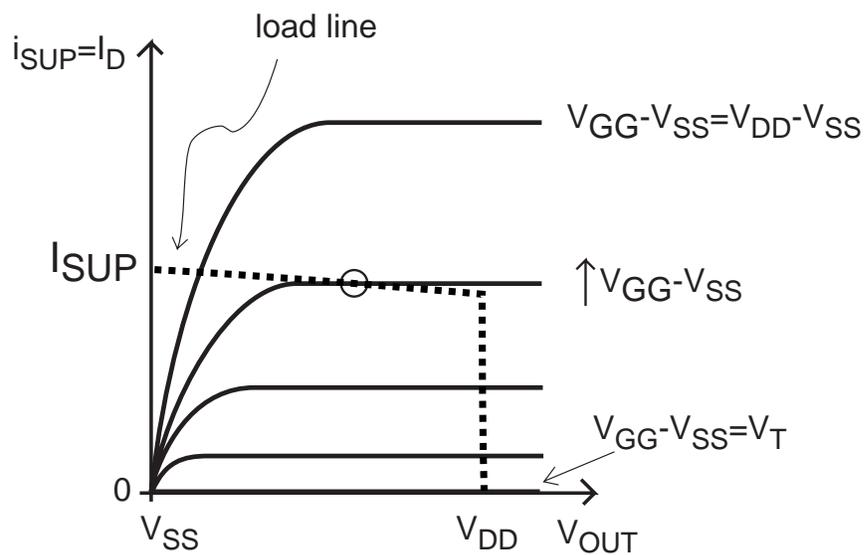
Also, it would be nice not to use any resistors at all!

\Rightarrow Need better circuit.

3. Common-source amplifier with current-source supply



Loadline view:



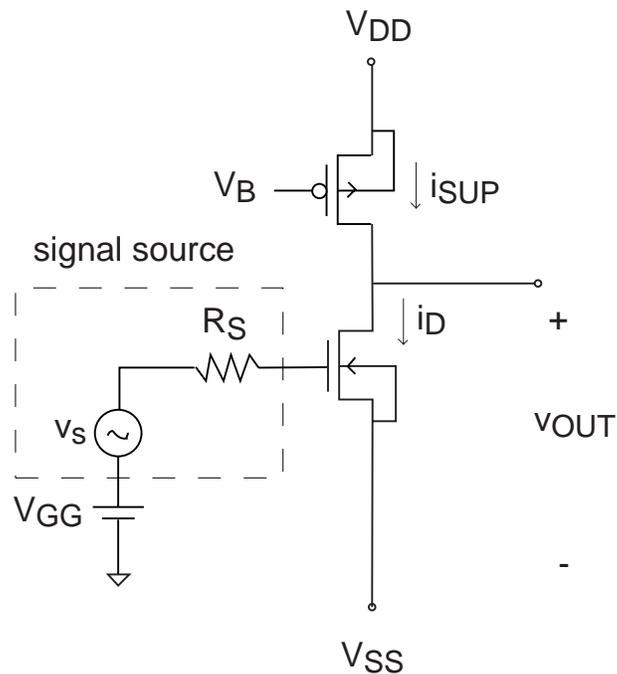
Current source characterized by high output resistance:
 r_{oc} .

Then, unloaded voltage gain of common-source stage:

$$|A_{vo}| = g_m(r_o // r_{oc})$$

significantly higher than amplifier with resistive supply.

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



- Relationship between circuit figures of merit and device parameters

Remember:

$$g_m = \sqrt{2 \frac{W}{L} \mu_n C_{ox} I_D}$$

$$r_o \simeq \frac{1}{\lambda_n I_D} \propto \frac{L}{I_D}$$

Then:

| Device * Parameters | Circuit Parameters | | |
|-------------------------|----------------------|----------|-----------------|
| | $ A_{vo} $ | R_{in} | R_{out} |
| | $g_m(r_o // r_{oc})$ | ∞ | $r_o // r_{oc}$ |
| $I_{SUP} \uparrow$ | \downarrow | - | \downarrow |
| $W \uparrow$ | \uparrow | - | - |
| $\mu_n C_{ox} \uparrow$ | \uparrow | - | - |
| $L \uparrow$ | \uparrow | - | \uparrow |

* adjustments are made to V_{GG} so none of the other parameters change

CS amp with current supply source is good voltage amplifier (R_{in} high and $|A_v|$ high), but R_{out} high too \Rightarrow voltage gain degraded if $R_L \ll r_o // r_{oc}$.

Key conclusions

- Figures of merit of an amplifier:
 - gain
 - signal swing
 - power consumption
 - frequency response
 - robustness to process and temperature variations
- Common-source amplifier with resistive supply: trade-off between gain and cost and frequency response.
- Trade-off resolved by using common-source amplifier with current source supply.
- Two-port network computation of voltage gain, input resistance and output resistance of amplifier.