

# A BRIEF INTRODUCTION TO OPERATIONAL AMPLIFIERS

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[4/94]

## Inverting Amplification

One of the most frequent applications of operational amplifiers is as an inverting amplifier (see Fig. 1).

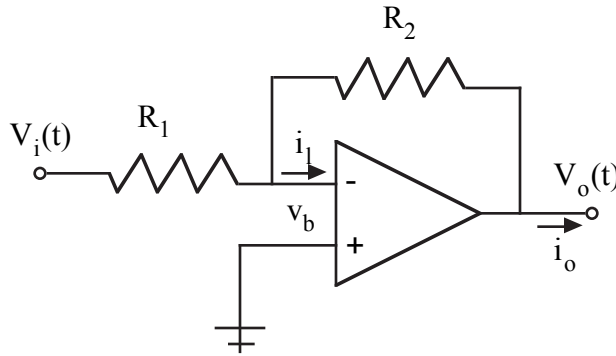


Figure 1. Inverting amplifier

There are four important assumptions useful in the analysis of circuits containing op-amps. These are:

- (1) infinite input impedance ( $\Rightarrow i_i = 0$ ).
- (2) zero bias voltage ( $\Rightarrow v_b = 0$ ).
- (3) zero output impedance ( $\Rightarrow i_o = \infty$ ).

Since  $i_i$  is assumed to be zero, and  $i_o$  is unknown, it is best to apply Kirchoff's current law (KCL) to the inverting input node. Thus we have

$$\frac{V_b - V_i}{R_1} + \frac{V_b - V_o}{R_2} = 0 \quad , \quad (1)$$

but  $V_b$  is also zero, so we get

$$\boxed{V_o = -\frac{R_2}{R_1} V_i} \quad (2)$$

A fourth assumption is that gain is unlimited. Thus,  $R_2 \gg R_1 \Rightarrow |V_o| \gg |V_i|$ . In actuality, the

voltage gain is limited to less than the supply voltage which is usually  $\pm 15$  Volts. When  $V_o$  approaches  $\pm 13$  Volts, saturation occurs. That is, no further gain is possible. Furthermore, all three of the other assumptions are violated to a greater or lesser extent. All op-amps exhibit some bias voltage, and some leakage current (input impedance very large but not infinite). In modern op-amps, these quantities are extremely small, however, so little is lost in the first two assumptions. The third assumption is dependent upon the power requirements of the rest of the circuit. Again, if the power requirements remain bounded by the maximum which the op-amp is capable of, in a manner similar to the voltage gain limitation, the output impedance may be assumed to be negligible. The principal benefit of this property of op-amps is that the input side of the op-amp may be considered to be isolated from its output side. Thus, op-amps may be used to separate or decouple one circuit from another. Hence, a series of op-amp circuits may be cascaded together to modify an input signal – **without significant attenuation**.

### Typical Op-Amp Layout

A prototypical op-amp is the Texas Instruments 741 (TI741). This op-amp is housed in a eight-pin, dual in-line package (DIP) as shown in Figure 2.

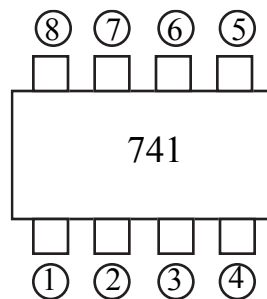


Figure 2 Top view of a TI741 chip

The schematic of the pin layout is shown in Figure 3.

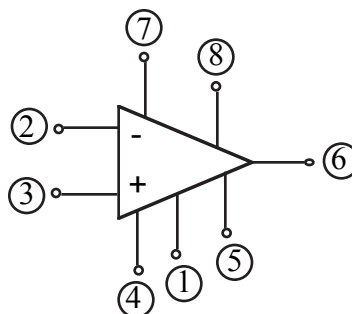


Figure 3 Schematic of pin layout

Table 1 identifies the use of each pin.

Table 1 Op-amp pin usage

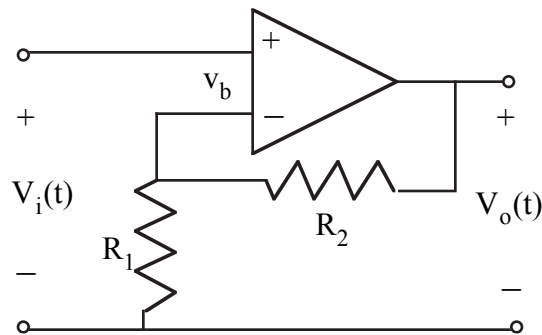
<u>Pin</u>	<u>Use</u>
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1	Offset null
2	Inverting input
3	Non-inverting input
4	-15 Volts
5	Offset null
6	Output
7	+15 Volts
8	Not connected

A potentiometer is usually connected between the two null offset terminals to adjust the offset voltage to a minimum. Also, a supply voltage lower than  $\pm 15$  Volts may be used.

### **Non-inverting Amplification**

The op-amp may also be used in a non-inverting voltage configuration as shown in Figure 4.



**Figure 4 Non-inverting amplifier**

Noting that  $V_b = 0$ , application of KCL yields

$$\frac{V_i}{R_1} + \frac{V_i - V_o}{R_2} = 0 \quad (3)$$

Thus, we obtain

$$V_o = \left( 1 + \frac{R_2}{R_1} \right) V_i \quad (4)$$

### **Integration**

Op-amps may be used to integrate input signals. A typical integrator circuit is shown in figure 5.

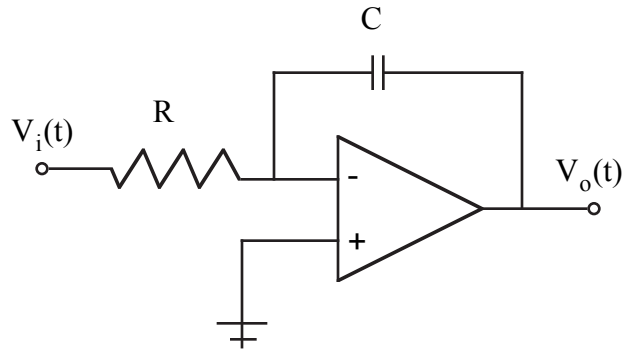


Figure 5 Integrator circuit

Again, application of KCL at the inverting input yields

$$\frac{-V_i}{R} - C \frac{dV_o}{dt} = 0 \quad (5)$$

Integrating Equation (5) with respect to time yields

$$V_o(t) = -\frac{1}{RC} \int_0^t V_i(\tau) d\tau \quad (6)$$

### Differentiation

An op-amp configured to differentiate an input signal is shown in Figure 6.

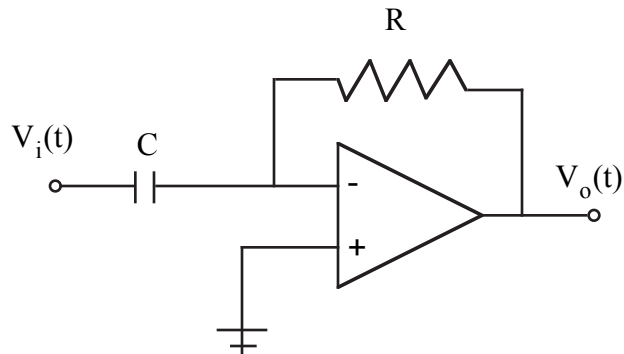


Figure 6 Differentiator circuit

Kirchoff's current law again yields the appropriate input-output relationship given by equation 7.

$$\boxed{V_o(t) = -RC \frac{dV_i(t)}{dt}} \quad (7)$$

### Current Amplification

Op-amps may also be used to amplify current, and hence, power. This configuration is shown in Figure 7.

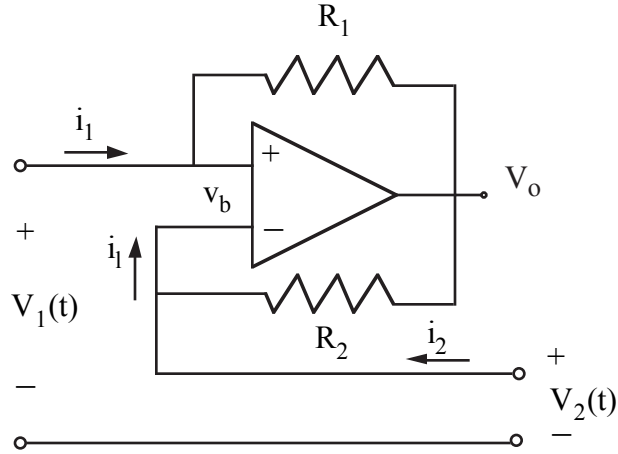


Figure 7 Current amplification circuit

Since  $V_1 = V_2$ , by KCL at the inverting input, we have

$$-i_1 - \frac{V_2 - V_o}{R_1} = 0 \quad (8)$$

Similarly at the non-inverting input

$$-i_2 - \frac{V_2 - V_o}{R_2} = 0 \quad (9)$$

Combining (8) and (9) yields

$$\boxed{i_1 = \left( \frac{R_2}{R_1} \right) i_2} \quad (10)$$

### Voltage Comparator

A voltage comparator is shown in Figure 8.

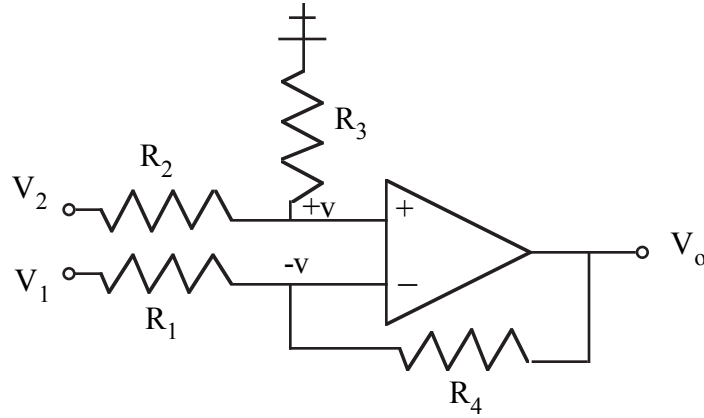


Figure 8 Voltage comparator

Noting that there is ideally zero voltage drop across the input terminals, we have that  $+v = -v = v$ . Application of KCL at both input nodes yields

$$\frac{V}{R_3} + \frac{V - V_2}{R_2} = 0 \quad (11)$$

and

$$\frac{V - V_1}{R_1} + \frac{V - V_o}{R_4} = 0 \quad (12)$$

From (11) we have

$$V = \frac{R_3}{R_2 + R_3} V_2 \quad (13)$$

Substitution into (12) yields

$$V_o = \frac{R_1 + R_4}{R_1} \left( \frac{R_3}{R_2 + R_3} \right) V_2 - \frac{R_4}{R_1} V_1 \quad (14)$$

Thus, if  $R_2 = R_1$  and  $R_4 = R_3$ , we have

$$\boxed{V_o = \frac{R_3}{R_1} (V_2 - V_1)} \quad (15)$$

### Adder Circuit

Multiple input signals may also be summed together as shown in Figure 9.

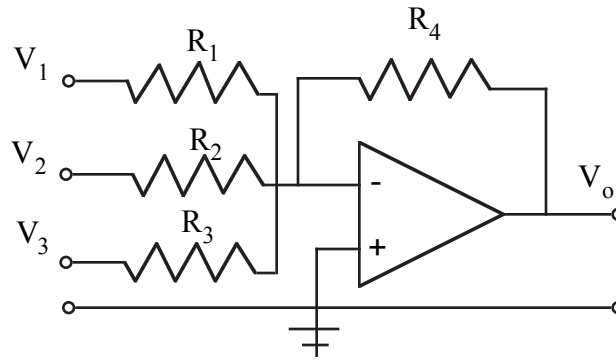


Figure 9 Adder circuit

Application of KCL at the inverting input yields

$$V_o = -\left( \frac{R_4}{R_1} V_1 + \frac{R_4}{R_2} V_2 + \frac{R_4}{R_3} V_3 \right) \quad (16)$$

If  $R_1 = R_2 = R_3 = R$ , we obtain

$$V_o = -\frac{R_4}{R} (V_1 + V_2 + V_3) \quad (17)$$

### **Conclusion**

Op-amps may be used in a variety of configurations to perform mathematical operations on voltage and current signals. The examples presented here are meant to provide a basic guide in the analysis and use of simple op-amp circuits. These examples may be used in the construction of much more complex systems for use as control circuits, filter circuits, and analog computers. For a more detailed examination of the internal workings of op-amps, consult any modern electronics text, or op-amp manufacturer's data book.

### **Additional Notes on Op-Amps**

1. Op-Amps are almost always used in the feedback mode. That is, a follower usually connects one or both of the input nodes with the output node.
2. If only one input is followed, it is always the inverting input.
3. There are dozens of different op-amps to choose from. The choice depends on the application. Some design variables include: maximum power output, minimum leakage current and offset voltage, and frequency response. The price of op-amps has come down significantly over the last 10 years. They vary in price from 25¢ to about \$75.