Electrical Tech Note — 530

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Operational Amplifiers

When amplifying a voltage signal the desirable characteristics of the amplifying device is a very high input impedance (resistance) and a very low output impedance. If the letter **A** represents the voltage gain of an amplifier, then the output voltage (V_{out}) is the product of the input voltage (V_{in}) and the gain (A) as represented by Equation 530.1.

$$v_{out} = A \times v_{in}$$ **Equation 530.1**

An operational amplifier (op-amp) is an electronic device that has two inputs and one output, and amplifies the voltage difference between the two inputs. It has the characteristics of an ideal amplifier of a very high input impedance and a very low output impedance. From the standpoint of drawing an operational amplifier in a schematic circuit the major terminals of importance are the two input terminals and the one output terminal. An operational amplifier is generally represented by a triangle as shown in Figure 530.1 with the inputs on the flat side and the output at the point of the triangle opposite the flat side. Note that one input is marked with a minus symbol (−) and the other with a plus symbol (+). These symbols have nothing to do with input polarity. The minus symbol indicates that if a voltage is applied to this terminal, the amplified output voltage will be inverted with respect to input polarity. The sign will be changed. If the input signal is positive with respect to ground, the output will be amplified and negative with respect to ground. The plus symbol means the output polarity will not be inverted. It will simply be amplified with the same polarity as the input. Another important characteristic of an operational amplifier is that the voltage gain (A) or amplification of the input voltage is extremely high and is generally 100,000 or greater. This means that if one micro-volt is applied between the two input terminals, the output will be at least one volt.

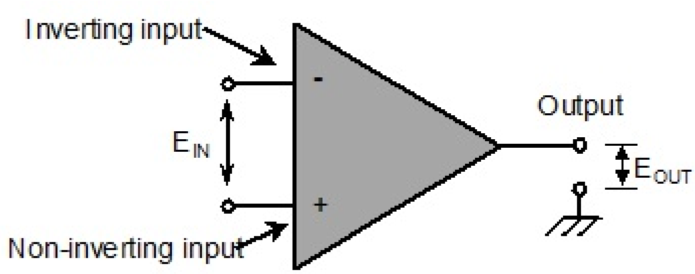

Figure 530.1 *An operational amplifier (op-amp) is represented by a triangle with two input terminals with a very high impedance between these two terminals and having one output terminal with very low impedance with respect to ground.*

Power Connections of an Operational Amplifier: A typical operational amplifier has seven active terminals. Sometimes it is mounted into an eight pin package where pin 8 has no purpose. Two terminals are for making adjustments and will be discussed later. Two are the inputs and one is the output. Two are for making connection to the power supply. A standard operational amplifier requires a three terminal power supply, a positive supply, a negative supply, and a ground. There is a positive voltage terminal ($+V_S$) and a negative voltage terminal ($-V_S$). There is no ground terminal. Ground is connected to the operational amplifier through one of the input terminals. This connection will be discussed for each of the applications of the operational amplifier later in this Tech Note. A typical power supply for an operational amplifier is +12 Vdc, −12 Vdc, and ground. Figure 530.2 shows a typical operational amplifier symbol with the power supply connections along with a typical eight pin package with the terminals labeled.

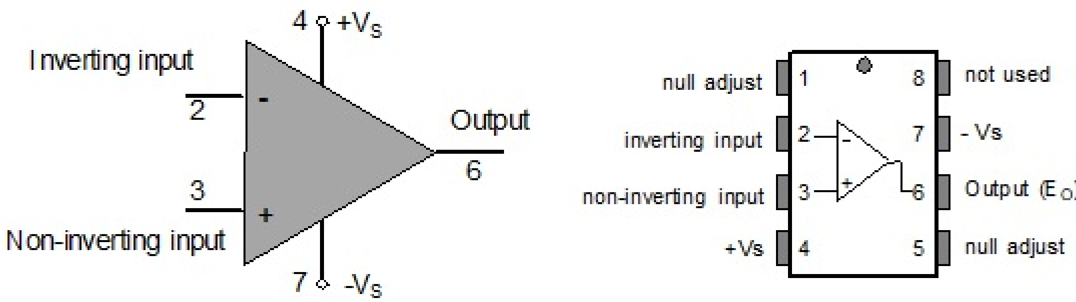

Figure 530.2 *Power is supplied to the op-amp by means of a +Vs and a −Vs terminal which are generally not shown on a schematic diagram since it is understood these connections are required. The terminals are labeled on an op-amp eight pin socket arrangement.*

Principles of Op-Amp Operation: An op-amp is rarely connected open circuit (open loop) which means that there is no direct connection external to the op-amp form the output back to an input. When there is a connection from the output back to one of the input terminals this is called a closed circuit connection or a feedback connection (closed loop). Another connection that is sometimes used for adjustment purposes is called a common mode input where the two input terminals are connected to a common voltage source in an attempt to establish a zero voltage between the two inputs. These connections are illustrated in Figure 530.3.

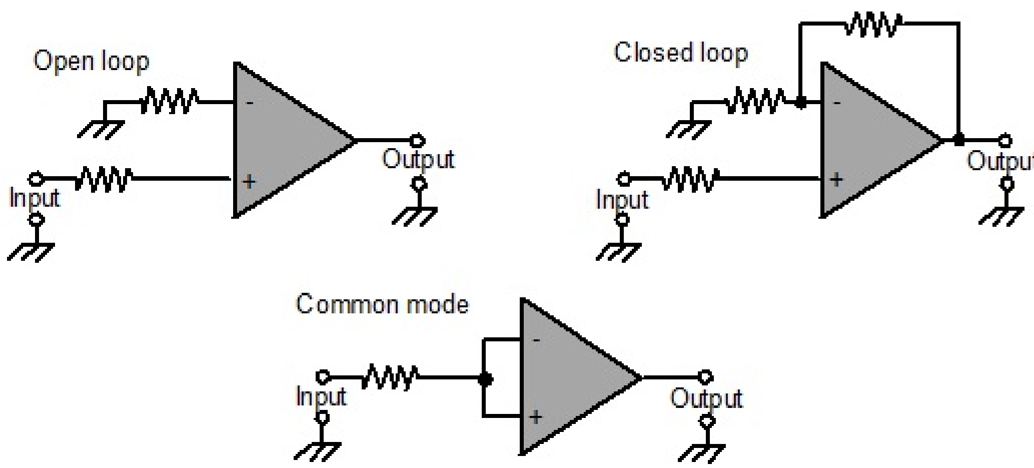

Figure 530.3 *For open-loop operation there is no external connection between output and input, where in the case of closed-loop operation there is a feedback connection. For the common mode connection the two inputs are connected together to the same source.*

An operational amplifier is a generic electronic amplifying device that can be used for a large number of different purposes depending upon how it is connected to a circuit. It is the selection of external circuit components that determines how the op-amp will function in a circuit. There are several basic operating characteristics that govern how the op-amp functions in a circuit. Assuming the limits of a particular op-amp are not exceeded, the basic principles of operation are as follows:

1. The amplification of the difference of voltage between the two input terminals is assumed to be infinite. This is not exactly true, but it is at least 100,000 to one.
2. The input impedance to the op-amp is infinite. It is not exactly infinite, but it is extremely high.
3. No current flows into the inputs of the op-amp. The internal impedance is so high it is assumed the input current to the device is zero. ($+I_{IN} = 0$ and $-I_{IN} = 0$)
4. The voltage at each input is assumed to be the same. ($-V_{IN} = +V_{IN}$) This means that whatever voltage is applied to one input terminal, the same voltage is assumed to be at the other input terminal. For open loop operation this condition cannot be maintained and when there is a difference in voltage between the input terminals the output will saturate which means it will be a little less than the supply voltage which is either +Vs or -Vs.
5. The output voltage of the op-amp will not exceed the supply voltage which is the value of +Vs or −Vs. When the output reaches either of these values it is considered to be in saturation. Prolonged operation at saturation may damage the op-amp.

When analyzing an op-amp in a circuit, always keep points 3 and 4 above in mind. Points 3 and 4 are the result of points 1 and 2. It is the function of the op-amp in the circuit to maintain points 3 and 4 unless the operating ability of the op-amp is exceeded.

Inverting Amplifier: The basic circuit for using an operational amplifier to amplify a voltage (E_S) is shown in Figure 530.4. In this case the voltage (E_S) to be amplified is supplied to the inverting input (−) of the op-amp through an input resistance (R_1). The non-inverting (+) input of the op-amp is connected to ground. In order for the op-amp to perform it's intended function, a feedback connection is required from the output to the inverting input (−) through a feedback resistor (R_F).

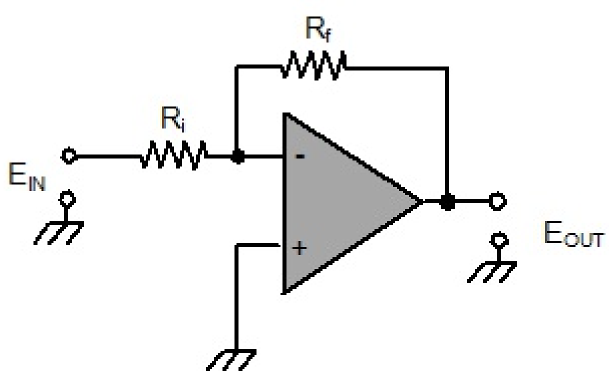

Figure 530.4 *When a voltage is supplied to the inverting input of an op-amp, the amplified output voltage will have a polarity that is opposite to the polarity of the input voltage.*

If the non-inverting input (+) of an op-amp is connected to ground, then the inverting input (−) will also be at ground potential. That means the voltage drop across the input resistor (R_1) will be the source voltage (E_S) and Ohm's law can be used to determine the current (I_1) through the input resistor (R_1). The current (I_1) through the input resistor (R_1) is determined using Equation 530.2.

$$I_1 = \frac{E_S}{R_1}$$ **Equation 530.2**

Since the current flow into the minus (−) op-amp terminal is assumed to be zero, than the current (I_1) through the input resistor (R_1) must also be the current through the feedback resistor (R_F). If this is true, then the voltage drop (E_F) across the feedback resistor is the product of the input current (I_1) and the value of the feedback resistor (R_F) as shown by Equation 530.3. Since the inverting input of the op-amp is at ground potential, then the output voltage is equal to the voltage drop across the feedback resistor. The sign will be negative and this is considered to be the inverting input of the op-amp. If the input voltage (E_S) is positive and the minus (−) input is at ground potential, the output voltage (E_O) must be negative.

$$E_O = E_F = -I_1 \times R_F$$ **Equation 530.3**

Amplifier voltage gain is the output voltage of the circuit (E_O) divided by the input voltage (E_S) as was described by Equation 530.1. Since the output voltage is the product of the input current (I_1) and the value of the input resistance (R_1), and the output voltage is the product of the same input current (I_1) and the feedback resistance (R_F), than voltage gain (A_V) can be expresses as the ratio of feedback resistance (R_F) over the input resistance (R_1) as shown by Equation 530.4.

$$A_V = \frac{-E_O}{E_S} = \frac{I_1 \times R_F}{I_1 \times R_1} = -\frac{R_F}{R_1}$$ **Equation 530.4**

Non- Inverting Amplifier: An operational amplifier can be connected so that the sign of the output voltage will be the same as the sign of the input voltage. Figure 530.5 shows an op-amp connected to a circuit so that the output voltage will have the same sign as the input voltage. This is accomplished by supplying the input voltage signal to the plus input (+) of the op-amp and grounding the minus input (−). In the case of the non-inverting op-amp connection, the source voltage (E_S) is supplied to the plus (+) input, and the minus input (−) is connected to ground through a input resistor (R_1). The feedback resistor (R_F) is connected between the minus input (−) and the op-amp output. If the input voltage (E_S) is supplied to the plus input (+) terminal, then the minus (−) terminal is also at the same voltage (E_S). The current (I_1) through the input resistor (R_1) can be determined using Ohm's law since the voltage drop across the input resistor (R_1) is the same voltage that is applied to both op-amp inputs. This current is determined the same as for the inverting op-amp connection using Equation 530.2. The current through the feedback resistor (R_F) must be the same as the current through the input resistor (R_1) since no current enters the op-amp minus terminal (−). The voltage drop across the feedback resistor (E_F) is the product of the current (I_1) through the input resistor (R_1) and the value of the feedback resistor (R_F). Since the input resistor (R_1) is connected to ground the voltage drop across the input resistor (E_1) and the voltage drop across the feedback resistor (E_F) will add to give the value of the output voltage (E_O) of the op-amp.

$$E_O = E_S + E_F = I_1 \times R_1 + I_1 \times R_F$$ **Equation 530.5**

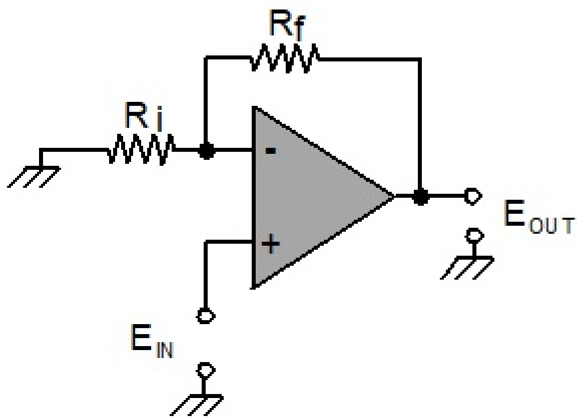

Figure 530.5 *By applying the input signal voltage to the non-inverting input of the op-amp, the output voltage has the same sign as the input voltage.*

The current flow through the feedback resistor is such that the voltage drop produced adds to the voltage drop across the input resistor and the polarity of the output voltage remains the same as the polarity of the input voltage. As a result the plus input is considered the non-inverting input of the op-amp.

The voltage gain (A_V) of the op-amp where the voltage signal is applied to the plus (+) input is also the output voltage (E_{out}) divided by the input (E_{in}) voltage. Note that E_{in} and E_s are the same voltage. The output voltage in this case is the input current (I_1) times the sum of the values of the input resistance (R_1) and the feedback resistance (R_F). The voltage gain will be slightly higher if the input signal is applied to the non-inverting input rather than the inverting input if the same values of input and feedback resistors are used. The formula for determining voltage gain (A_V) for a non-inverting op-amp circuit is given by Equation 530.6.

$$A_V = \frac{E_O}{E_S} = \frac{I_1 \times (R_1 + R_F)}{I_1 \times R_1} = \frac{R_1 + R_F}{R_1}$$ **Equation 530.6**

$$A_V = \frac{R_F + R_1}{R_1} = \frac{R_F}{R_1} + \frac{R_1}{R_1} = \frac{R_F}{R_1} + 1$$

Examples of Inverting and Non-inverting Op-Amp Circuits: Figure 530.6 shows a circuit where a dc voltage is applied to the inverting input of an op-amp and the non-inverting input is connected to ground. The value of the input resistance (R_1) is 2,200 Ω, and the value of the feedback resistor (R_F) is 27,000 Ω. Remember that the actual current flowing into both op-amp input terminals is assumed to be zero. Also remember that what voltage is at one input terminal is also at the other input terminal. Since the non-inverting input terminal is at ground potential, the inverting input terminal is also at ground potential. Figure 530.7 is the same circuit with the values of voltage and current at various points in the circuit shown. Note that one end of the 2.2 kΩ resistor is connected to +0.4 Vdc and the other end is at ground potential or 0.0 Vdc. Divide the 0.4 Vdc by 2,200 Ω to get a current flow (I_1) of 0.18×10^{-3} ampere or 0.18 mA. Since no current flows into the inverting input of the op-amp, this current must all flow through the 27 kΩ feedback resistor to produce a voltage drop (E_F) of 4.90 Vdc. Note the direction of current flow through the feedback resistor.

Since the inverting input is at ground potential, the voltage at the output terminal produced by the feedback resistor voltage drop must be less than ground potential or negative. The output voltage (E_O) in this case of an inverting op-amp is −4.90 Vdc.

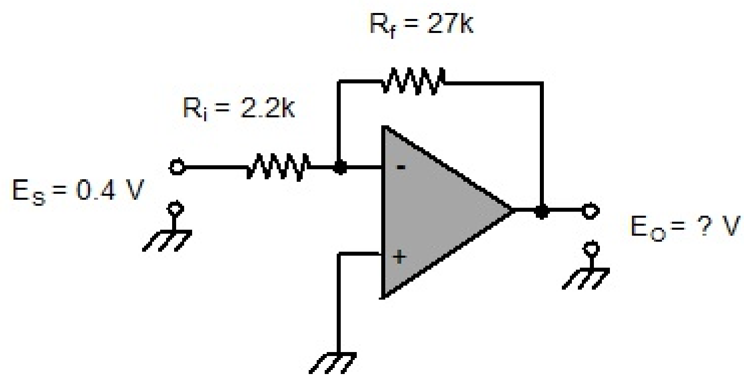

Figure 530.6 *A value of 0.4 vdc is applied to the inverting input of an op-amp through a 2.2k ohm resistor with feedback resistor value of 27k ohm.*

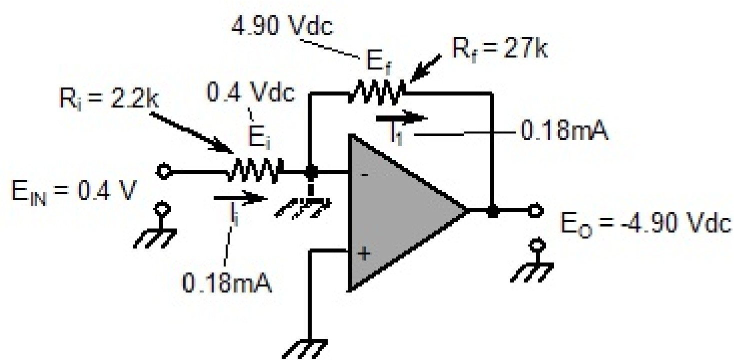

Figure 530.7 *This is the same inverting op-amp circuit as in Figure 530.6 but with the voltage and current shown at various points in the circuit.*

The voltage gain (A_V) of the inverting op-amp circuit is the output voltage (-4.90 Vdc) divided by the input voltage (0.40 Vdc) which gives a gain magnitude (A_V) of 12.25. Using Equation 530.4 the magnitude of the expected gain can be determined without knowing any of the voltages by dividing the value of the feedback resistor (27 kΩ) by the value of the input resistor (2.2kΩ) which in this case gives a voltage gain magnitude (A_V) of 12.27.

Next consider the case of a **non-inverting op-amp circuit** where the same value of input resistor and feedback resistor are used as for the previous example. Note that the input resistor and the feedback resistor remain connected to the inverting (−) input terminal while the voltage is applied to the non-inverting (+) input terminal. Also note that the input resistor has been connected to ground. The non-inverting op-amp circuit is shown in Figure 530.8. The 0.4 Vdc is applied to the non-inverting (+) input of the op-amp, and therefore, the voltage at the inverting input (−) will also be 0.4 Vdc. Since the other end of the 2.2 kΩ input resistor is connected to ground, the voltage across the input resistor (E_1) will be 0.4 Vdc. The current through the input resistor can be determine using Ohm's law by dividing 0.4 Vdc by 2,200 Ω to get a current flow (I_1) of 0.18×10^{-3} ampere or 0.18 mA. Voltages and current through the resistors is shown in Figure 530.9. Note the direction of current flow through the input resistor (R_1). This current is not coming from the op-amp input terminal, therefore, it must all be passing through the feedback resistor (R_F).

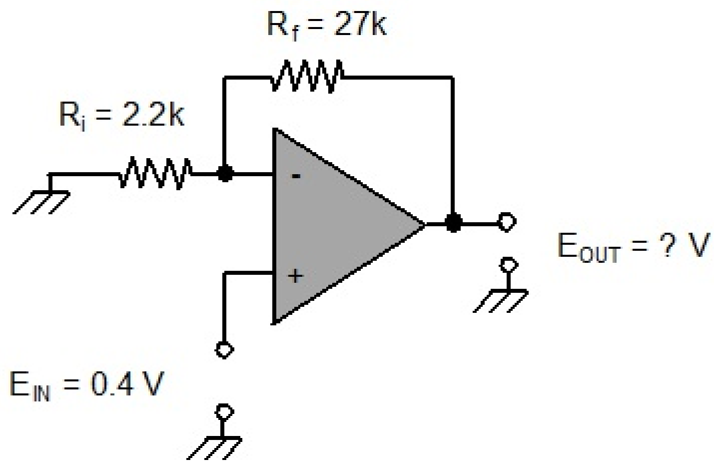

Figure 530.8 *A value of 0.4 Vdc is applied directly to the non-inverting input terminal of the op-amp with the input resistor and feedback resistor connected to the inverting input. One end of the input resistor is connected to ground.*

The output voltage from the non-inverting op-amp circuit will be the sum of the voltage drops across the input resistor (R_1) and across the feedback resistor (R_F). In this example the values are E_1 = 0.40 Vdc and E_F = 4.90 Vdc to give an output voltage (E_O) of 5.30 Vdc. The voltage gain (A_V) can be obtained by dividing the output voltage (5.30 Vdc) by the input voltage (0.40 Vdc) to get 13.25. Or the voltage gain (A_V) can be determined by using Equation 530.6 and dividing the sum of the values of the input and feedback resistors by the value of the input resistor to get a voltage gain (A_V) of 13.27.

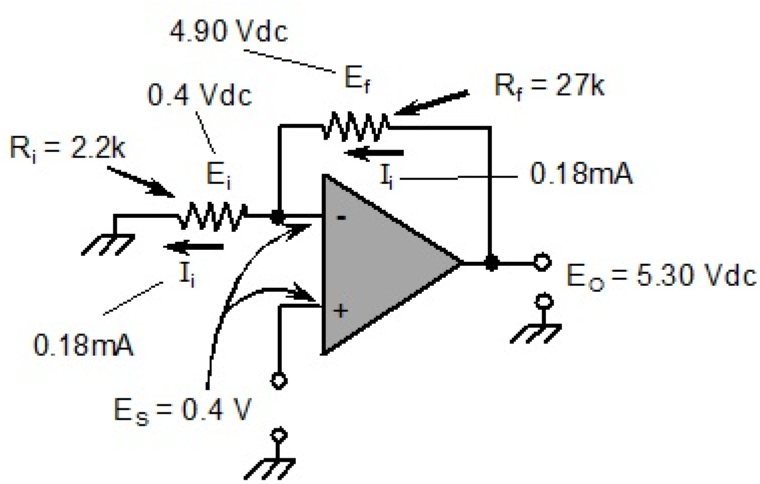

Figure 530.9 *This is the same as the non-inverting op-amp circuit of Figure 530.8 with voltages and current indicated for various points on the circuit.*

Summing Amplifier: This amplifier will actually produce an output that is the sum of multiple circuits supplied to a common point and then supplied to one input of an operational-amplifier. The output may be simply the sum of the input circuits or it may be amplified to a greater multiple. From the previous discussion of an inverting op-amp circuit, the current through the feedback resistor (R_F) is the sum of the currents through the input resistors R_1 and R_2 in the case of Figure 530.10. For the case of the circuit of Figure 530.10, both op-amp input terminals are at ground potential or zero volts. This means the current through R_1 is the input voltage E_{S1} divided by the value of R_1 and the current through R_2 is the input voltage E_{S2} divided by the value of R_2. These two currents combine and both flow through the feedback resistor. The output voltage in this case is an inverted version of the sum of the input voltages with a magnitude that is determined by multiplying the value of the feedback resistance (R_F) by the sum of the input currents ($I_{S1} = I_{S2}$). In the case of Figure 530.10 the output is -3 volts.

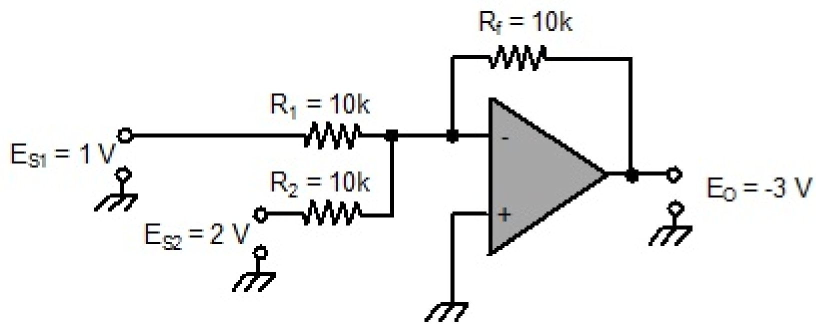

Figure 530.10 *Two voltage sources are supplied to the inverting input and the outp0ut voltage is the sum of the two input voltages. in this case the gain is unity (1.0) and the sign of the output is opposite to the sign of the input voltages.*

For the summing op-amp circuit of Figure 530.11 note that the values of the input resistors are chosen so that the current through the second resistor will draw two times as much current as the first. The third will draw two times as much current as the second. If the input to the op-amp circuit is a four bit binary circuit, the circuit is adding the input currents and converting a binary number of a decimal number at the output. This demonstrates another useful application of a summing op-amp circuit.

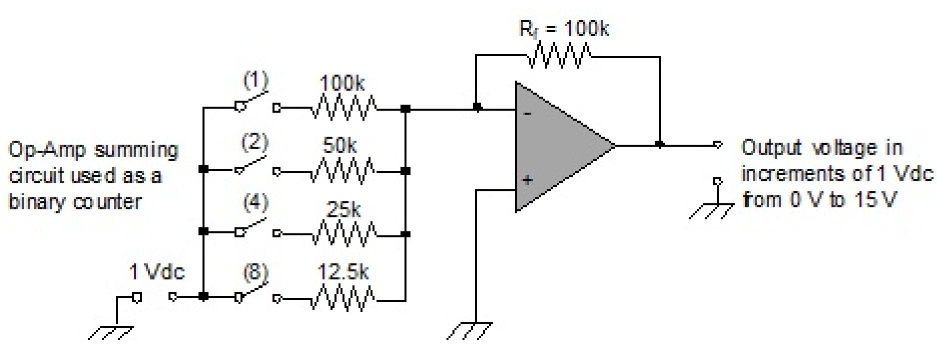

Figure 530.11 *The inputs to this op-amp summing circuit is set up to simulate a four bit binary input where the output is the decimal equivalent of the binary input. Each resistor is half the value of the previous resistor in order to double the current from the previous resistor.*

Differential Amplifier: An operational amplifier can be supplied a separate voltage source into each input so that the output will be the difference between the two input voltages. This is called a differential amplifier. A simple version of a differential amplifier is shown in Figure 530.12 where the input resistor R_1 and the feedback resistor R_F are chosen to give a gain of one (1.0). The example is also inverting so the output will be the opposite sign as the difference between the input voltages. Note in Figure 530.12 that there are two input voltages. For this example a value of +4 volts is supplied to the non-inverting input. In previous examples that input was connected to common or zero volts. If the non-inverting input is at +4 volts, the inverting input will also be at +4 volts. This means the voltage drop (E_2) across the input resistor (R_1) will be the difference between the voltage supplied to the input resistor (+6 volts) and the voltage at the inverting input (+4 volts). In this case the difference is 2 volts. The current through the input resistor (I1) is then 2 volts divided by the value of the input resistor which is 10 kΩ. The current in this case is 0.2 mA. Since the input current also flows through the feedback resistor the magnitude of the output voltage will be the product of the feedback current and the value of the feedback resistor (2 mA × 10 kΩ = 2 volts) which will be -2 volts. This op-amp is set up to invert the sign of the input voltage.

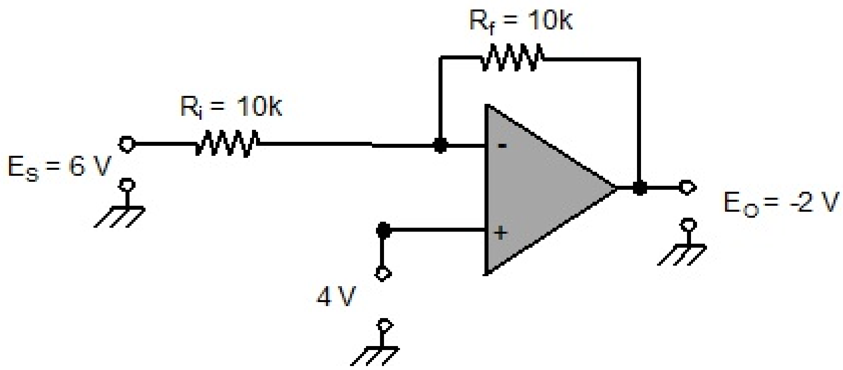

Figure 530.12 *Since 4 volts is supplied directly to the non-inverting input of the op-amp, the inverting input will also be at 4 volts. The voltage drop across the input resistor is then the difference between the voltage supplied to the input resistor and the voltage supplied to the non-inverting input. The input resistor and feedback resistor are chosen to give a unity gain.*

The operational amplifier circuit of Figure 530.13 is also a differential amplifier, but the voltage supplied to the non-inverting input (+) is not immediately obvious. The non-inverting input in this case is connected to the junction of two resistors forming a voltage divider. The voltage divider is connected to a 12 volt supply and the voltage applied to the non-inverting input is the voltage drop across the 1 k ohm resistor which in this case is 2 volts. Refer to Tech Note 511 for discussion of voltage dividers. If 2 volts is at the non-inverting input there will also be 2 volts at the inverting input. The voltage drop across the input resistor (R_1) will be the difference between the voltage applied to the input resistor (5 volts) and the voltage at the inverting input (2 volts). Remainder of on the calculation is the same as for the example of Figure 530.12 and the output will be -3 volts.

$$E_i = 6\text{ V} - 4\text{ V} = 2\text{ V}$$

$$I_i = \frac{2\text{ V}}{10\text{ k ohm}} = 0.0002\text{ A} = 0.2\text{ mA}$$

$$E_O = -E_F = -(I_F \times R_F) = -(0.0002\text{ A} \times 10\text{ k ohm}) = -2\text{ V}$$

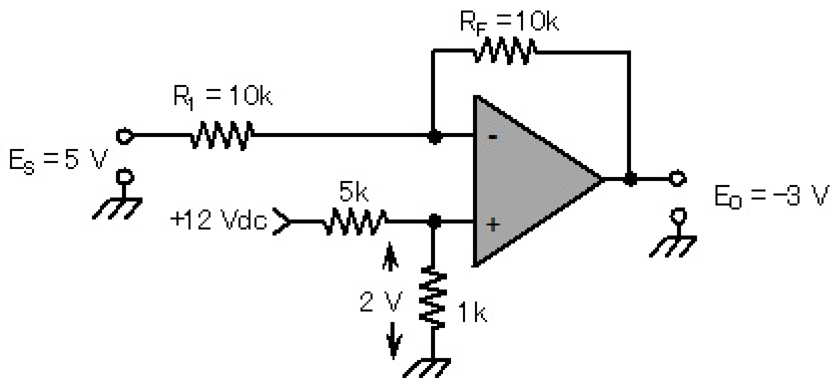

***Figure 530.13** For this differential amplifier the voltage supplied to the non-inverting input is determined by the voltage divider which is the 2 volts across the 1 kΩ resistor. Since this op-amp circuit has unity gain, the magnitude of the output voltage will be the difference between the voltage supplied to the input resistor and the voltage at the inverting input of the op-amp.*

Voltage Follower: Sometimes a sensor or some device providing an input voltage to a data acquisition system or electronic device can only provide a very weak signal. The device producing the voltage has a high impedance and lacks the ability to provide enough current to drive the next component. This is where an op-amp voltage follower can be helpful. Since the input impedance of an op-amp is very high it's inputs are very sensitive and draw negligible current from the source. The op-amp voltage follower has a high input impedance and a relatively low output impedance. It can act as a buffer between a weak source and the next component. An op-amp voltage follower is shown in Figure 530.14. Whatever voltage is supplied to the non-inverting input will also be at the inverting input. Since the inverting input is connected directly to the op-amp output, the same voltage will be at the output. The output voltage will be the same as the input voltage.

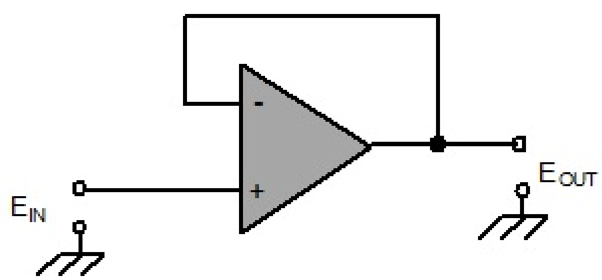

***Figure 530.14** An op-amp voltage follower acts as a high impedance buffer between a weak voltage source and the next electrical component. The output voltage will be the same as the input voltage.*

Integrating Amplifier: An operational amplifier can function as an integrator when the feedback connection consists of a capacitor. For a detailed discussion of capacitors in electrical circuits refer to Tech Note 512. Note in Figure 530.15 that the inverting input of the op-amp is connected to common or ground through an input resistor (R1). The feedback from the output is through a capacitor connected to the inverting input. The input voltage is supplied directly to the non-inverting input. Whatever voltage is supplied to the non-inverting input will also be at the inverting input. This voltage will set up a current flow to ground through the input resistor (R1). That same current must flow through the feedback capacitor. The op-amp output voltage must be sufficient to charge the capacitor at a rate necessary to supply the current through the input resistor. The output voltage of the op-amp circuit will be a constant times the time integral of the input voltage (ES) as described by Equation 530.7.

$$E_O = \frac{-1}{R_1 C} \int E_S dt$$ **Equation 530.7**

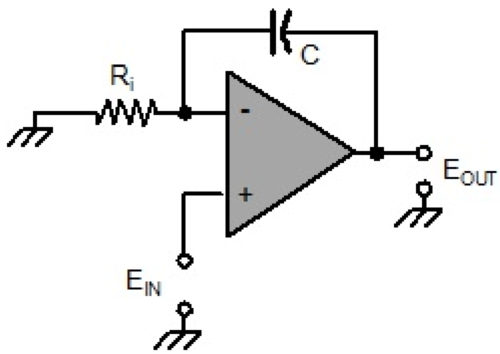

Figure 530.15 *By using a capacitor as the feedback component to the op-amp circuit inverting input and connecting the input resistor to ground, the output voltage will be the integral of the voltage applied to the non-inverting input.*

If the input voltage ES to the integrating circuit of Figure 530.15 is a positive step function the op-amp output will be a negative ramp voltage. The slope of the ramp will be negative and one over the product of the input resistance (R1) and the feedback capacitance (C). This ramp output where the magnitude is a function of time is very useful in instrumentation. An example of the input voltage to an op-amp integrator and the output ramp voltage is shown in Figure 530.16.

$$E_O = \frac{-1}{R_1 \times C} \times E_S \times t$$

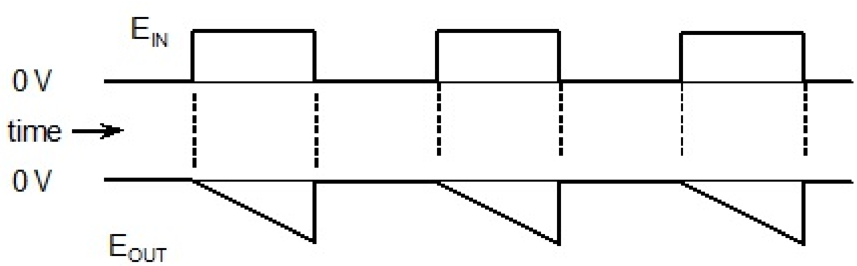

Figure 530.16 *If a positive step voltage is applied to the non-inverting input of the integrating op-amp circuit of Figure 530.15, the output will be a negative ramp.*

Differentiating Amplifier: By connecting the inverting input of an op-amp to ground through a capacitor and using a resistor as the feedback connection from the output to the inverting input, a circuit is created that will differentiate the input voltage applied to the non-inverting input. Such a circuit is shown in Figure 530.17. To understand this concept it may be helpful to review Tech Note 512 on capacitors. When a voltage is applied to the non-inverting input, that same voltage is also applied to the inverting input. A voltage will be set up across the capacitor and current will be drawn from the op-amp output to charge that capacitor to the level of voltage at the inverting input. That current will flow through the feedback resistor and set up a voltage across the feedback resistor. If a step voltage is applied to the non-inverting input of the op-amp differentiating circuit the current flow through the capacitor will be the value of the capacitor (C) times the time derivative of the input voltage. Current will flow quickly when the sept voltage is applied and current will decay to zero once the capacitor if fully charged. The result is a short duration voltage pulse at the output of the op-amp every time a step voltage is applied to the non-inverting input. This is a very useful operation where a triggering pulse is produced every time there is a step voltage change at the input to the op-amp circuit. An example of an op-amp differentiating circuit producing a series of output voltage pulses is shown in Figure 530.18.

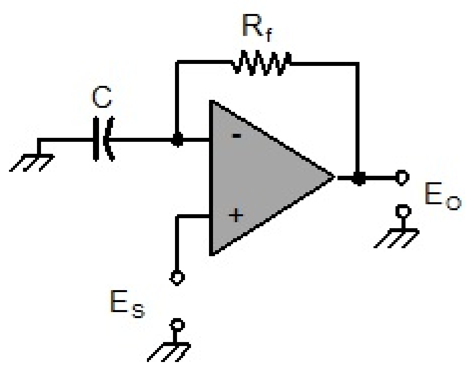

Figure 530.17 *An op-amp output voltage will be the derivative of the input voltage when the inverting input is connected to ground through a capacitor and a resistor is used as the feedback component. The input voltage is supplied to the non-inverting input.*

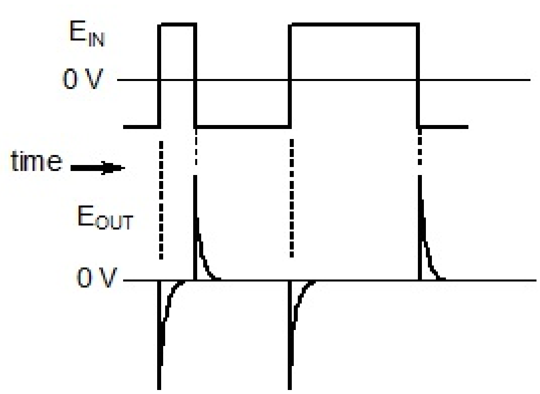

Figure 530.18 *When a step function is applied to the input of the differentiating op-amp circuit of Figure 530.17, the output will be a pulse voltage every time there is a step change in the input voltage. Such a circuit is useful in converting changes in voltage to triggering pulses.*

Comparator: An operational amplifier connected to form a comparator circuit is operated in the open loop mode which means there is no feedback connection from the output to an input. This means the op-amp will amplify any difference in voltage that develops between the input terminals. Even a slight difference in voltage between the input terminals will cause the op-amp to saturate meaning the output will either go to a positive maximum or a negative maximum. The maximum voltage will be slightly less than the voltage supplied to operate the op-amp. A basic comparator op-amp is shown in Figure 530.19 where the inverting input is connected to ground through an input resistor and an analog voltage is supplied to the non-inverting input. This comparator circuit will give a positive output voltage when the input voltage is positive and a negative output voltage when the input voltage is negative. This type of op-amp circuit can be used to convert an analog signal into a digital signal.

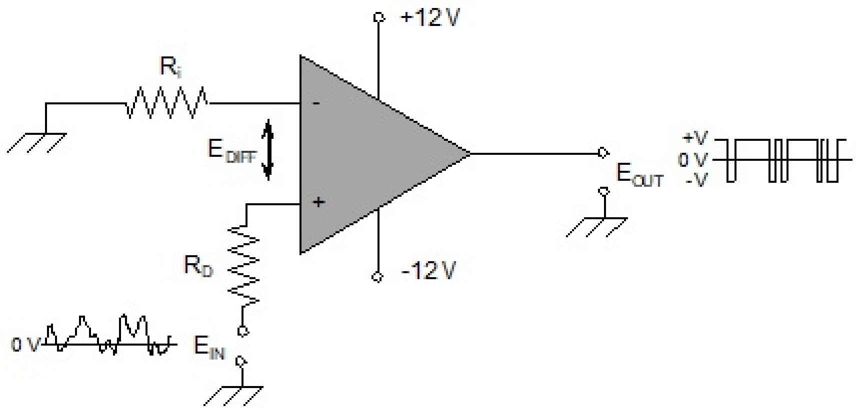

Figure 19. *This comparator uses zero as the reference and provides a square wave ouput that is either +12 volts or -12 volts. A varying signal is turned into a square wave.*

If an op-amp circuit is required to provide a positive or negative output with respect to some reference voltage other than zero, a variable voltage divider can be set up that has one end connected to the positive supply voltage and the other end connected to the negative supply voltage. By adjusting the tap point of the voltage divider the desired reference voltage can be set. Figure 530.20 shows such an op-amp comparator circuit with the reference input set a 2 volts. Note that the output is either positive maximum or negative maximum depending upon whether the analog input voltage is above or below the reference voltage.

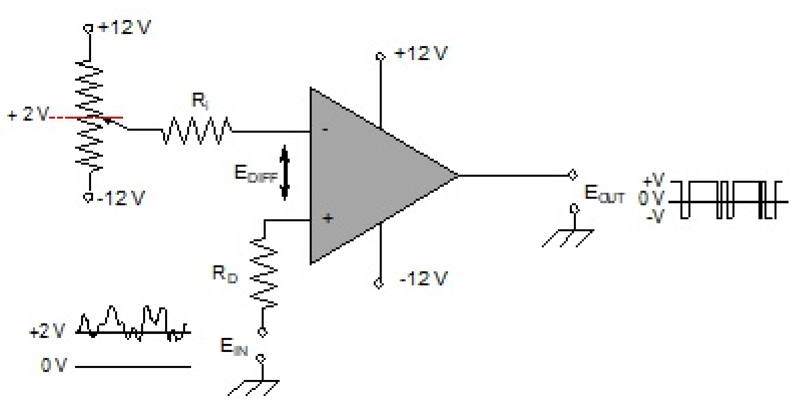

Figure 530.20. *The op-amp comparator is set up using a potentiometer to so the reference point can easily set at some positive or negative value other than zero.*

Output Offset: Even though for analysis purposes it is assumed that there is zero input current to the operational amplifier, that is not actually the case. In the case of the 741 op-amp there is an input current of about 80nA. This current is much too small to have any significant effect on the overall operation of the device, but sometimes it does result in a small dc offset at the output. The gain is determined by the input resistance to the minus input and the feedback resistance. The plus input often is connected directly to ground with no resistance. This is illustrated in Figure 530.21. The result is that the input current must travel through a resistance to get to the minus input where it does not travel through a resistance to get to the plus input. The result is that the plus input current may be as much as 20nA higher than the minus input current. This small current difference gets amplified and end up as a small bias voltage at the output. This means that instead of the output voltage being centered around zero volts it is centered around some small voltage that is to the negative or positive side of zero. Most of the time output offset is not an issue, but in the few cases where it is a problem the effect can easily be minimized by adding a resistor to the plus input. This resistor (R_D) is generally sized equal to the minus input resistor (R_1) and the feedback resistor (R_f) assumed to be in parallel. The size of this offset compensating resistor (R_D) is determined using Equation 530.8.

$$R_D = \frac{R_1 \times R_f}{R_1 + R_f}$$

Equation 530.8

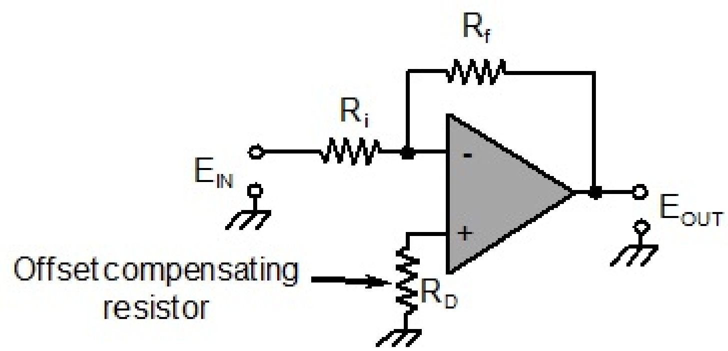

Figure 530.21 *The actual input current to the op-amp though small can result in a small dc offset at the output because the current at the plus and minus inputs experience different input resistance. A compensating resistor can be installed at the plus input to minimize the effect of this offset.*

Slew Rate: The slew rate of an operational amplifier is the maximum rate at which the output of an operational amplifier can change. The 741 and most other operational amplifiers have a compensating capacitor in their circuitry to prevent unwanted output voltage oscillations. When an input voltage change is applied to the op-amp this capacitor (about 30pF for a 741) must charge before a voltage is applied to the output. For a 741 op-amp charging occurs at an output voltage rate of about 0.5v/µs. This is called the slew rate. Some op-amps have a slew rate of up to 5v/µs. The slew rate means that if the input to the op-amp is a step change in voltage the output will be a sloped line not a vertical line. For many applications this slope is not a problem because frequency is low and amplification is also low. If the output must change from zero to 10 volts, it will take the 741 op-amp 20µs to accomplish the task. Slew rate for a step change input voltage is illustrated in Figure 530.22.

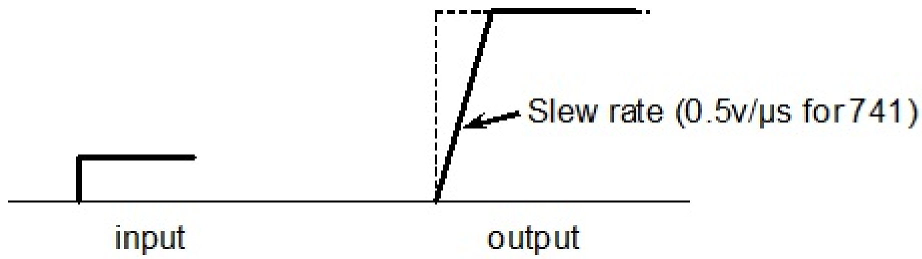

Figure 530.22 *When the input to an op-amp is a step voltage, the charging of the internal capacitor results in a slope to the output voltage which for the 741 op-amp is about 0.5 v/μs.*

If the amplified output wave form is to be a good representation of the input wave form, the rate of change of the input signal (frequency) must be slow enough that the op-amp has time to properly respond to the signal. In the case of a sine wave input signal, to prevent distortion of the output wave form the slew rate of the op-amp must be not greater than the slope of sine wave at the moment it crosses the zero voltage line. This is illustrated in Figure 530.23. Consider two sine waves with the same peak voltage magnitude, but different frequencies. The higher the frequency the greater will be the slope of the wave form at the zero crossing. Note that in the case of the lower frequency the slope of the wave form at the zero crossing is less than the slew rate of the op-amp. For the wave form with the higher frequency the slew rate of the op-amp is less than the slope of the wave form at the zero crossing. For this higher frequency there will begin to be distortion of the output wave form.

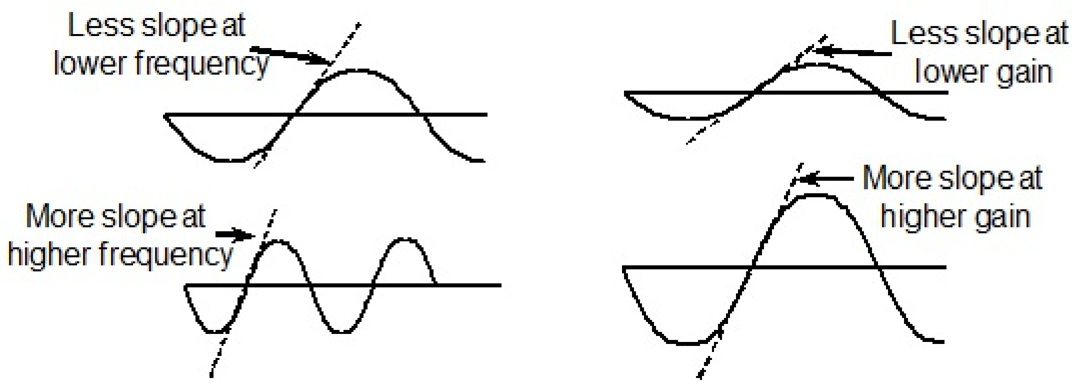

Figure 530.23 *Frequency and amplitude will determine the slope of the wave form at zero crossing which if greater than the slew rate of the op-amp will result in output voltage wave form distortion.*

The slope of a sine wave at the zero crossing is also affected by the peak magnitude of the sine wave. In Figure 530.20 the zero crossing sine wave slope is compared for the same frequency but with a different peak magnitude. When the peak magnitude is low, the zero crossing sine wave slope is less than the slew rate of the op-amp. In the case with the high peak magnitude the slew rate is less than the zero crossing slope of the sine wave. The end result of slew rate is that there is a maximum amplification and frequency for the op-amp beyond which the output will become distorted with respect to the input wave form. In the case of a sine wave input, the output will be a triangular wave form with a reduced maximum amplitude when the frequency and or the magnitude become too high for the slew rate of the op-amp. This is illustrated in Figure 530.24.

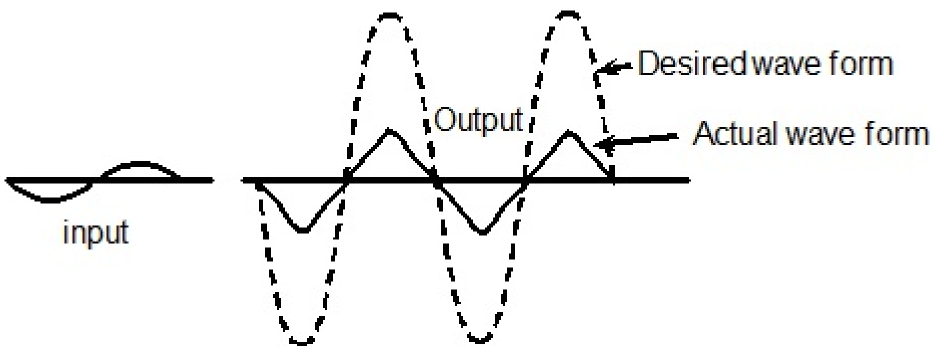

Figure 530.24 *When the frequency and level of amplification is too great for the slew rate of the op-amp, the amplified output for a sine wave input approaches a triangular wave form with a peak magnitude that is severely attenuated.*

Output amplitude if reduced will allow the op-amp to handle higher frequencies. Rather than one op-amp performing the entire job of amplification, several op-amps can be cascaded in series. Amplification is discussed in detail in Tech Note 502. In the case of a sine wave input signal, the maximum recommended frequency can be determined by dividing the op-amp slew rate (S_R) by two pi (2π) times the peak output voltage (V_P) as in Equation 530.9.

$$f_{\max} = \frac{S_R}{2\pi V_p}$$ **Equation 530.9**

A more convenient method of determining the maximum recommended frequency for the desired level of amplification of an op-amp is to examine a log-log plot of amplification verses frequency for the particular op-amp involved. For the 741 op-amp with a slew rate of 0.5v/μs the maximum recommended amplification decreases at a rate of 20dB per frequency decade. This is illustrated with the following Bode Plot for a 741 op-amp, Figure 530.22. It is recommended that the reader review Tech Note 502 if not familiar with gain in dB, power gain and voltage gain. Bode Plots have power gain as the vertical axis which is the square of the voltage gain. Figure 530.25 gives gain both is voltage gain and power gain as dB. Some Bode Plots only give gain as power gain in dB. If voltage gain (A_v) is desired (an it usually is desired) the power gain (dB) can be converted to voltage gain using Equation 530.10.

$$A_v = 10^{\frac{dB}{20}}$$ **Equation 530.10**

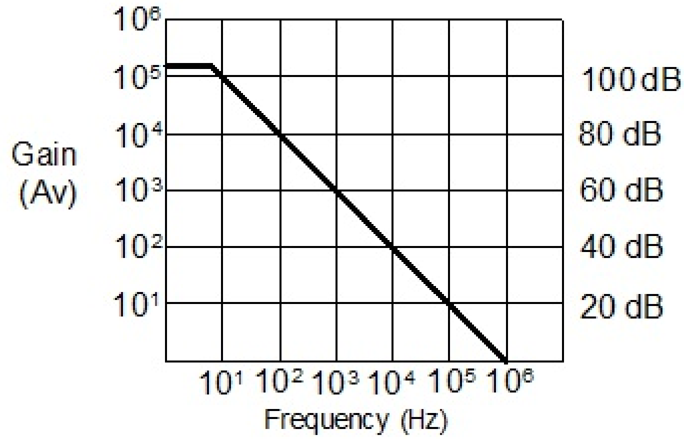

Figure 530.25 *Bode Plot for the gain verses frequency response of a 741 op-amp to prevent distortion or attenuation of the amplified output wave from. The gain in dB is the power gain and the numeric gain (A_v) is the output over input voltage gain.*

To determine the maximum recommended gain an op-amp can provide without distortion go to the Bode diagram for the op-amp and find the maximum frequency rate. Project straight up from the maximum frequency to the diagonal maximum amplification line. Then project horizontally to the left to find the maximum amplification. If you need the maximum frequency rate given the amplification needed, just reverse the process. An example is shown in Figure 530.26.

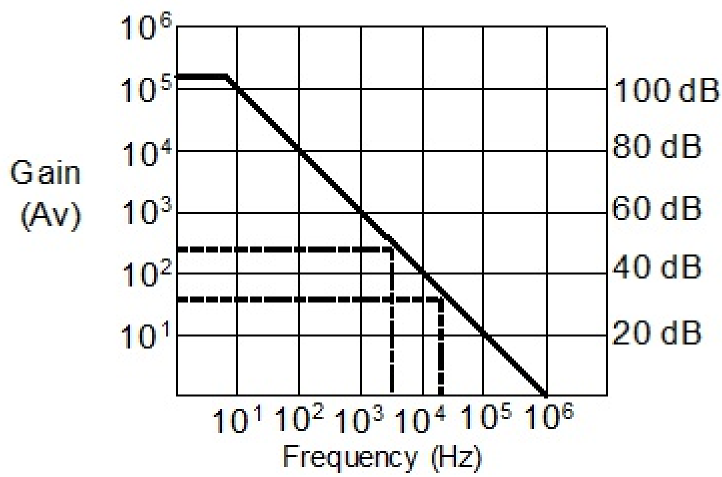

Figure 530.26 *Given the maximum frequency the maximum amplification can be determined by using the Bode diagram provided for the op-amp.*

Figure 530.27. *One of the first op-amps produced was the 741. The components are shown in the schematic diagram. In the middle of this diagram there is a capacitor that determines the frequency rate. It is an RC timing circuit. The greater the amplification that is required the longer it takes to charge this capacitor.*