Non-inverting negative feedback *(nfb) amplifier*

General description:

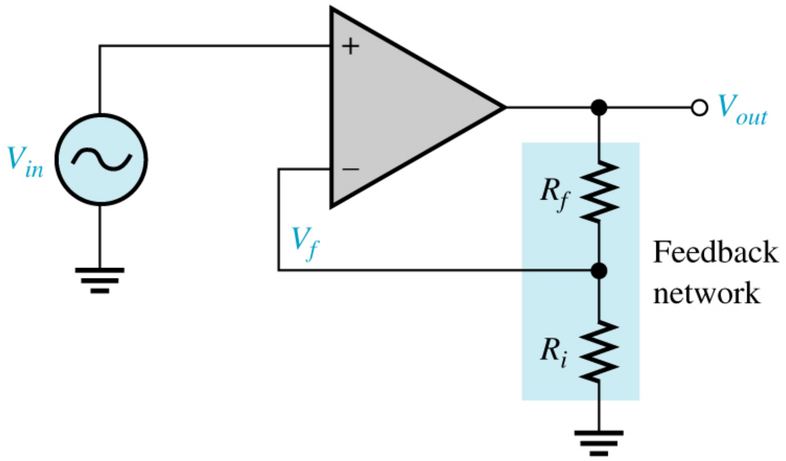
- The input signal to the op-amp is applied to its (+) input (***non-inverting***)
- A portion of its output is applied back to the inverting (−) input through the feedback network (*negative feedback*)

The input voltage can be labeled V_s, V_i, V_{in}, V_+
The output voltage can be labeled V_O, V_{out}
Differential input can be labeled V_d, V_{diff}, ρ
Feedback voltage can be labeled V_- ,V_f

Those labels vary in textbooks outlining the description of the amplifier.

<u>Basic Circuit</u>

The circuit consists of an op-amp with the negative feedback generated by a two resistor network.



The input voltage V_{in} (ac or dc) is applied to the non-inverting + terminal of the operational amplifier. This produces an output V_O that is in phase with the input.
Negative feedback is obtained by feeding back to the inverting – terminal the fraction of V_{out} that is developed across the resistor R_i in the potential divider formed by R_f and R_i in series across V_{out}

We know that the closed-loop gain for an amplifier with negative feedback is given by $A_c = \frac{V_o}{V_i} = \frac{A_o}{1+\beta A_o}$

If $\beta A_o \gg 1 \; then \; A_c \approx \frac{1}{\beta}$

In the circuit above the voltage at the inverting input V_- *is labelled* V_f *i.e*. the potential difference across R_i

$$V_{Ri} = V_f - 0 = V_f$$

Using the potential divider equations, since R_i and R_f are in series across the output voltage V_o

$$V_{Ri} = \left(\frac{R_i}{R_i + R_f}\right) V_o \; = V_f \; = V_-$$

$$\therefore \; \beta V_o = \left(\frac{R_i}{R_i + R_f}\right) V_o$$

However, before we can use this equation we must check:

- If the circuit is loaded?
- If it is, we must check that the current drawn from the potential divider is approx. equal to zero.

Recall loading a potential divider

When a load current is drawn from a potential divider the value of the voltage, across the component that the load is connected to, will drop.

However if the load impedance is large when compared to the resistor across which it has been connected, then the current drawn will be negligible and therefore the change in the voltage value is very small.

Since the input impedance Z_i of the op-amp is very high (this is the load impedance of the potential divider) then I_- *(the current* *drawn from the potential divider to the input of the 741)* is negligible and therefore the equation holds.

Therefore for the op-amp circuit the feedback fraction

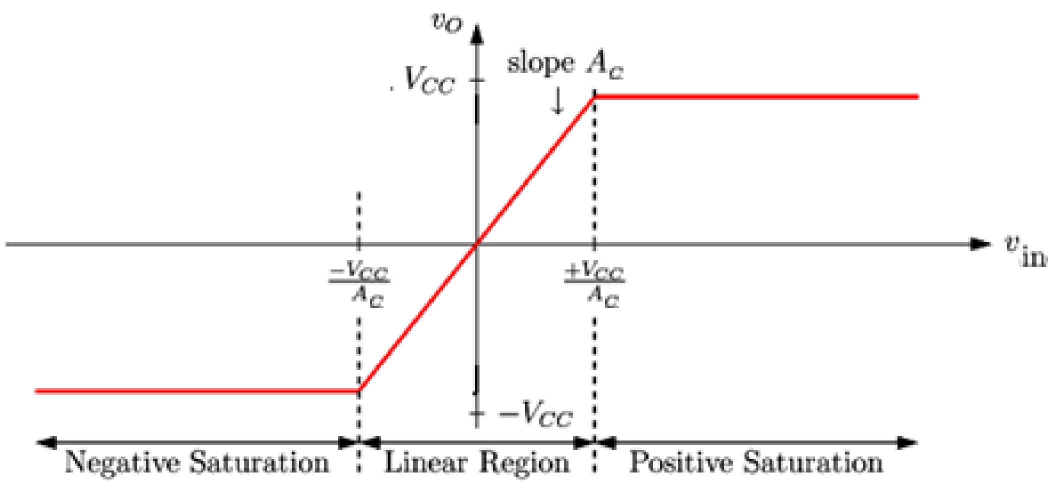
$$\beta = \left(\frac{R_i}{R_i + R_f}\right)$$

And since $A_c = \frac{1}{\beta} \therefore A_c = \frac{R_i+R_f}{R_i} = 1 + \frac{R_f}{R_i}$

The closed-loop gain therefore is less than the open-loop gain and is determined by the values of the two resistors in the feedback network.

Voltage transfer Characteristic of a non-inverting negative feedback amplifier

A typical voltage characteristic show the linear region has been extended due to the reduction in the gain of the system



Note:

1. The gain is independent of A_O and is determined by the values of two resistors R_i and R_f.

2. In the case of an AC input to the amplifier the frequency response of the amplifier is determined by the gain bandwidth constant of the amplifier:

$$gain \times bandwidth = constant$$

3. The bandwidth describes the range of frequencies for which the gain is constant

4. The circuit will go to saturation level once the output voltage reaches the positive and negative V_{CC} values

5. A decibel scale is sometimes used instead of the linear value of the gain, where

$$dB = 20 \log\left(A_V\right)$$

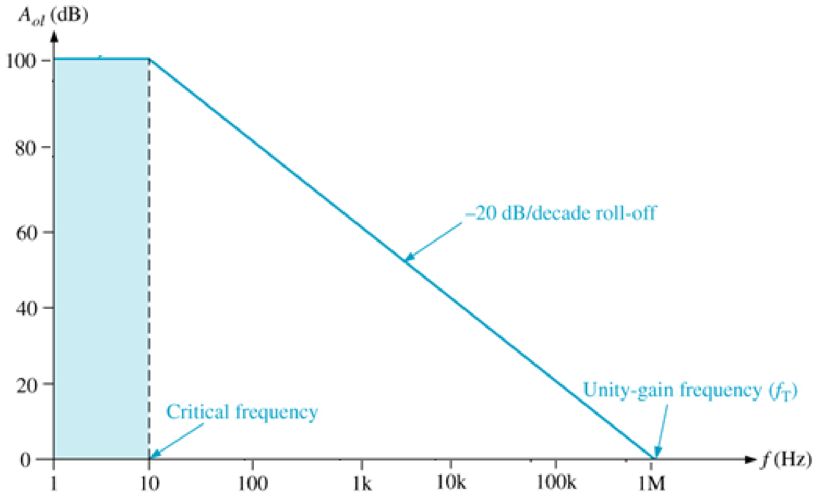
Example:

Linear gain of 100 gives a *dB value = 20 log (100) = 40 dB*

Frequency response of a non-inverting nfb operational amplifier

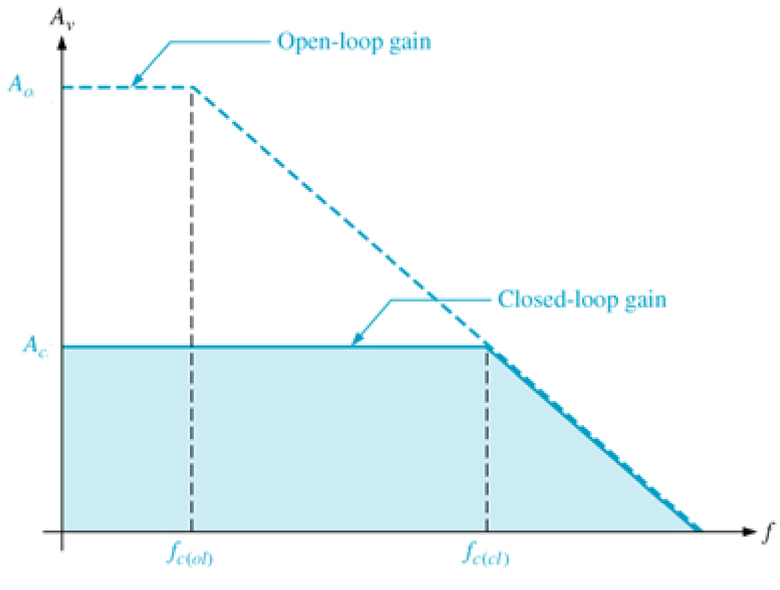
An open-loop response curve (Bode plot) for an op-amp is shown below. The curve rolls off (decreases) at – 20 dB per decade.

Typically, the open-loop gain of a 741 op-amp is 10^5 i.e. 100 dB and the critical frequency is approximately 10 Hz.



Unity-gain bandwidth
The gain steadily decreases to a point where it is equal to unity (0 dB), the value of the frequency at which this unity gain occurs is the *unity-gain bandwidth*. (The value is typically 10^6 for the 741)

Gain-bandwidth product
When the open-loop gain of an op-amp is reduced by negative feedback, the bandwidth is increased. The closed-loop gain is independent of the open-loop gain up to the point of intersection of the two curves. Beyond that point the closed-loop gain has the same roll-off rate as the open-loop gain.



A decrease in the closed-loop gain causes an increase in the bandwidth such that the product of *gain X bandwidth is a constant.*
The gain-bandwidth product is equal to the frequency at which the op-amp's gain is unity (unity gain bandwidth)

For the 741 $gain \times bandwith = 1 \times 10^6$

Taking the 741 operational amplifier in open-loop its DC gain is typically 10^5 but for frequencies greater than 10 Hz this decreases dramatically.

For a gain of 100 where $\beta = 0.01$ the gain is reduced but the bandwidth increases to 10^4 Hz.

For a gain of 10 where $\beta = 0.1$ the bandwidth is 10^5 Hz

<u>Question.</u>

(a) Design a 40dB non-inverting operational amplifier with an open-loop gain $A_O = 2 \times 10^5$ using a feedback resistor of 990k.

(b) Check the accuracy of the closed-loop approximation of the gain.

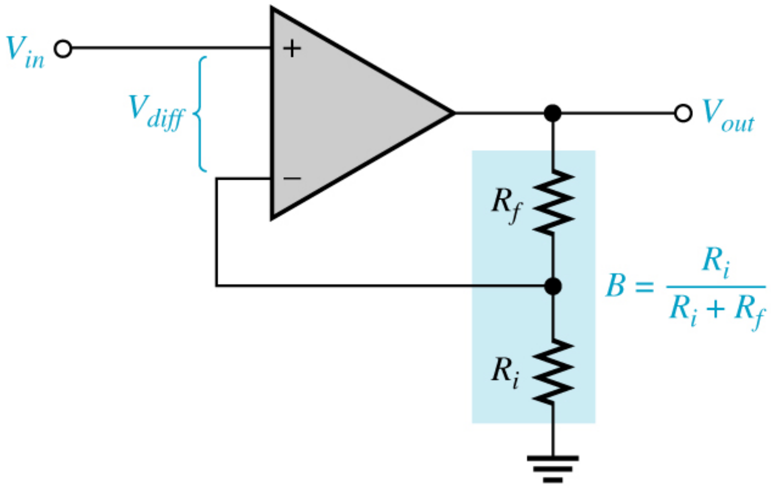
Input Impedance of an non-inverting nfb amplifier

For maximum voltage transfer from the source to the amplifiers input we require a very high value of input impedance.

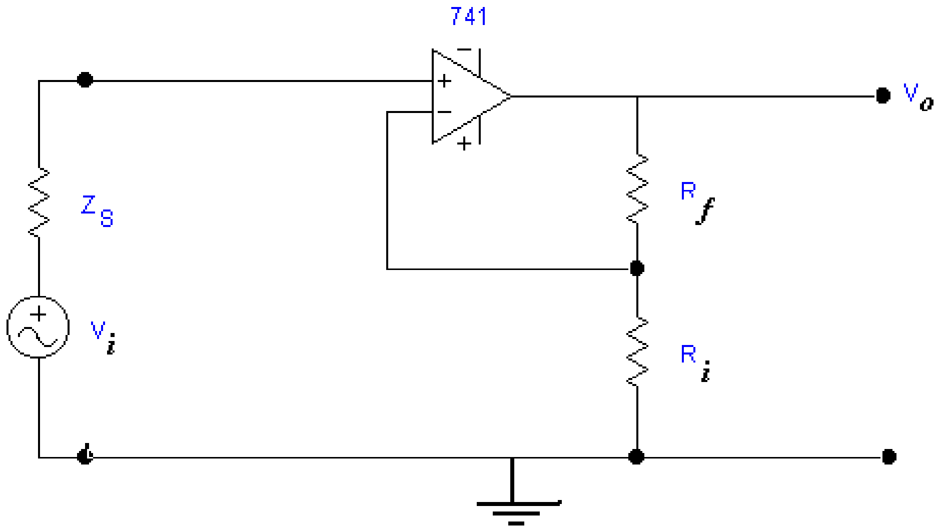
For the 741 operational amplifier open-loop (i.e. no feedback) the input impedance is approximately $10^6\ \Omega$.

We now need to calculate the input impedance for the non-inverting nfb amplifier which consists of a 741 op-amp and two resistors R_F and R_i.

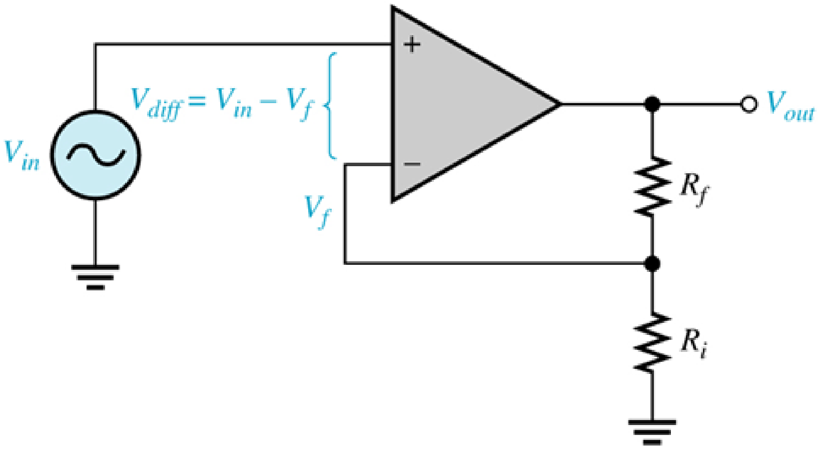
Input impedance of the non-inverting nfb amplifier



A voltage source which consists of an ideal voltage source in series with a source impedance is connected to the non-inverting input of the amplifier and the circuit becomes



It is reasonable to assume that Z_S is small relative to Z_i since the input impedance of the op-amp is approx.$10^6\ \Omega$. Therefore, we can ignore the impedance of the source and the circuit can be re-drawn as:



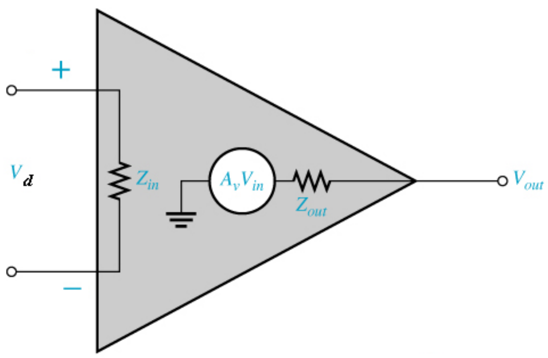
We need to find the input impedance of the complete amplifier in terms of the input impedance of the 741op-amp.

We know that the 741 itself is an amplifier with an input impedance Z_i and also that the non-inverting amplifier is an amplifier with its own input impedance value, Z_{if}.

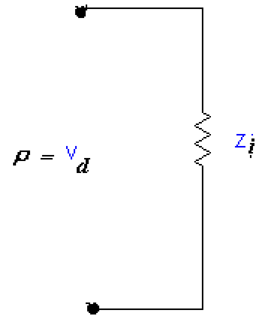
Recall that for every amplifier circuit the equivalent circuit contains an input impedance value at its input terminals.

Let:
Z_i = the input impedance of the 741op-amp
Z_{if} = the input impedance of the complete non-inverting amplifier.

The 741 amplifies the differential input V_d (ρ) by its gain A_O the equivalent circuits shown below:

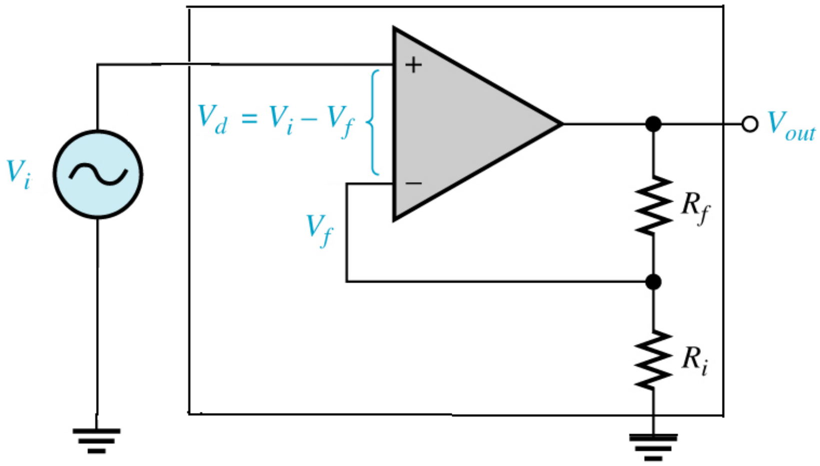


Equivalent circuit of 741 only amplifier input

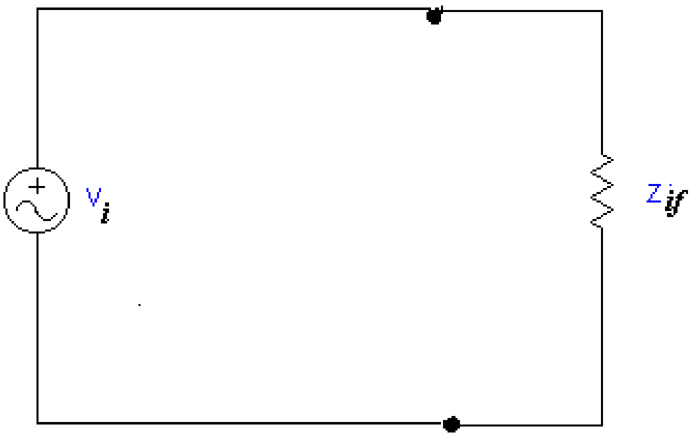


$$Z_i = \frac{\rho}{I_+} \therefore I_+ = \frac{\rho}{Z_i}$$

The non-inverting amplifier consisting of the 741 and two resistors amplifies V_i by A_C



Equivalent circuit of source to complete amplifier input



$$Z_{if} = \frac{V_i}{I_+} \therefore I_+ = \frac{V_i}{Z_{if}}$$

The value of the current that flows into the 741 op-amp and the non-inverting amplifier I_+ is the same in both circuits (i.e. the current flowing into the non-inverting input of both the 741 op-amp only circuit and the complete amplifier circuit are the same current) therefore,

$$\frac{\rho}{Z_i} = \frac{V_i}{Z_{if}} \therefore \frac{Z_i}{Z_{if}} = \frac{\rho}{V_i}$$

However, we know that the differential input

$$V_d = \rho = V_+ - V_f = V_i - \beta V_o$$

Therefore the ratio of the input impedance of the 741 only to the complete amplifier can be written as:

$$\frac{Z_i}{Z_{if}} = \frac{V_i - \beta V_o}{V_i} = 1 - \beta\left(\frac{V_o}{V_i}\right)$$

Rearranging the equation gives

$$\frac{V_o}{V_i} = A_c = \frac{A_o}{1 + \beta A_o}$$

$$\frac{Z_i}{Z_{if}} = 1 - \beta\left(\frac{A_o}{1 + \beta A_o}\right) = \frac{1 + \beta A_o - \beta A_o}{1 + \beta A_o} = \frac{1}{1 + \beta A_o}$$

$$\therefore Z_{if} = Z_i(1 + \beta A_o)$$

Thus the input impedance is greater than the impedance of the 741 only and we get extremely high values of Z_{if}

Example: Non-inverting amplifier using 741 operational amplifier, $Z_i = 10^6$ Ohms $A_O = 1\text{x}10^5$ with a gain of 100

$\beta = 0.01$

$$Z_{if} = Z_i(1 + \beta A_o) = 1.001 \times 10^9 \Omega$$

Output Impedance of the Non-inverting Amplifier

Z_O = the output impedance of the 741op-amp
Z_{Of} = the output impedance of the complete non-inverting amplifier.

It can be shown that:

$$Z_{0f} = \frac{Z_o}{(1 + \beta A_o)}$$

Therefore, the output impedance of the nfb amplifier is less than the output impedance of the amplifier in open-loop. The inclusion of the negative feedback reduces the output impedance.

Typically for a 741 op-amp the output impedance Z_o = 100 Ω. Taking our earlier example of a nfb amplifier with a gain of 100 the output impedance of the complete amplifier with negative feedback Z_{of} = 0.0999 Ω.

<u>Question</u>

(a) Determine the closed-loop gain, input impedance and output impedance of a non-inverting amplifier consisting of an 741 op-amp and two fixed resistors R_F is 220 kΩ and R_i is 10 kΩ.
The 741 parameters are as follows Z_i = 2 MΩ,
Z_o = 75 Ω, and $A_O = 2 \times 10^5$

(b) Draft an actual circuit diagram for the amplifier

(c) Draft an equivalent circuit diagram

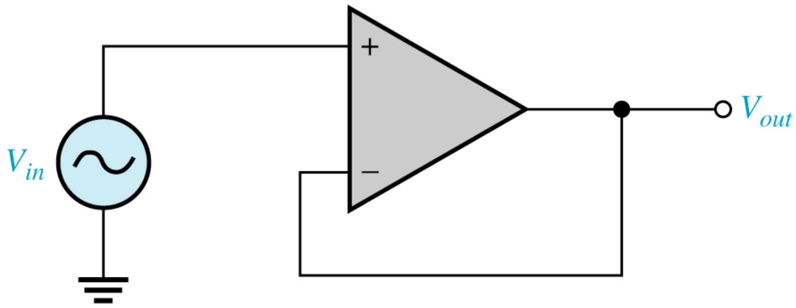
(d) Determine the value of the output voltage across a 15 kΩ load when real a voltage source of amplitude 400 mV and impedance 5 kΩ is connected to the amplifier.

Unity Gain Buffer (Voltage Follower)

Voltage follower: A non-inverting amplifier that has zero resistance in its feedback path.

The smallest value of gain for a non-inverting amplifier occurs when the closed-loop gain $A_V = 1$. The resistor values in this case are: $R_f = 0$ and $R_i = \infty$

For $R_f = 0$ replace by a short circuit and for $R_i = \infty$ replace by an open circuit. The circuit becomes

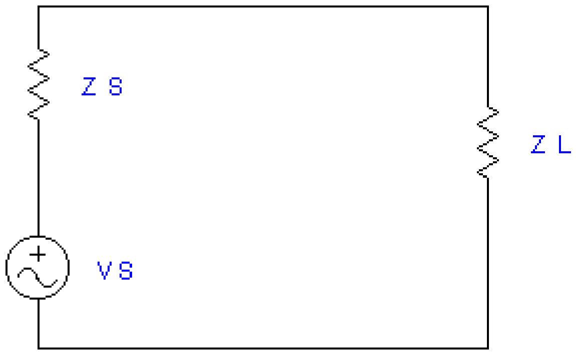


In this case $\beta = 1$ therefore $A_C = 1$ and assuming a 741 op amp $Z_{if} = 1\times10^{11}\ \Omega$ and $Z_{of} = 0.999\times10^{-3}\ \Omega$.

The ***input impedance*** of a voltage follower is greater than that of a non-inverting amplifier with a voltage divider feedback network. The ***output impedance*** of a voltage follower is lower than that of a non-inverting amplifier with a voltage divider feedback network. This circuit can be used in applications where the source has a high impedance.

Consider the following question

Is it possible to accurately measure the voltage of a source with a high source impedance (order of 1MΩ) using a standard dmm?



The load impedance of the dmm is typically the order of 1MΩ and the system determines the voltage by drawing current from the source across its own impedance, Z_L which produces a voltage which it displays.

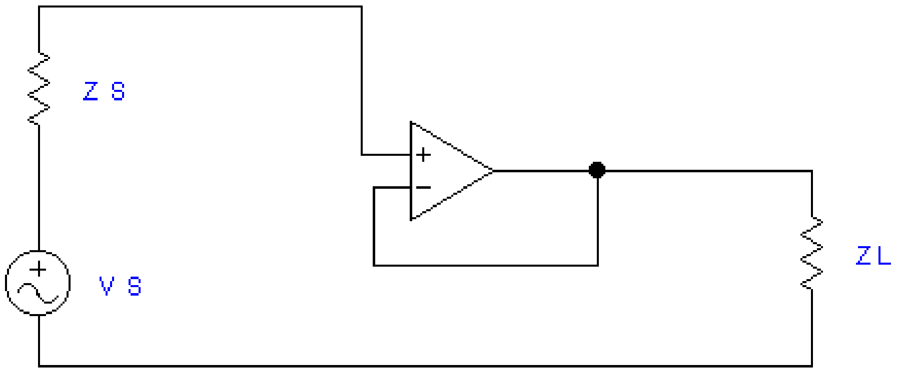
Applying the potential divider equation gives us a load/displayed voltage

$$V_L = \left(\frac{Z_L}{Z_L + Z_S} \right) V_S$$

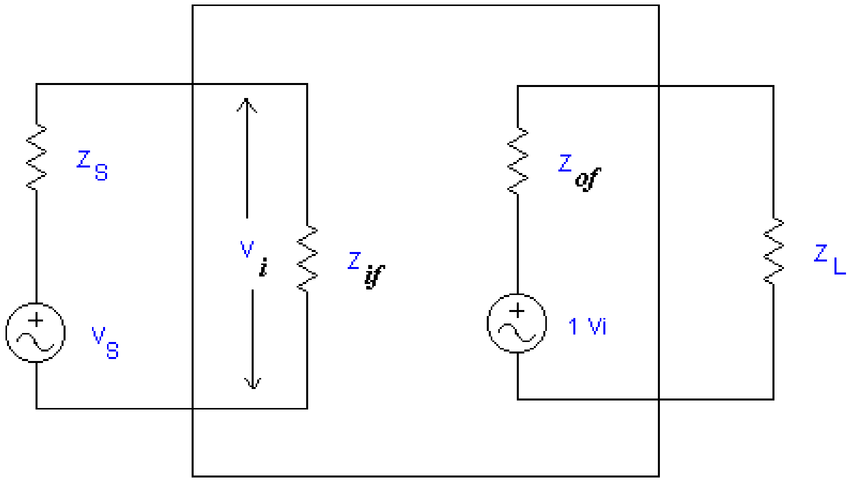
For $V_L \approx V_S$ requires $Z_L >> Z_S$ which is **<u>NOT</u>** the case here.

We need therefore to make Z_L *appear* to have a much larger impedance in relation to the source impedance. This can be achieved by inserting a voltage follower circuit between the source and the load as shown below:

Actual circuit



Equivalent circuit



Form the equivalent circuit we can see that the input voltage i.e. the voltage across the input impedance of the voltage follower

$$V_i = \left(\frac{Z_{iF}}{Z_{iF} + Z_S} \right) V_S$$

since $Z_{if} = 1x10^{11}\ \Omega >> 1x10^{6}\,\Omega$, then $V_i \approx V_S$.

Also from the equivalent circuit we can determine the voltage across the load: $V_L = \left(\dfrac{Z_L}{Z_L + Z_{OF}} \right) V_O$

since $V_O = V_i$ then the equation becomes

$$V_L = \left(\frac{Z_L}{Z_L + Z_{OF}} \right) V_i$$

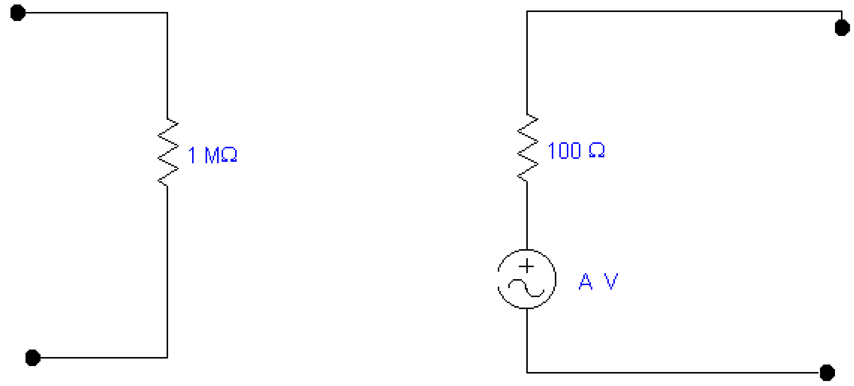
Since Z_{of} ($1x10^{-3}$ Ω) << Z_L ($1x10^6$ Ω) then

$V_L \approx V_i \approx V_S$ as required.

Thus the inclusion of the buffering stage has ensured that the value of V_L is transferred to the meter input is equal to the value of V_S the source voltage.

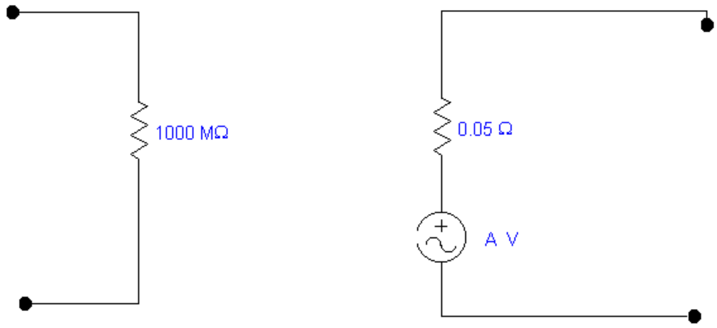
Summary

1. The equivalent circuit for the 741 op-amp in open-loop is



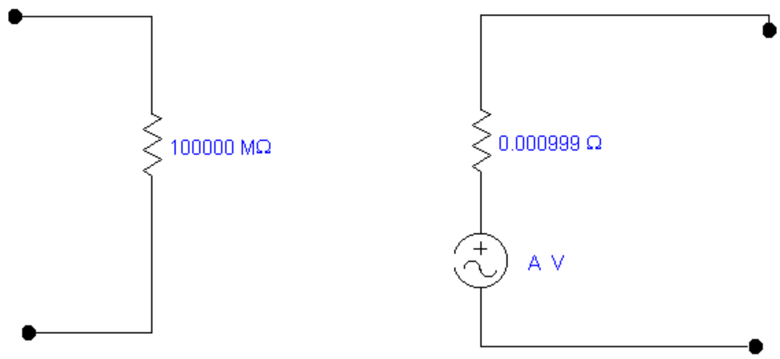
A = 10^5 and bandwidth = 10Hz

2. Equivalent circuit of non-inverting amplifier with gain of 100



A = 100 and bandwidth = 10^4 Hz

3. Voltage Follower Equivalent circuit



A = 1 and bandwidth = 10^6 Hz

Question

A voltage source produces voltage values of 0 – 20 mV and has a source impedance of 40k – 50 kΩ. Design a 741 based amplifier circuit so that the source can be connected to a pc (of impedance 20 kΩ) that reads voltage levels of 0 – 2.5 V

(a) Show actual and equivalent circuits

(b) Check the matching of the circuit