EEC 332 - Analog Integrated Circuits

Lecture 7
Basic gain cell
The Common-Gate Amplifier as Current Buffers

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1 Basic gain cell

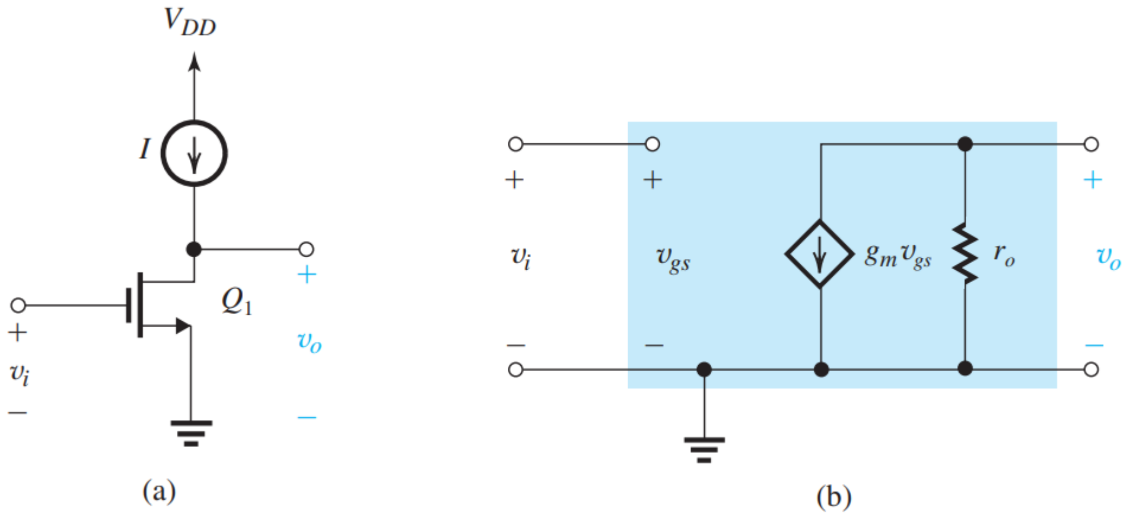


Figure 1: The basic gain cells of IC amplifiers: (a) current-source- or active-loaded common-source amplifier; (b) small-signal equivalent circuit of (a).

$$\boldsymbol{R_{\text{in}} = \infty} \tag{1}$$

$$\boldsymbol{A_{\text{vo}} = -g_m r_o} \tag{2}$$

$$\boldsymbol{R_o = r_o} \tag{3}$$

2 Effect of the Output Resistance of the Current-Source Load

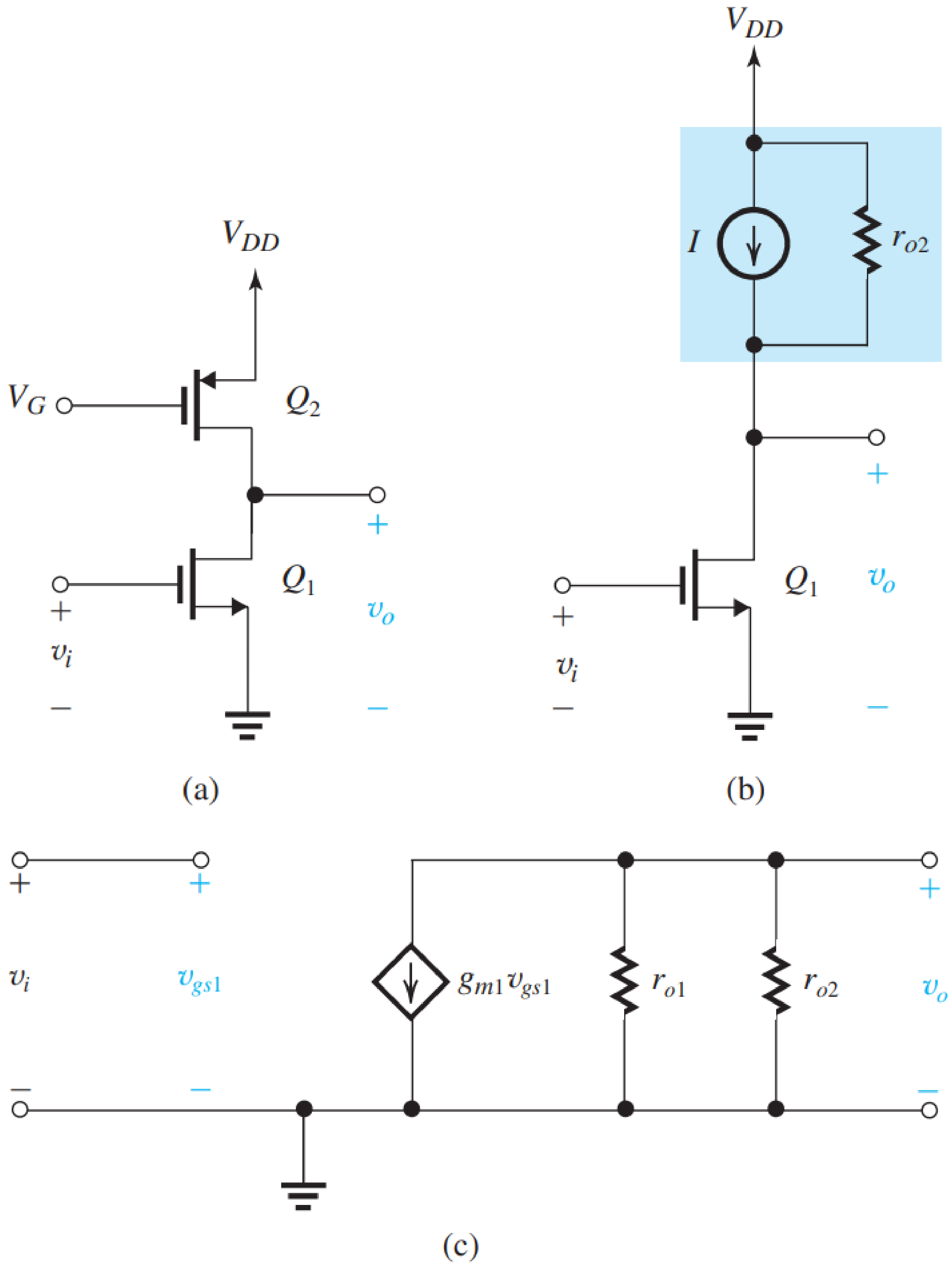


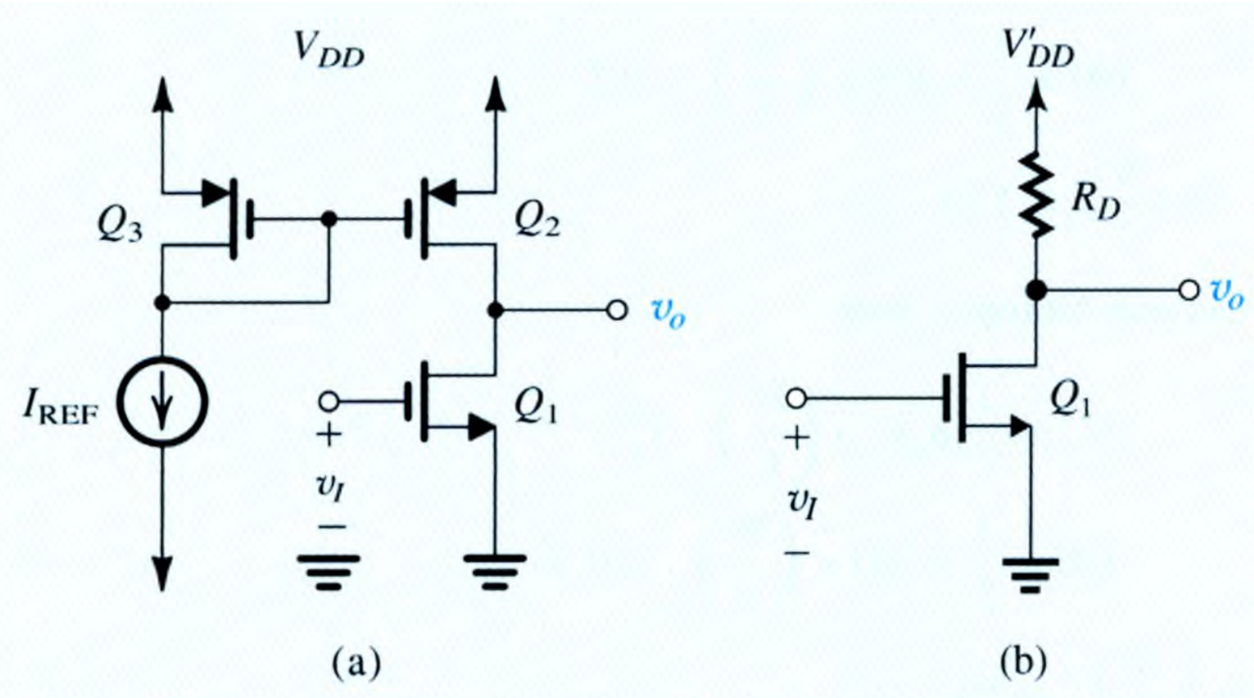
Figure 2: (a) The CS amplifier with the current-source load implemented with a p-channel MOSFET Q_2; (b) the circuit with $_Q\mathbf{2}$ replaced with its large-signal model; and (c) small-signal equivalent circuit of the amplifier.

$$A_{vo} = -g_{m1}(r_{o1}||r_{o2}) \tag{4}$$

$$\text{If } r_{o1} = r_{o2} \tag{5}$$

$$\therefore A_{vo} = -\frac{1}{2} g_m r_o \tag{6}$$

$\boxed{\text{1. Q}}$ A practical circuit implementation of the common-source amplifier with a current-source load is shown in the following figure. Here the current-source transistor Q_2 is the output transistor of a current mirror formed by Q_2 and Q_3 and fed with a reference current I_{REF}. Assume that Q2 and Q3 are matched.



Let $V_{DD} = 1.8$ V, $V_{tn} = -V_{tp} = 0.5$ V, $\mu_n C_{ox} = 4\mu_p C_{ox} = 400\mu\text{A/V}^2$, $|V_A| = 5$ V for all transistors, and $I_{REF} = 100\mu$A.

(a) Find the dc component of v_1, and the W/L ratios so that all transistors operate at $|V_{ov}| = 0.2V$.

(b) Determine the small-signal voltage gain.

(c) What is the allowable range of signal swing at the output for almost-linear operation?

(d) If the current-source load is replaced with a resistance R_D connected to a power supply V'_{DD} as shown in the figure , find the value of R_D and V'_{DD} to keep I_D, the voltage gain, and the output signal swing unchanged.

$\boxed{\text{1. A}}$

(a) To operate Q_1 and $V_{OV} = 0.2$ V, V_{GS1} must be

$$V_{GS1} = V_{tn} + V_{oV} = 0.5 + 0.2 = 0.7 \text{ V}$$

and thus the dc component of v_l must be

$$V_I = V_{GS1} = 0.7 \text{ V}$$

Next, we determine (W/L), from

$$I_{D1} = \frac{1}{2}\left(\mu_n C_{ox}\right)\left(\frac{W}{L}\right)_1 V_{oV}^2$$

Substituting $I_{D1} = I_{\text{REF}} = 100\mu\text{A}$,

$$\begin{aligned} 100 &= \frac{1}{2} \times 400 \times \left(\frac{W}{L}\right)_1 \times 0.2^2 \\ \Rightarrow \left(\frac{W}{L}\right)_1 &= 12.5 \end{aligned}$$

The W/L ratios for Q_2 and Q_3 can now be found from

$$\begin{aligned} I_{D2,3} &= \frac{1}{2}\left(\mu_p C_{ox}\right)\left(\frac{W}{L}\right)_{2,3} V_{OV}^2 \\ 100 &= \frac{1}{2} \times 100 \times \left(\frac{W}{L}\right)_{2,3} \times 0.2^2 \\ \Rightarrow \left(\frac{W}{L}\right)_{2,3} &= 50 \end{aligned}$$

(b) To obtain the small-voltage signal voltage gain, we first determine the small-signal parameters g_{m1} : r_{o1}, and r_{o2} as follows:

$$\begin{aligned} g_{m1} &= \frac{2 I_{D1}}{V_{OV1}} = \frac{2 \times 0.1 \text{ mA}}{0.2 \text{ V}} = 1 \text{ mA/V} \\ r_{o1} &= \frac{V_{A1}}{I_{D1}} = \frac{5 \text{ V}}{0.1 \text{ mA}} = 50\text{k}\Omega \\ r_{o2} &= \frac{|V_{A2}|}{I_{D2}} = \frac{5 \text{ V}}{0.1 \text{ mA}} = 50\text{k}\Omega \end{aligned}$$

The voltage gain A_v can now be found as

$$\begin{aligned} A_v &= -g_{m1}\left(r_{o1} \| r_{o2}\right) \\ &= -1(50 \| 50) \\ &= -25 \text{ V/V} \end{aligned}$$

(c) The upper limit of the output signal swing is determined by Q_2 leaving the saturation region. This will occur if v_O reaches $V_{DD} - |V_{OV2}|$, thus

$$v_{\text{Omax}} = 1.8 - 0.2 = 1.6 \text{ V}$$

The lower limit of the output signal swing is determined by Q_1 leaving the saturation region. This will occur if v_0 falls below V_{OV1}, thus

$$v_{0\,\min} = 0.2 \text{ V}$$

Thus, the range of linear signal swing at the output is given by

$$0.2 \text{ V} \leq v_o \leq 1.6 \text{ V}$$

(d) If the current-source load is replaced with a resistance R_D as in Fig. 8.16(b), to keep the gain unchanged,

$$R_D = r_{o2} = 50\text{k}\Omega$$

To keep the output signal swing unchanged, we bias Q_1 so that V_{DS1} is equal to the mid point of the output swing, that is,

$$V_{DS1} = 0.9 \text{ V}$$

Now, for I_D to be the same as before, that is, $I_D = 0.1$ mA, the new supply voltage must be,

$$\begin{aligned} V'_{DD} &= V_{DS1} + I_D R_D \\ &= 0.9 + 0.1 \times 50 = 5.9 \text{ V} \end{aligned}$$

which is much larger than the supply voltage possible with this $0.18 - \mu$m CMOS technology (1.8 V). Needless to say, fabricating a $50\text{k}\Omega$ resistance with precise value on the IC is an expensive endeavor This illustrates the need for using current-source

loads.

3 The Common-Gate and Common-Base Amplifiers as Current Buffers

3.1 The CG Circuit

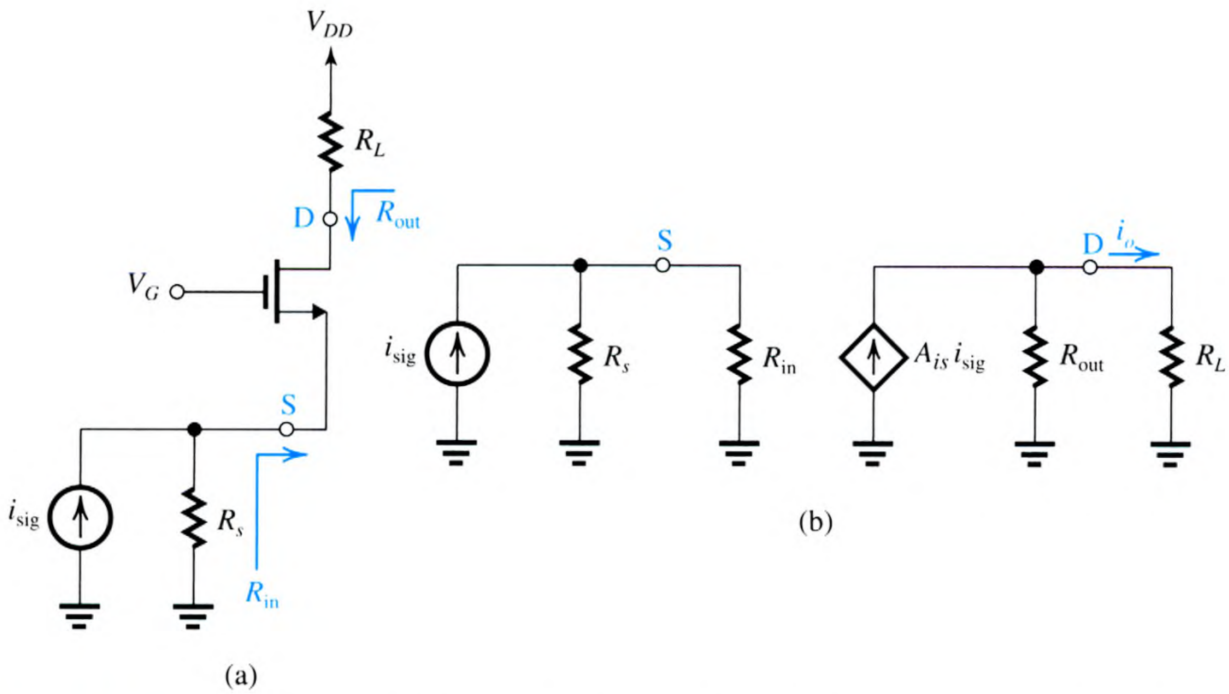


Figure 3: (a) A CG amplifier with the bias arrangement only partially shown, (b) Equivalent circuit model of the CG amplifier in (a).

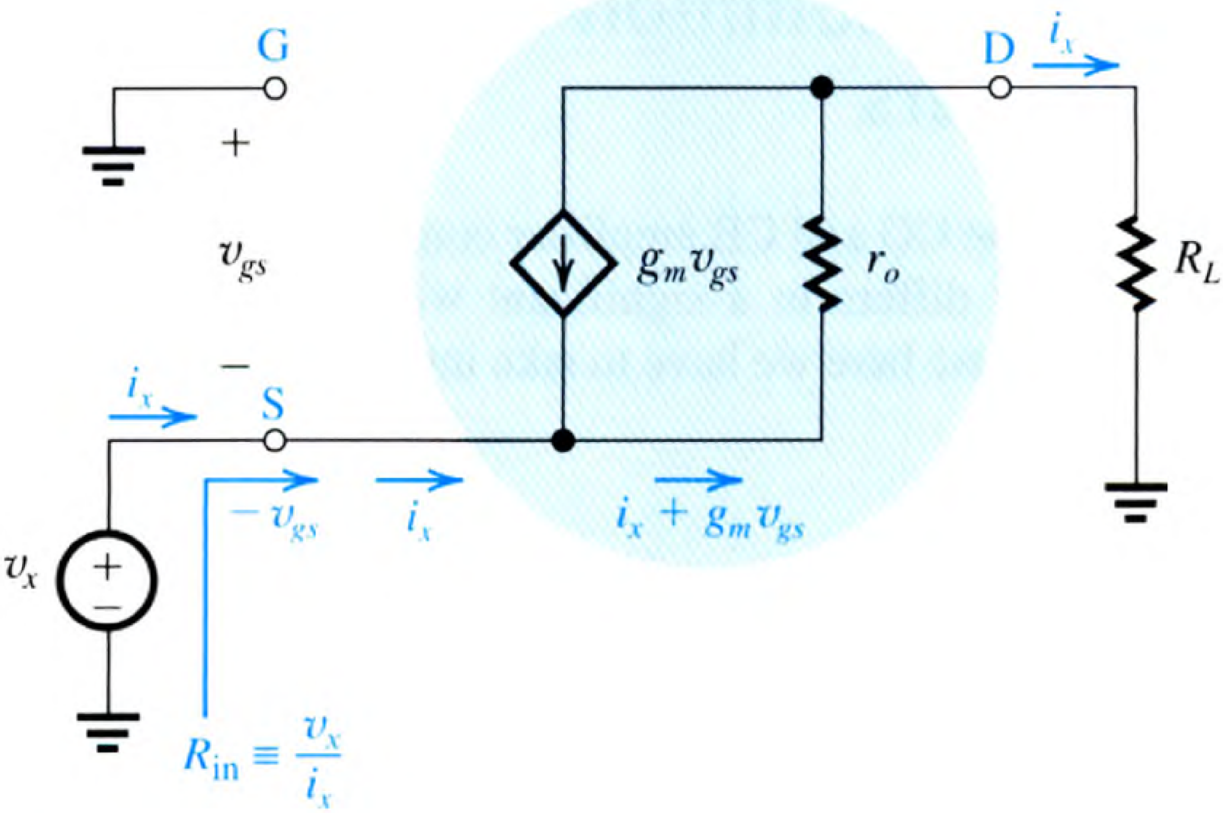


Figure 4: Determining the input resistance R_{in} of the CG amplifier.

Input resistance :

$$R_{\text{in}} = \frac{v_s}{i_s}$$

Some of the analysis is shown in Fig. 4. Now, writing a loop equation for the loop comprising v_x, r_o, and R_L gives

$$v_x = (i_x + g_m v_{gs})\, r_o + i_x R_L$$

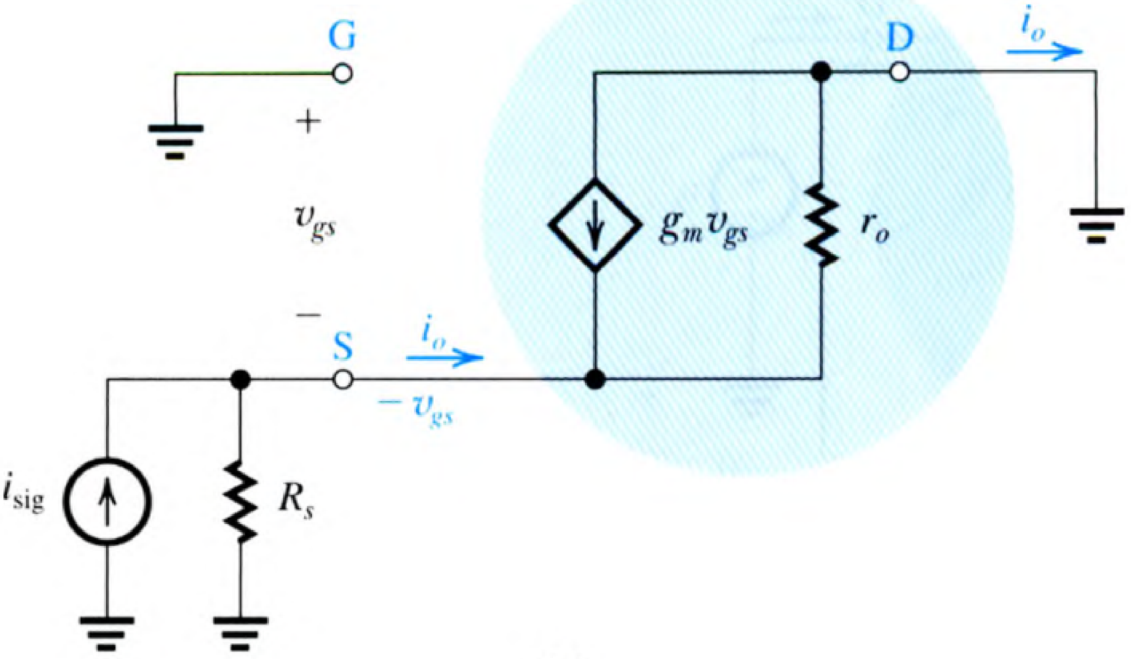
Since the voltage at the source node v_x is equal to $-v_{gs}$, we can replace v_{gs} by $-v_x$ and rearrange terms to obtain $R_{\text{in}} \equiv v_x/i_x$

$$R_{\text{in}} = \frac{r_o + R_L}{g_m r_o + 1}$$

For $g_m r_o \gg 1$

$$R_{\text{in}} \simeq \frac{1}{g_m} + \frac{R_L}{g_m r_o}$$

short circuit gain



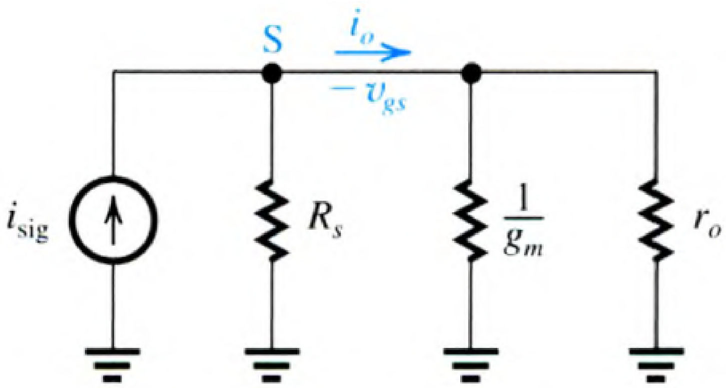


Figure 5: (a) Determining the short-circuit current gain $\boldsymbol{A_{is}} = \boldsymbol{i_o/i_{\text{sig}}}$ of the CG amplifier, (b) A simplified version of the circuit in (a).

$$\boldsymbol{A_{is}} \equiv \frac{\boldsymbol{i_o}}{\boldsymbol{i_{\text{sig}}}}$$

circuit shown in Fig. 5, from which we can find i_o/i_{sig} by using the current-divider rule:

$$A_{is} \equiv \frac{i_o}{i_{\text{sig}}} = \frac{g_m + \frac{1}{r_o}}{g_m + \frac{1}{r_o} + \frac{1}{R_s}}$$

Thus,

$$A_{is} = \frac{1 + \frac{1}{g_m r_o}}{1 + \frac{1}{g_m r_o} + \frac{1}{g_m R_s}}$$

For $g_m r_o \gg 1$ and $g_m R_s \gg 1$

$$A_{is} \simeq 1$$

which is an important characteristic of a current buffer.

Output Resistance

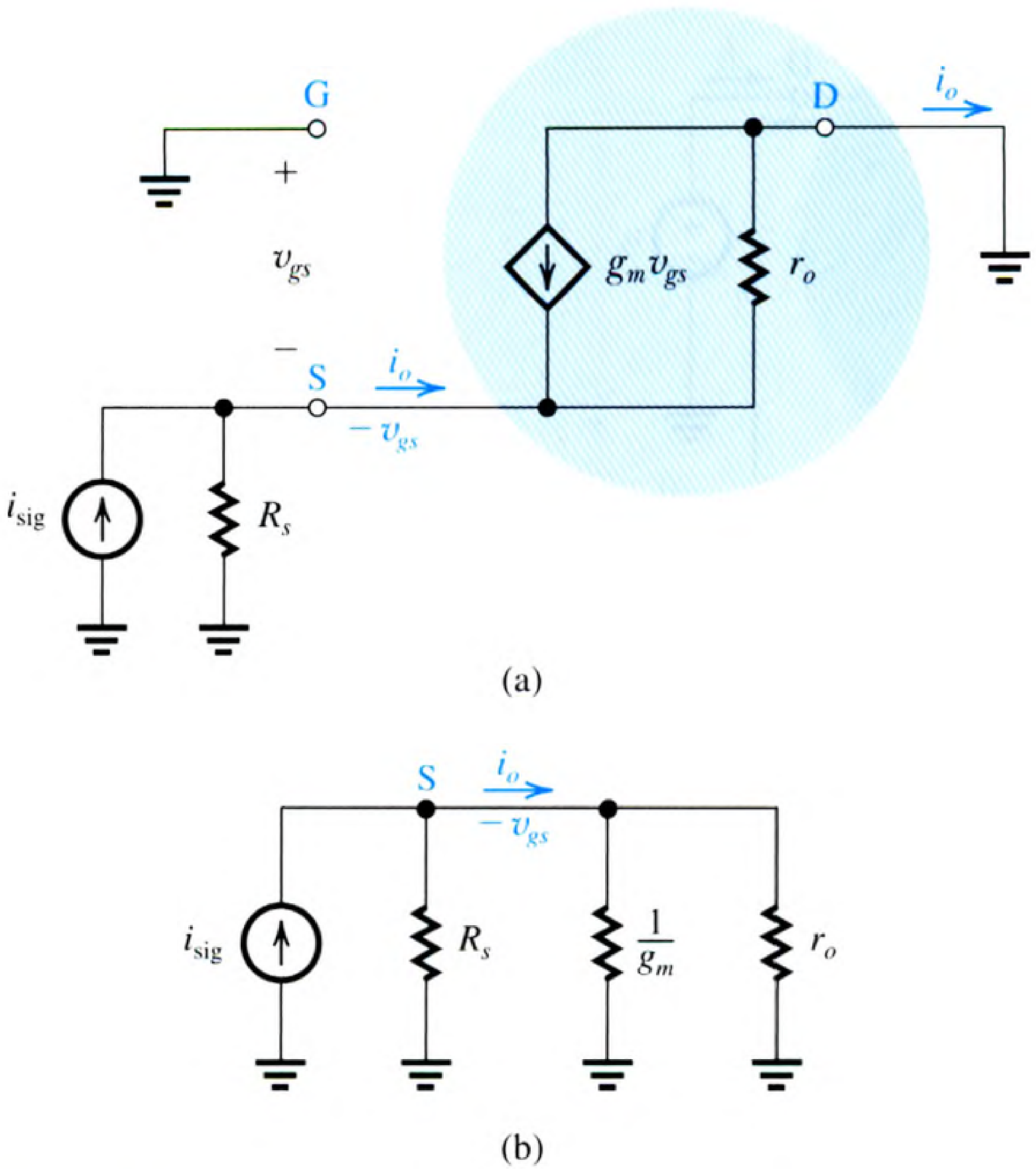


Figure 6: Determining the output resistance R_{out} of the CG amplifier.

$$R_{\text{out}} = \frac{v_x}{i_x}$$

Some of the analysis is shown in Fig. 6. Now, a loop equation for the loop comprising v_x, r_o, and R_s gives

$$v_x = (i_x - g_m v_{gs})\, r_o + i_x R_s$$

Notice that the voltage at the source terminal is $-v_{gs}$ and thus can also be expressed as

$$-v_{gs} = i_x R_s$$

Substituting this value for v_{gs} in the previous equation and rearranging terms to obtain $R_{\text{out}} \equiv v_x / i_x$ yields

$$R_{\text{out}} = r_o + R_s + g_m r_o R_s$$

which can be written in the alternate form

$$R_{\text{out}} = r_o + (1 + g_m r_o)\, R_s$$

For $g_m r_o \gg 1$

$$R_{\text{out}} \simeq r_o + (g_m r_o)\, R_s$$

and if we also have $g_m R_s \gg 1$, then

$$R_{\text{out}} \simeq (g_m r_o)\, R_s$$

Summary

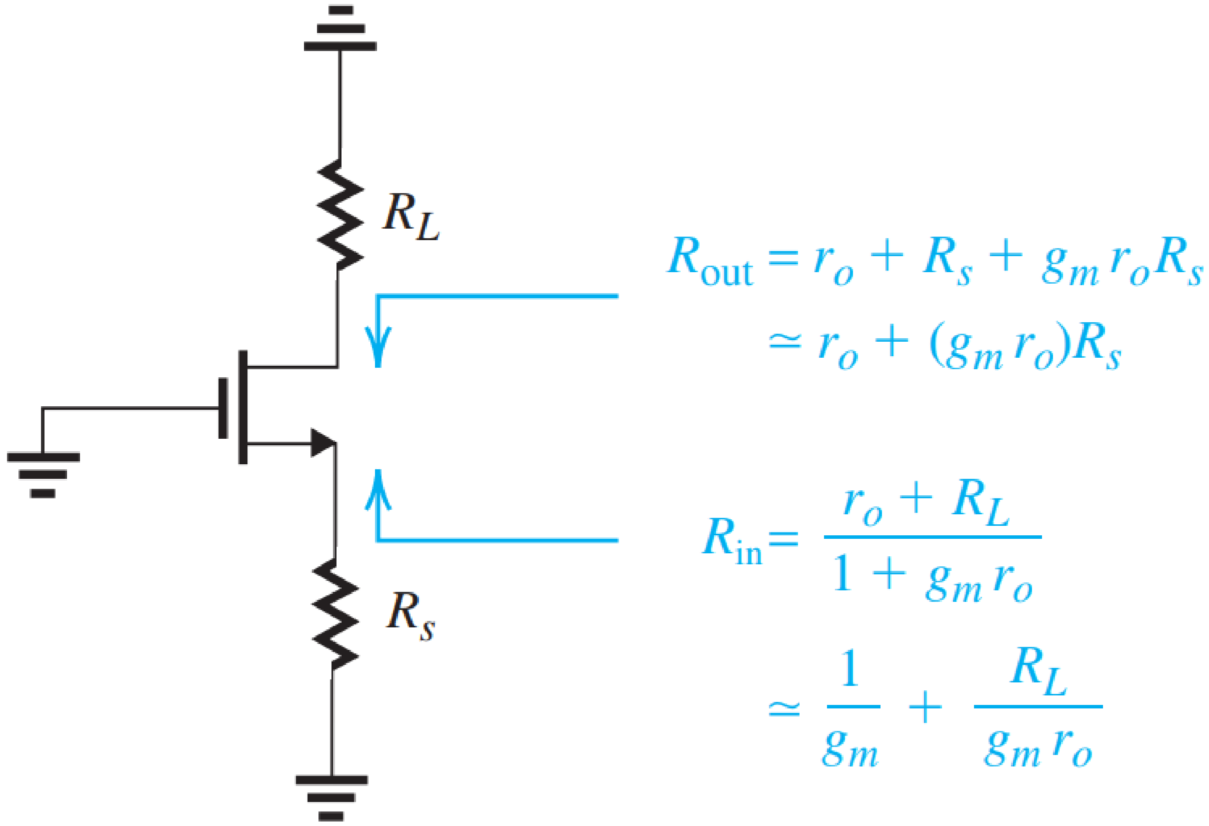


Figure 7: The impedance transformation properties of the common-gate amplifier. Depending on the values of $\boldsymbol{R_s}$ and $\boldsymbol{R_l}$, we can sometimes write and $\boldsymbol{R_{in} \approx R_L/(g_m r_o)}$ and $\boldsymbol{R_o \approx R_s(g_m r_o)}$. However, such approximations are not always justified