# Circuits for Controlling Slope and Offset

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March 13, 2011

## Introduction

In signal processing the most common type of process needed is to adjust the gain (slope of the transfer function) and remove an offset voltage. The math is identical to that of the familiar straight line, y = mx + b. Equation 1 is an adaptation for voltages.

Vo = Vin * Gain + Voffset (1)

The most general op-amp circuit that can achieve any value of gain and offset is shown in Figure 1. Any specific transfer function like Equation 1 can always be implemented with fewer than the five resistors shown as summarized below.

| | |
|---|---|
| R1 and R2 | Always required |
| R3 | Required if non-inverting gain is to be higher than inverting gain |
| R4 and R5 | Required if non-inverting gain is to be less than unity |

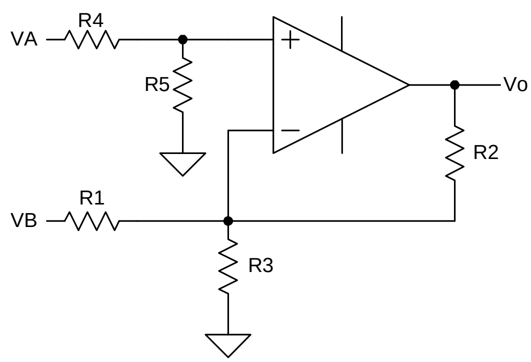


Figure 1: Generic Signal Processing Circuit

## A simple approach when the slope is positive

Figure 2 shows the basic circuit to provide non-inverting gain and remove an output offset. The input voltage is Vin = 0.003*T + 0.8. The variable, T represents the temperature in Celsius. The 0.003 factor is the input slope and has units of volts per C. There is an offset of 0.8 volts as part of the temperature sensor. The desired output of the op-amp is Vo = 0.012*T with no offset. Thus, for a room temperature of 25 C the output voltage would be 0.25 volts.

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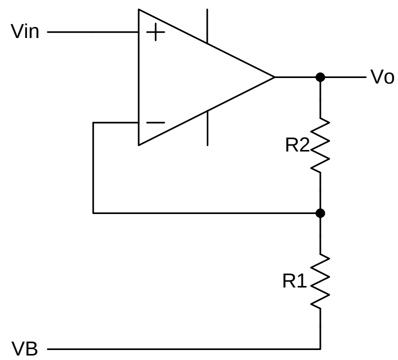


Figure 2: Simple Circuit for non-inverting Gain

The design problem is to determine values for R1, R2, and VB. The non-inverting gain is the output slope factor divided by the input slope factor or 0.012/0.003 = 4.00. Thus, R2/R1 should be 3.00. There are a wide variety of resistors that can achieve this ratio. All we have to do is pick a reasonable one. We choose R2 to be 30K and then R1 calculates to be 10K. We could have chosen R1 first and then calculated R2 – it really makes no difference.

With a gain of 4.00 then Vo = 0.012*T + 3.2. We need to remove the 3.2 volt offset. What value of VB will accomplish that? By superposition, the effect of VB on the output voltage is –VB*(R2/R1). This effect needs to be -3.2 volts to eliminate the 3.2 volt offset. Since (R2/R1) is fixed at 3.00 then VB must be 3.2/3.00 = 1.067 volts. This completes our design. It is left as an exercise for the student to check this to be sure that it works.

**Practice problems:**

1. Given: Vin = 100*X – 3.33. The output of the amplifier is to be Vo = 500*X. Use R2 = 100K and find the required values for R1 and VB. Hint: Do not be surprised when VB computes to be a negative voltage.

2. The transfer function of the circuit is to be 25.64*(Vin – 0.1). Use R2 = 100K and find the required values for R1 and VB.

Rework the above problems if R1 was chosen to be 10K in both cases.

**Using a standard voltage for VB when the slope is positive**

In the previous examples, VB computed to be some odd voltage. This is an illustration of the fact that the simple and obvious approaches do not necessarily have the best operation. Less obvious, but more advanced circuits do. It is generally desirable for VB to be a standard voltage such as 1.250, 2.500, or 5.000 that are available from precision voltage references (the negatives of these voltages are also easily created). How do we modify the circuit for this situation? **Important reasoning:** No matter what we do, the non-inverting gain of the circuit must remain the same. If we choose a VB higher than required by the previous examples, then the R2/R1 ratio must be reduced to achieve the same effect on the output offset voltage. The reduction in non-inverting gain can be corrected by adding R3 as shown in Figure 3.

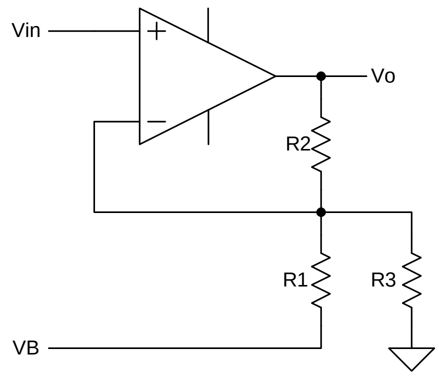


Figure 3: Advanced Circuit for non-inverting Gain

Equation 2 is the transfer function of the circuit shown in Figure 3.

$$Vo = Vin * \left(1 + \frac{R2}{R1 \parallel R3}\right) - VB * \left(\frac{R2}{R1}\right) \qquad (2)$$

In all cases, VB will be chosen (rather than calculated) to be a standard reference voltage. The design problem is that we have three components to meet two criteria. Infinite solutions are possible. However, all we need is a practical solution.

The example of the previous section will be reworked using this new concept. We know that the non-inverting gain is going to be 4.00. But now we first calculate (R2/R1) to satisfy the needed offset. For this example R2/R1 = (3.2/5.00) = 0.640. If we chose R2 to be 30K as before, then R1 is 30K/0.640 = 46.88K.

With the value of R1 and R2 known then R3 can be calculated to provide the desired non-inverting gain. We do this in two steps. First, we calculate the value of (R1 || R3) for the desired non-inverting gain as before to be 30K/3 = 10K. Next, we calculate R3 using the equation for parallel resistance in reverse.

$$R3 = \frac{46.88K * 10K}{46.88K - 10K} = 12.71K$$

The final step would be to consider the required accuracy of the transfer function and either round the resistors to standard values if low accuracy is acceptable or provide some method to fine adjust the values if high accuracy is required. That step will be the topic of another note.

# Circuits for Controlling Slope and Offset

**Practice problems:**

Rework the previous problems using this method and with VB = 5.00 volts (positive or negative as required). You will be calculating the value for R3 instead of VB. Then rework them again using R1 = 10K.

**A simple approach when the slope is negative**

In all of the previous examples the slopes were positive. There are situations where the input slope is negative and a slope inversion is required to make a positive output slope. The circuits and concepts are identical to the previous examples except that Vin and VB are applied differently as shown in Figure 4.

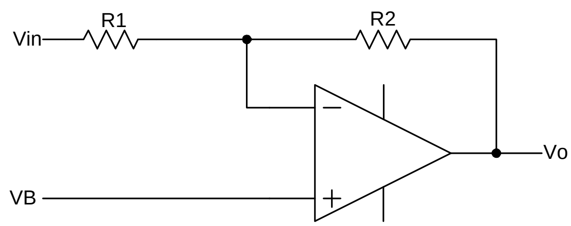


Figure 4: Simple Circuit for inverting Gain

As an example Vin = 0.8 – 0.0025*T where T is the temperature in Celsius and the 0.0025 factor has units of volts per C. The desired output voltage is 0.01*T which means that if the temperature is 40 C then the output voltage would be 0.4 volts.

The design problem is to determine values for R1, R2, and VB. The inverting gain is the output slope factor divided by the input slope factor or 0.010/-0.0025 = -4.00. Thus, R2/R1 should be 4.00. There are a wide variety of resistors that can achieve this ratio. All we have to do is pick a reasonable one. We choose R2 to be 40K and then R1 calculates to be 10K. We could have chosen R1 first and then calculated R2 – it really makes no difference.

With a gain of -4.00 then Vo = 0.010*T – 3.20. We need to remove the -3.2 volt offset. What value of VB will accomplish that? By superposition, the effect of VB on the output voltage is VB*(1 + R2/R1). This effect needs to be +3.2 volts to eliminate the -3.2 volt offset. Since (R2/R1) is fixed at 4.00 then VB must be 3.2/5.00 = 0.640 volts. This completes our design. It is left as an exercise for the student to check this to be sure that it works.

# Circuits for Controlling Slope and Offset

**Practice problems:**

3. Given: Vin = -100*X – 3.33. The output of the amplifier is to be Vo = 500*X. Use R2 = 100K and find the required values for R1 and VB. Hint: Do not be surprised when VB computes to be a negative voltage.

4. The transfer function of the circuit is to be -25.64*(Vin – 0.1). Use R2 = 100K and find the required values for R1 and VB.

Rework the above problems if R1 was chosen to be 10K in both cases.

**Using a standard voltage for VB when the slope is negative**

In the previous examples, VB computed to be some odd voltage. This is an illustration of the fact that the simple and obvious approaches do not necessarily have the best operation. Less obvious, but more advanced circuits do. It is generally desirable for VB to be a standard voltage such as 1.250, 2.500, or 5.000 that are available from precision voltage references (the negatives of these voltages are also easily created). How do we modify the circuit for this situation? **Important reasoning:** No matter what we do, the inverting gain of the circuit must remain the same. Keep in mind that R3 has no effect on the inverting gain. If we choose a VB lower than required by the previous examples, then R3 can be used to increase the non-inverting gain on VB to achieve the desired effect on the output offset voltage. However, this approach fails if VB is chosen to be a higher magnitude than required in the previous examples. The next section illustrates how to handle that situation.

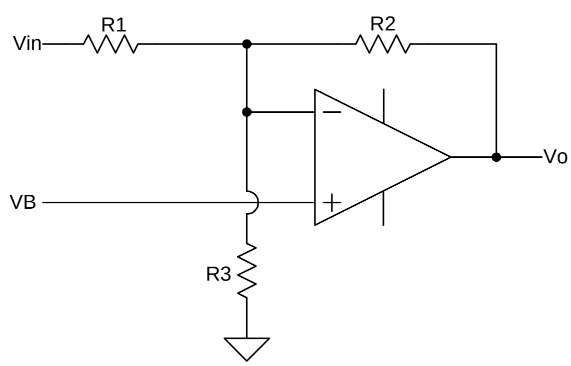


Figure 4: Advanced Circuit for inverting Gain

Equation 3 is the transfer function of the circuit shown in Figure 4.

$$Vo = VB * \left(1 + \frac{R2}{R1 \| R3}\right) - Vin * \left(\frac{R2}{R1}\right) \quad (3)$$

# Circuits for Controlling Slope and Offset

In all cases, VB will be chosen (rather than calculated) to be a standard reference voltage. The design problem is that we have three components to meet two criteria. Infinite solutions are possible. However, all we need is a practical solution.

The example of the previous section will be reworked using this new concept. We know that the inverting gain is going to be -4.00. This means that the ratio, R2/R1, remains the same and R1 = 10K and R2 = 40K as before. The output voltage is Vo = 0.010*T -3.20.

The next question is how to eliminate the -3.2 output offset voltage. There is a 0.500 reference voltage available (how that was derived is not important here). By superposition the required non-inverting gain on the 0.500 reference voltage is 3.2/0.500 = 6.40. The ratio, R2 / (R1 || R3) will be 5.40. With the value of R1 and R2 known then R3 can be calculated to provide the desired non-inverting gain. We do this in two steps. First, we calculate the value of (R1 || R3) for the desired non-inverting gain as before to be 40K/5.4 = 7.407K. Next, we calculate R3 using the equation for parallel resistance in reverse.

$$R3 = \frac{10K * 7.047K}{10K - 7.047K} = 25.08K$$

The final step would be to consider the required accuracy of the transfer function and either round the resistors to standard values if low accuracy is acceptable or provide some method to fine adjust the values if high accuracy is required. That step will be the topic of another note.

**Practice problems:**

Rework the previous problems using this method and with VB = 0.1 volts (positive or negative as required). You will be calculating the value for R3 instead of VB. Then rework them again using R1 = 10K. Do not be surprised if you calculate a negative resistor value for R3 in some cases – the math is telling you that the circuit can not provide the desired result. A different circuit is needed as described in the next section.

**General case solution for inverting slopes for any VB**

For the previous scheme to work for typical situations the magnitude of VB generally must be much less than one volt – not practical when using standard voltage references. The solution is to use a different circuit as shown in Figure 5 where the gains of the different paths can be independently made as high or low as necessary.

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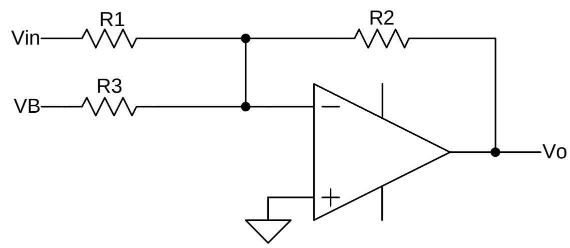


Figure _: Generic Circuit for Inverting Gain

We will use the previous example and choose VB to be -5.00 volts (we need a negative voltage). As before, R2/R1 is 4.00 and R1 = 10K and R2 = 40K. The required gain from the -5.00 volt input to make +3.2 volts on the output is 3.2/(-5.00) = -0.640. Thus, R2/R3 should equal 0.640 and R3 then calculates to be 62.5K.

**General problems:**

The student will have to choose which of the methods discussed in this note apply to each problem. In some cases more than one method can be used. The important thing is not which method you use but that you understand how to pick an appropriate method and apply it. In some cases you may have to include the R4, R5 voltage divider from the generic circuit. Work the problems both ways – without a standard reference voltage (R3 not needed) and with a standard reference voltage: 1.250, 2.500, or 5.000 and R3 will be needed. In some cases your chosen value might be too high or too low – you will compute negative resistors. The problems are rigged so that there is a lot of room to make errors in the approach so do not be surprised if a particular approach you take ends up not working. That just means you should try an alternate approach. That is just part of the learning process – mistakes are going to happen – but that is OK – just understand what you did wrong and learn. Answers are not provided. You should be able to set up a spreadsheet with the standard transfer functions so that you can enter your results and prove that you are right (or wrong). In real life no one gives you the answers – it is the job of the engineer to determine the answers and prove it.

1. Vin = 0.025*X -4.2. Vo = 0.2*X.

2. Vin = 0.00115*X+.56. Vo = 0.01*X

3. Vin = 1.2 – 0.004X. Vo = 0.25*X

4. Vin = 4 – 0.1X. Vo = X

5. Vin = 2.5*X – 1. Vo = X

6. Vin = -2.5X+1. Vo = X