Lecture 19

Transistor Amplifiers (I)

Common-Source Amplifier

Outline

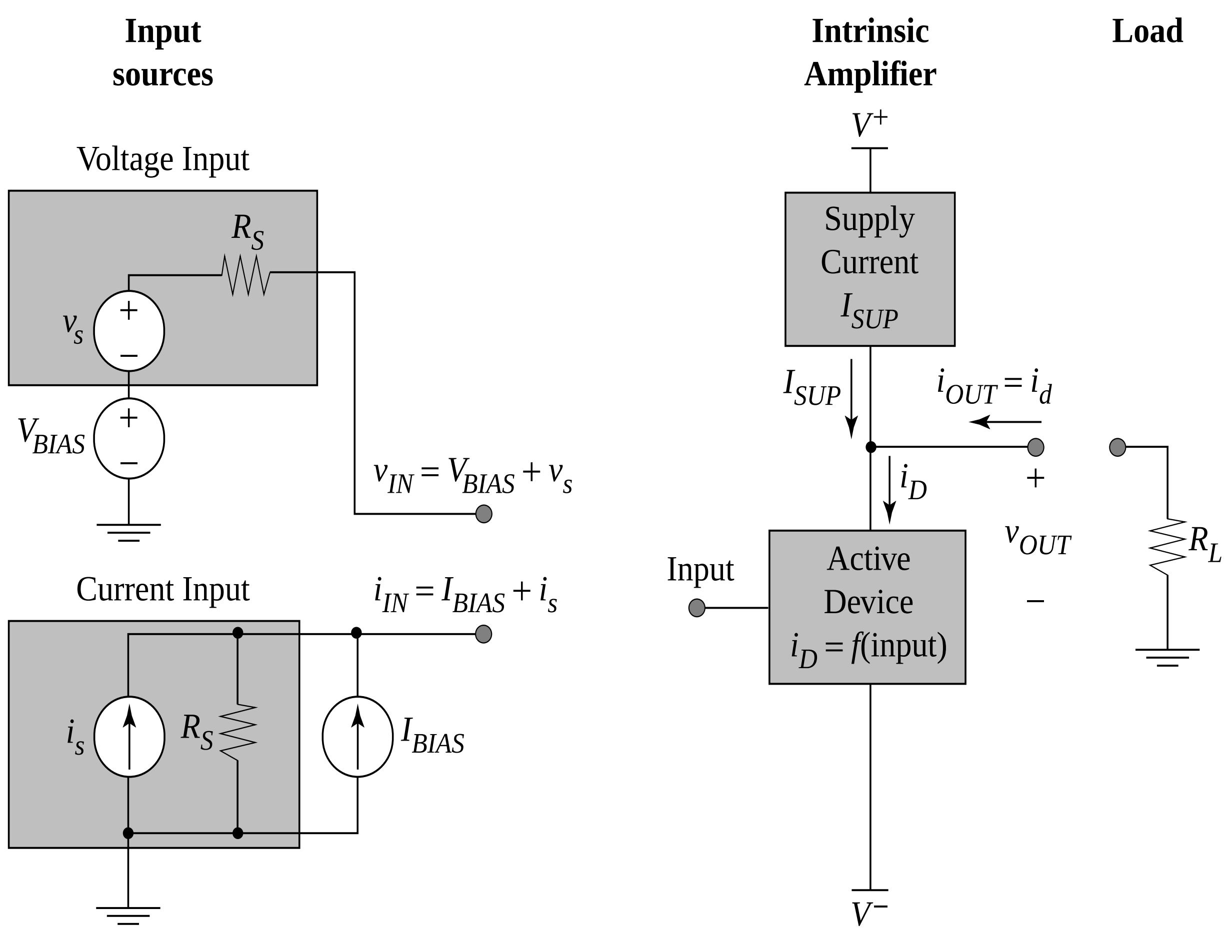
- Amplifier fundamentals
- Common-source amplifier
- Common-source amplifier with current-source supply

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

Announcement:
Quiz #2: April 25, 7:30-9:30 PM at Walker. Calculator Required. Open book.

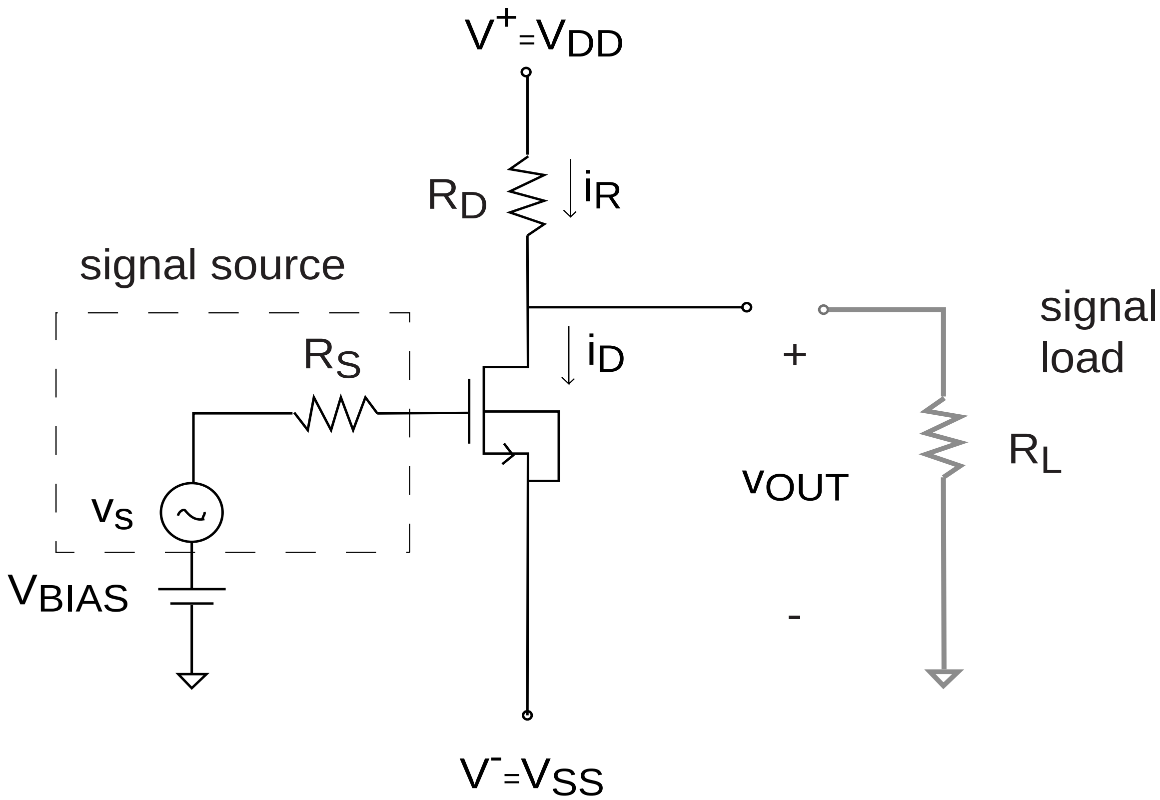
Amplifier Fundamentals

- Source resistance R_S is associated *only* with small signal sources
- Choose $I_D = I_{SUP}$ ---> DC output current
  - $I_{OUT} = 0$
  - $V_{OUT} = 0$



2. Common-Source Amplifier:

Consider the following circuit:

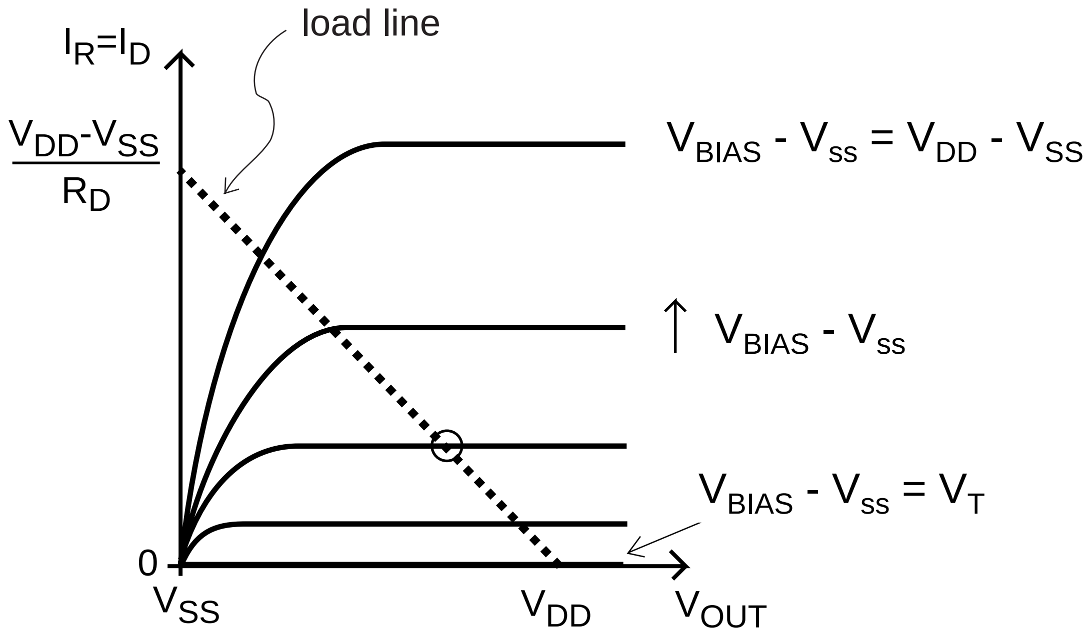


- Consider intrinsic voltage amplifier - no loading
  - $R_S = 0$
  - R_L ---> ∞
  - $V_{GS} = V_{BIAS} - V_{SS}$

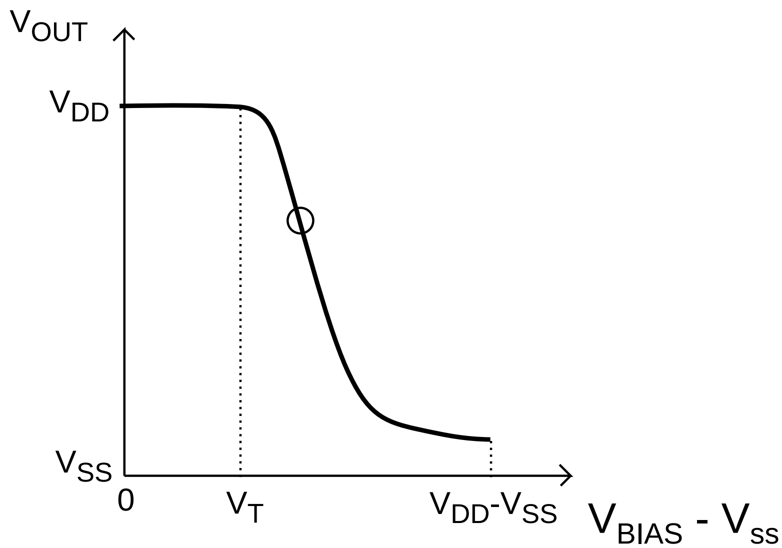
- V_{BIAS}, R_D and W/L of MOSFET selected to bias transistor in saturation and obtain desired output bias point (i.e. $V_{OUT} = 0$).

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

Load line view of amplifier:



Transfer characteristics of amplifier:



Want:

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

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

Assume MOSFET is in saturation:

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

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

If we select V_{OUT}=0:

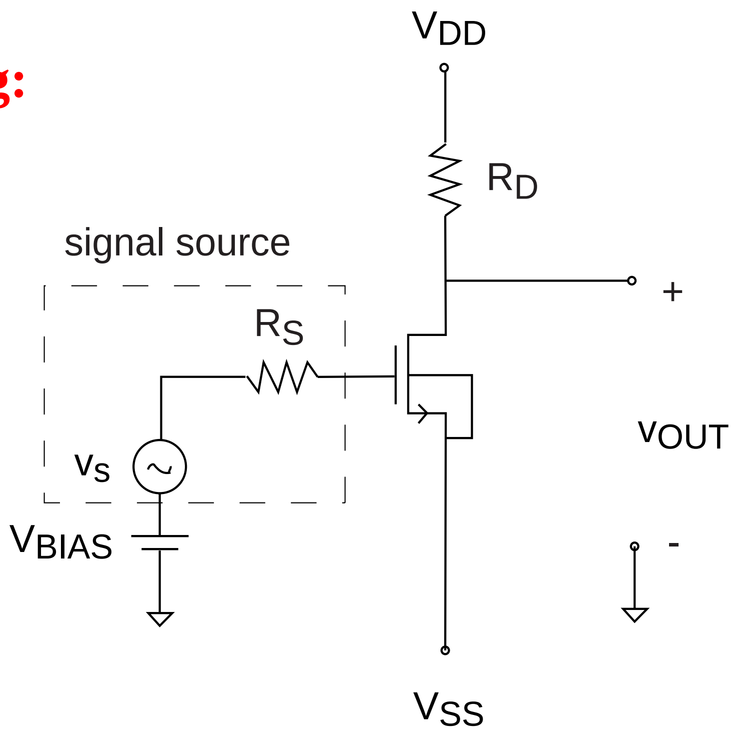
$$I_D = I_R = \frac{W}{2L}\mu_n C_{ox}\left(V_{BIAS} - V_{SS} - V_T\right)^2 = \frac{V_{DD}}{R_D}$$

Then:

$$V_{BIAS} = \sqrt{\frac{2I_D}{\frac{W}{L}\mu_n C_{ox}}} + V_{SS} + V_T$$

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

Signal swing:



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

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

- Downswing: limited by MOSFET leaving saturation.

$$V_{DS,sat} = V_{GS} - V_T = \sqrt{\frac{2I_D}{\frac{W}{L}\mu_n C_{ox}}}$$

or

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

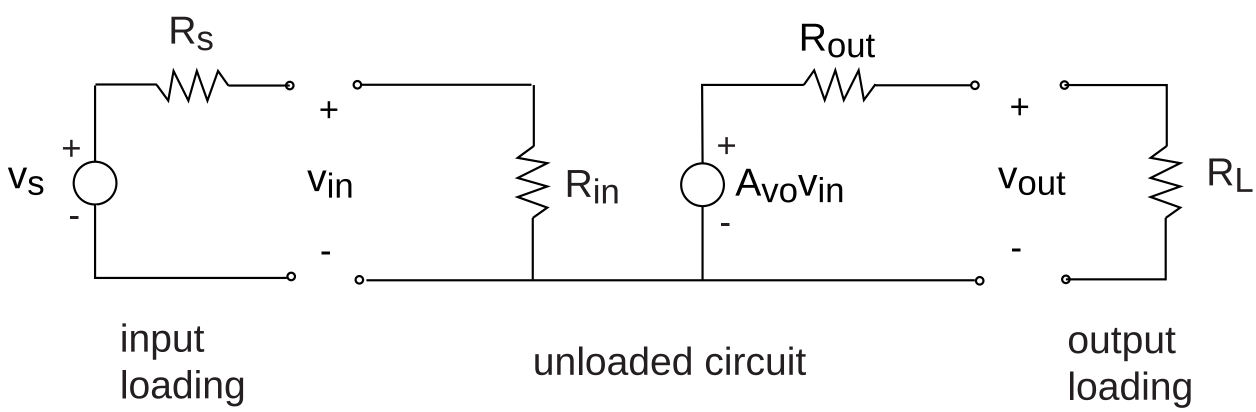
Then:

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

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:

$$v_{in} = R_{in} \frac{v_s}{R_{in} + R_s}$$

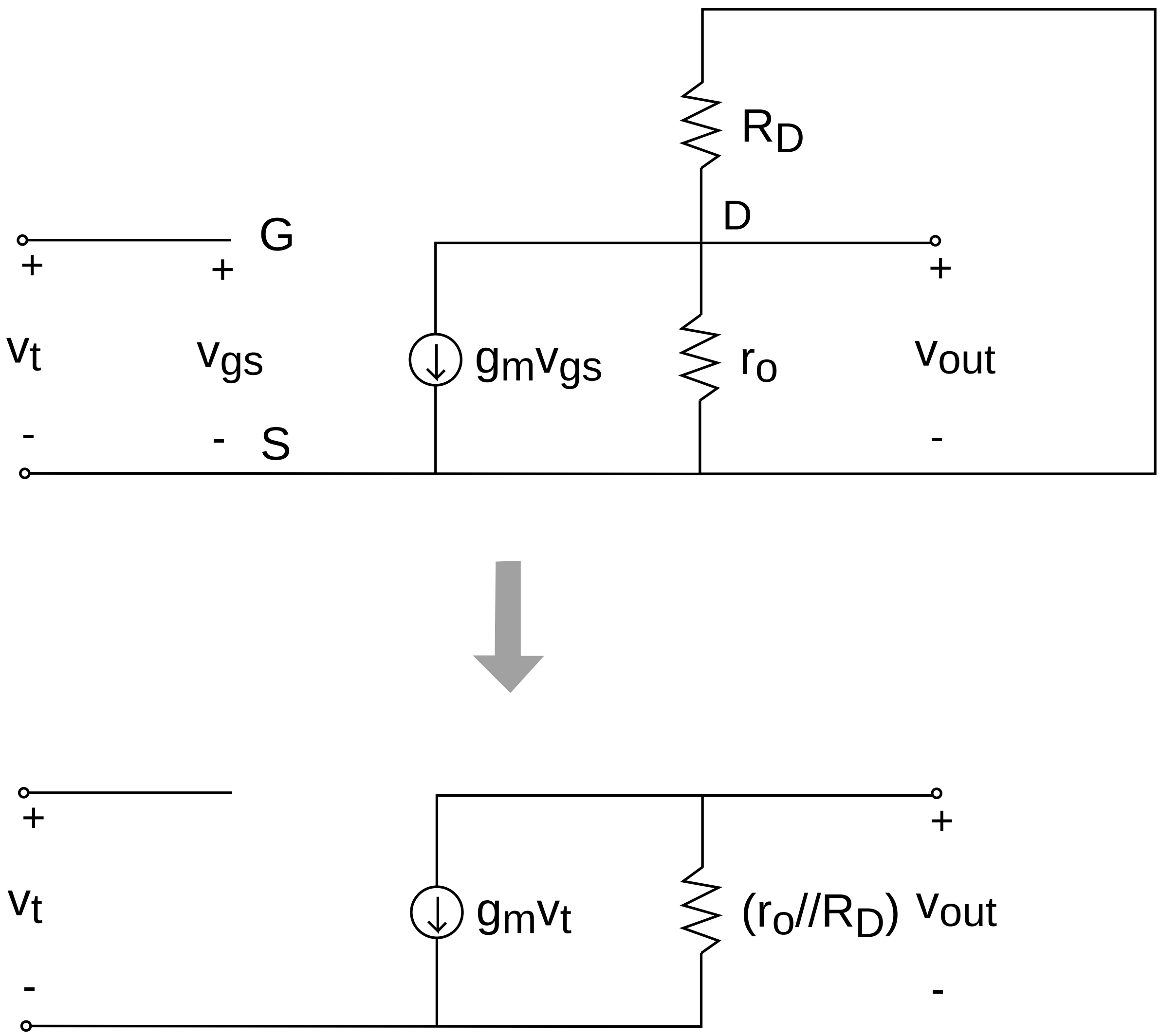
Voltage divider at output:

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

Loaded voltage gain:

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

Small-signal voltage gain A_{vo}: draw small-signal equivalent circuit model: Remove R_L and R_S



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

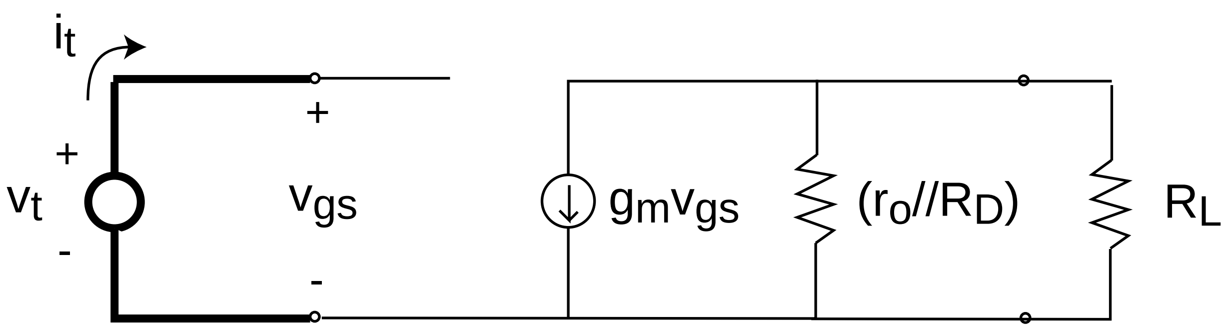
Then unloaded voltage gain:

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

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:



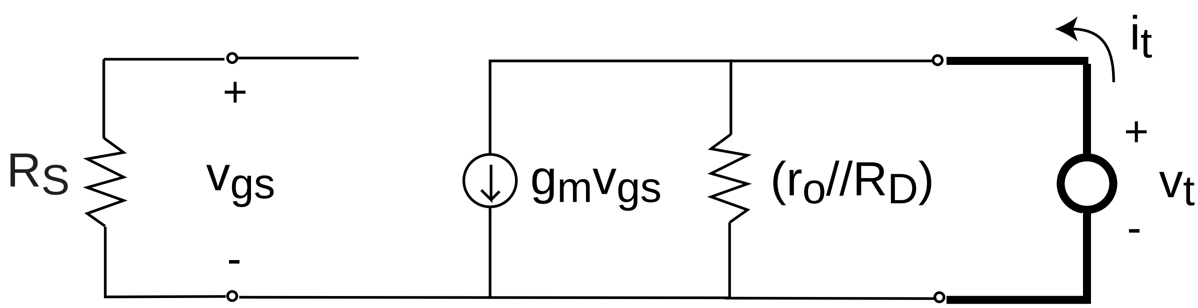
$$i_t = 0 \Rightarrow R_{in} = \frac{v_t}{i_t} = \infty$$

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).
  - Set input source equal zero

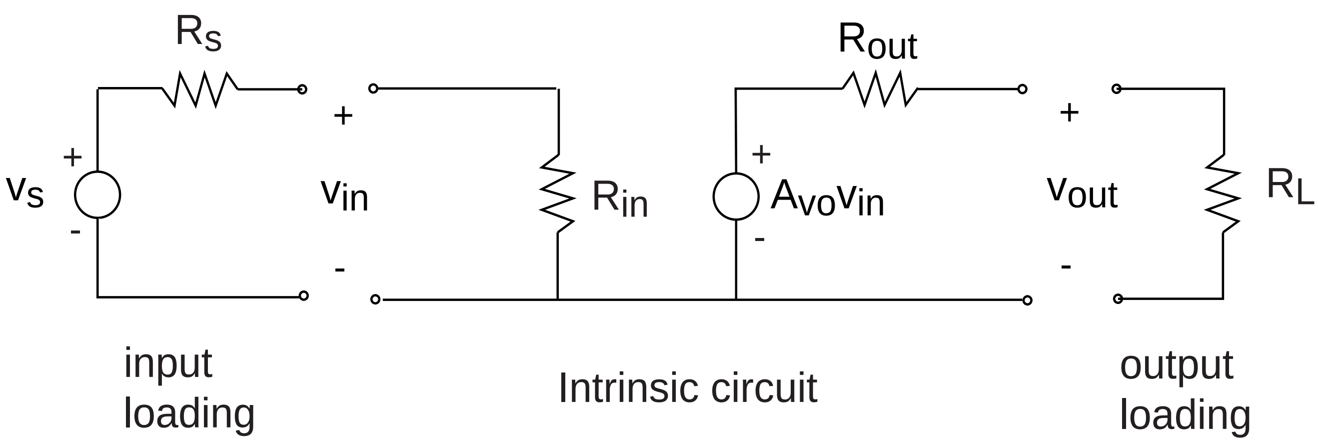
For common-source amplifier:



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

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

Two-port network view of common-source amplifier
Voltage Amplifier

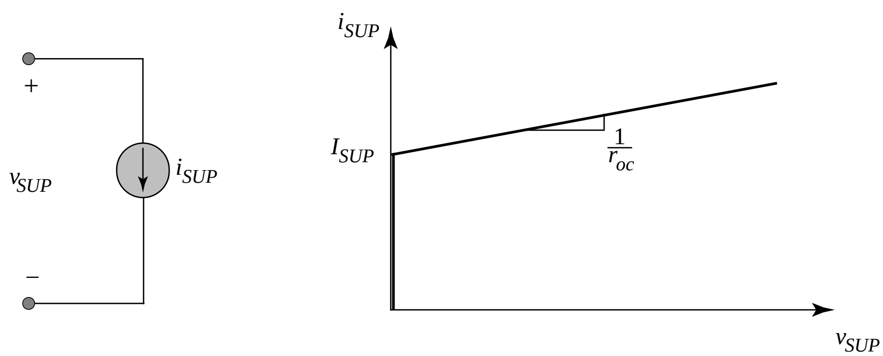


$$\frac{v_{out}}{v_s} = \frac{R_{in}}{R_{in} + R_S} A_{vo} \frac{R_L}{R_L + R_{out}}$$

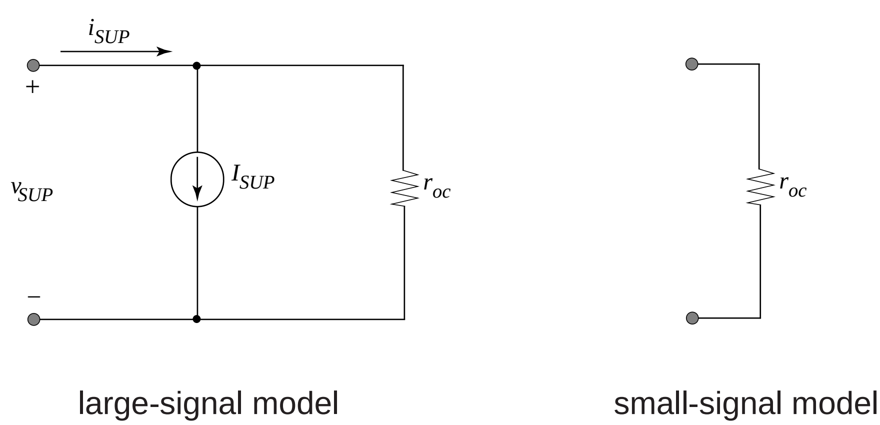
$$\frac{v_{out}}{v_s} = -g_m(r_o // R_D)\frac{R_L}{R_L + r_o // R_D} = -g_m(r_o // R_D // R_L)$$

Current Source Supply

I—V characteristics of current source:

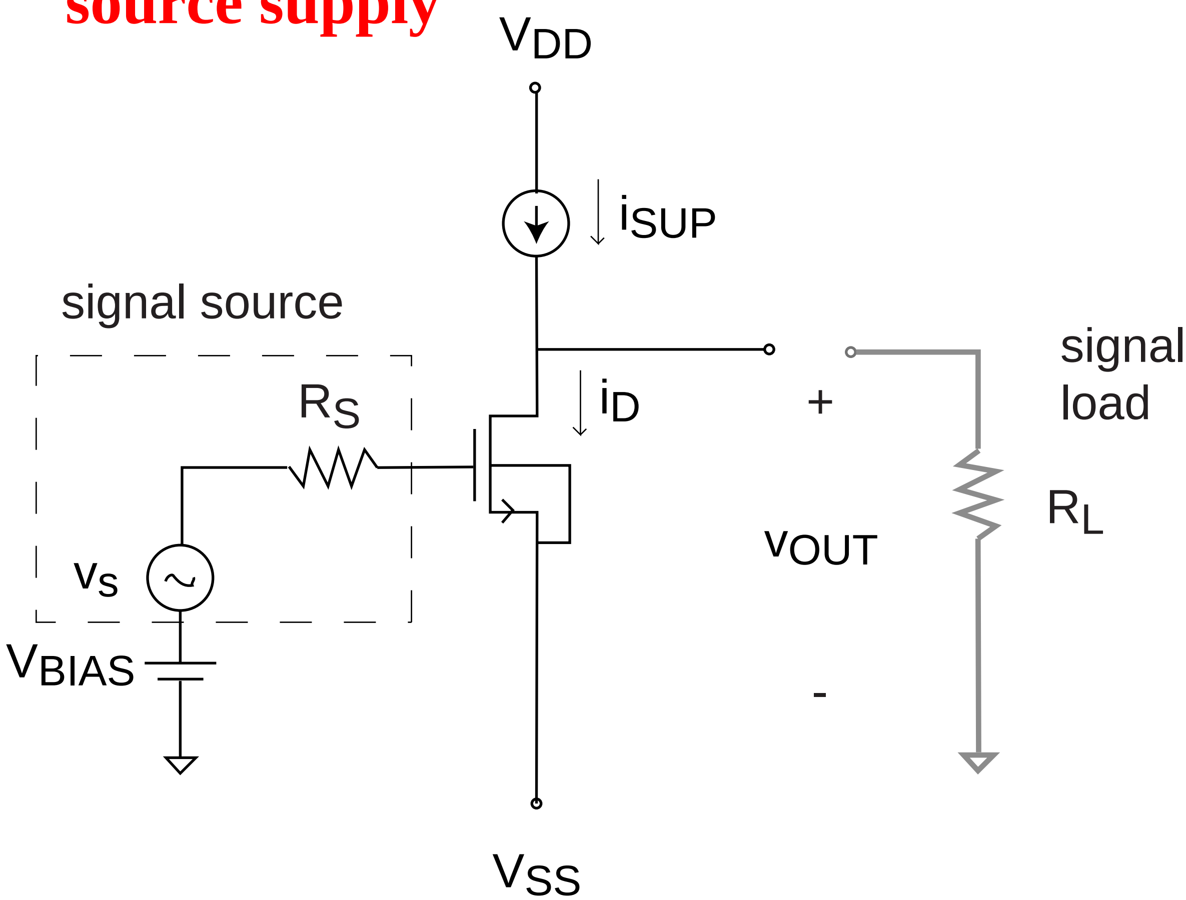


Equivalent circuit models :

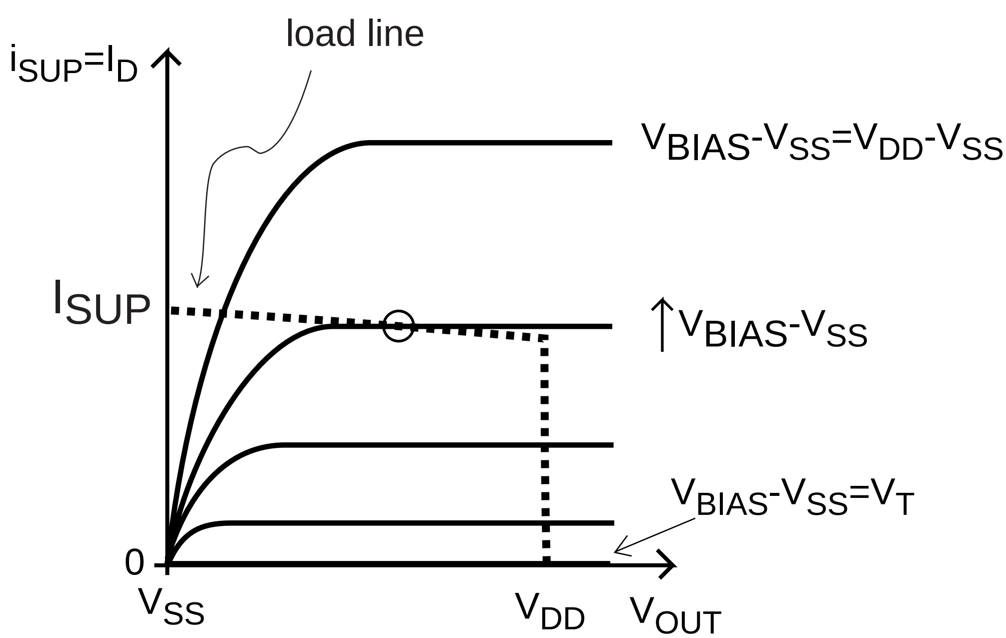


- $i_{SUP} = 0$ for $v_{SUP} \leq 0$
- $i_{SUP} = I_{SUP} + v_{SUP} / r_{oc}$ for $v_{SUP} > 0$
- High small-signal resistance r_{oc}.

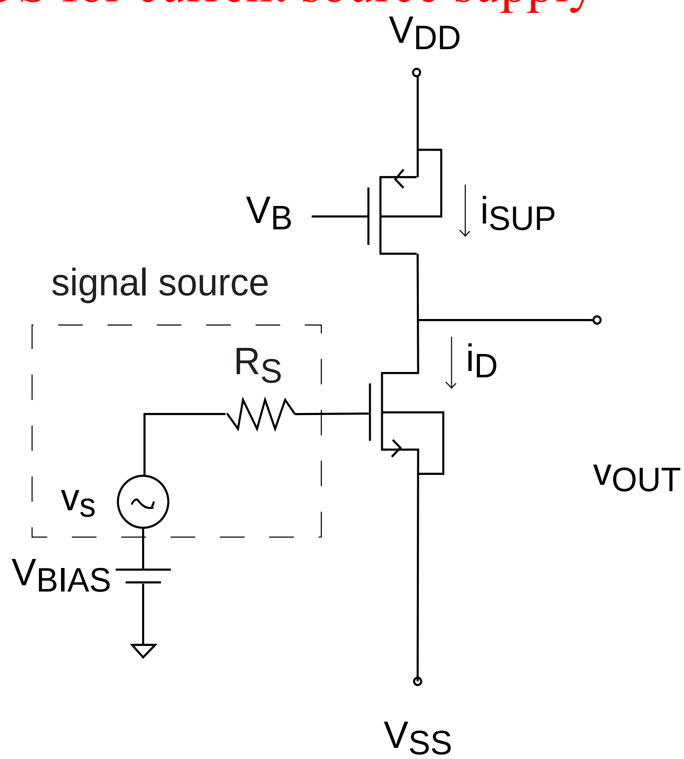
3. Common-source amplifier with current-source supply



Loadline View



Use PMOS for current source supply



Bias point: Assume both transistors in saturation
$V_{OUT} = 0$. Choose I_{SUP} and determine V_B.

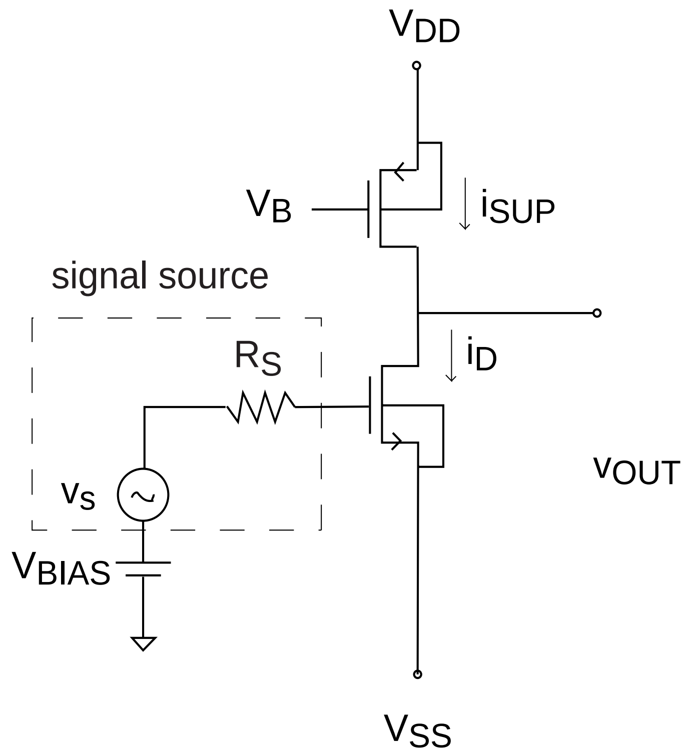
$$I_{SUP} = -I_{Dp} = \left(\frac{W}{2L}\right)_p \mu_p C_{ox} \left(V_{DD} - V_B + V_{Tp}\right)^2$$

Set $-I_{Dp} = I_{Dn}$ for $V_{OUT} \sim 0$

$$I_{SUP} = I_{Dn} = \left(\frac{W}{2L}\right)_n \mu_n C_{ox} \left(V_{BIAS} - V_{SS} - V_{Tn}\right)^2$$

$$V_{BIAS} = \sqrt{\frac{2I_{SUP}}{\left(\frac{W}{L}\right)_n \mu_n C_{ox}}} + V_{SS} + V_T$$

Signal swing:



- Upswing: limited by PMOS leaving saturation.

$$V_{SD,sat} = V_{SG} + V_{Tp} = V_{DD} - V_{B} + V_{Tp}$$

$$V_{DD} - v_{out,\max} = V_{DD} - V_{B} + V_{Tp}$$

$$v_{out,\max} = V_{B} - V_{Tp}$$

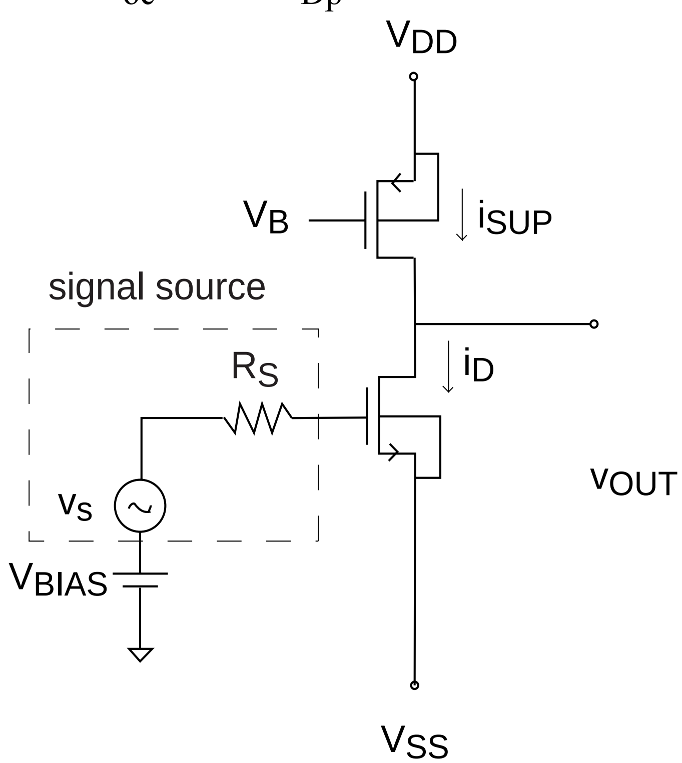
- Downswing: limited by NMOS leaving saturation.
- Same result as with resistive supply current.

$$v_{out,\min} = V_{BIAS} - V_{T}$$

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

Current source characterized by high output resistance: r_{oc}. Significantly higher than amplifier with resistive supply.

p-channel MOSFET: $r_{oc} = 1/\lambda I_{Dp}$



- Voltage gain: $A_{vo} = -g_m (r_o//r_{oc})$.
- Input resistance :$R_{in} = \infty$
- Output resistance: $R_{out} = r_o//r_{oc}$.

Relationship between circuit figures of merit and device parameters

Remember:

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

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

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} ↑	↓	-	↓
W ↑	↑	-	-
L ↑	↑	-	↑

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

CS amplifier with current source supply is a good voltage amplifier (R_{in} high and $\lvert A_{vo}\rvert$ high), but R_{out} high too ⇒ voltage gain degraded if $R_L << r_o//r_{oc}$.

What did we learn today?

Summary of Key Concepts for CS amplifier

- Bias Calculations
- Signal Swing
- Small Signal Circuit Parameters
  - Voltage Gain - A_{VO}
  - Input Resistance - R_{in}
  - Output Resistance - R_{out}
- Relationship between small signal circuit and device parameters