Lecture 19 - Transistor Amplifiers (I)

Common-Source Amplifier

April 17, 2003

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Reading assignment:

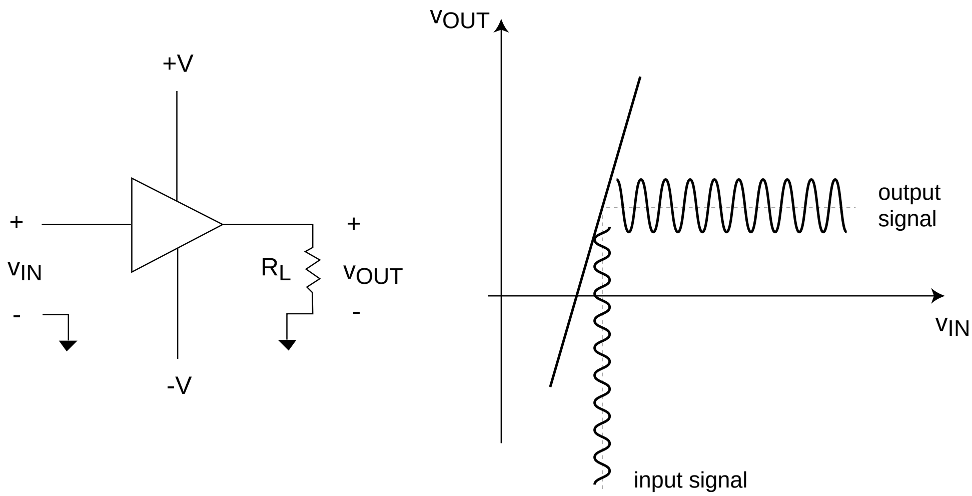
Howe and Sodini, Ch. 8, §§8.1-8.6

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

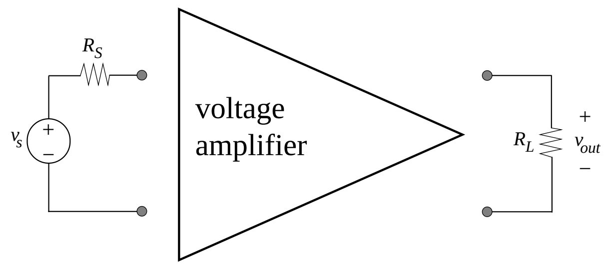
Goal of amplifiers: *signal amplification*.

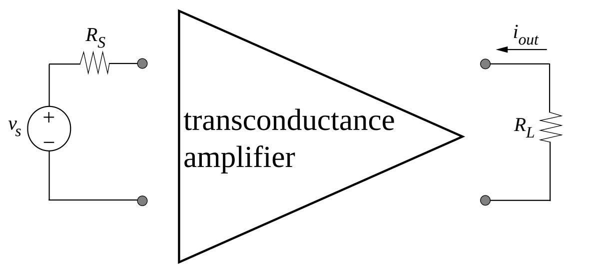


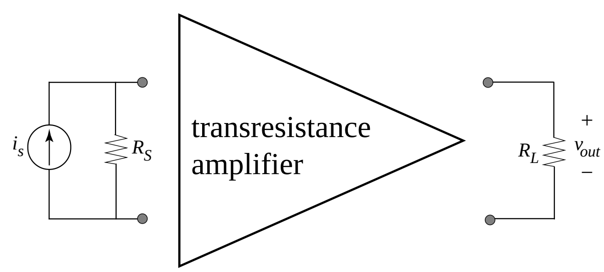
Features of amplifier:

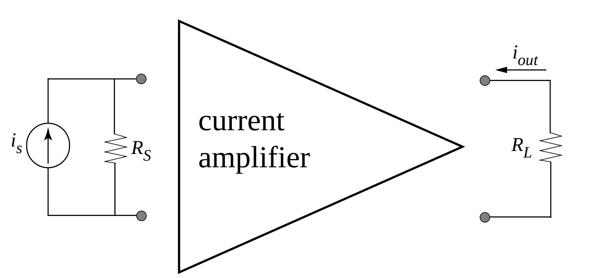
- *Output signal* is faithful replica of *input signal* but amplified in magnitude.
- *Active device* is at the heart of amplifier.
- Need *linear transfer characteristics* for distortion not to be introduced.

Signal could be represented by *current* or *voltage*
$\Rightarrow$ four broad types of amplifiers:

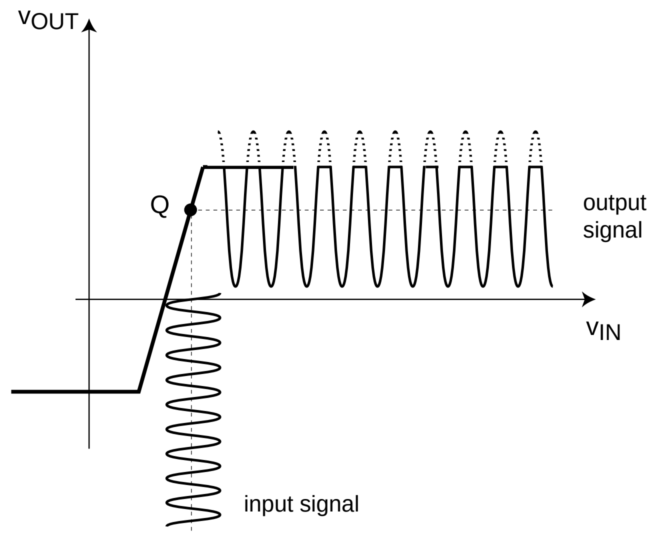








More realistic transfer characteristics:



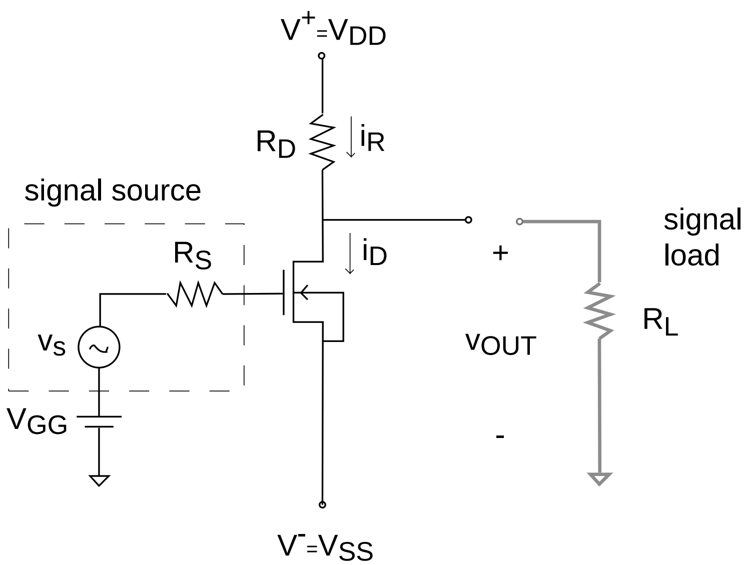
- Transfer characteristics linear over limited range of voltages: *amplifier saturation*.
- Amplifier saturation limits *signal swing*.
- Signal swing also depends on choice of *bias point*, Q (also called *quiescent point* or *operating point*).

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:

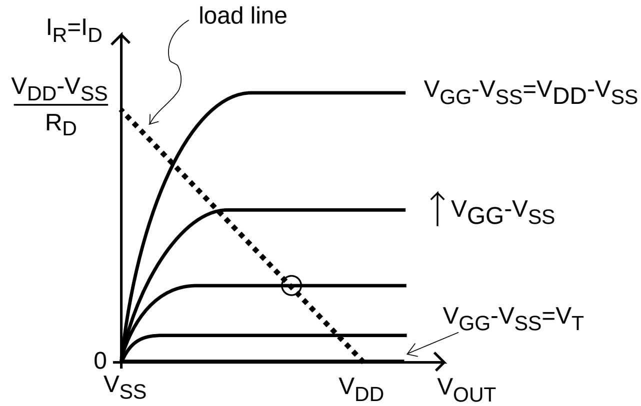


Consider it first unloaded by R_L. How does it work?

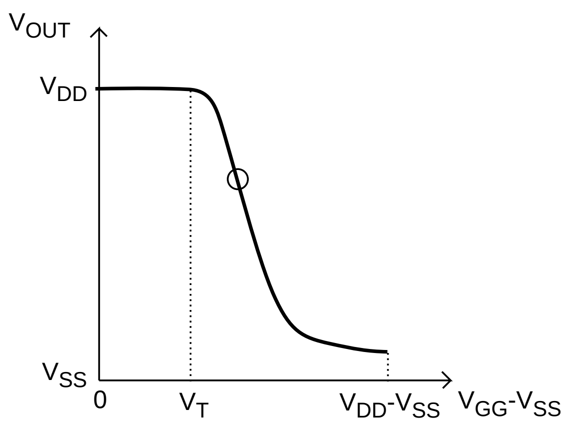
- V_{GG}, R_D and W/L of MOSFET selected to bias transistor in saturation and obtain desired output bias point ($i.e.$ $V_{OUT} = 0$).
- $v_{GS} \uparrow \Rightarrow i_D \uparrow \Rightarrow i_R \uparrow \Rightarrow v_{out} \downarrow$
- $A_v = \frac{v_{out}}{v_s} < 0$; output out of phase from input,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

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

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

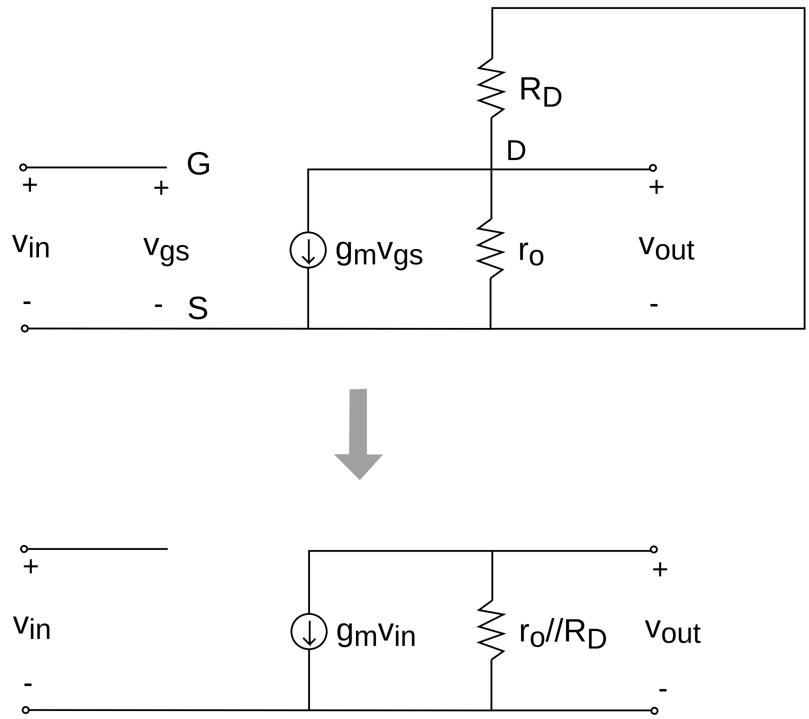
If we select $V_{OUT} = 0$:

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

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:

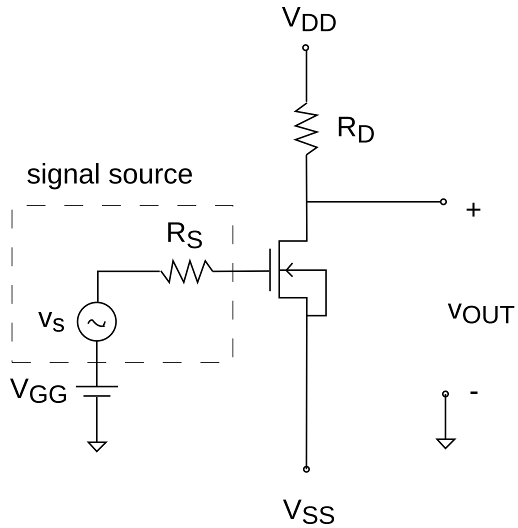


$$v_{out} = -g_m v_{in}(r_o//R_D)$$

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:

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

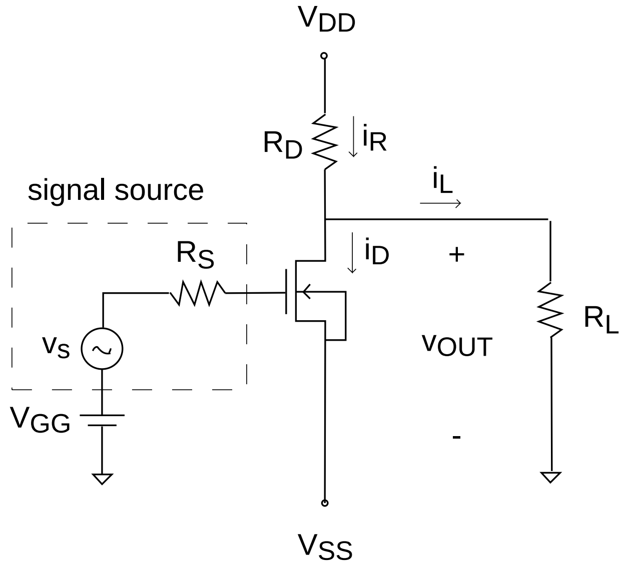
or

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

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:

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

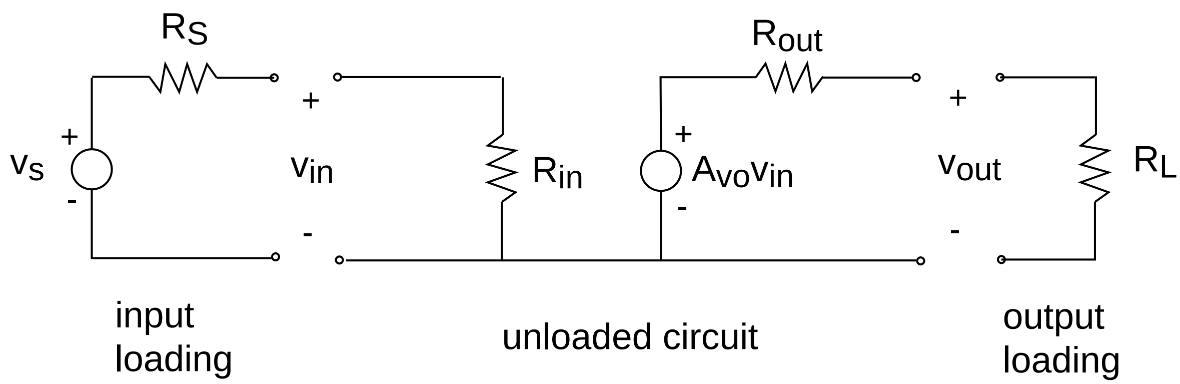
  - Downswing not affected by loading
- Voltage gain:
  - input loading (R_S): no effect because gate does not draw current;
  - output loading (R_L): R_L detracts from voltage gain because it draws current.

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

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

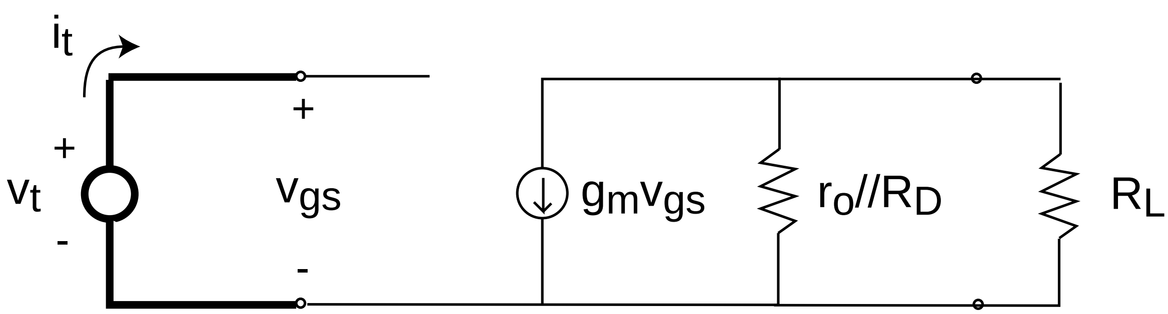
Loaded voltage gain:

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

- 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:



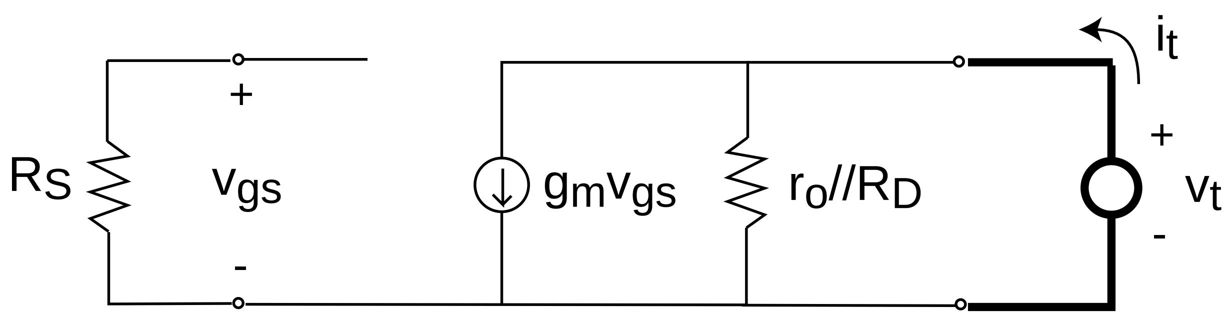
$$i_t = 0 \;\Rightarrow\; R_{in} = \frac{v_t}{i_t} = \infty$$

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)

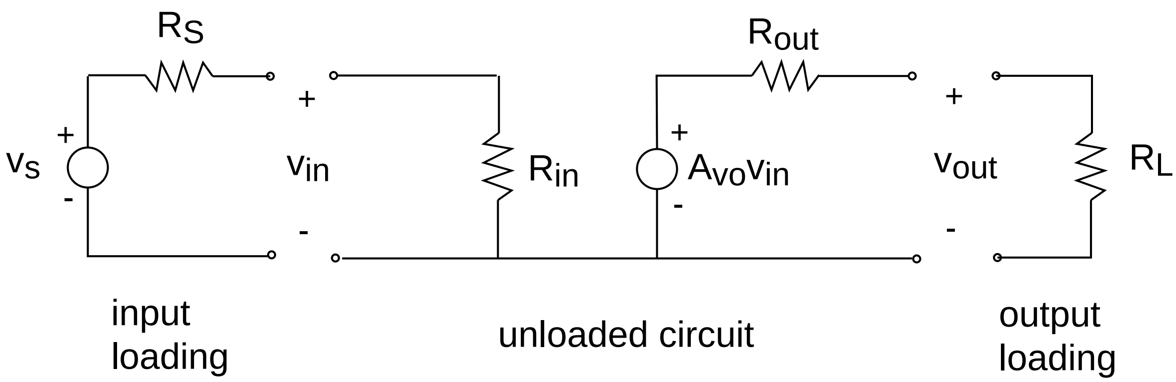
For common-source amplifier:



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

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

Two-port network view of common-source amplifier:



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

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

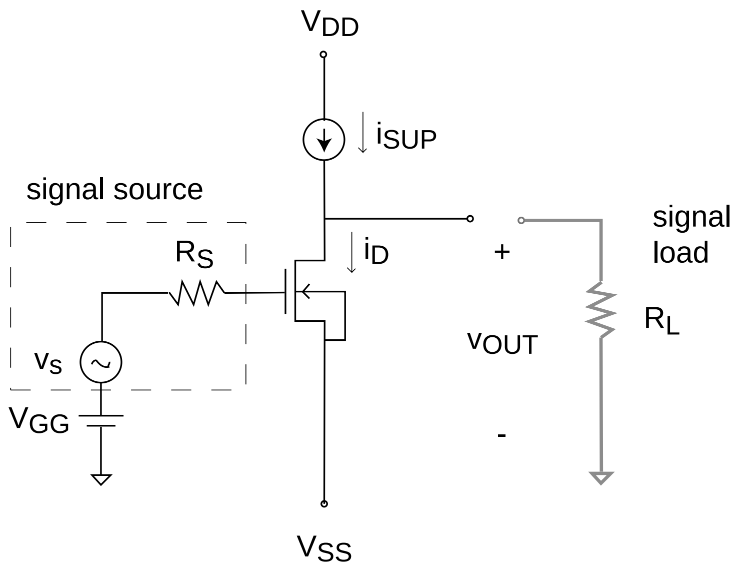
Consequences of high R_D:

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

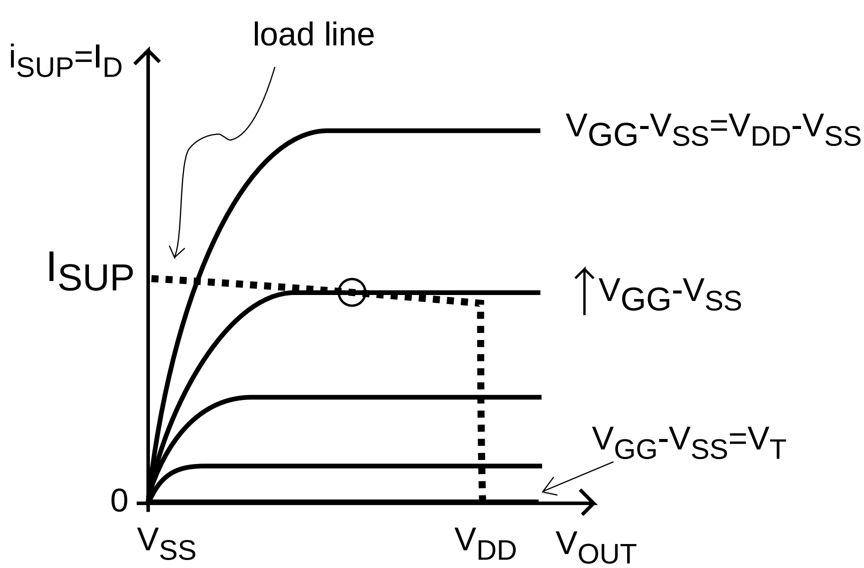
Also, it would be nice not to use any resistors at all!

$\Rightarrow$ Need better circuit.

3. Common-source amplifier with current-source supply



Loadline view:



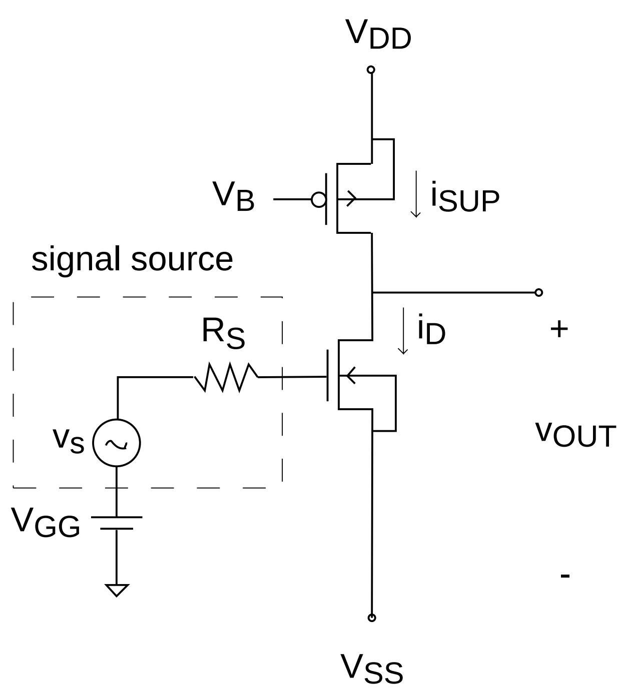
Current source characterized by high output resistance: r_{oc}.

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		
	$\lvert A_{vo}\rvert$	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.