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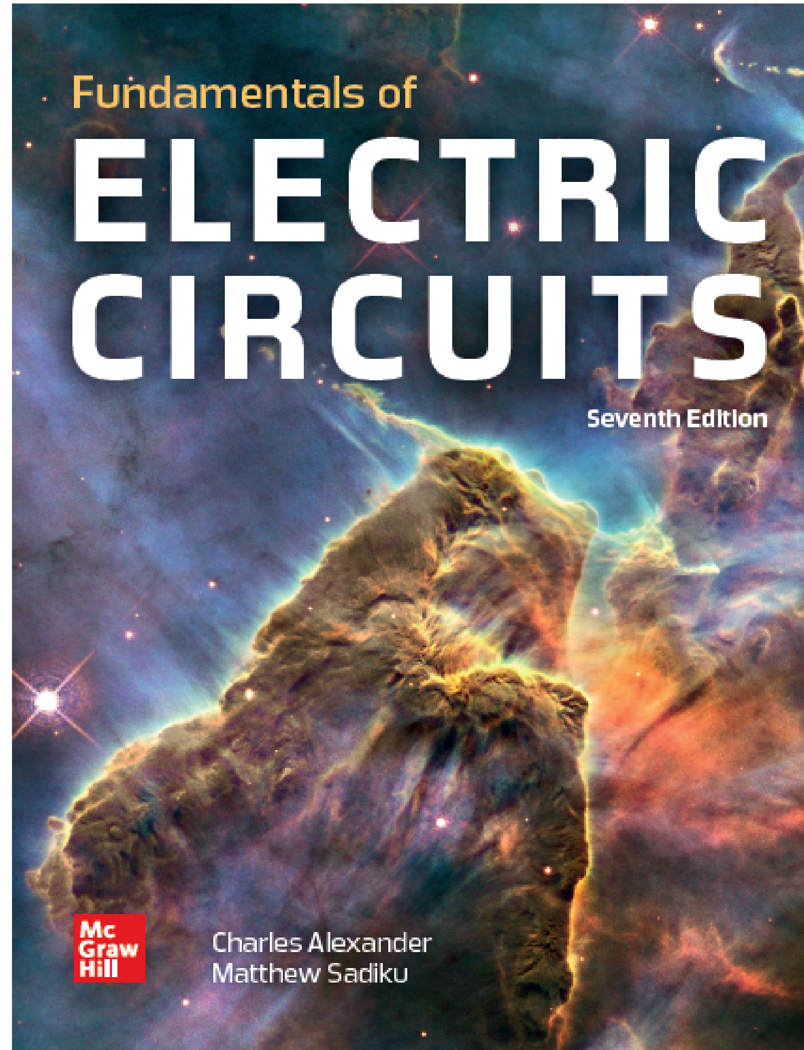
Fundamentals of Electric Circuits

Chapter 5



Overview

- In this chapter, the operation amplifier will be introduced.
- The basic function of this useful device will be discussed.
- Examples of amplifier circuits that may be constructed from the operation amplifier will be covered.
- Instrumentation amplifiers will also be discussed.

Operational Amplifier 1

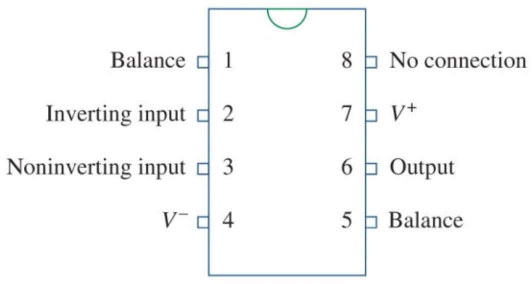
- Typically called ‘Op Amp’ for short.
- It acts like a voltage controlled voltage source.
- In combination with other elements it can be made into other dependent sources.
- It performs mathematical operations on analog signals.

Operational Amplifier 2

The op amp is capable of many math operations, such as addition, subtraction, multiplication, differentiation, and integration.

There are five terminals found on all op-amps.

- The inverting input.
- The noninverting input.
- The output.
- The positive and negative power supplies.



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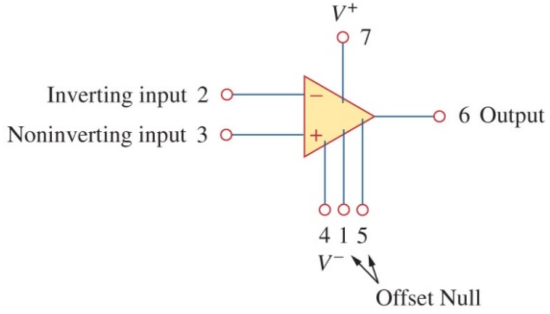

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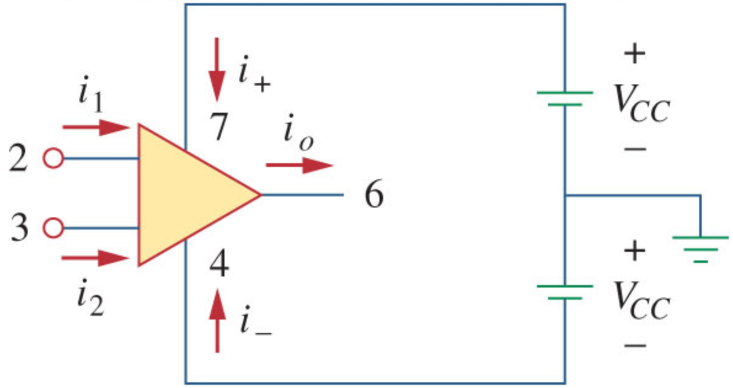
Powering an Op-amp

- As an active element, the op-amp requires a power source.
- Often in circuit diagrams the power supply terminals are obscured.
- It is taken for granted that they must be connected.
- Most op-amps use two voltage sources, with a ground reference between them.
- This gives a positive and negative supply voltage.



Output Voltage

- The voltage output of an op-amp is proportional to the difference between the noninverting and inverting inputs.

$$v_o = Av_d = A(v_2 - v_1)$$

- Here, A is called the open loop gain.
- Ideally it is infinite.
- In real devices, it is still high: 10^5 to 10^8 volts/volt

TABLE 5.1

Typical ranges for op amp parameters.

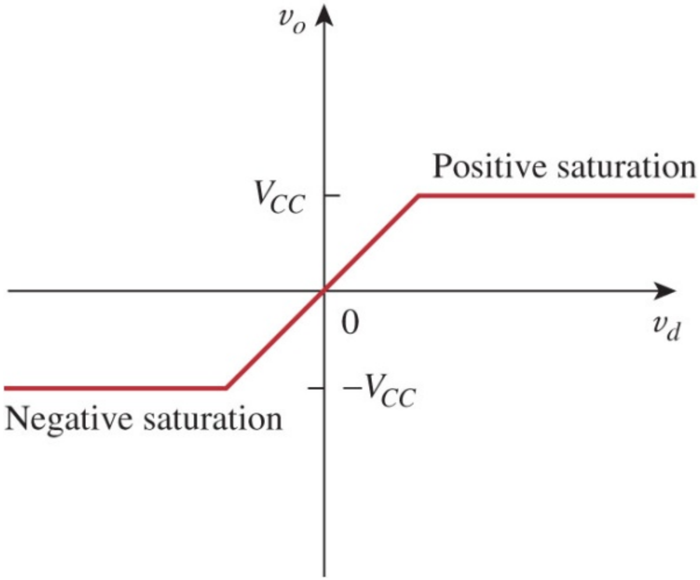
Parameter	Typical range	Ideal values
Open-loop gain, A	10^5 to 10^8	∞
Input resistance, R_i	10^5 to 10^{13} Ω	∞Ω
Output resistance, R_o	10 to 100 Ω	0Ω
Supply voltage, V_{CC}	5 to 24 V	

Feedback

- Op-amps take on an expanded functional ability with the use of feedback.
- The idea is that the output of the op-amp is fed back into the inverting terminal.
- Depending on what elements this signal passes through the gain and behavior of the op-amp changes.
- Feedback to the inverting terminal is called "negative feedback".
- Positive feedback would lead to oscillations.

Voltage Saturation

- As an ideal source, the output voltage would be unlimited.
- In reality, one cannot expect the output to exceed the supply voltages.
- When an output should exceed the possible voltage range, the output remains at either the maximum or minimum supply voltage.
- This is called saturation.
- Outputs between these limiting voltages are referred to as the linear region.



Ideal Op Amp [1]

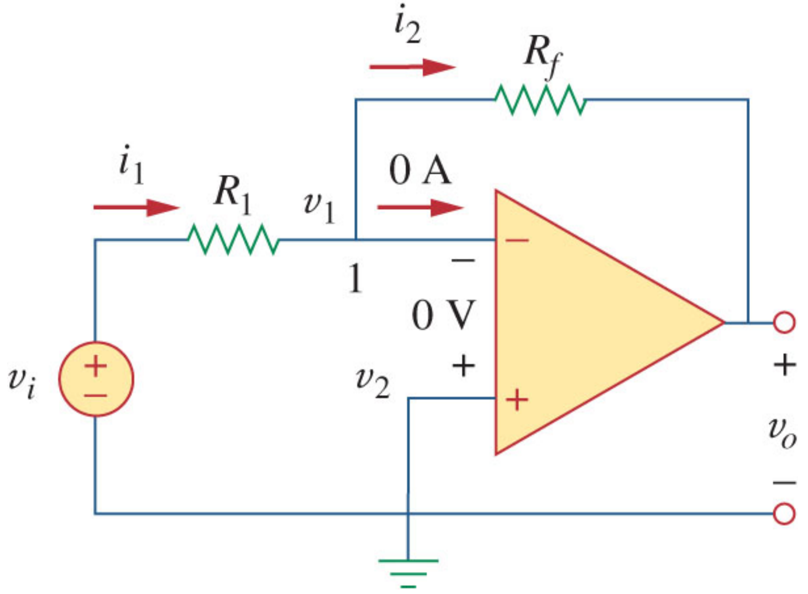
- We give certain attributes to the ideal op-amp.
- As mentioned before, it will have an infinite open-loop gain.
- The resistance of the two inputs will also be infinite.
- This means it will not affect any node it is attached to.
- It is also given zero output impedance.
- From Thevenin's theorem one can see that this means it is load independent.

Ideal Op Amp 2

- Many modern op-amp come close to the ideal values:
- Most have very large gains, greater than one million.
- Input impedances are often in the giga-Ohm to terra-Ohm range.
- This means that current into both input terminals are zero.
- When operated in negative feedback, the output adjusts so that the two inputs have the same voltage.

Inverting Amplifier [1]

- The first useful op-amp circuit that we will consider is the inverting amplifier.
- Here the noninverting input is grounded.
- The inverting terminal is connected to the output via a feedback resistor, R_f .
- The input is also connected to the inverting terminal via another resistor, R_1.



Inverting Amplifier 2

- By applying KCL to node 1 of the circuit, one can see that:

$$i_2 = i_2 \Rightarrow \frac{v_i - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$

- Also, in this circuit, the noninverting terminal is grounded.
- With negative feedback established through the feedback resistor, this means that v_1 is also zero volts.
- This yields:

$$\frac{v_i}{R_1} = -\frac{v_o}{R_f}$$

Inverting Amplifier 3

- This can be rearranged to show the relationship between the input and output voltages.

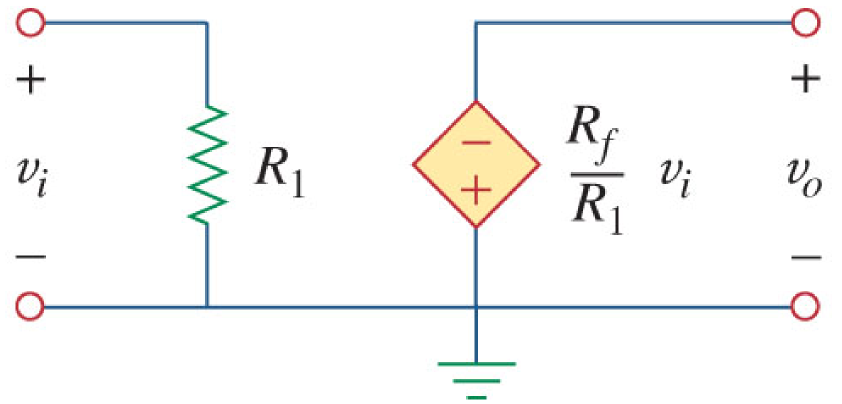
$$v_o = -\frac{R_f}{R_1} v_i$$

From this one can see that:

- The gain is the ratio of the feedback resistor and R_1.
- The polarity of the output is the reverse of the input, thus the name “inverting” amplifier.

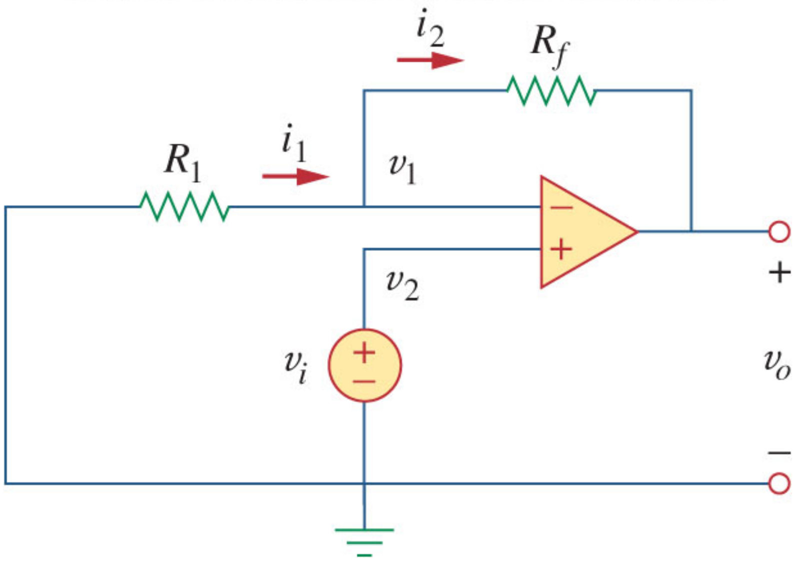
Equivalent Circuit

- The inverting amplifier's equivalent circuit is shown here.
- Note that it has a finite input resistance.
- It is also a good candidate for making a current-to-voltage converter.



Non-Inverting Amplifier 1

- Another important op-amp circuit is the noninverting amplifier.
- The basic configuration of the amplifier is the same as the inverting amplifier.
- Except that the input and the ground are switched.
- Once again applying KCL to the inverting terminal gives:



$$i_1 = i_2 \Rightarrow \frac{0 - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$

Non-Inverting Amplifier 2

- There is once again negative feedback in the circuit, thus we know that the input voltage is present at the inverting terminal.
- This gives the following relationship:

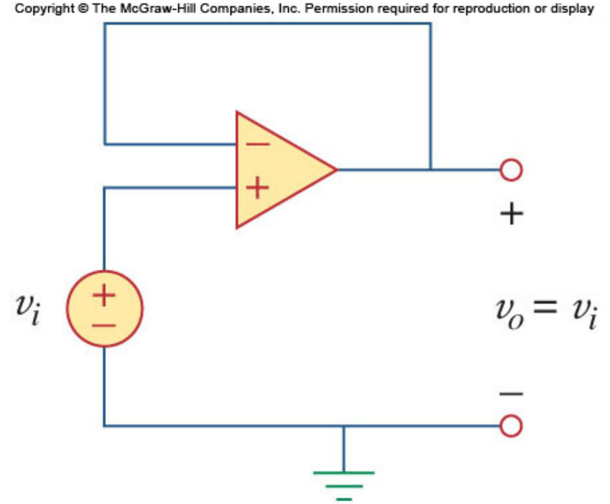
$$\frac{-v_i}{R_1} = \frac{v_i - v_o}{R_f}$$

- The output voltage is thus:

$$v_o = \left(1 + \frac{R_f}{R_1}\right) v_i$$

Non-Inverting Amplifier 3

- Note that the gain here is positive, thus the amplifier is noninverting.
- Also note that this amplifier retains the infinite input impedance of the op-amp.
- One aspect of this amplifier's gain is that it can never go below 1.
- One could replace the feedback resistor with a wire and disconnect the ground and the gain would still be 1.
- This configuration is called a voltage follower or a unity gain amplifier.
- It is good for separating two circuits while allowing a signal to pass through.

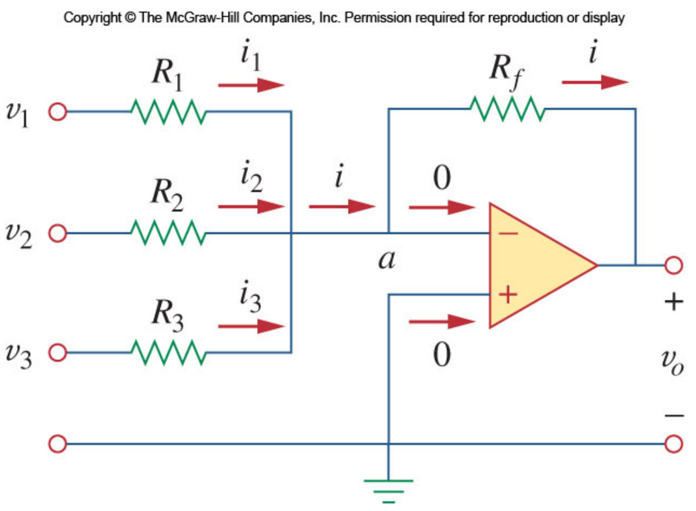


Summing Amplifier [1]

Aside from amplification, the op-amp can be made to do addition very readily

If one takes the inverting amplifier and combines several inputs each via their own resistor:

- The current from each input will be proportional to the applied voltage and the input resistance.



$$i_1 = \frac{(v_1 - v_a)}{R_1} \qquad i_2 = \frac{(v_2 - v_a)}{R_2} \qquad i_3 = \frac{(v_3 - v_a)}{R_3}$$

Summing Amplifier 2

- At the inverting terminal, these current will combine to equal the current through the feedback resistor.

$$i_a = \frac{(v_a - v_o)}{R_f}$$

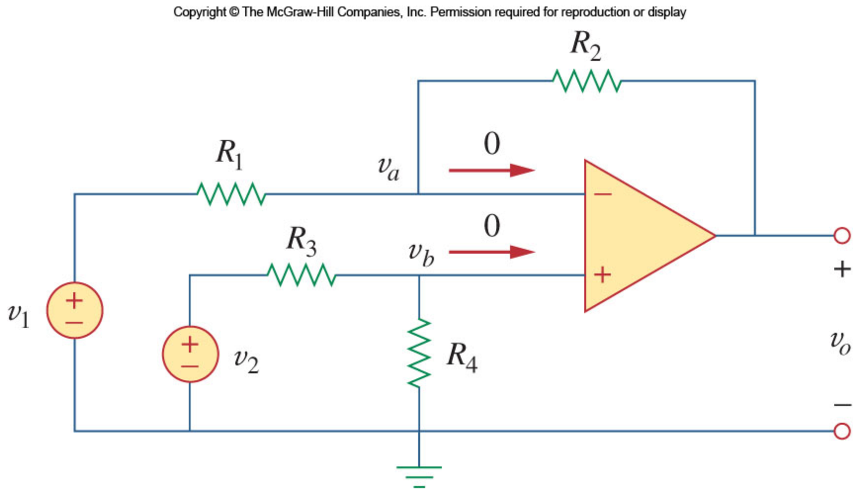
- This results in the following relationship:

$$v_o = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3 \right)$$

- Note that the output is a weighted sum of the inputs.
- The number of inputs need not be limited to three.

Difference Amplifier [1]

- Subtraction should come naturally to the op-amp since its output is proportional to the difference between the two inputs.
- Applying KCL to node a in the circuit shown gives:



$$v_o = \left(\frac{R_2}{R_1} + 1 \right) v_a - \frac{R_2}{R_1} v_1$$

Difference Amplifier 2

- Applying KCL to node b gives:

$$v_b = \frac{R_4}{R_3 + R_4} v_2$$

- With the negative feedback present, we know that $v_a = v_b$ resulting in the following relationship:

$$v_o = \frac{R_2\left(1 + R_1/R_2\right)}{R_1\left(1 + R_3/R_4\right)} v_2 - \frac{R_2}{R_1} v_1$$

Common Mode Rejection

- It is important that a difference amplifier reject any signal that is common to the two inputs.
- For the given circuit, this is true if:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

- At which point, the output is:

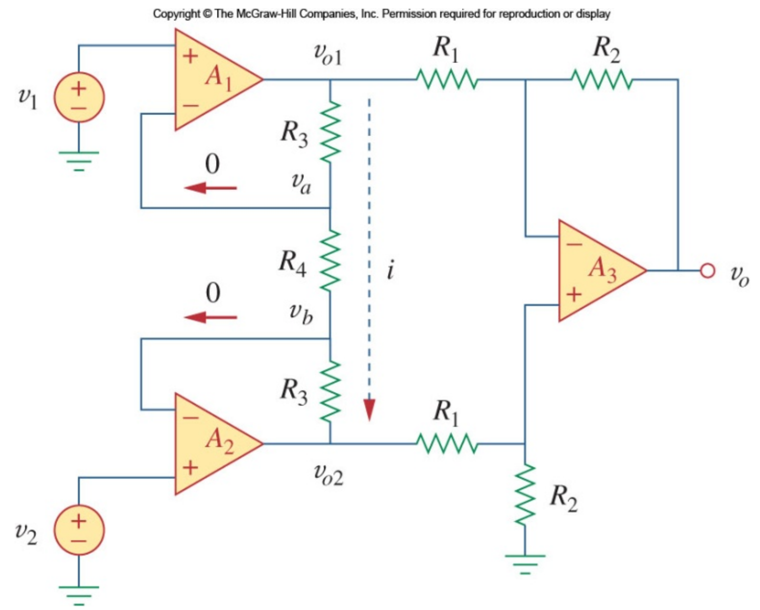
$$v_o = \frac{R_2}{R_1}(v_2 - v_1)$$

Instrumentation Amplifier 1

The difference amplifier has one significant drawback:

- The input impedance is low.

By placing a noninverting amplifier stage before the difference amplifier this can be resolved



Instrumentation Amplifier 2

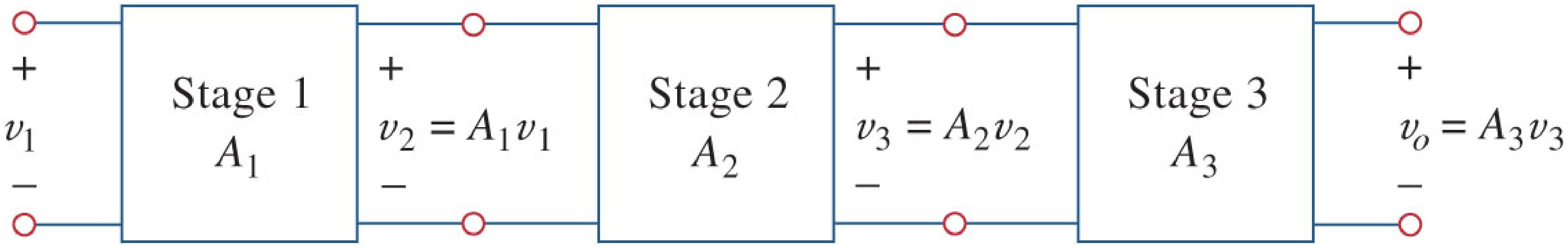
- A further trick of arranging the reference voltage to be equal to the common mode reduces errors due to differences in the gain of the input stages.
- In addition, the arrangement of the feedback and “reference” resistor such that they all share the same current further enables the circuit to remain precisely balanced.

Instrumentation Amplifier 3

- Instrumentation amplifiers are so useful, they are often packaged as a single chip with the only external component being the gain resistor.
- They are very effective at extracting a weak differential signal out of a large common mode signal.
- In circuits exposed to external electrical noise, this is important in order to maintain a high signal-to-noise ratio.

Cascaded Op Amps [1]

- It is common to use multiple op-amp stages chained together.
- This head to tail configuration is called "cascading."
- Each amplifier is then called a "stage."



Cascaded Op Amps 2

- Due to the ideal op-amps’s input and output impedance, stages can be chained together without impact the performance of any one stage.
- One reason to cascade amplifier stages is to increase the overall gain.
- The gain of a series of amplifiers is the product of the individual gains:

$$A = A_1 A_2 A_3$$

Cascaded Amplifiers

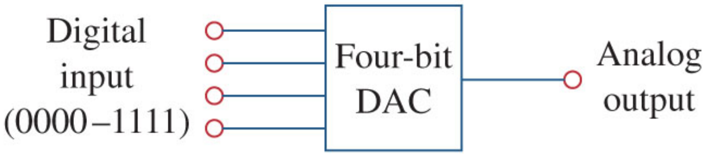
- For example, two stages each having a gain of 100, have a combined gain of 10,000.
- Mixing high gain and improved input impedance is another reason to cascade.

Digital to Analog Converter [1]

- The summing amplifier can be used to create a simple digital to analog converter (DAC).
- Recall that each input has its own multiplier resistor.
- In a digital signal, the input voltage will be either zero which represents ‘0’ or a non-zero voltage which represents ‘1’.
- The function of a DAC is to take a series of binary values that represent a number and convert it to an analog voltage.

Digital to Analog Converter 2

- By selecting the input resistors such that each input will have a weighting according to the magnitude of their place value.
- Each lesser bit will have half the weight of the next higher bit.
- The feedback resistor provides an overall scaling, allowing the output to be adjusted according to the desired range.



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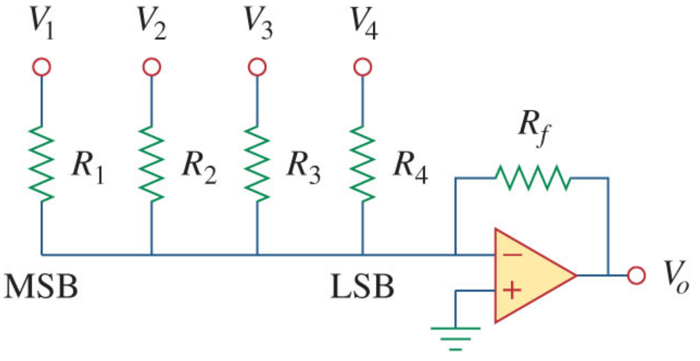

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