Basic Op Amps

The operational amplifier (Op Amp) is a staple item in electronic circuits and is a building block that often is one of the main components in linear audio and video circuitry. The op amp is basically a high gain amplifier that is used in conjunction with feedback networks to make up a circuit whose properties are determined by linear passive components, such as resistors, capacitors, inductors, as well as nonlinear components (diodes, varistors, thermistors, etc). The term "operational amplifier" comes from the use of these devices in analog computers that were used decades ago to perform mathematical operations (addition, multiplication, differentiation, integration, summation, etc) on input quantities. The term has stuck and is still used, even though analog computers have largely departed the scene, having been replaced by digital computers long ago. The operational amplifier of today is a sophisticated device, being composed of many transistors, diodes, and resistors, all in a chip, and packaged in various configurations. There are thousands of types of op amps available, from flea powered microwatt units to units capable of handling a few hundred watts of power, from a few cents to many dollars in cost. As you may imagine, the specs and performance requirements, as well as reliability, temperature range, and packaging, all affect cost. Op amps that can do many ordinary jobs very well are available for under 50 cents, owing to low cost plastic packages and large scale integration, and high volume production. Technologies commonly used are bipolar, FET, CMOS and combinations. Some large or high power op amps are made using monolithic fabrication methods.

From a circuit viewpoint, for the purposes of explanation, an ideal amplifier is used to represent an op amp. An ideal amplifier has the following properties: Infinite forward gain, bandwidth and input impedance, with zero output impedance, noise voltage, DC offset, bias currents, and reverse gain. See Fig 1. In practice, all op amps have some bias current that flows in the inputs, this being almost negligible for JFET and CMOS types, but more significant in bipolar types. This current must be considered in high impedance circuits, and in DC and instrumentation amplifiers, and in circuits that must operate over a wide temperature range. In addition, even if you were to short the op amp inputs together you may not get zero output voltage, but some random DC level. This DC voltage can be considered as an equivalent DC input offset voltage present at the input. DC offset can also be produced from equal input bias currents flowing through unequal resistances in the inverting and noninverting input circuits. This will produce a DC input voltage differential at the input. Some op amps have external pins to which a potentiometer can be connected to balance out or otherwise cancel this voltage, bringing the DC output to zero under zero signal input conditions. These are widely used in instrumentation amplifiers and related applications where nulling or zero adjustments are required. All amplifiers generate some noise, which is due to thermal and semiconductor junction effects, and can be considered as an equivalent input noise voltage. Amplifiers are available with low noise characteristics for those applications where noise must be kept to a minimum. A real world op amp has a lot

of gain (>1000X voltage gain) and a fairly high input impedance (>100K). Generally there are two inputs shown, an inverting and a non inverting input, and one output referenced to ground (but not always, differential outputs are sometimes used in certain applications). One of the inputs may be grounded in many common applications where a single ended signal source is present. This is a common situation. There are limitations on the DC levels allowable on the inputs, and limitations on the available output voltage swing. Op amps are available that allow a full output voltage swing between the positive (Vcc) supply and negative (Vdd) supply. These are sometimes referrred to as “rail to rail” capable. In addition, if the exact same voltage is present on the inverting and non-inverting inputs, ideally the output voltage should be zero. This is not always so, and the degree of imperfection is called the common mode rejection ratio. This is usually 60 dB or better, with 70-80 dB as a minimum. Note that this may vary with input voltage levels to some degree. Also, variations of power supply voltage may show up as equivalent input signals. The degree to which the op amp rejects this is called the supply voltage rejection ratio. It is usually better than 60 dB and typically 70 to 80 dB or better. After all, nothing is perfect in life.

Op amp power supply connections are sometimes shown in diagrams, especially if decoupling capacitors and resistors are necessary, but more often shown elsewhere in the schematic, as they play no part in the primary circuit function other than to power the amplifier. Many general-purpose op amp chips have two or four separate operational amplifiers in one package, with common power supply connections. In practice the ideal amplifier criteria requirements are met only approximately, but as will be shown, close enough for most purposes. Practically, an op amp will have a gain of 10,000 or more, an input impedance of megohms, and a 3 dB bandwidth of several tens of hertz or more. If an amplifier has a 3 dB bandwidth of 40 Hz and a gain of 100,000 times, this is a gain bandwidth product of 4 million hertz, or 4 MHz. (40 x 100,000). It is advantageous in many feedback applications to have the gain falling at 6 dB per octave or 20 dB per decade at frequencies beyond the corner frequency (that frequency at which the amplifier gain has fallen 3 dB or 70.7 percent of its DC value). Since the op amp is used in mainly in feedback circuits having much lower closed loop gain, these performance figures are good enough in many cases. In fact, even a single high gain (100X) common emitter transistor amplifier stage can be treated as an op amp if feedback is employed, with surprisingly little error. In many cases a single transistor will work almost as well as a more expensive op amp device. One example is a simple audio amplifier stage from which a moderate gain (5-20X) is required. This will be shown in an example later.

One of the most popular op amps of all time is the venerable LM741, its dual version LM747 and their many descendents. The JFET input TLO8X series is also very popular, coming in single (TLO81), double (TLO82) and quadruple (TLO84) units. The TLO81 and TLO82 come in 8 pin DIP packages, while the TLO84 comes in a 14-pin DIP package. These op amps operate well from 5 to 12 volt experimenter supplies, and require both a plus and a minus supply. These are also cheap and

widely available. Other general purpose types are the LM324 and LM1458 (bipolar) and LM3900, and all their variations and flavors. There are many others, but these types mentioned are easily obtained by the hobbyist wishing to experiment with them, and are cheap and in plentiful supply. Many manufacturers make them, so obsolescence should not be a problem for a long time. We will use the TLO8X series for circuit examples, as they are general purpose JFET types, allowing the use of higher resistance values and therefore smaller capacitor values, which is often more convienient from a design standpoint. The TLO8X series have an open loop (no feedback used, the full gain the amp can deliver) voltage gain of over 10000 and having JFET inputs, an input impedance of a million megohms. The gain bandwidth product (obtained by measuring frequency where gain falls to unity) is rated at at 4 MHz for the TLO8X series. Op amps are available with gain bandwidth products to several hundred MHz and even higher, and these are used in video and RF applications.

A word first to the nitpickers. (You know who you are). The exact explanation of op amp and feedback principles requires the use of network equations that while not difficult, can contain several terms and fractional expressions, leading to rather messy algebraic manipulation of these terms. This can confuse, intimidate, and scare away many readers. It is easy to get wrapped up in the math and then spend way too much time trying to figure out what is being done or what is meant. If you have ever studied algebra or calculus you will surely have been through this. You also lose sight of the intended goal and the subject being discussed. What was to be a discussion of circuits turns into a time wasting digression, usually a tedious and frustrating algebra exercise. This proves little except that you might be a complete bonehead because you do not immediately see the "obvious" meaning of these complex expressions. (Often the authors needed several hours correctly deriving them the first time, or maybe just copied them from elsewhere so as to impress readers and look like a genius). This will be avoided. We are going to make some simplifying approximations to get rid of the second and higher order stuff. This can be studied later after some basics are covered. Simplified approximations will still yield results accurate to a percent or so, and avoid confusing trivial details which, while interesting, have dubious practical consequences for things the experimenter will get involved with. Even five or ten percent accuracy is good enough in many cases, if you are not doing instrumentation work.

See Fig 2 for the following discussion. Fig 2 is a basic op amp application, a simple gain stage. Amplifier A is a basic op amp with a very high input resistance. R1 and R2 make up a feedback network, a simple voltage divider. The voltage at the junction of R1 and R2 is R2/(R1+R2). In feedback amplifier work, the "gain" of the feedback network is commonly designated by the Greek letter β (beta). This "gain" is the ratio of output voltage to input voltage and is usually less than one, and in many cases much smaller than one. It may often be a complex number, having both real and imaginary components, as practical feedback networks consist of resistors, capacitors, and sometimes inductors, and therefore have defined magnitude and

phase characteristics. It may also be nonlinear, using diodes, varistors, and other nonlinear devices. For the following discussions we will limit β to being linear and a purely real number, as this simplifies the math. Most experimenter circuits will not involve complex feedback networks, but the reader should be made aware that this is not always the case. Referring to Fig 2, the output voltage from the op amp is Vout = A x e in. A is the gain of the amplifier (generally 10000 X or more). Since in a practical op amp circuit powered by 5 to 15 volt supplies, Vout will be at most ± 5 to ±15 volts. Therefore e in will be this voltage, V out divided by the gain of the op amp (10000 or more). What this says is that e in is very, very small, in the millivolt or microvolt range. However, Vin from the outside world is the input voltage we are applying to the circuit, and this could be a volt or more, such as a line level audio signal, etc., while e in is very much smaller. What really is happening is that the circuit adjusts itself so that the ratio of Vout to e in equals the gain of the amplifier, which we will take as 10000. This requires Vout to be such that the portion of Vout at the junction of feedback network R1 and R2 exactly equals V in minus e in, so the total voltage difference across the inverting and noninverting outputs is e in. This occurs when:

Equation 1: $$\text{Vout}\ \{ R2(R1+R2)\} = \text{V in} - \text{e in}$$

But: V out = A x e in, where A is gain of amplifier. Define R2(R1+R2) as β, the feedback factor equal to the ratio of R2 to R1 and R2. For example if R1 = 9K and R2 = 1 K then β equals (1) / (9+1) or 1/10, or 0.1. This means that one tenth the output voltage is being fed back via the feedback network. By substituting the previously mentioned equalities in Equation 1:

Equation 2: $$A \times \text{e in}\ \{\beta\} = \text{V in} - \text{e in}$$

If you add like quantities to both sides of the equation it still is valid. Therefore if you add e in to both sides of the equation:

Equation 3: $$A \times \text{e in}\ \{\beta\} + \text{e in} = \text{V in}$$

Noting that e in is common to both terms in the left side of Equation 3 it can be factored out:

Equation 4: $$\text{e in} \times [A \times \beta + 1\} = \text{V in}$$

But e in must equal V out divided by A the gain of the op amp so that :

Equation 5: $$(\text{V out}/A)\ \{A \times \beta + 1\} = \text{V in}$$

The effective circuit gain is what we want, i.e. the ratio of V out to V in. We are inputting a signal represented by V in and would like to know the magnitude of V out that will result. If both sides of the equation 5 are first multiplied by A, then

divided by V in, and then finally by the the entire quantity in brackets { A x β + 1} we get an equation that expresses the ratio of Vout to Vin as a function of A , the op amp gain, and β, the feedback factor:

Equation 6: $$\text{Gain} = (V_{out}/V_{in}) = A/(A \times \beta + 1)$$

A x β means the product of these two quantities. Since the order of multiplication does not change the product, A x β = β x A = βA (Realizing the x stands for multiplication we can get rid of it). Also, the order of addition of two quantities does not affect the sum. Then Equation 6 appears as

Equation 7: $$\text{Gain} = A/(1+ \beta A)$$

This is a very important equation when working with op amps or most any feedback amplifier. It applies to a lot of things. The ratio of A to (1+βA) yields not only the gain, but affects other circuit performance factors as well. In a real world case, if A is 10000 and if β is 0.01 or more (it generally is), note that the product of β and A will be greater than 100. Then, a very nice simplifying approximation can be made. It is true that for any quantity X much larger than 1 (10 times or more would qualify) 1 plus X approximately equals X with an error of around 1/X times 100 percent. As an example if X were 10 then 10 ≈ 11 approximately with an error of 1/10 x 100 percent, or ten percent, which is obviously true. If X were 100, then (1+ 100) ≈ 100 with an error of 1/100 x 100 percent, or 1 percent. Note that in our case where A is 10000 and β is 0.01, the product βA is 100 and 1+ βA ≈ βA within one percent. Therefore if in any case βA >>1 we can rewrite equation 7 as:

Equation 8: $$\text{Gain} = A/(1+ \beta A) \approx A/(\beta A) = 1/\beta$$

(Note that A is common to numerator and denominator and can be cancelled out.)

What this says is, IF THE PRODUCT OF THE OP AMP GAIN (A) AND THE FEEDBACK FACTOR (β) IS MUCH LARGER THAN ONE, THE VALUE OF β DETERMINES THE OVERALL GAIN OF THE OP AMP CIRCUIT. The product of βA is called the open loop gain. The overall circuit gain with the feedback loop in place is called the closed loop gain. The beauty of this concept is that, GIVEN A LARGE ENOUGH VALUE OF (A), THE GAIN AND OTHER PARAMETERS OF A FEEDBACK AMPLIFIER, OR ANY OTHER SYSTEM EMPLOYING FEEDBACK, CAN BE CLOSELY CONTROLLED BY A NETWORK OF COMPONENTS THAT CAN BE SPECIFIED TO ANY DEGREE OF ACCURACY NEEDED. The value of A, component tolerances, drift, noise, temperature effects, and all things affecting A become less and less relevant to the circuit performance as the value of βA increases

We do not mean to pull a "snow job" here, but you should spend whatever time is needed to understand these concepts, as they are the "heart" of the theory and once understood, op amp circuits will be a breeze to work with.

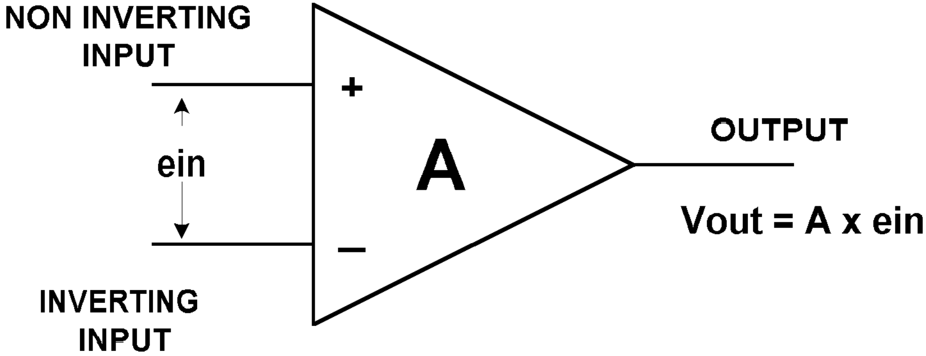
Note that in a practical op amp circuit e in is very small, since the value of A is at least several thousand. Since e in is that voltage appearing across the input of the op amp (See Fig 3) if one input terminal of the op amp is connected to ground or has zero signal on it, the other input will also be very close to ground. Note again that e in is at most a few millivolts in practical circuits. Under all signal levels this will be true, provided the op amp is not driven into saturation or other region where toe gain falls to a low value. This gives rise to the term "virtual ground" since the op amp input is always very close in voltage to ground. The input terminal in many applications is the inverting input, with the non inverting input grounded or connected to a source of zero signal. Additionally, the amplifier itself has a high input impedance, often measured in megohms. The input current to the op amp itself is negligible and zero for all practical purposes. Therefore, in Fig 3, the input current I in in R1, equal to Vin/R1, has to equal the feedback current in R2, equalling Vout/R2 Since these currents entering and leaving any junction must equal zero (Kirchoffs current law, the law of continuity, and plain common sense), it follows that the positive current flowing in R1 must be cancelled by a current flowing in R2, except for a tiny current flowing into the op amp, which is zero for all practical purposes. The only way this can happen is if Vout equals –Vin (R2/R1). Note that there is an inversion in phase, since the currents must cancel. Note that the voltage gain is simply the ratio of R2 to R1. The two resistors set the gain. If multiple inputs are desired, extra input resistors and input sources can be added as in Fig 4. The output voltage is given as

V out = -[Vin 1 x Rf/R1 + Vin2 x Rf/R2 + Vin3 x Rf/R3 + ------- + VinN x Rf/RN]

This is called a summing amplifier (See Fig. 4) and the junction of all the resistors at the input is called the summing junction. Note that since the input of the amplifier is a "virtual ground" there is almost complete isolation between all the input sources. This circuit makes an excellent audio mixer with virtually no crosstalk effects. By varying the values of the input resistors R1 thru RN, different gains can be obtained for the various inputs.

Note that as far as AC signals are concerned, a high gain single transistor amplifier circuit can approximate the behavior of an op amp in these circuits if the collector is considered the output, the base the inverting input, and the emitter the noninverting input. Naturally DC biasing arrangements are needed and there are DC level considerations, but the principles of feedback still apply. See Fig 5.

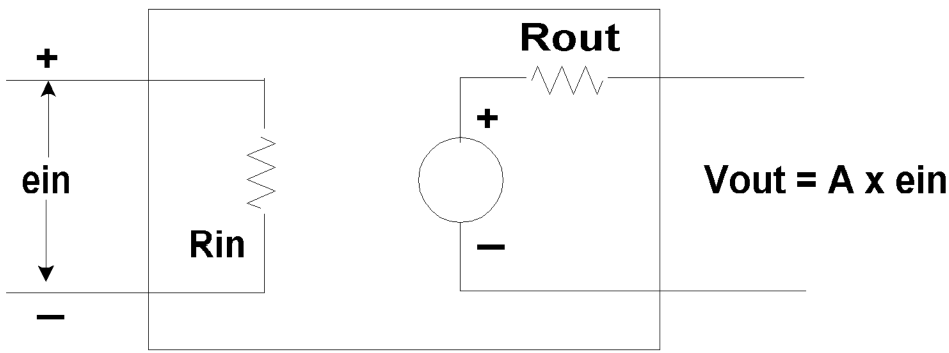
Several Op amp circuits will be discussed in the next part of this article.



ein = input voltage

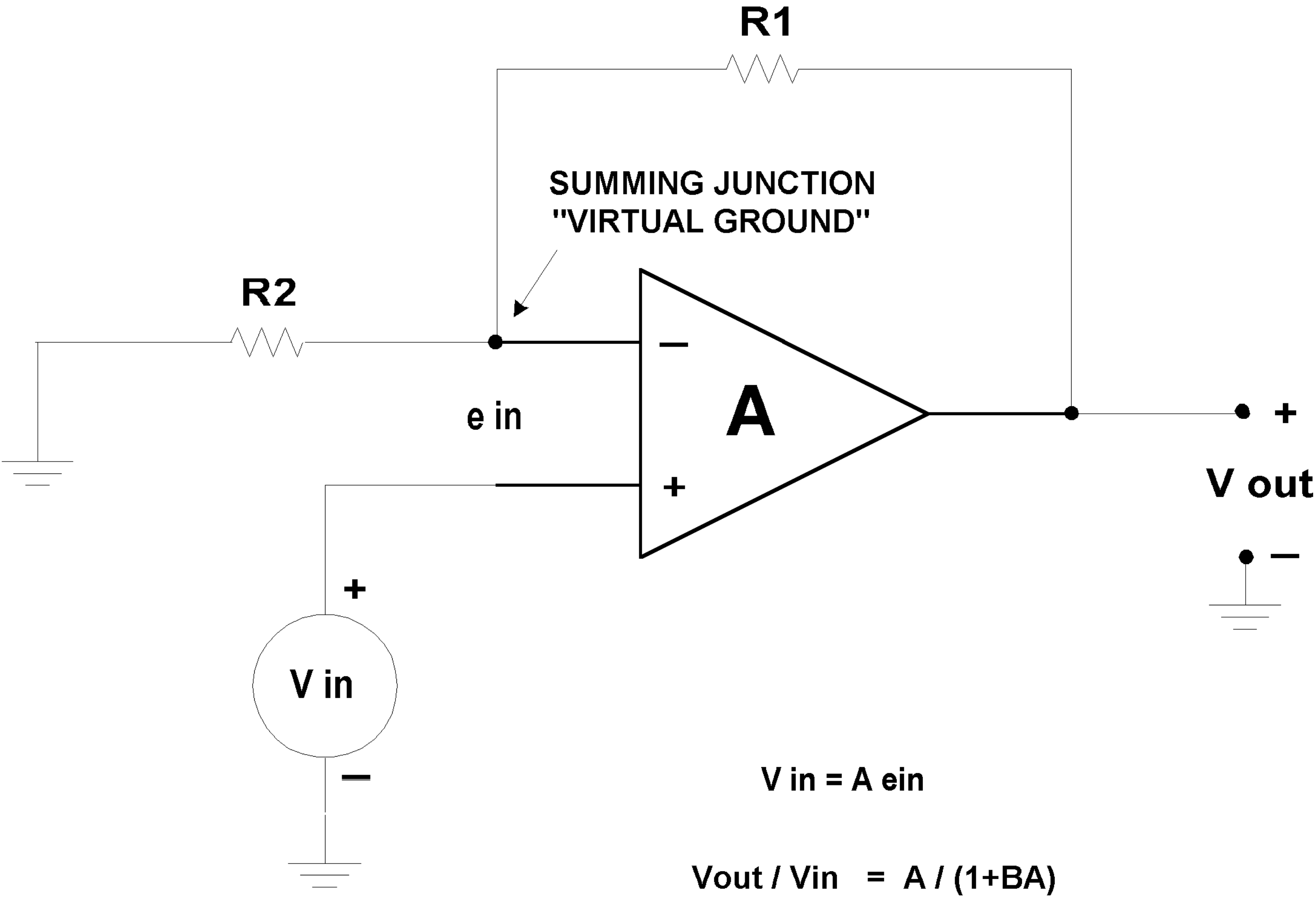
A = Amplifier gain

Vout = output voltage



Equivalent Circuit

Fig. 1
BASIC OPERATIONAL AMPLIFIER



$$V_{in} = A\, e_{in}$$

$$V_{out} / V_{in} = A / (1+BA)$$

$$B = R2 / (R1 + R2)$$

FIG 2
BASIC OP AMP VOLTAGE AMPLIFIER
NONINVERTING CONFIGURATION

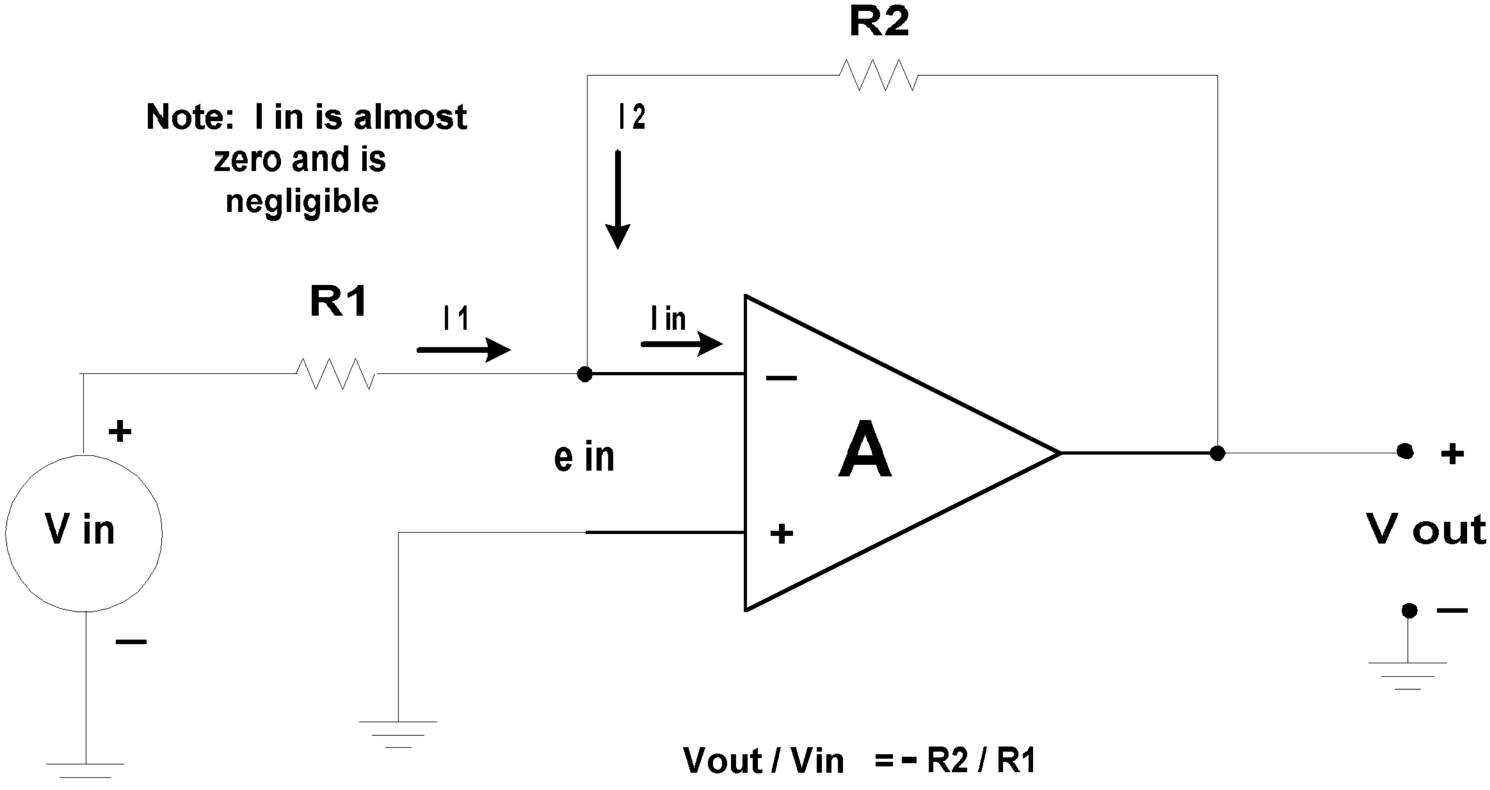
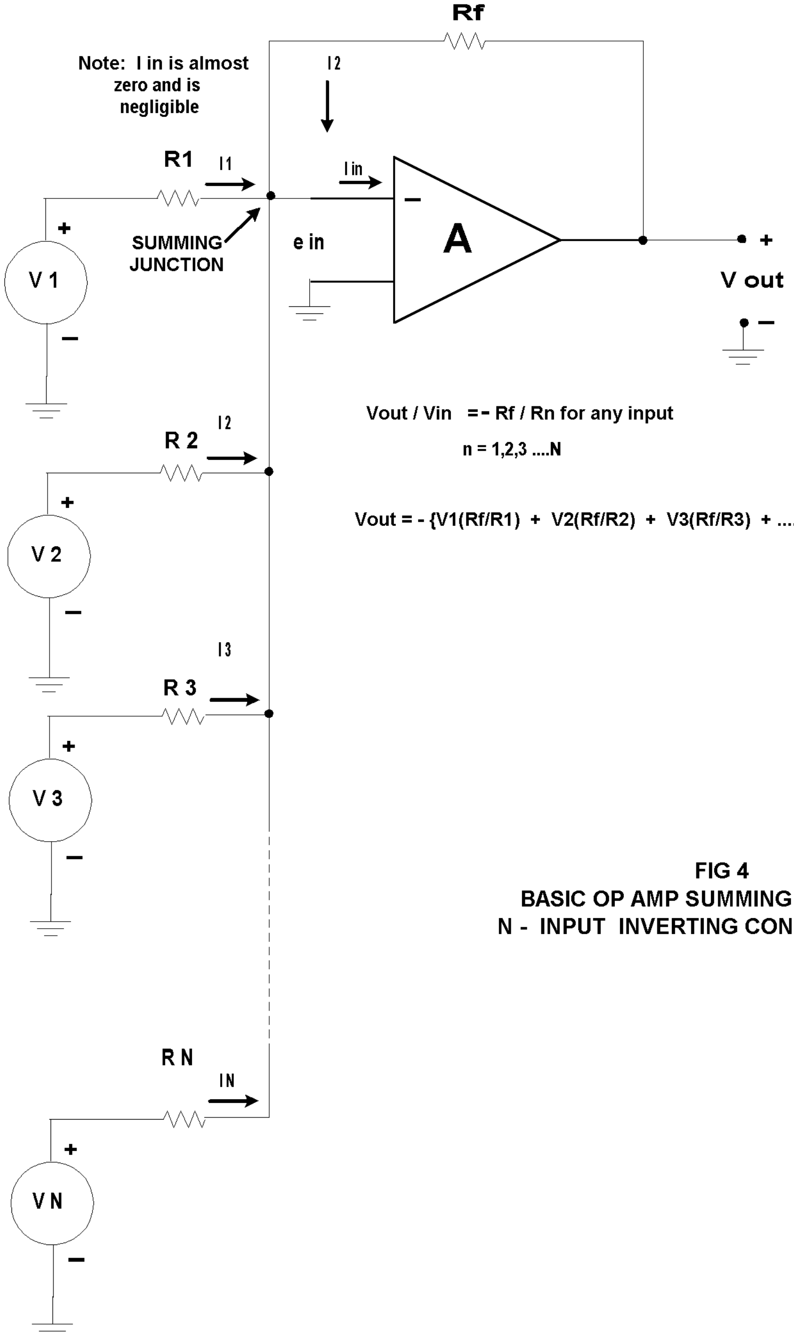


FIG 3
BASIC OP AMP VOLTAGE AMPLIFIER
INVERTING CONFIGURATION

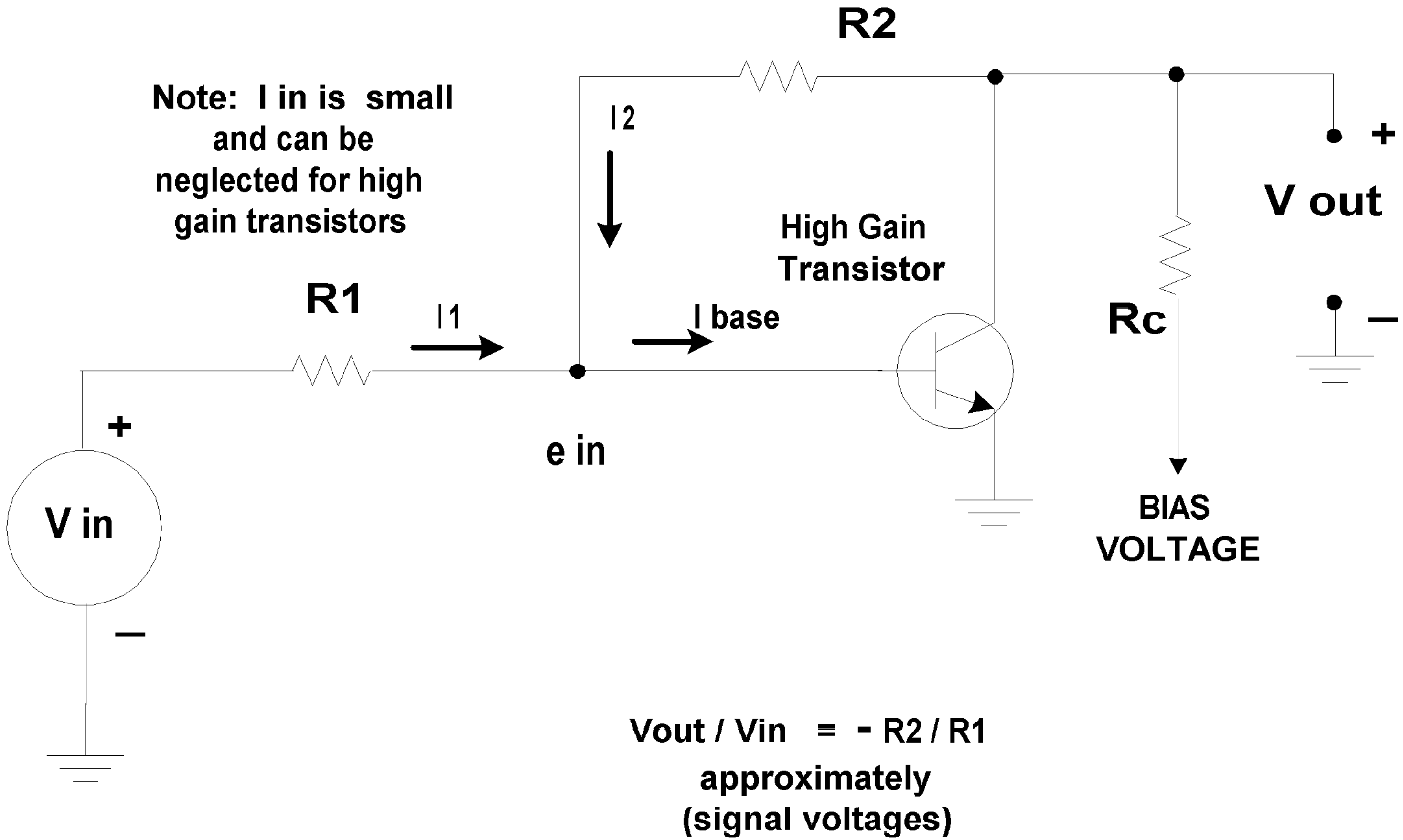


$$V_{out} / V_{in} = - R_f / R_n \text{ for any input}$$

$$n = 1,2,3 \ldots N$$

$$V_{out} = - \{V_1(R_f/R_1) + V_2(R_f/R_2) + V_3(R_f/R_3) + \ldots + V_N(R_f/R_N)\}$$

FIG 4
BASIC OP AMP SUMMING AMPLIFIER
N - INPUT INVERTING CONFIGURATION



Note: DC Biasing for transistor not shown

FIG 5
BASIC TRANSISTOR VOLTAGE AMPLIFIER INVERTING CONFIGURATION