Lecture 16: Operational Amplifiers - Part 3: Circuit Design

OBJECTIVES:

1. Understand how to cascade Op Amps to design more complex circuits

READING

Required :

- Textbook, section 4.5, pages 201–208

Optional : None

1 Review of our Op Amp *Building Blocks*

In this section, I will offer a quick review of our four Op Amp building block circuits plus one new one:

1. Non-inverting Amplifier
2. Inverting Amplifier
3. Inverting Summer
4. Differential Amplifier or Subtractor
5. Buffer

This list is not all inclusive.

In addition, I will show figures with the Op Amps inputs connected to thevenin circuits. These circuits can represent non-ideal sources (with internal resistances) or any resistive circuit. This will allow us to further explore the concept of loading at the input terminals.

1.1 Non-inverting Amplifier

Figure 1 shows a non-inverting amplifier connected to a thevenin circuit; as mentioned above, this input circuit can represent a non-ideal source or any other resistive circuit. Since we know that zero current flows into the input terminals of the Op Amp, we can deduce that there is no input loading that results from R_T; that is there is no voltage drop or change to the transfer characteristic.

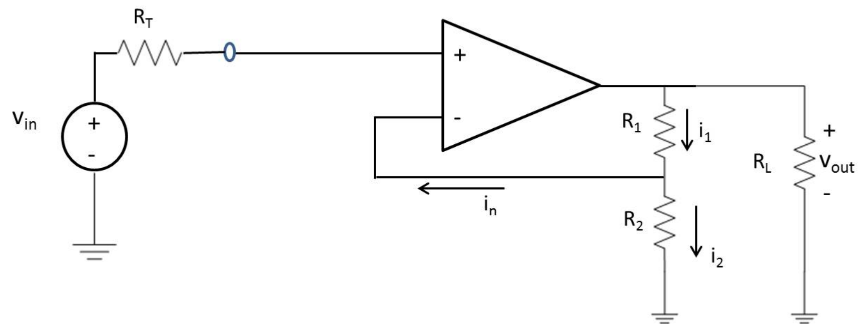


Figure 1: Non-Inverting Amplifier connected to a Thevenin Circuit

1.2 Inverting Amplifier

Figure 2 shows an inverting amplifier connected to a thevenin circuit; as mentioned above, this input circuit can represent a non-ideal source or any other resistive circuit.

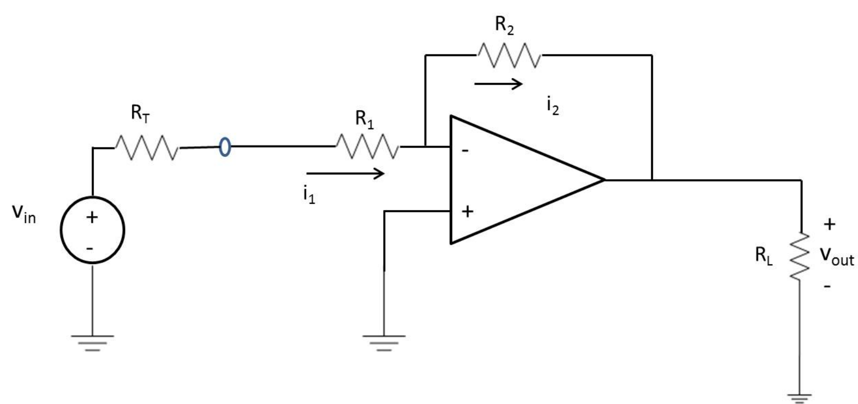


Figure 2: Inverting Amplifier connected to a Thevenin Circuit

In this circuit R_T *loads* the input. This can be thought of a couple of different ways.

1. R_T is in series with R_1. This will change the transfer characteristic from $K = -\frac{R_2}{R_1}$ to $K = -\frac{R_2}{R_T+R_1}$
2. Since in this circuit current can flow through R_T, V_{in} is no longer the input voltage to the Op Amp

1.3 Summing Amplifier

Figure 3 shows a summing amplifier with each input connected to a thevenin circuit; as mentioned above, these input circuits can represent non-ideal sources or any other resistive circuits. Using the same logic as for the Inverting Amplifier, it should be obvious that input loading does exist and has to be accounted for.

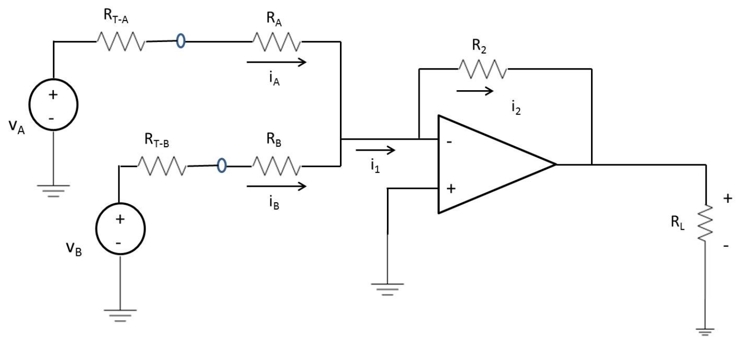


Figure 3: Summing Amplifier connected to a Thevenin Circuit

1.4 Differential Amplifier

Figure 4 shows a differential amplifier with each input connected to a thevenin circuit; as mentioned above, these input circuits can represent non-ideal sources or any other resistive circuits. Using the same logic as above, it should be obvious that input loading does exist and has to be accounted for.

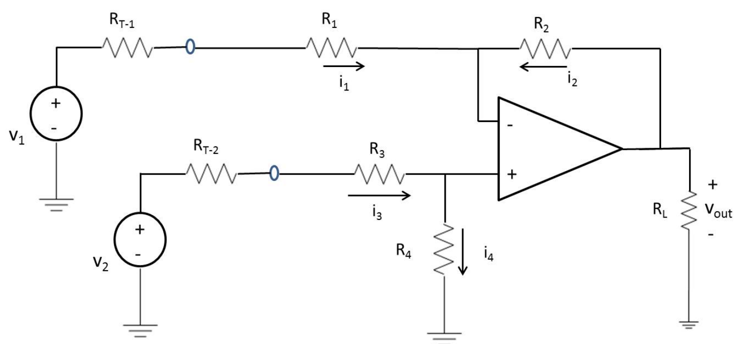


Figure 4: Differential Amplifier connected to a Thevenin Circuit

1.5 Buffer Amplifier

One way to eliminate input loading is by using a buffer amplifier; see Figure 5. It should be obvious that this is a unity gain amplifier and is unaffected by the attached R_T. Placing this circuit before any circuit that is affected by loading will eliminate the effect.

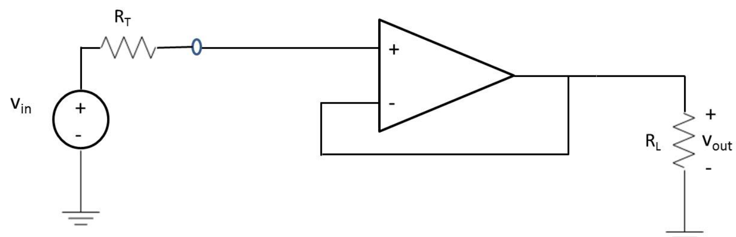


Figure 5: Buffer Amplifier connected to a Thevenin Circuit

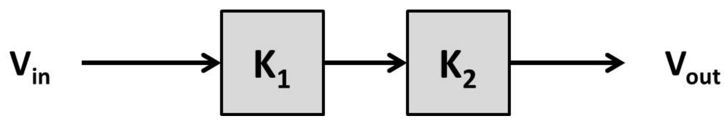
2 Op Amp Circuit Design

This is one of those topics that is best explained just by working examples. Note that because these are design problems, the solutions are not unique; there may be many designs that satisfy the requirements.

2.1 Example 1 - Cascading

Design a circuit that gives a gain of 100,000, where the gain of each stage cannot excede 1,000.

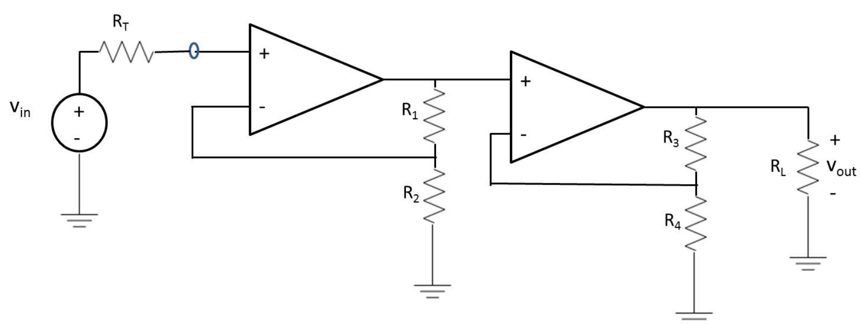
To start our design, lets do a quick block diagram:



The transfer characteristic of this block diagram is

$$V_{out} = K_1 K_2 V_{in} \tag{1}$$

Let's look first at a design that cascades two non-inverting amplifiers:



Let's try for a stage 1 gain of $K_1 = 500$

For stage 1 let's select $R_2 = 1\ k\Omega$ *and solve for* R_1 *(recall for a non-inverting amp* $K = \frac{R_1+R_2}{R_2}$*)*

$$R_1 = R_2 K_1 - R_2 = 1\ k\Omega \times 500 - 1\ k\Omega = 499\ k\Omega \tag{2}$$

The closest standard resistance value to $499\ k\Omega$ *is* $470\ k\Omega$ *which give an actual gain of*

$$K_1 = \frac{R_1 + R_2}{R_2} = \frac{470\ k\Omega + 1\ k\Omega}{1\ k\Omega} = 471 \tag{3}$$

We need a stage 2 gain of $\frac{100{,}000}{471} = 212.3$ *Let's use* $R_2 = 2\ k\Omega$ *and solve for* R_1*:*

$$R_1 = R_2 K_1 - R_2 = 2\ k\Omega \times 212.3 - 2\ k\Omega = 422.6\ k\Omega \tag{4}$$

so we can use an actual value of $R_1 = 430\ k\Omega$ *which gives a stage gain of*

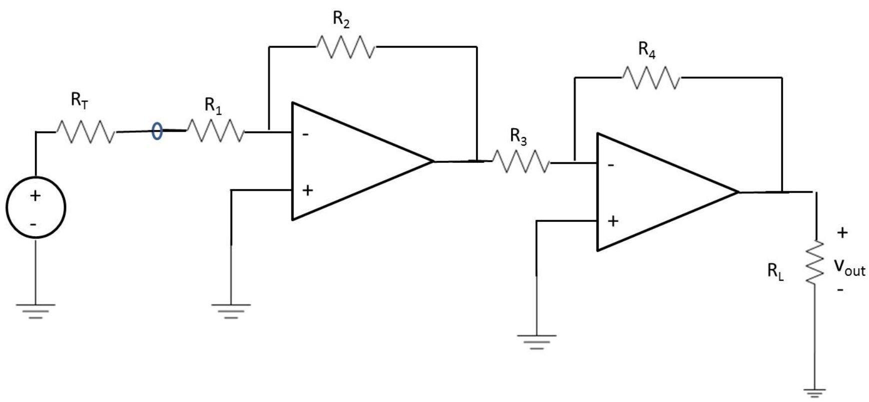
$$K_2 = \frac{R_1 + R_2}{R_2} = \frac{430\ k\Omega + 2\ k\Omega}{2\ k\Omega} = 216 \tag{5}$$

Total gain is

$$K = K_1 K_2 = 417 \times 216 = 101{,}740 \tag{6}$$

Because we used non-inverting amplifiers we do not have any loading issues.

Let's redo the design with inverting amplifiers:



Since we cascaded two inverting amps we will get a positive overall gain which is what we are after.

But, we have to examine any loading issues.....

What is the gain of the first stage?

$$K_1 = -\frac{R_2}{R_1 + R_T} \tag{7}$$

It should be already obivious that the resistance of the source is going to affect the gain of the first stage and ultimately the entire system. Good news is stages do not load each other, so there will be no loading problems on the second stage.

Let's finish the design assuming an $R_T = 100\ \Omega$*... Try and get a stage 1 gain of* $K_1 = -500$*; select* $R_1 = 1\ k\Omega$ *and solve for* R_2*:*

$$R_2 = -K_1(R_1 + R_T) = 500(1\ k\Omega + 100\ \Omega) = 550\ k\Omega \tag{8}$$

the closest standard value is $R_2 = 560\ k\Omega$ *which gives an actual first stage gain of*

$$K_1 = -\frac{560\ k\Omega}{1\ k\Omega + 100\ \Omega} = -509 \tag{9}$$

so for our second stage we need a gain of $\frac{100{,}000}{-509} = -196.5$*. Let's use* $R_3 = 1\ k\Omega$ *and since there is no stage loading:*

$$R_4 = -K_2 R_3 = 196.5 \times 1\ k\Omega = 196.5\ k\Omega \tag{10}$$

the closest standard value is $R_4 = 200\ k\Omega$ *which gives an actual stage 2 gain of*

$$K_2 = -\frac{R_4}{R_3} = -\frac{200\ k\Omega}{1\ k\Omega} = -200 \tag{11}$$

giving a total gain of

$$K = K_1 K_2 = -509 \times -200 = 101,800 \tag{12}$$

What happens to the total gain if $R_T = 1\ k\Omega$*? Stage one gain changes to*

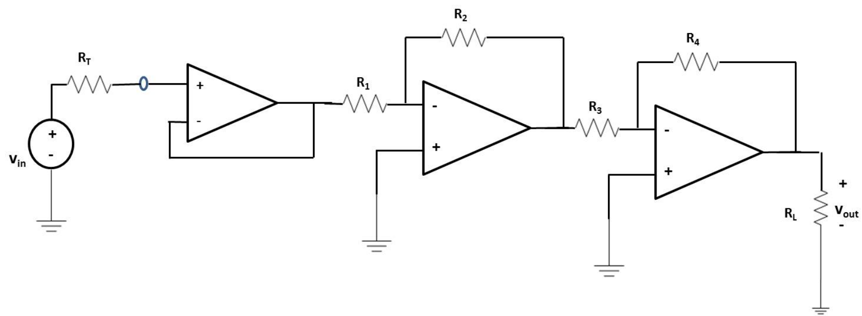
$$K_1 = -\frac{560\ k\Omega}{1\ k\Omega + 1\ k\Omega} = -280 \tag{13}$$

so total gain is now

$$K = K_1 K_2 = -280 \times -200 = 56,000 \tag{14}$$

Is there anything we can do to our last design to avoid loading the first stage?

We can add a buffer amplifier. Remember a buffer is a unity gain amplifier that does not suffer from stage loading. The hew design would look like:



Since there is no current flowing into the buffer, there is no voltage drop across R_T; therefore, there is no loading

2.2 Example 2

Design an Op Amp circuit that implments the block diagram shown in Figure 6

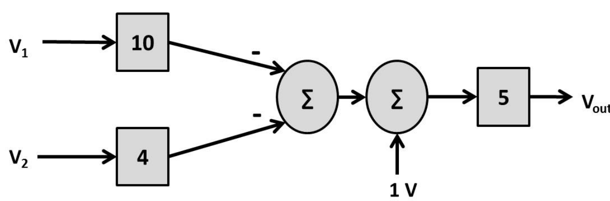


Figure 6: Block diagram for example 2

Designs are nout unique.... We will do three designs that work in this example

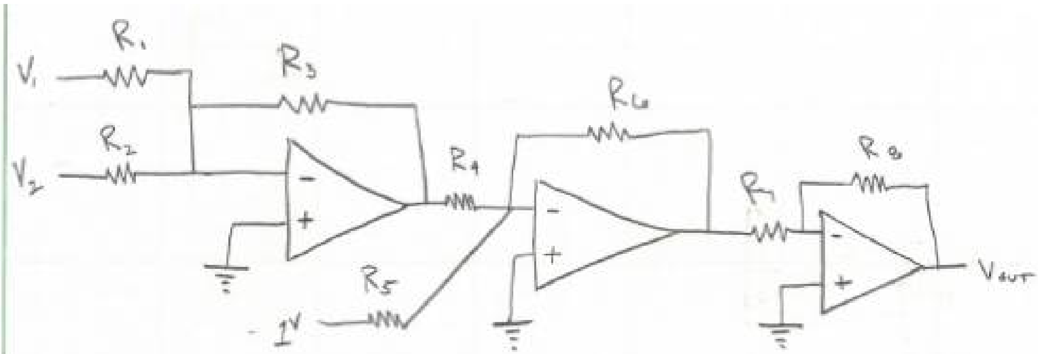
Start by writing an equation for the transfer characterisitic

$$V_{out} = 5(-10V_1 - 4V_2 + 1\ V) \tag{15}$$

or

$$V_{out} = -50V_1 - 20V_2 + 5\ V) \tag{16}$$

For our first design let's build it just like it is drawn with two summers and a final gain stage:



<u>STAGE 1</u>

$K_1 = -10$ & $K_2 = -4$

LET $R_3 = 10K\Omega$

$\therefore \quad R_1 = \frac{10\,K\Omega}{10} = 1K\Omega$ & $R_2 = \frac{10K\Omega}{4} = 2.5K\Omega$

STAGE 1 OUTPUT $\rightarrow$ $\boxed{V_{OUT\,1} = -10V_1 - 4V_2}$

<u>STAGE 2</u>

$K_1 = -1$ & $K_2 = -1$

LET $R_6 = 1\,K\Omega$

$\therefore \; R_4 = R_5 = 1\,K\Omega$

STAGE 2 OUTPUT $\rightarrow$ $\boxed{V_{OUT\,2} = 10V_1 + 4V_2 - 1}$

<u>STAGE 3</u>

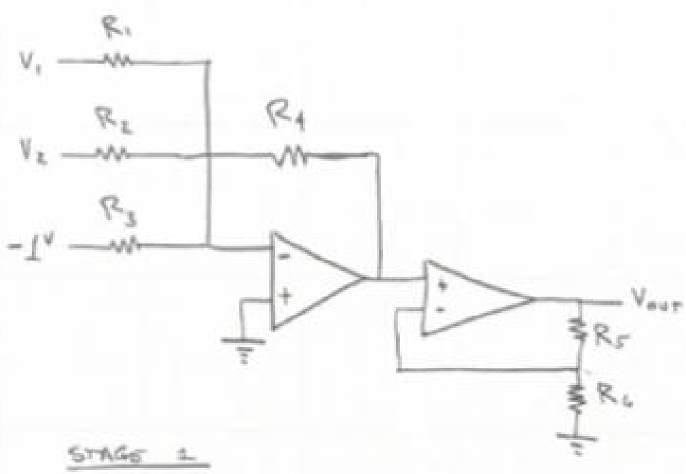
$K = -5$

LET $R_8 = 5\,K\Omega$ $\therefore$ $R_7 = 1\,K\Omega$

STAGE 3 OUTPUT $\longrightarrow$ $\boxed{\begin{aligned} V_{OUT} &= -5\left(10V_1 + 4V_2 - 1\right) \\ V_{OUT} &= 5\left(-10V_1 - 4V_2 + 1\right) \end{aligned}}$

This design uses 3 Op Amps and 8 resistors, I think we can be more efficient....

Let's combine the summing stages into a single stage; recall we said we can extend the summer design to more than 2 inputs.



STAGE 1

$K_1 = -10 \qquad K_2 = -4 \qquad K_3 = -1$

LET $R_4 = 10\,k\Omega$

$\therefore R_1 = 1\,k\Omega, \quad R_2 = 2.5\,k\Omega, \quad R_3 = 10\,k\Omega$

STAGE 1 OUTPUT – $\boxed{V_{out\,1} = -10V_1 - 4V_2 + 1^V}$

STAGE 2

$K = 5$

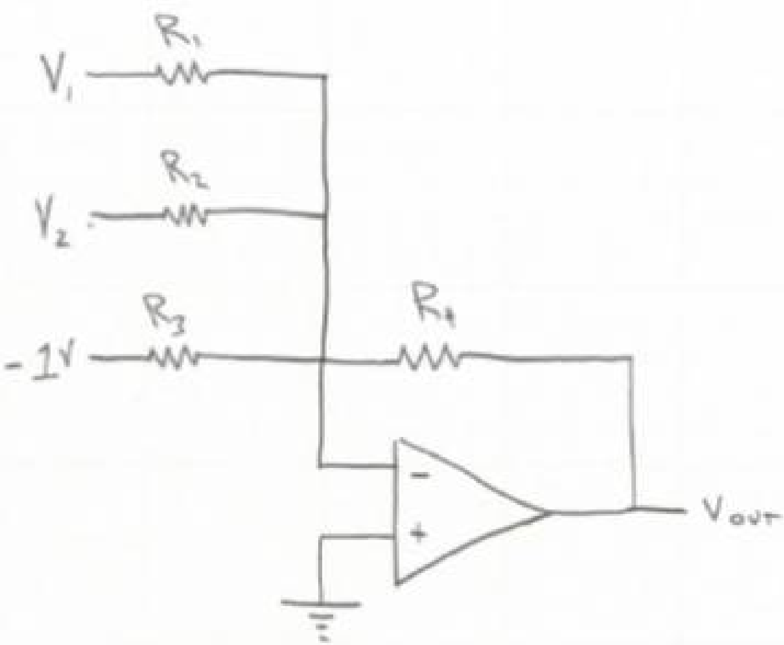
$K = \frac{R_5 + R_6}{R_6} \rightarrow 5R_6 - R_6 = R_5 \rightarrow 4R_6 = R_5$

$R_6 = \frac{R_5}{4}$ LET $R_5 = 20\,k\Omega$ $\therefore R_6 = 5\,k\Omega$

STAGE 2 OUTPUT – $\boxed{V_{out} = 5(-10V_1 - 4V_2 + 1)}$

This design uses 2 Op Amps and 6 resistors, I still think we can be more efficient....

Here is a single stage design that uses 1 Op Amp and 4 resistors



REQUIRED GAINS

$K_1 = -50$ $\quad$ $K_2 = -20$ $\quad$ $K_3 = -5$

LET $R_4 = 100K\Omega$

$$R_1 = \frac{100K\Omega}{50} = 2K\Omega$$

$$R_2 = \frac{100K\Omega}{20} = 5K\Omega$$

$$R_3 = \frac{100K\Omega}{5} = 20K\Omega$$

$$\boxed{V_{OUT} = -50V_1 - 20V_2 + 5^V}$$