

The term operational amplifier itself induces one to ask, "what is this"? Most people in science and engineering know, or have a good idea, what amplification is and basically what it does. The "operational" part may be puzzling.

First, to shorten the writing perhaps, operational Amplifiers becomes op amp. These devices were more or less introduced in the 1930's — with George Philbrick being recognized for pioneering work with the devices.

Second, we shall shortly see how op amps can be used to

- add signals
- subtract signals
- integrate signals
- differentiate signals (not recommended)
- multiply signals (not directly but in conjunction with other electronics)

It is because the device can perform those mathematical operations, that it was referred to (still is) as an operational Amplifier.

In the text;

"Fundamentals of Electric Circuit";

Alexander & Sadiku; 3rd Edition,

Copyright 2007, ISBN-13 978-0-07-297718-9,

McGraw-Hill Book Company

the statements are made

- measurements are a tool for understanding the physical world,

- instruments are tools for measurement,

- the operational amplifier is a building block for modern electronic instrumentation

(one might add signal processing and control)

It behooves a person of science and engineering to have a basic understanding (at least from the standpoint of using as a device) how an operational amplifier functions.

### Physical Structure & History

In the 1940-1960 time frame the operational amplifier was constructed with vacuum tubes. The circuitry was encapsulated in the base that held the vacuum tubes (usually 2 dual 12AU6).

A picture of the GAP/R Model  $\times 2$ -W  
Op Amp can be seen on my web site  
<http://www.ece.utk.edu/ngreen/>

Look under ECE 300 Sp'06; Operational Amplifier (power point). These devices were expensive; ranging from \$50-\$90 per unit. They were the backbone of the analog computer. Basically the analog computer was used to solve differential equations that represented the models of physical systems. The vacuum tube op amp has been replaced by solid state semi-conductors (chip) op amps. The price for a garden variety op amp ( $\mu A741$ ) is less than one dollar. At the same time, analog computers (which can be readily constructed from low-cost solid state op-amps) have all but faded into the past. Most simulation today is performed using digital computers with software packages such as MATLAB/Simulink. We continue now on looking at the physical properties of the modern day op amp.

# Basic Electric Circuits

## Operational Amplifiers

The Philbrick Operational Amplifier is a high gain, low drift, high precision amplifier. It is designed for use in a wide variety of applications, including automatic control systems, signal processing, and data acquisition systems.

**OPERATIONAL AMPLIFIER**  
 The Philbrick Operational Amplifier is a high gain, low drift, high precision amplifier. It is designed for use in a wide variety of applications, including automatic control systems, signal processing, and data acquisition systems.

**6AP7R MODEL 12W**  
 The Philbrick Operational Amplifier is a high gain, low drift, high precision amplifier. It is designed for use in a wide variety of applications, including automatic control systems, signal processing, and data acquisition systems.

**PHILBRICK OPERATIONAL AMPLIFIER**  
 The Philbrick Operational Amplifier is a high gain, low drift, high precision amplifier. It is designed for use in a wide variety of applications, including automatic control systems, signal processing, and data acquisition systems.

**George A. Philbrick Researches, Inc.**  
 285 Columbus Avenue, Boston 16, Massachusetts

(C) Doug Coward

## The Philbrick Operational Amplifier.

From "Operational Amplifier", by Tony van Roon: <http://www.uoguelph.ca/~antoon/gadgets/741/741.html>

Perhaps the work horse of op amps is the low cost LM741. One can purchase these with from one to four op-amps on a DIP (dual in-line pack). The "half chip" op. Amp is very popular, selling for under 50¢ per unit. A pin connection for the device is shown in Figure 18.1

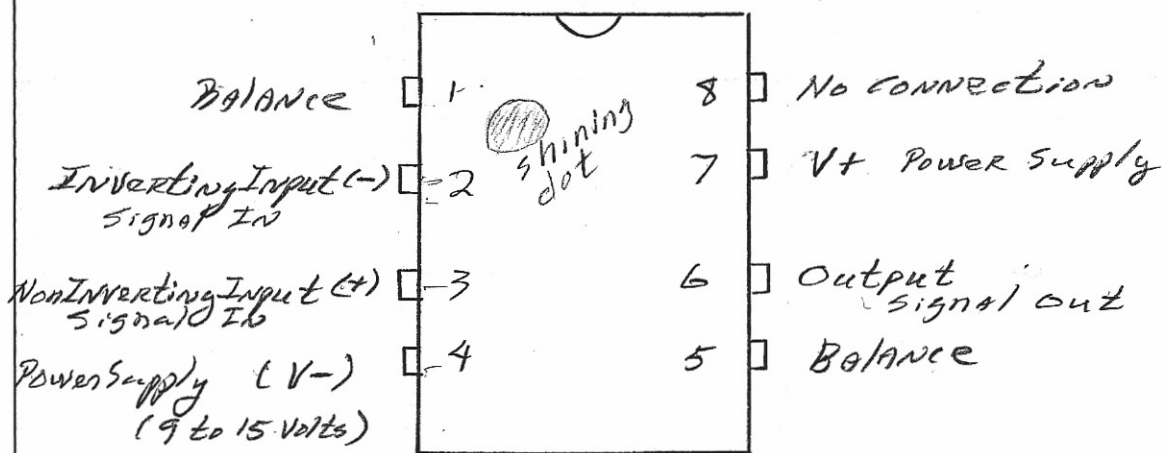


Figure 18.1: Pin layout for the LM741 op amp.

The physical size is in the order of 0.25" by (3/8)", top view, by (1/8)" deep.

In single connections, it is most often not necessary to use the "Balance" input. The no connection pin is there simple because of manufacturing format of an 8 pin chip.

5

The presentation of the op amp as shown in Figure 18.1 is non-descript as a device. The conventional display (drawing) is shown in Figure 18.2.

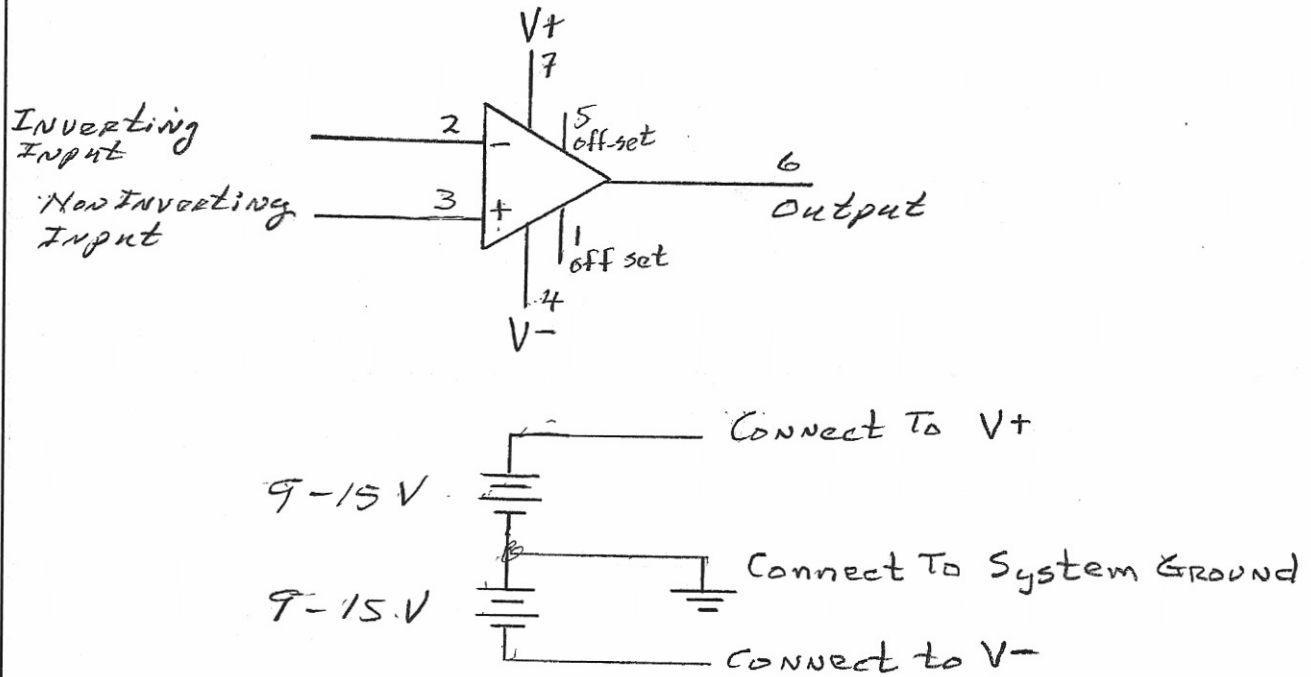


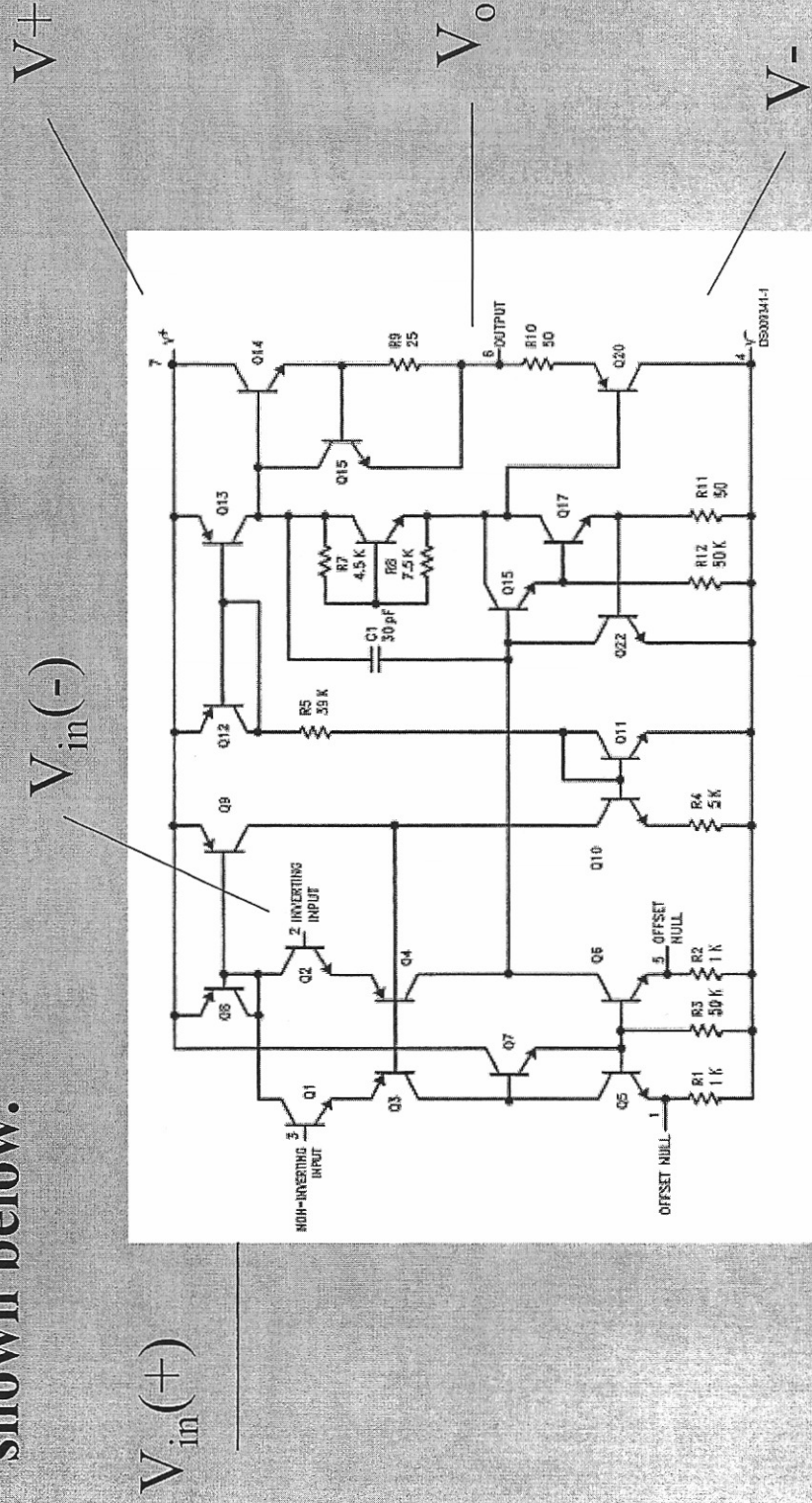
Figure 18.2: Showing Hook-Up of The LM741 Op Amp.

It is not uncommon for the first-time student to forget (or not realize) that the supply voltage must externally be connected to the device. Most op amps have an upper/lower voltage rating (this case  $\pm 15V$ ), often called the rail-to-rail voltage, but will operate quite successfully on lower voltages ( $\pm 9V$  is shown above).

# Basic Electric Circuits

## Operational Amplifiers

The op amp is built using VLSI techniques. The circuit diagram of an LM 741 from National Semiconductor is shown below.



5

Figure 8.1: Internal circuitry of LM741.

Taken from National Semiconductor data sheet as shown on the web.

We will see later that an op amp does not include pin numbers and voltage supply pins identification when the op amp is connected to external circuitry. When this happens, one must keep in mind that the current for the device comes from the external power supply and input signals as shown in Figure 18.3.

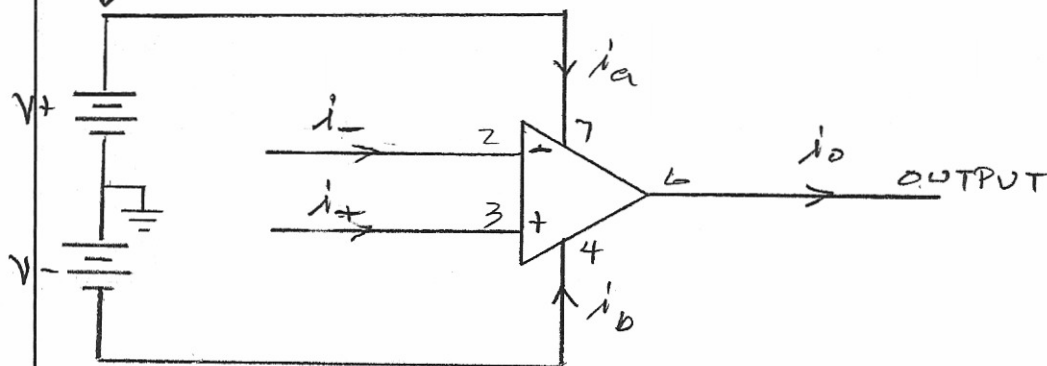


Figure 18.3: Reminder. Circuit showing external currents for an op amp.

obviously, from this diagram;

$$i_o = i_a + i_b + i_+ + i_- \quad (18.1)$$

In our earlier study of circuits, we have seen dependent and independent sources. The model (typical model) of the op amp relies on dependent sources.



A model of the op-amp that gives reasonably good results is shown in Figure 18.4

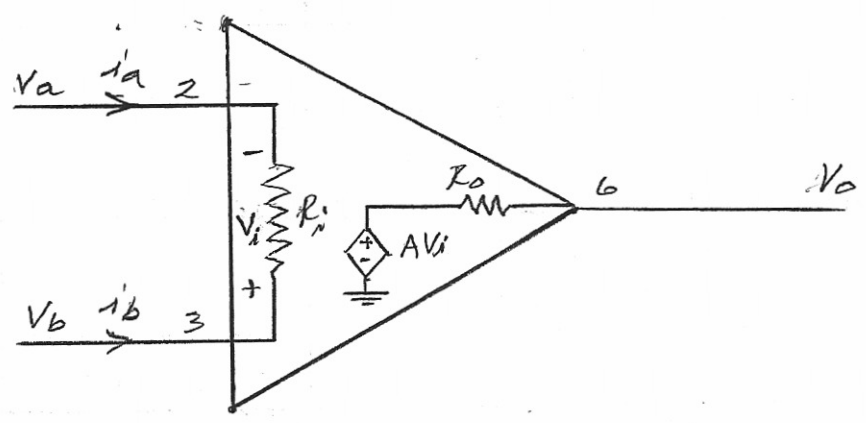


Figure 18.4: A basic model of the op-amp. We note that a dependent voltage controlled voltage source is present at the output. The output voltage is given by

$$V_o = A (V_b - V_a) \tag{18.2}$$

A is the open-loop gain (no external feedback) of the op-amp.

Table 18.1 gives some typical values of op-amp parameters

Parameter	Range	Ideal Values
Open Loop Gain, A	$10^5 - 10^8$	$\infty$
Input Resistance, $R_i$	$10^4 - 10^{12} \Omega$	$\infty \Omega$
Output Resistance, $R_o$	$10 - 100 \Omega$	$0 \Omega$
Supply Voltage	$15 - 20 \text{ V}$	

Table 18.1: Typical Op Amp Parameter Values.

There are limitations on how much current the op amp can output and how much the voltage can swing.

The typical output swing is judged by the approximate sketch shown in Figure 18.5.

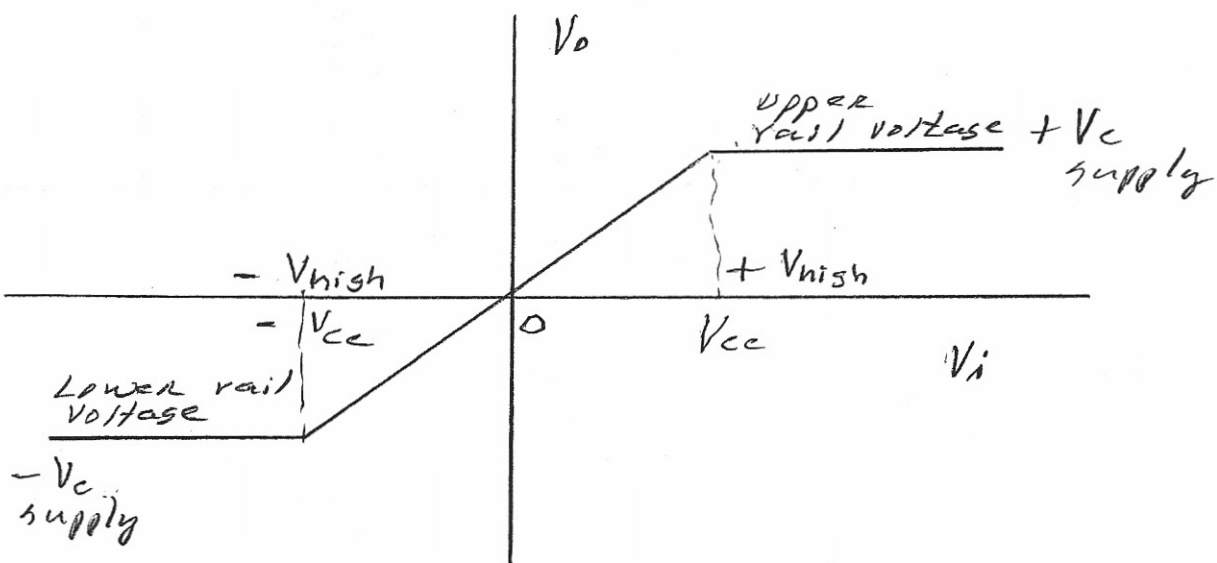


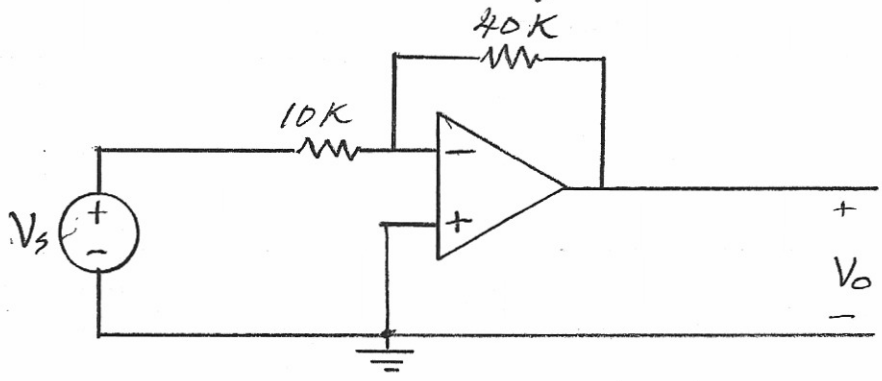
Figure 18.5: Sketch showing linear range of operation for an op amp

The device can successfully operate over  $\pm V_{high}$ , which is the range of the supply voltage applied at pins 7 and 4 on the 741. This range,  $-V_{cc}$  to  $V_{cc}$  is sometimes called the rail to rail voltage.

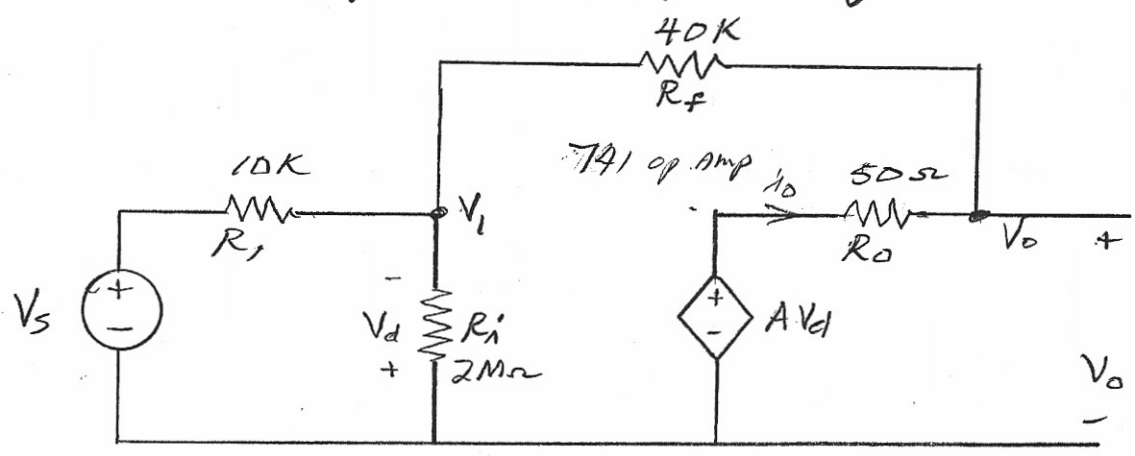
### Analysis

We now consider a typical application of the op amp.

A normal way of showing external circuitry connected to an op amp is shown in Fig 18.5a. Using the model of Figure 18.4, produces the circuit of Figure 18.6b.



(a) A popular op amp configuration.



(b) Circuit of Figure 18.6a but using full model of the op amp.  
Figure 18.6

We desire to find the transfer function  $V_o/V_s$ . An important note: We carry out the analysis of op amp circuits use nodal analysis. A great deal of this has to do with us adopting a simpler model later in which case we would have difficulty using, say mesh analysis.

At node  $V_1$ :

$$\frac{V_1 - V_s}{10K} + \frac{V_1}{2M} + \frac{V_1 - V_o}{40K} = 0$$

OR

$$200V_1 - 200V_s + V_1 + 50V_1 - 50V_o = 0$$

$$200V_s = 251V_1 - 50V_o$$

OR

$$V_1 = 0.7968V_s + 0.1992V_o \quad (18.3)$$

At  $V_o$ :

$$\frac{V_o - V_1}{40K} + \frac{V_o - AV_d}{50} = 0$$

OR

$$\frac{V_o - V_1}{40K} + \frac{V_o - AV_1}{50} = 0$$

Using  $A = 200,000$  (741 typical)

$$V_o - V_1 + 800V_o - 160 \times 10^6 V_1 = 0 \quad (18.4)$$

Using (18.3) in (18.4)

$$V_o - 0.7968V_s - 0.1992V_o + 800V_o - 160 \times 10^6 (0.7968V_s + 0.1992V_o) = 0$$

OR

$$V_o - 0.7968V_s - 0.1992V_o + 800V_o - 127.488 \times 10^6 V_s - 31.872 \times 10^6 V_o = 0$$

essentially

$$V_o = - \frac{127.488 \times 10^6 V_s}{31.872800} = -3.9998996 V_s$$

OR

$$\frac{V_o}{V_s} = -3.9998996$$

(really close to 4)

## A Simpler Model

11

We have seen that

$$|V_o| < V_c \quad (\text{supply})$$

which means

$$A(V_b - V_a) < V_c$$

$$\text{OR} \quad (V_b - V_a) < \frac{V_c}{A}$$

but  $V_c$  is very finite, say 15V;  
"A" runs on the order of  $1 \times 10^6$  or more  
OR

$$(V_b - V_a) \approx 15 \text{ micro volts}$$

so we make the approximation

$$\boxed{V_b = V_a} \quad 18.5$$

An implication of this is that

$$i_b = -i_a = \frac{V_b - V_a}{R_{in}} \quad 18.6$$

$V_b - V_a$  is very, very small;  $R_{in}$  is very large, so we say

$$i_b = -i_a = 0 \quad 18.7$$

This sets the stage for our simpler model. We make the following assumptions.

- (1)  $A_v$  gain, is  $\infty$
- (2)  $R_i$ , input resistance, is  $\infty$
- (3)  $R_o$ , output resistance, is 0
- (4)  $i_a = i_b = 0$
- (5)  $V_a = V_b$

Some of this is portaid in Figure 18.7

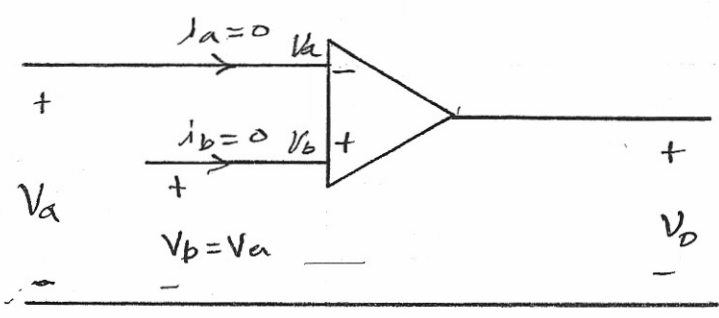


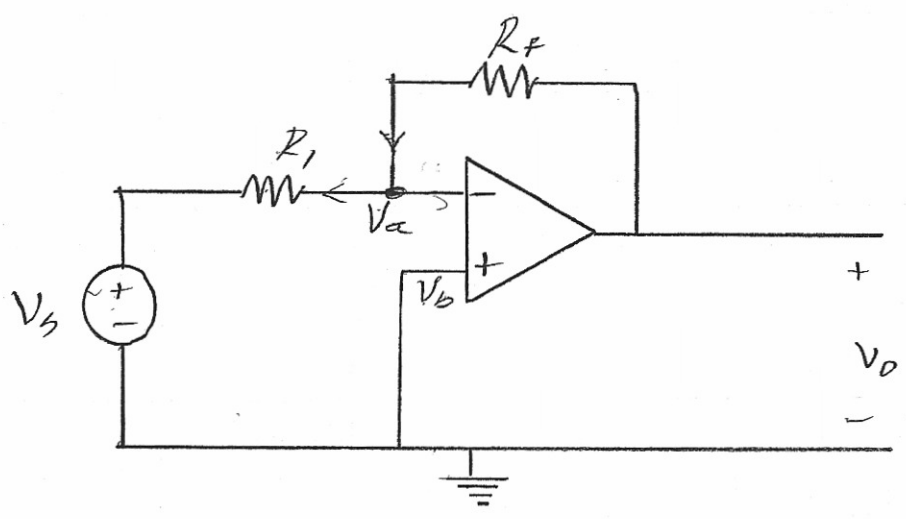
Figure 18.7: Simplified Op Amp Model.

Two important things to remember:

- $i_a = i_b = 0$  (no current enters the non-inverting and inverting terminals)
- $V_a$  follows the voltage of  $V_b$ .

This greatly simplifies the analysis of op amps. These approximations work very good in most all cases.

Return and analyze the earlier example



At  $V_a$ :

$$\frac{V_a - V_s}{R_1} = \frac{V_o - V_a}{R_f} \quad (18.8)$$

Since  $V_a = V_b$  and  $V_b$  is tied to ground, (0 volts) then  $V_a = 0$ . Then (18.8) becomes

$$-\frac{V_s}{R_1} = \frac{V_o}{R_f}$$

OR

$$\boxed{\frac{V_o}{V_s} = -\frac{R_f}{R_1}} \quad (18.9)$$

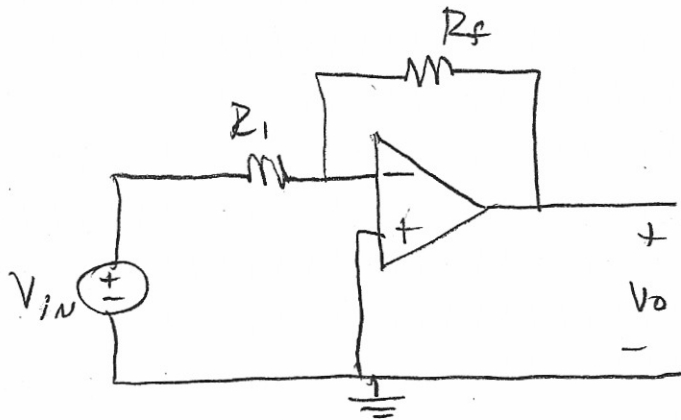
which is sort of a famous equation for an op amp. Using 40k and 10k we get

$$\frac{V_o}{V_s} = -4$$

As compared to

$$\frac{V_o}{V_s} = -3.9998996$$

# Gain Configuration



$$V_O = - \frac{R_F}{R_1} V_{IN} \quad (18.10)$$

Figure 18.8: A voltage controlled voltage

# Summing Amplifier

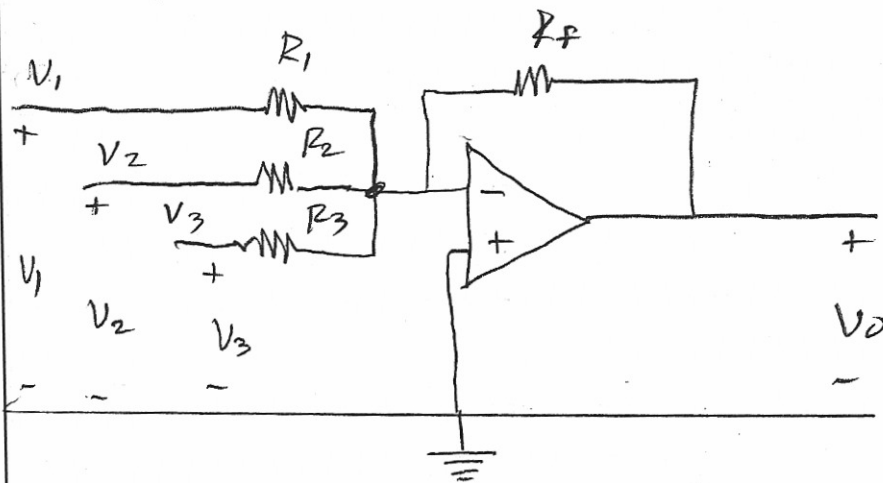


Figure 18.9: A summing op amp configuration.

It is easy to show

$$V_O = - \left[ \frac{R_F}{R_1} V_1 + \frac{R_F}{R_2} V_2 + \frac{R_F}{R_3} V_3 \right]$$

making  $R_1 = R_2 = R_3$  gives

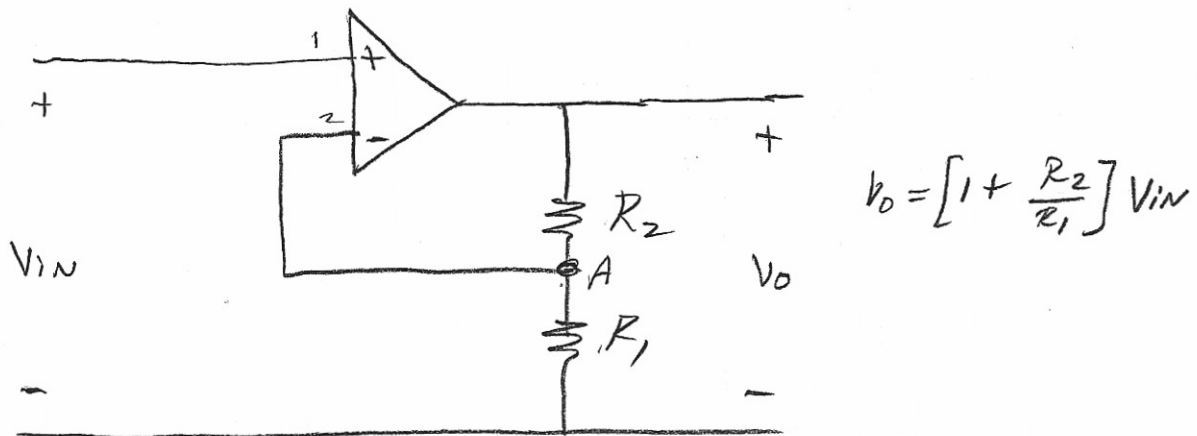
$$V_O = - \left[ V_1 + V_2 + V_3 \right] \frac{R_F}{R_1} \quad (18.11)$$



## Non-Inverting Configuration.

In all cases up to now the output polarity is the negative of the input signal.

Consider the configuration shown in Figure 18.10.



$$V_o = \left[ 1 + \frac{R_2}{R_1} \right] V_{in}$$

Figure 18.10; A non-inverting op amp.

Now the voltage at 1 = voltage at 2 = voltage at A. So we can write the following nodal equation at A.

$$\frac{V_{in} - V_o}{R_2} + \frac{V_{in}}{R_1} = 0$$

OR

$$R_1 V_{in} - R_1 V_o + R_2 V_{in} = 0$$

$$R_1 V_o = (R_1 + R_2) V_{in}$$

$$V_o = \frac{[R_1 + R_2] V_{in}}{R_1}$$

OR

$$V_o = \left[ 1 + \frac{R_2}{R_1} \right] V_{in}$$

(18.12)

Famous equation

### Voltage Controlled Current Source

Considered the op amp configuration shown in Figure 18.11.

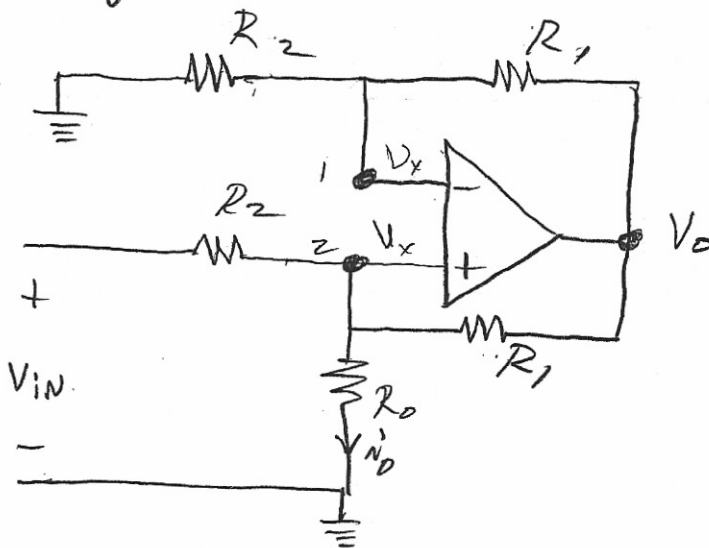


Figure 18.11; A voltage controlled current source configuration.

We write nodal equations at (1) and (2).

At (1)

$$\frac{V_x}{R_2} = \frac{V_0 - V_x}{R_1} \quad (18.13)$$

At (2)

$$\frac{V_x - V_{in}}{R_2} + \frac{V_x - V_0}{R_1} + i'_0 = 0 \quad (18.14)$$

From (18.13)

$$R_1 V_x = R_2 V_0 - R_2 V_x$$

$$\text{or } V_0 = \frac{(R_1 + R_2) V_x}{R_2} \quad (18.15)$$

From (18.14), getting a common denominator,

$$R_1 V_x - R_1 V_{in} + R_2 V_x - R_2 V_0 + R_1 R_2 i'_0 = 0$$

$$(R_1 + R_2) V_x - R_1 V_{in} - R_2 V_0 + R_1 R_2 i'_0 = 0 \quad (18.16)$$

Substitute (18.15) into (18.16)

$$(R_1 + R_2) V_x - R_1 V_{in} - R_2 \left( \frac{R_1 + R_2}{R_2} \right) V_x + R_1 R_2 i'_0 = 0$$

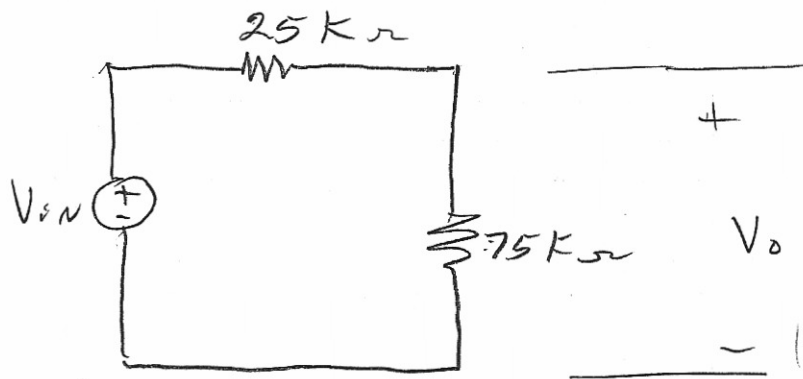
$$\text{or } R_1 R_2 i'_0 = R_1 V_{in}$$

$$\boxed{i'_0 = \frac{V_{in}}{R_2}} \quad (18.17)$$

So the output current is controlled by the input voltage.

# Buffer Amplifier

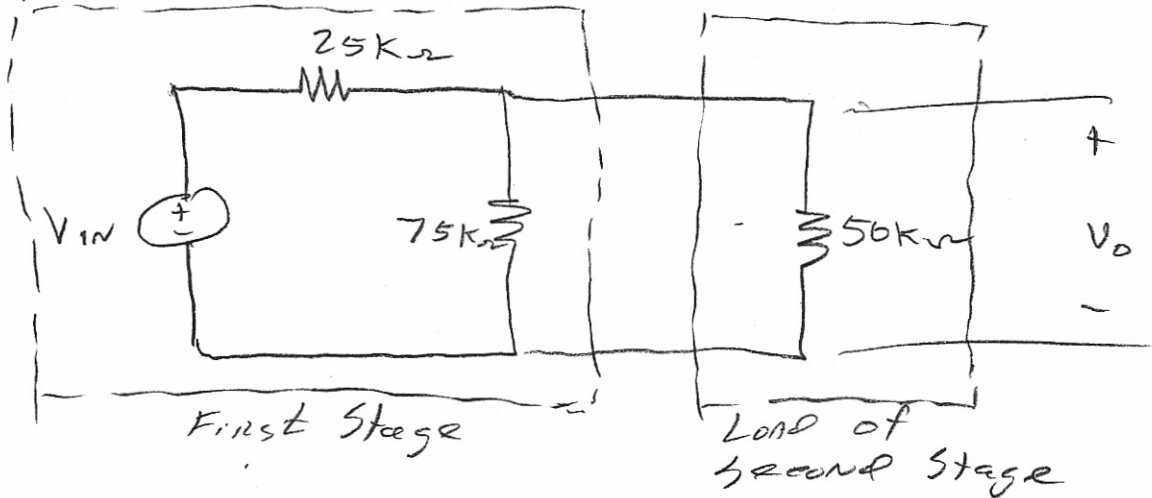
We often need a "buffer" between two stages of a process so that the final stage, when connected to the initial stage, does not load-down the initial stage. Consider the oversimplified following case.



We see that

$$\frac{V_O}{V_{IN}} = \frac{75K}{25K + 75K} = 0.75$$

Suppose we now have the case,



$$\text{With } 75\text{K} \parallel 50\text{K} = \frac{75 \times 50}{125} = 30\text{K}$$

Therefore;

$$\frac{V_o}{V} = \frac{30\text{K}}{30\text{K} + 25\text{K}} = 0.545$$

We see the 50K load has loaded down the first stage and changed  $V_o$ . We can avoid this by placing a buffer between the two stages. The buffer, as an operational amplifier is shown in Figure 18.12

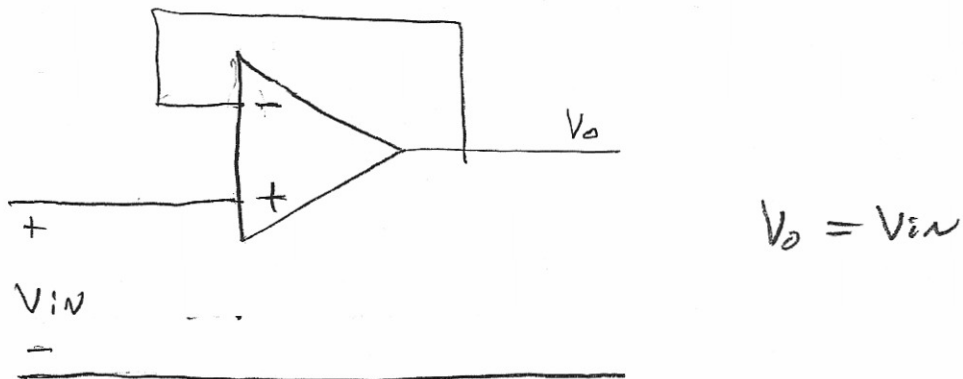


Figure 18.12: Buffer amplifier.

The input impedance is very high ( $> 1 \text{ meg } \Omega$ ), the output impedance (looking back in the op-amp) is low (normally  $< 50 \Omega$ ).

with the buffer amplifier inserted

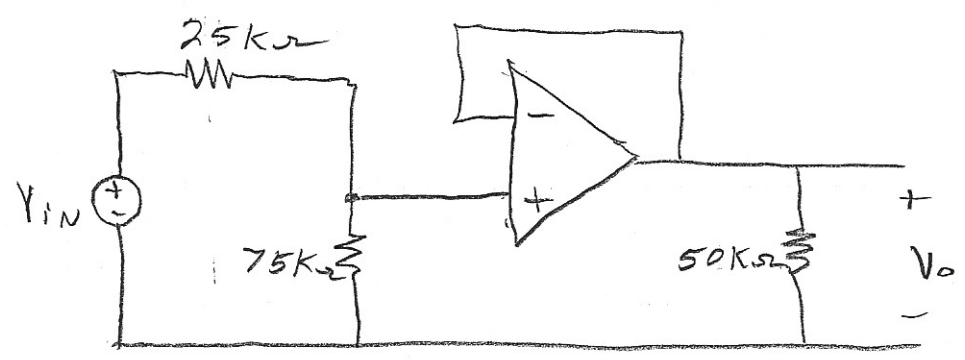


Figure 18.13: Two stages separated by a buffer amplifier.

The ratio of  $V_O/V_{IN}$  should now return to 0.75. You are encouraged to try this on your own to see if it works.

### A Difference Amplifier

Suppose you have two signals  $V_1$  and  $V_2$  and you would like to subtract  $V_2$  from  $V_1$ . Consider the configuration of Fig 18.14

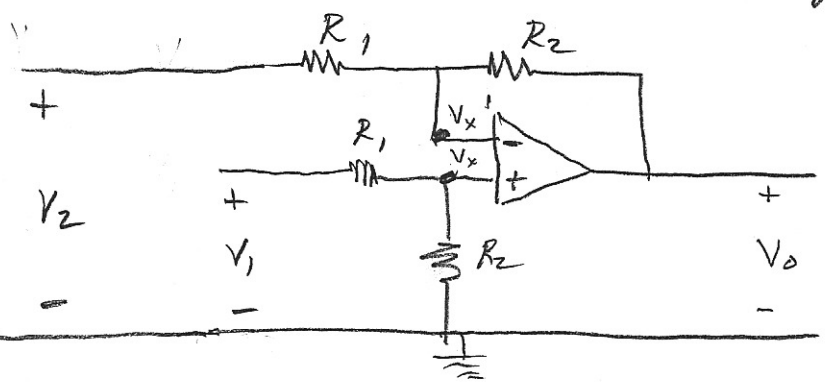


Figure 18.14: A difference amplifier.

At the upper  $V_x$  in Fig 18.14

$$\frac{V_x - V_2}{R_1} + \frac{V_x - V_0}{R_2} = 0$$

OR

$$V_x \left[ \frac{1}{R_1} + \frac{1}{R_2} \right] = \frac{V_2}{R_1} + \frac{V_0}{R_2} \quad (18.18)$$

At the lower  $V_x$  of Figure 18.14

$$\frac{V_x - V_1}{R_1} + \frac{V_x}{R_2} = 0$$

OR

$$V_x \left[ \frac{1}{R_1} + \frac{1}{R_2} \right] = \frac{V_1}{R_1} \quad (18.19)$$

Equate (18.18) to (18.19)

$$\frac{V_1}{R_1} = \frac{V_2}{R_1} + \frac{V_0}{R_2}$$

$$\frac{V_0}{R_2} = \frac{V_1}{R_1} - \frac{V_2}{R_1}$$

OR

$$V_0 = \frac{R_2}{R_1} [V_1 - V_2] \quad (18.20)$$

One can control gain by a selection of the resistors  $R_1$  &  $R_2$