上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

Lecture 19

Transistor Amplifiers (I)

Contents:

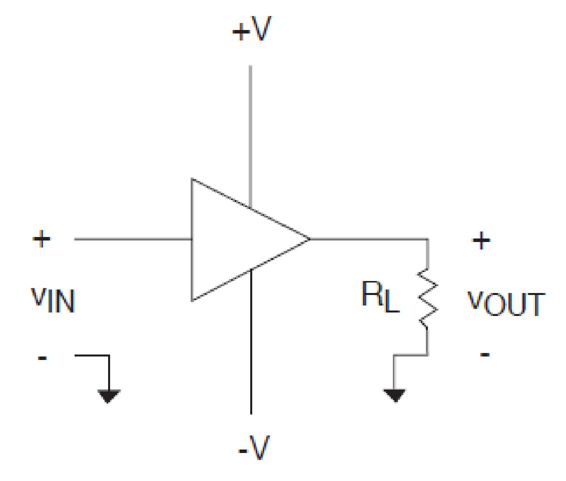
1. **Amplifier fundamentals**
2. **Common source amplifier**
3. **Common source amplifier with current source supply**

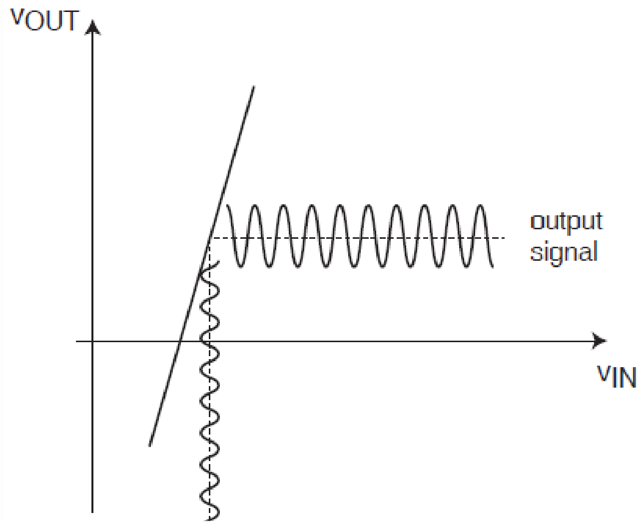
Key questions

- **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?**

Amplifier fundamentals

◆ Goal of amplifiers: signal amplification

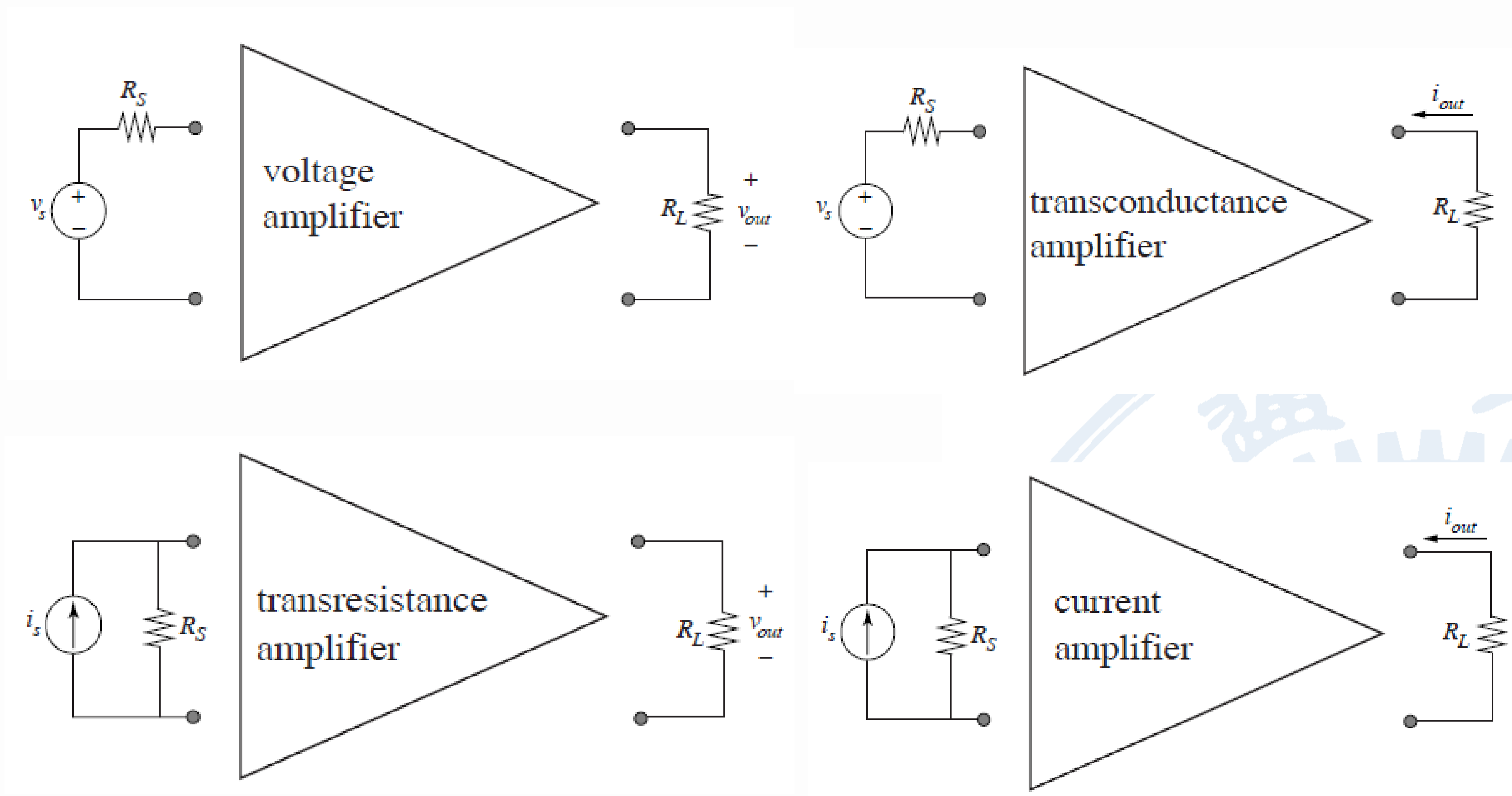




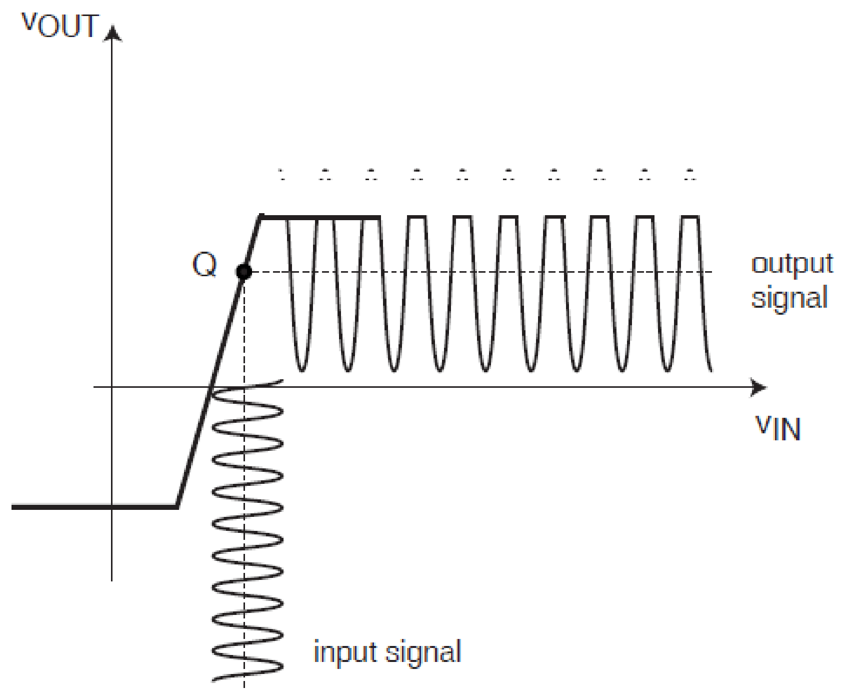
Features of amplifier:

- 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.

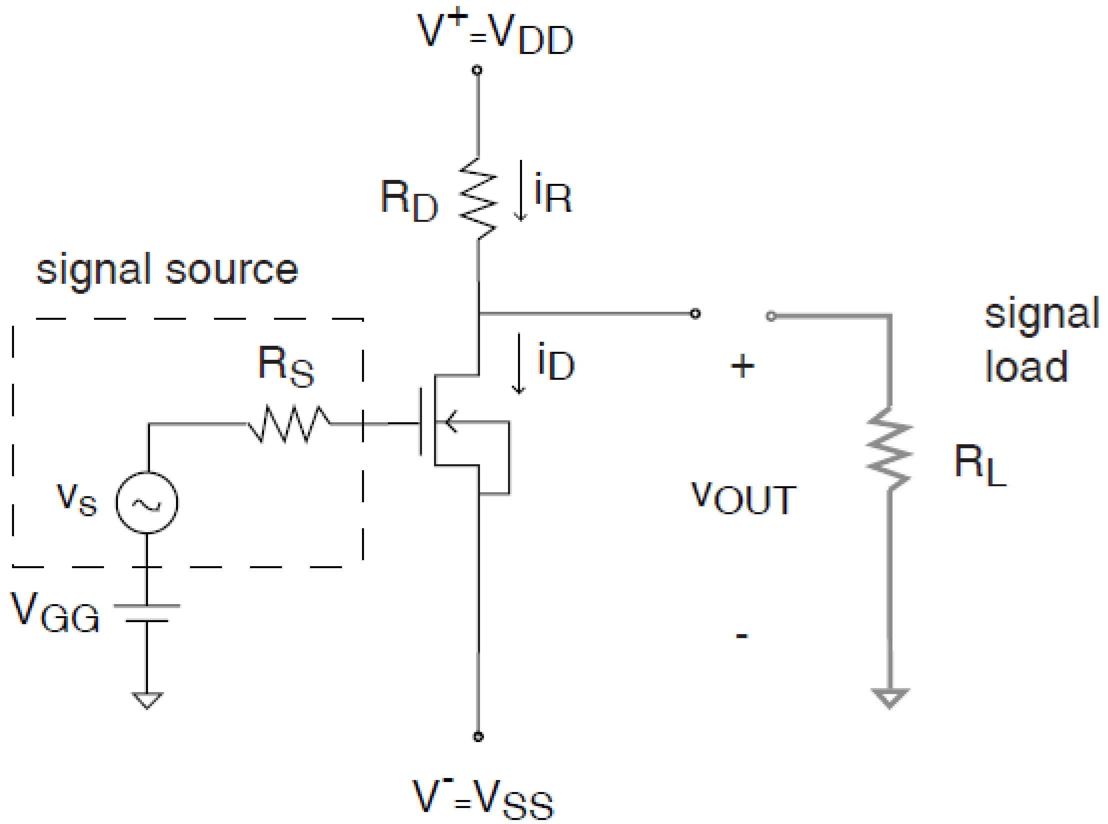
•Amplifier saturation limits signal swing.

•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
- Robustness to process and temperature variations.
- Inexpensive: must minimize use of unusual components, must be small (in Si area) .

1. Common Source Amplifier

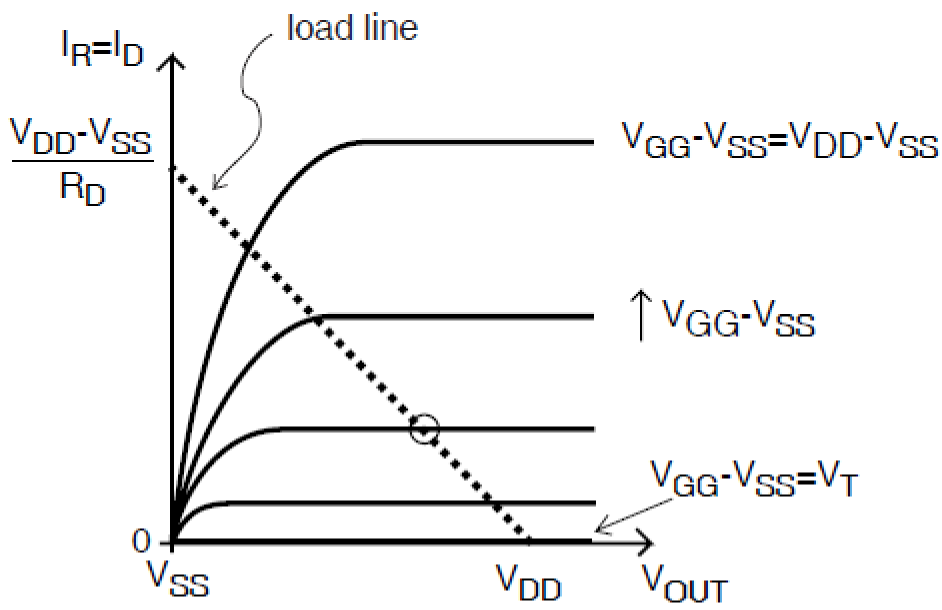


Consider it first unloaded by R_L. How does it work?

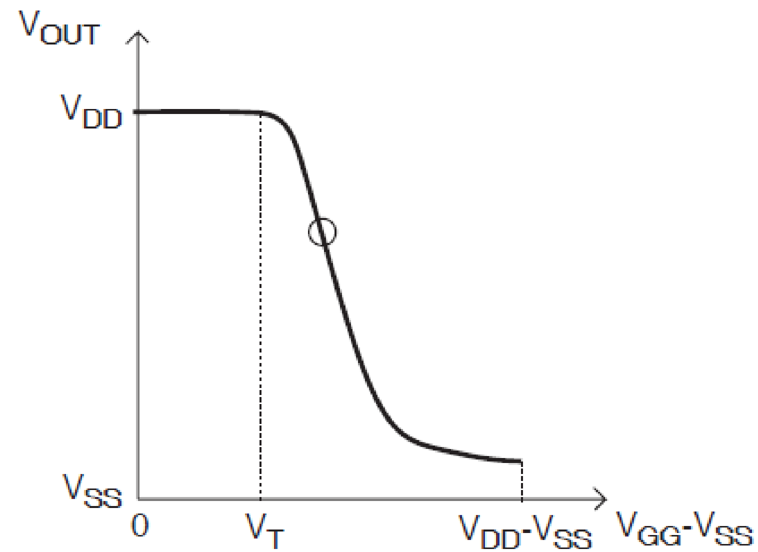
- V_{GG}, R_D and *W/L* of MOSFET selected to bias transistor in saturation and obtain desired output bias point (i.e. V_{OUT}=0)
- $v_{GS} \uparrow \Rightarrow i_D \uparrow \Rightarrow i_R \uparrow \Rightarrow v_{out} \downarrow$
- $A_v = \frac{v_{out}(t)}{v_s} < 0$;output out of phase from input, but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

- 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:

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

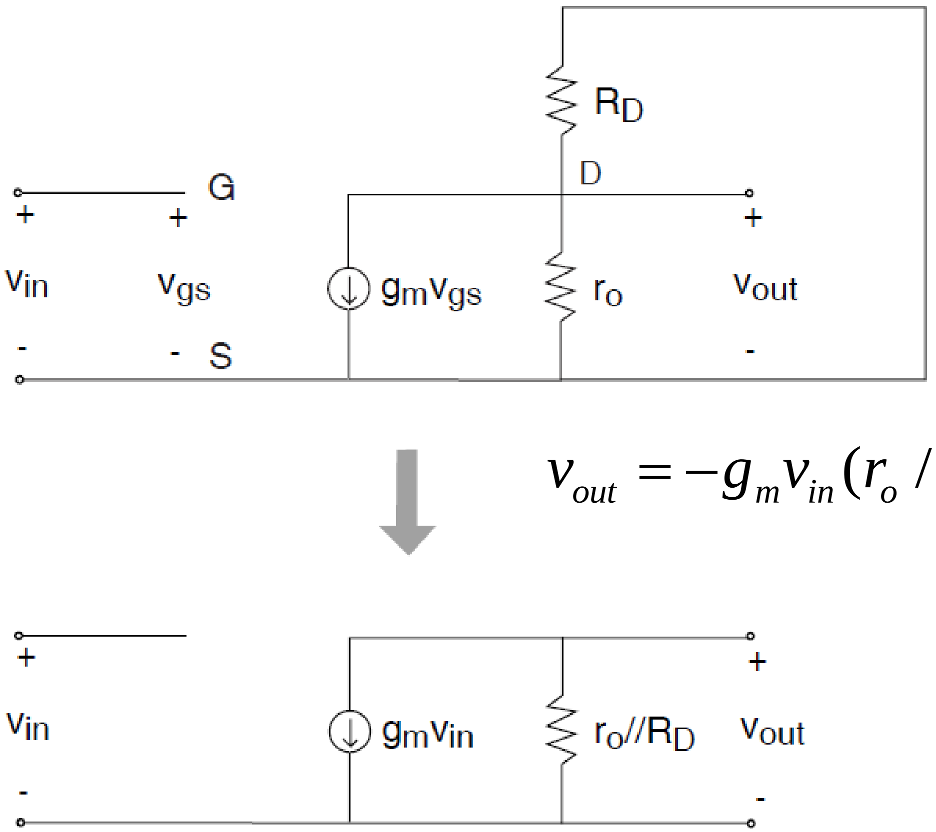
$$I_R = \frac{V_{DD} - V_{OUT}}{R_D}$$

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

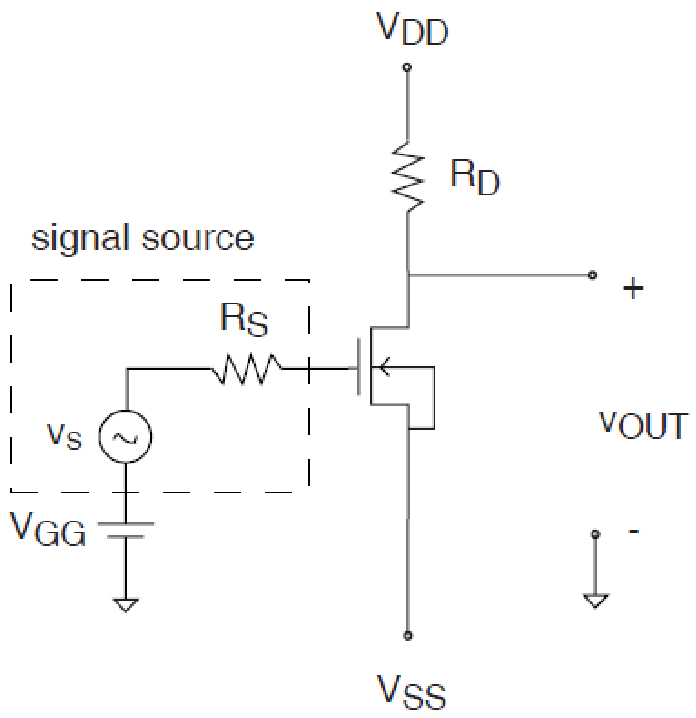
□ Small signal voltage gain: draw small signal equivalent circuit model:



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

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 cutoff:

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

- Downswing: limited by MOSFET entering linear regime:

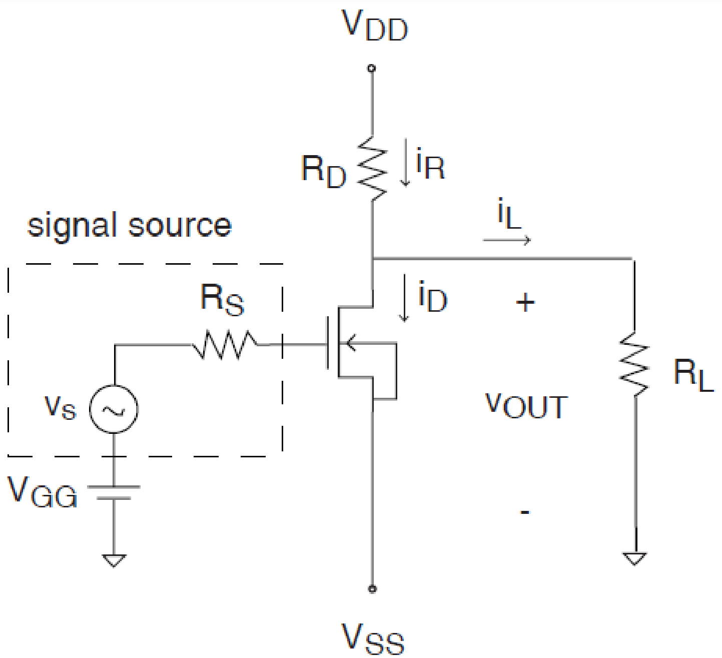
$$V_{DS,sat} = V_{GS} - V_T$$

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

Then:

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

Effect of input/output loading:



- Bias point is 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

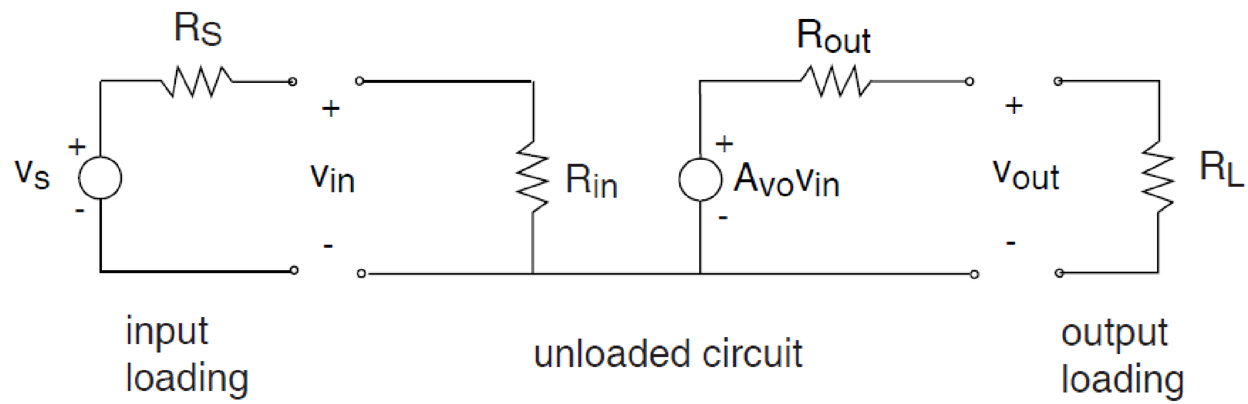
- Voltage gain:
  - input loading (R_S): no effect because gate does not draw current;
  - output loading (R_L): R_L detracts from voltage gain because it draws current.

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

- 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: $v_{in} = R_{in} \dfrac{v_s}{R_{in} + R_S}$

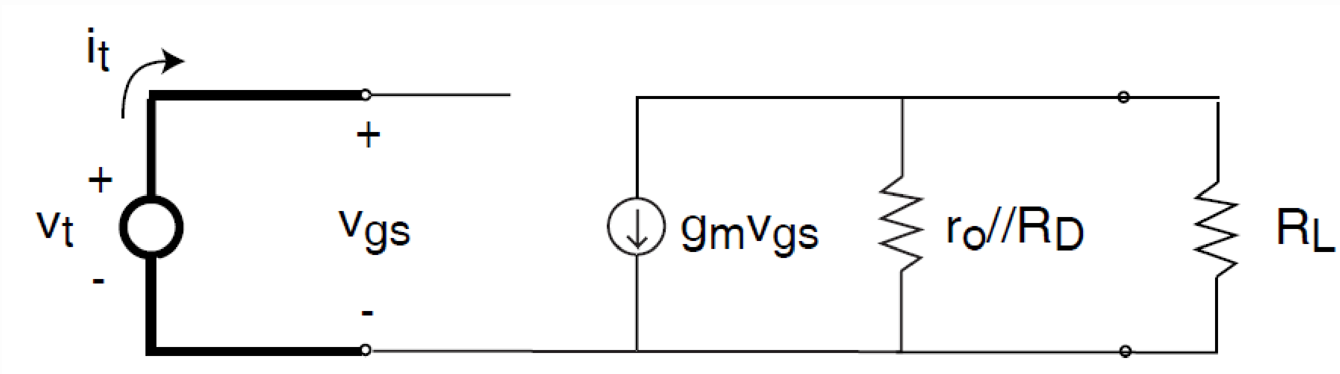
Voltage divider at output: $v_{out} = R_L \dfrac{A_{vo} v_{in}}{R_{out} + R_L}$

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

- 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:



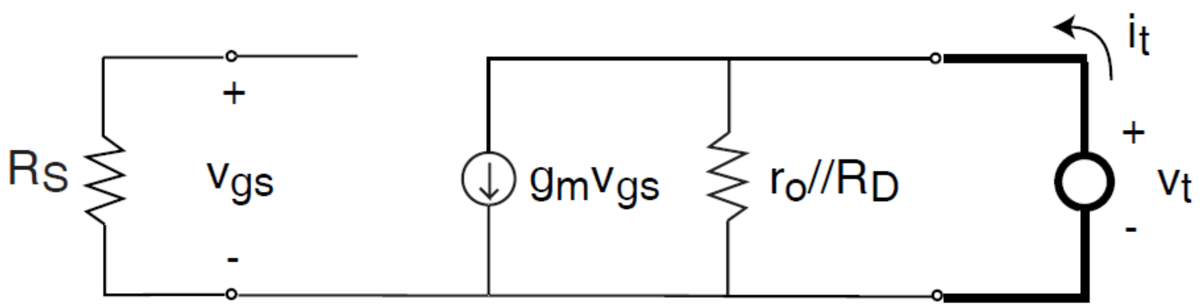
$$i_t = 0 \Rightarrow R_{in} = \frac{v_t}{i_t} = \infty$$

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)

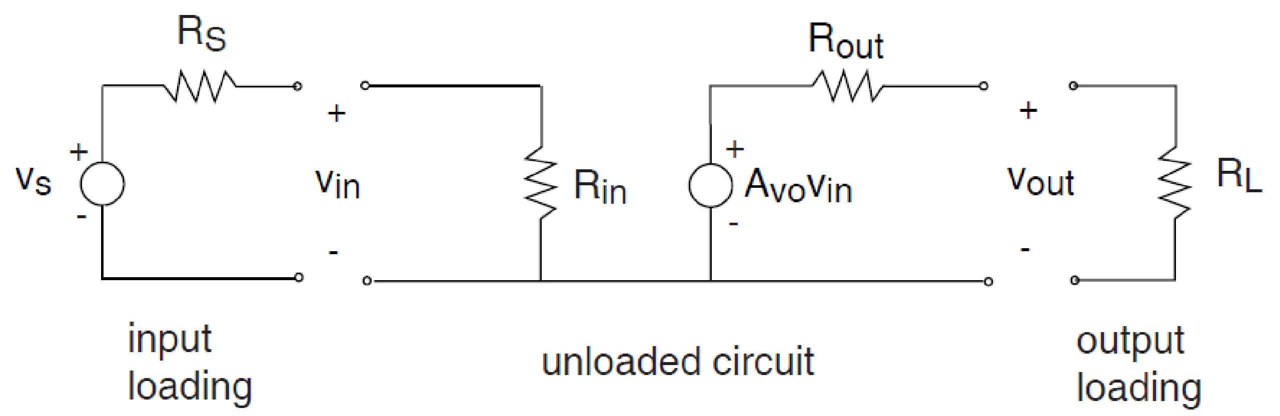
For common source amplifier:



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

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

Two port network view of common source amplifier:



$$A_v = \frac{v_{out}}{v_s}$$

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

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

- Design issues of common source amplifier (unloaded):

Examine bias dependence:

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

Rewrite A_{vo} in the following way:

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

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

$\Rightarrow V_{DD}\uparrow$

$\Rightarrow I_D\downarrow$

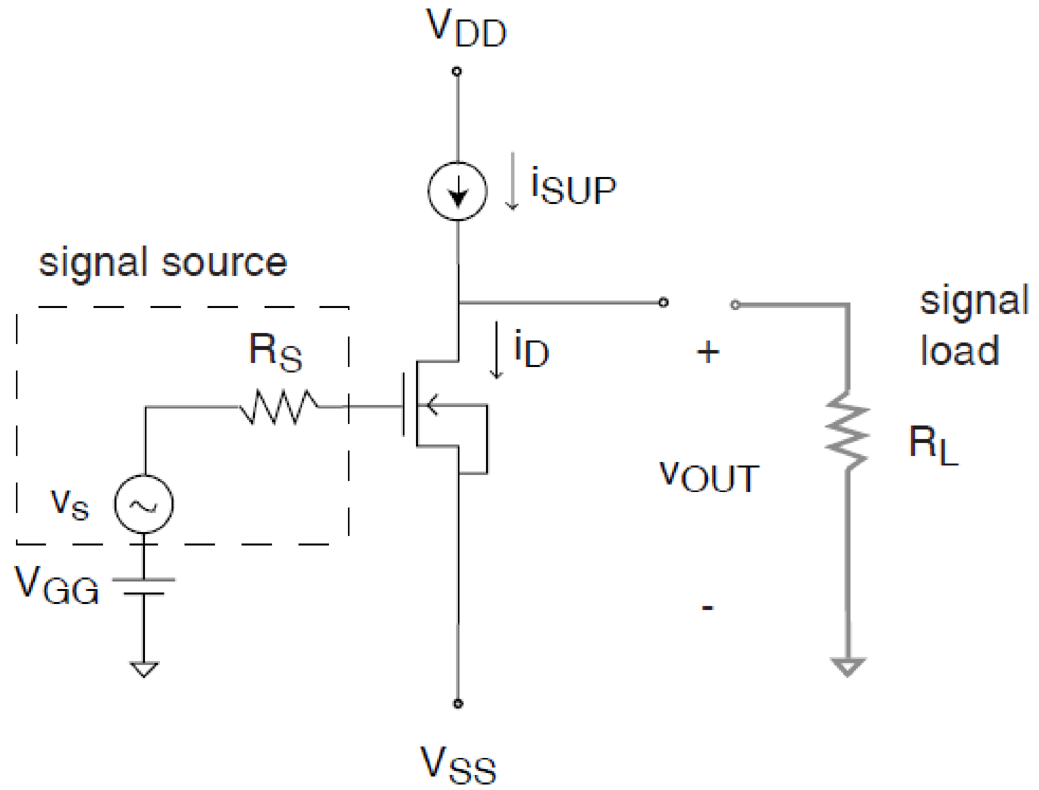
Both approaches imply $\Rightarrow \quad R_D = \frac{V_{DD}}{I_D}\uparrow$

Consequences of high R_D:

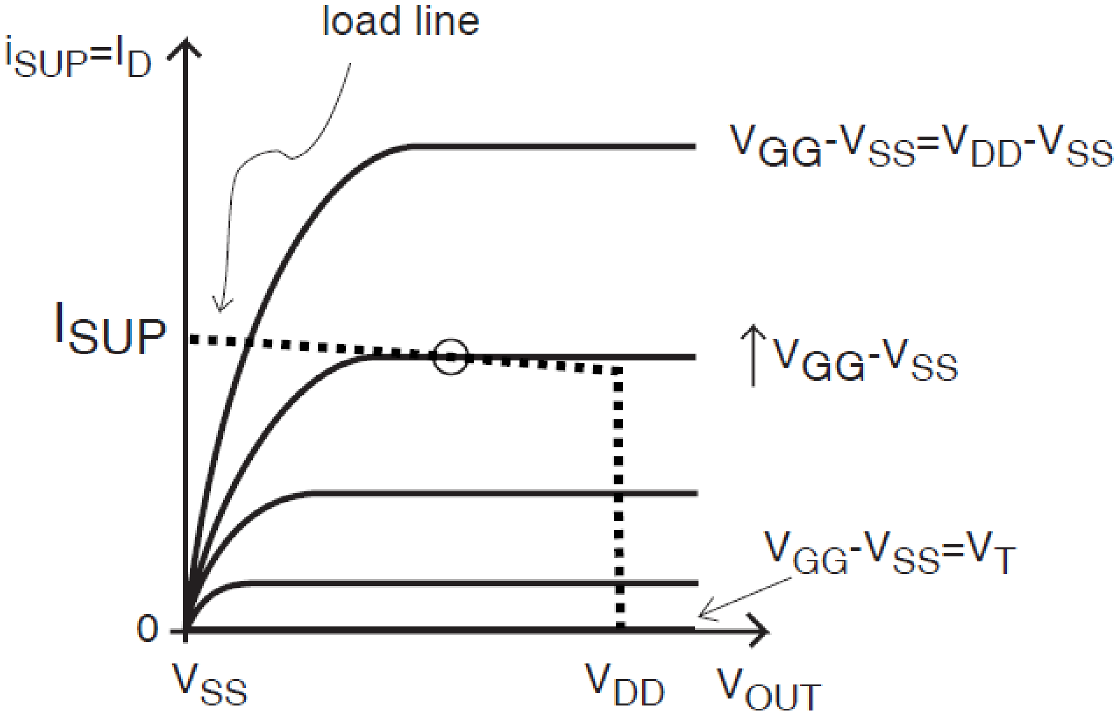
large R_D consumes a lot of Si real state

large R_D eventually compromises frequency response

2. Common source amplifier with current source supply



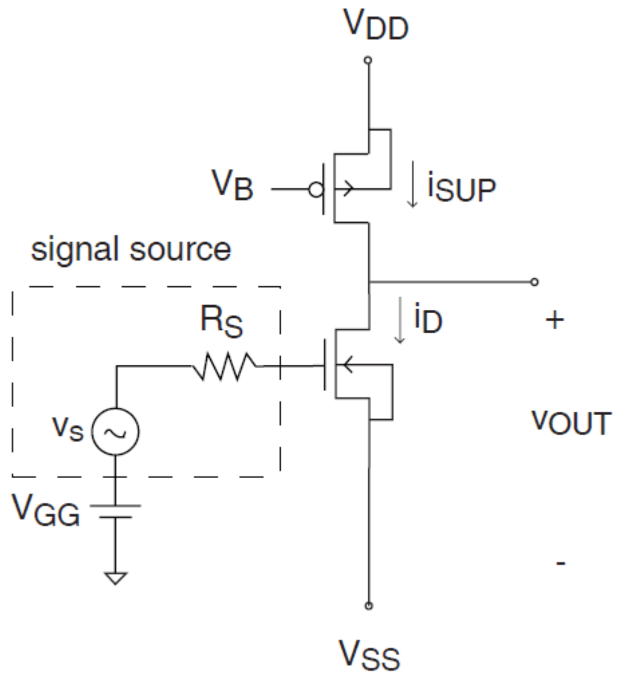
Loadline view:



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:



Upswing limited by PMOS entering linear regime

$$V_{out,max} = V_B - V_{Tp}$$

- Relationship between circuit figures of merit and device parameters

Remember:

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

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

Then

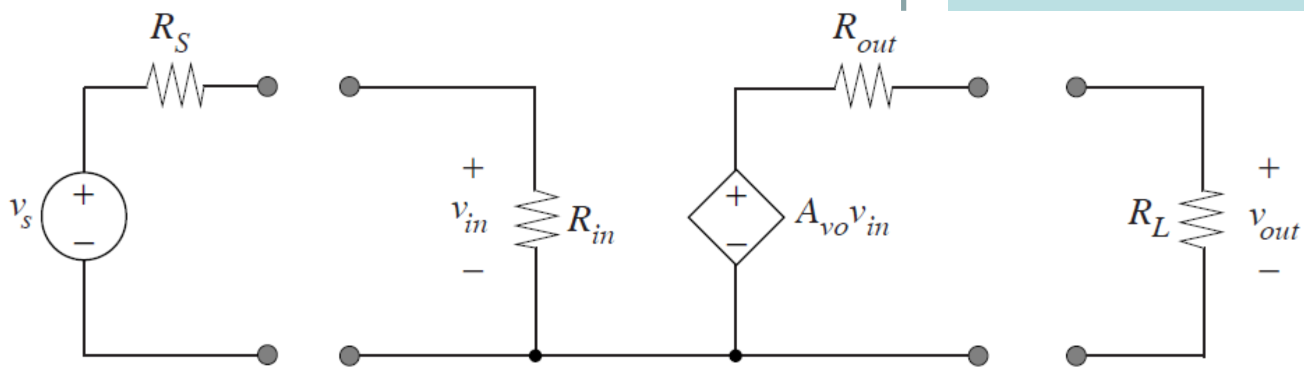
Device * Parameters	Circuit Parameters		
	$\lvert A_{vo}\rvert$	R_{in}	R_{out}
	$g_m(r_o//r_{oc})$	∞	$r_o//r_{oc}$
$I_{SUP} \uparrow$	$\downarrow$	-	$\downarrow$
$W \uparrow$	$\uparrow$	-	-
$\mu_n C_{ox} \uparrow$	$\uparrow$	-	-
$L \uparrow$	$\uparrow$	-	$\uparrow$

CS amp with current supply source is voltage amplifier (R_{in} high and $|A_v|$high), but R_{out} high too

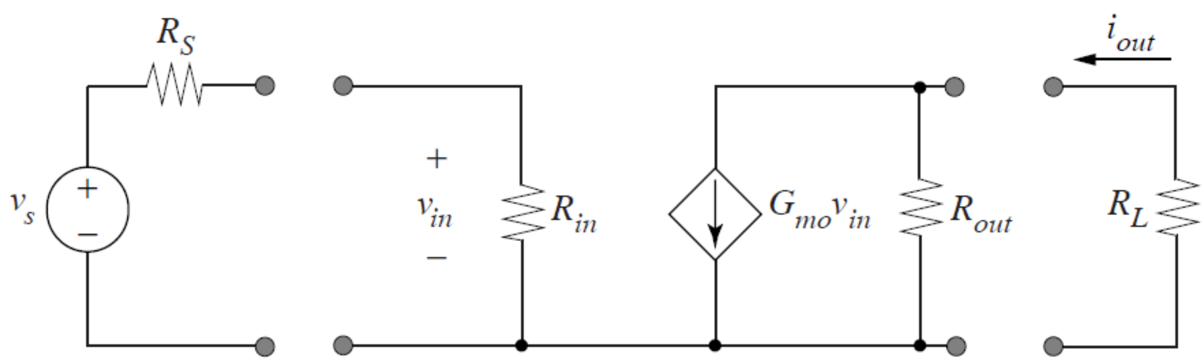
$\Rightarrow$ voltage gain degraded if $R_L << r_o // r_{oc}$

Common-source amplifier is acceptable voltage amplifier (want high R_{in}, high A_{vo}, low R_{out}):

This is the problem

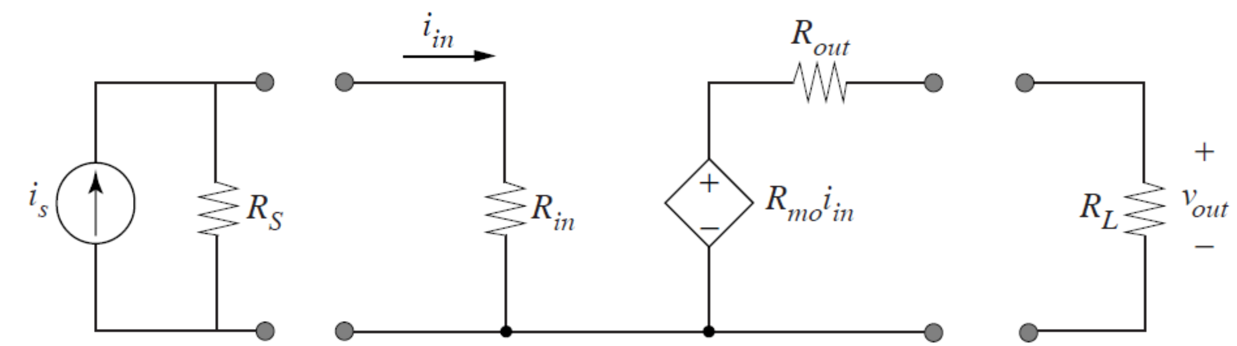


... but excellent transconductance amplifier (want high R_{in}, high G_{mo}, high R_{out}): $G_{mo} = g_m$

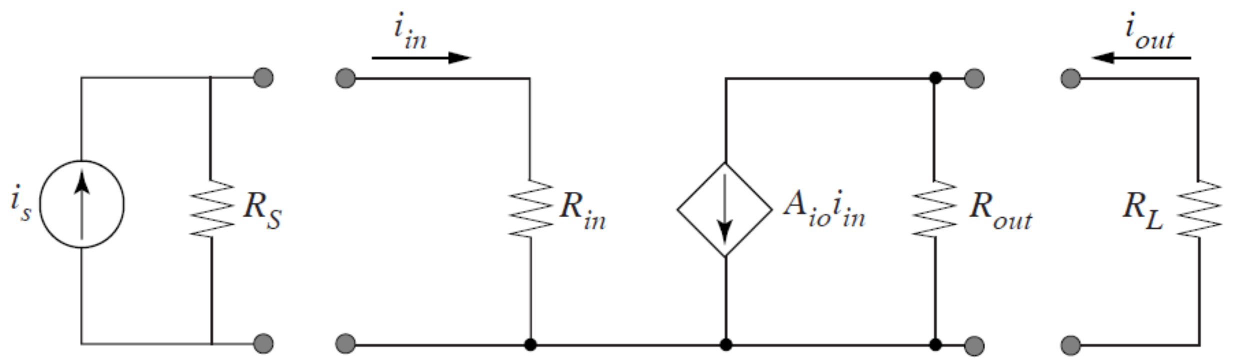


Common-source amplifier does not work as transresistance amplifier (want low R_{in}, high R_{mo}, low R_{out}):

Key problem



not as current amplifier (want low R_{in}, high A_{io}, high R_{out}):



Need new amplifier configurations.

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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: tradeoff between gain and cost and frequency response.
- Tradeoff resolved by using common source amplifier with current source supply.
- Two port network computation of voltage gain, input resistance and output resistance of amplifier.