

Chapter 11

Operational Amplifier

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Electronics: Principles, Concepts and Practices

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Intro

Operational Amplifier

- An Operational Amplifier is a two-input directly coupled multistage differential amplifier with high voltage gain and high input impedance designed to perform mathematical operations.
- The Operational Amplifier, or Op-Amp, has been widely used for many decades. It serves as a fundamental building block in electronic circuits, encompassing the differential amplifier, voltage amplifier, and, in certain cases, the class B push-pull amplifier at the output stage.
- Figure 1 depicts the basic internal arrangement of an Op-Amp, an in-depth discussion of its internal circuit elements falls outside the scope of this class.
- Instead, we shall treat the Op-Amp as a black box and present models that accurately represent its behavior within an electrical circuit in the following section.



Operational Amplifier continued ...

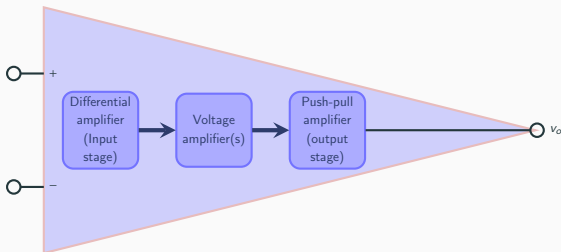


Figure 1: Basic building block of the Op-Amp



Operational Amplifier continued ...

Figure 2 is the circuit symbol of an Op-Amp. Pin 1 and pin 2 serve as the two input terminals. Pin 1 is the inverting input, while pin 2 is the non-inverting input. Pin 3 represents the output terminal, referenced to ground. Pins 4 and 5 are the DC power supply pins. Typically, pin 4 is connected to the positive voltage V_{CC} , while pin 5 is connected to the negative voltage V_{EE} . It is worth noting that practical Op-Amps may have additional pins for specific purposes, such as terminals for frequency compensation and offset nulling.

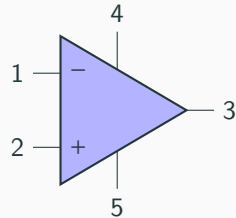


Figure 2: Circuit symbol of the Op-Amp



Modeling an Op-Amp

Modeling an Op-Amp

An Op-Amp can be considered as a differential amplifier with a single-ended output. This means that the output is equal to the difference between the two inputs, v_1 and v_2 , multiplied by a gain factor A_V . This relationship is illustrated by the functional block diagram shown in Figure 3.

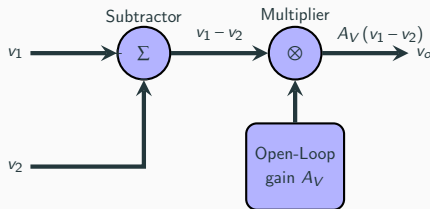


Figure 3: Functional block diagram of an Op-Amp



Dependent Sources

Op-Amp's are typically modeled as dependent sources.

A dependent source is a voltage or current source whose output value is controlled by a voltage or current elsewhere (usually on the input side) in the circuit.

There are four categories of dependent sources which are

1. Voltage-Controlled Voltage Source;
2. Current-Controlled Voltage Source;
3. Voltage-Controlled Current Source; and
4. Current-Controlled Current Source.

Figure 4 shows the circuit representations of dependent sources.



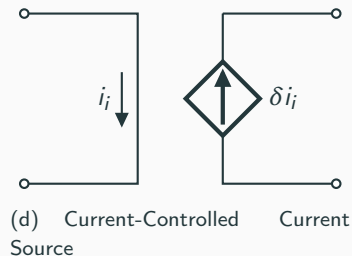
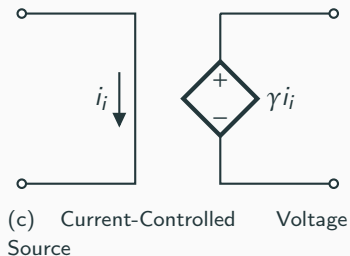
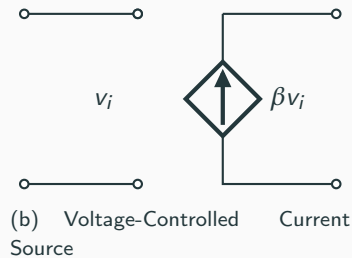
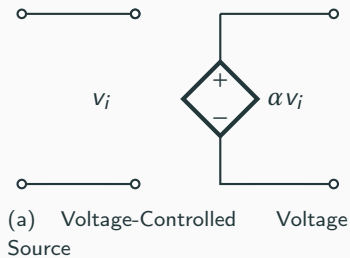


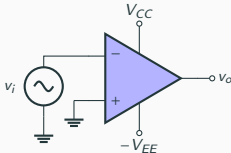
Figure 4: Dependent sources



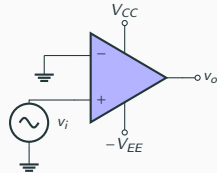
Op-Amp Input Modes

Op-Amp Input Modes

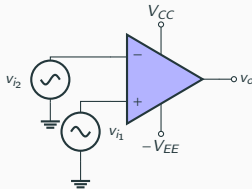
The Op-Amp builds upon the concept of the differential amplifier.



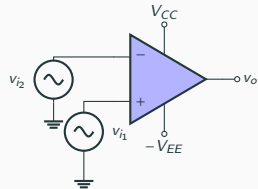
(a) single-ended, inverting mode



(b) Single-ended, non-inverting mode



(c) Double-ended, differential mode



(d) Double-ended, common-mode mode



Figure 5: Op-Amp input modes

Op-Amp Input Modes continued . . .

Fig. 5(a) and 5(b) illustrate the single-ended input operation.

Fig. 5(c) and 5(d) illustrate the double-ended or dual-ended input mode. This input configuration can be categorized as common-mode or differential-mode.

In the differential-mode, two opposite-polarity signals, equal in magnitude but out of phase, are applied to the inputs (Fig. 5(c)).

In the common-mode operation, the two signals applied to the input terminals have the same magnitude and phase (Figure 5(d)).

The ability of an amplifier to reject common-mode signals is quantified by the common-mode rejection ratio (CMRR) given as

$$CMRR = \frac{A_{v_d}}{A_{V_{cm}}} \quad (1)$$

where A_{v_d} is the differential mode voltage gain and $A_{V_{cm}}$ is the common-mode voltage gain.



Need for Feedback in Op-Amp

Need for Feedback in Op-Amp

The amplification level of an Op-Amp is solely determined by its internal open-loop gain. However, this dependence on the open-loop gain can lead to undesirable consequences for the following reasons:

1. As a design engineer, it is preferable to have control over the system's gain through external circuitry. Relying solely on the Op-Amp's open-loop gain limits flexibility in adjusting the amplification as needed.
2. The open-loop gain of an Op-Amp is typically very high, which means even a small differential input voltage can drive the system into the saturation region. This can result in distorted output signals and loss of accuracy.

To resolve this, the concept of negative feedback is introduced.

A negative feedback is a self-regulatory mechanism in which part of the output signal is fed back into the input so as to curtail the changes in the output.



Need for Feedback in Op-Amp ...

The goal of the negative feedback is to keep the Op-Amp in the linear region, this is achieved by the following;

1. reduce the differential voltage V_d at the input to the barest minimum,
2. reduce the effective gain of the Op-Amp such that the output does not depend on the open-loop gain.

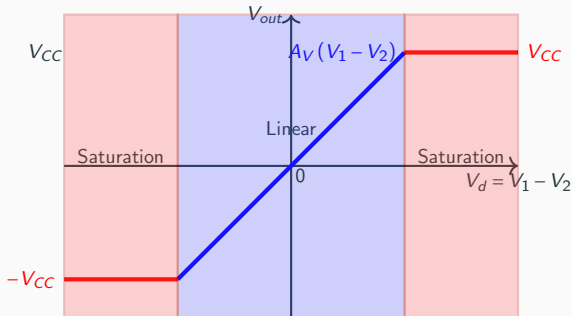


Figure 6: Voltage Transfer Characteristics

Need for Feedback in Op-Amp

Let us consider the negative feedback network arrangement of Figure 7.

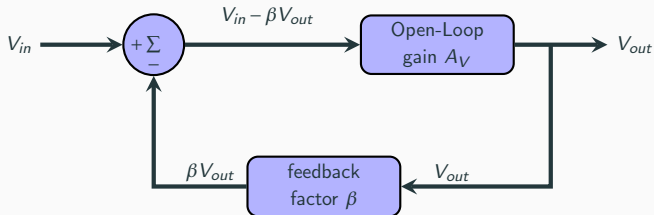


Figure 7: Functional Block Diagram of Feedback System

The close loop gain can be obtained from the functional block diagram as

$$A_{vc} = \frac{A_v}{1 + \beta A_v}$$

(2) 

Effects of Negative Feedback

Effects of Negative Feedback

The effects of negative feedback is as follow:

1. Forces the system to operate in the linear region thus reducing the effect of device non-linearity as well as stabilizing the gain.
Consequently distortions such as total harmonic distortion are reduced;
2. Increases the bandwidth of the system;
3. Increases the input impedance as well as reduces the output impedance.
4. A reduction in gain.



Effects of Negative Feedback

To conclude on the effect of negative feedback, let's take a look at the Bode plot of Figure 8. We immediately see the effect of reducing the gain as it results to increase in the bandwidth. The reduction in gain is known as the **sacrifice factor**, which is the difference between the close loop gain and the open loop gain.

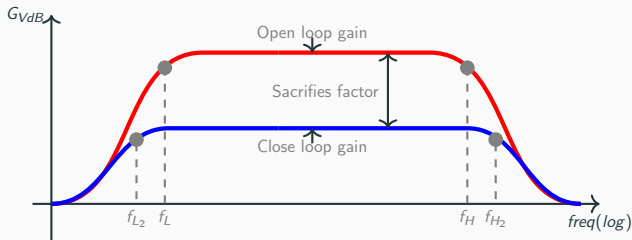


Figure 8: Gain Vs Frequency Response with and without Feedback



Op-Amp Characteristic

Op-Amp Characteristic

The Op-Amp representation is shown in Figure 9. The ideal Op-Amp is shown in Figure 9(a) and the practical Op-Amp in Figure 9(b) for contrast purpose.

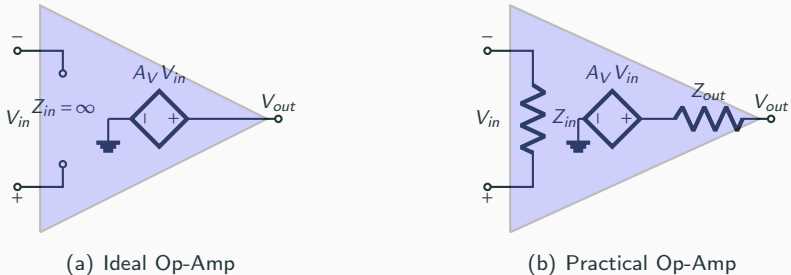


Figure 9: Basic Op-Amp Representation



Practical Op-Amp

We can state the following facts about the practical Op-Amp from the discussion thus far;

1. The Op-Amp circuit with feedback operates by maintaining a tiny differential voltage V_d at its inputs to tame the Op-Amp's huge internal/open loop gain;
2. The Op-Amp with feedback regulates its own differential voltage by adjusting its output voltage V_{out} , whose fraction is feed back to the input through the feedback loop; and
3. As the open loop gain A_v is increased, the input differential voltage V_d moves closer to zero. That is $V_1 \approx V_2$.



Ideal Op-Amp

We can state the following facts about the ideal Op-Amp from the discussion thus far;

1. Infinite open-loop gain $A_V = \infty$;
2. Infinite input resistance $Z_{in} = \infty$ and so zero input currents, $I_1 = I_2 = 0$;
3. Zero output resistance $Z_{out} = 0$;
4. Infinite bandwidth with zero phase shift and slew rate¹; and
5. Infinite common-mode refection ratio (CMRR).

¹Slew rate will be defined in later section



Ideal Op-Amp golden rules

Let us emphasize the golden rules of the ideal Op-Amp that shall be of great importance in subsequent circuit analysis of the Op-Amp.

1. The differential voltage is zero so that $V_1 = V_2$ in a closed loop or better stated, with the feedback configuration.
2. The Op-Amp's inputs draw no current given input impedance is infinity, so that currents into the Op-Amp internal circuitry through the two input pins 1 and 2 are zero. That is, $I_1 = I_2 = 0$.



Op-Amp Configurations and Applications

Non-inverting Op-Amp

The name Non-inverting is because the input signal is fed into the non-inverting terminal, that is, the negative terminal. Equation 3 is the close-loop gain for a non-inverting Op-Amp.

$$\therefore A_{V_c} = 1 + \frac{R_F}{R_1} \quad (3)$$

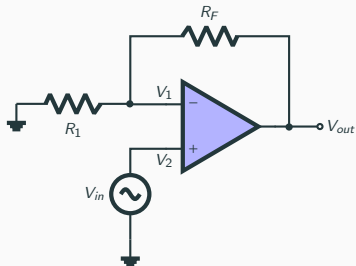


Figure 10: Non-Inverting Op-Amp



Inverting Op-Amp

This configuration is known as the inverting Op-Amp configuration because the input signal is feed into the inverting terminal, V_1 . Equation 4 is the close-loop gain for the inverting amplifier.

$$\therefore A_{v_c} = -\frac{R_F}{R_{in}} \quad (4)$$

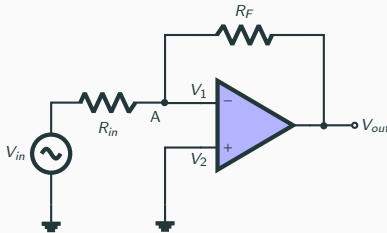


Figure 11: Inverting Op-Amp



Buffer Op-Amp

It is also known as the unity follower or voltage follower. The buffer is a non-inverting amplifier without a feedback resistor.

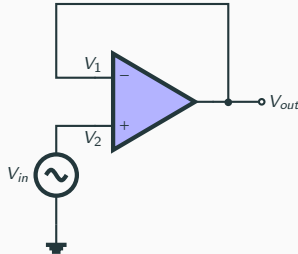


Figure 12: Buffer Amplifier

The close loop gain is

$$A_{V_c} = \frac{V_{out}}{V_1} = 1$$

(5) 

Summer Amplifier

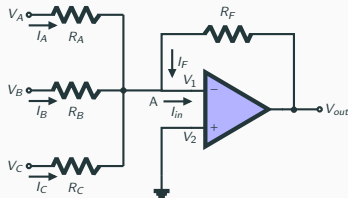


Figure 13: Summer Amplifier

The output voltage is

$$V_{out} = -\frac{R_F}{R_A} V_A - \frac{R_F}{R_B} V_B - \frac{R_F}{R_C} V_C \quad (6)$$

If we set $R_i = R_A = R_B = R_C$, then

$$V_{out} = -\frac{R_F}{R_i} (V_A + V_B + V_C) \quad (7)$$



Digital to Analogue Converter

The DAC transforms digital signal to analogue signal. It is actually a weighted summing amplifier.

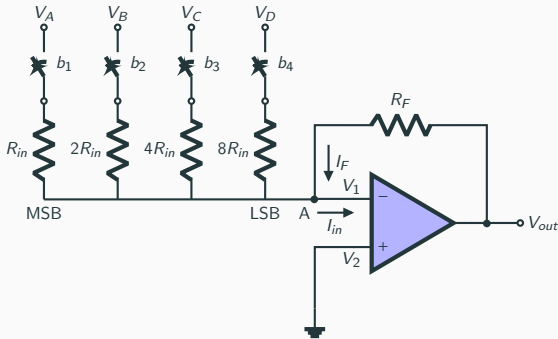


Figure 14: DAC: Digital to Analogue Converter



Subtractor

The Subtractor also known as the Difference Amplifier, amplifies the difference between two inputs while rejecting common signal to the two inputs.

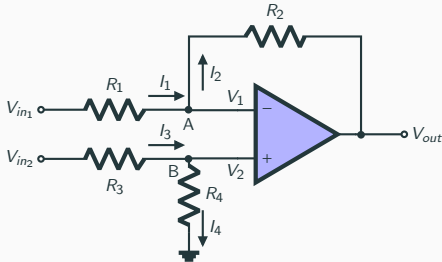


Figure 15: Difference Amplifier



The output voltage is given as

$$V_{out} = \frac{R_2 (1 + R_1/R_2)}{R_1 (1 + R_3/R_4)} V_{in2} - \frac{R_2}{R_1} V_{in1} \quad (8)$$

for our difference amplifier, we wish that common signals be cancelled, that is $V_{out} = 0$, to obtain this, we need to set $R_1 = R_3$ and $R_2 = R_4$, so that equation 8 becomes

$$V_{out} = \frac{R_2}{R_1} (V_{in2} - V_{in1}) \quad (9)$$



Integrator Circuit

The integrator circuit is an inverting amplifier with a capacitor replacing the feedback resistor. The output voltage is

$$V_{out} = -\frac{1}{R_{in}C_F} \int V_{in} dt + K \quad (10)$$

where K is the constant of integration.

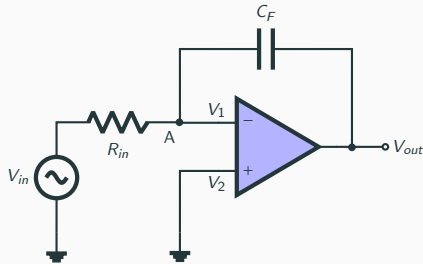


Figure 16: Integrator



Differentiator Circuit

This configuration is an inverting amplifier as with the integrator, however the input resistor R_{in} is replaced by an input capacitor, C_{in} . The output voltage is

$$V_{out} = -R_F C_{in} \frac{dV_{in}}{dt} \quad (11)$$

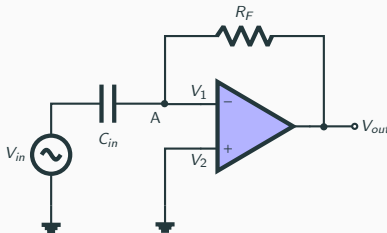


Figure 17: Differentiator Circuit



Instrumentation Amplifier

The instrumentation amplifier is a special and versatile extension of difference amplifiers. It is used for precision measurement and process control. It uses Op-Amp in such way as to amplify small difference in input voltages. Typical application includes isolation amplifiers, thermocouple amplifiers and data acquisition systems. Figure 18 is the circuit implementation of the instrumentation amplifier, it consists of three Op-Amps and seven resistors. The resistor R_4 is typically an external resistor and serve for gain modulation or control as the user can change the value to suit design purposes. The output voltage of the Instrumentation Amplifier is

$$V_{out} = \frac{R_2}{R_1} \left(1 + \frac{2R_3}{R_4} \right) (V_{in2} - V_{in1}) \quad (12)$$



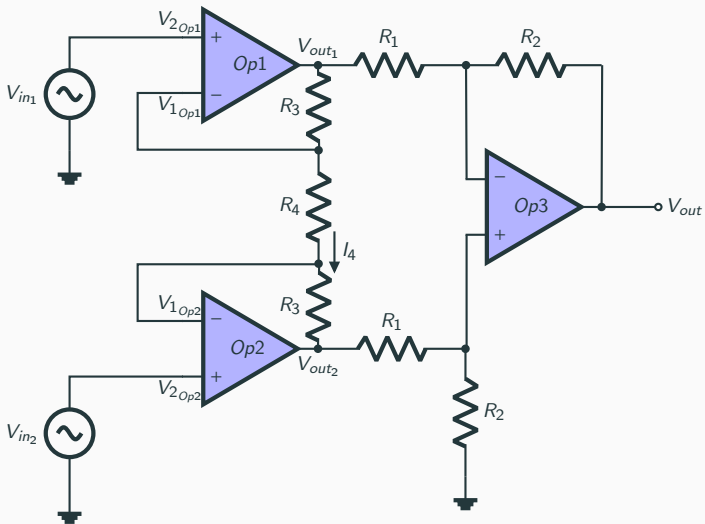


Figure 18: Instrumentation Amplifier



Logarithm Amplifier

A logarithm amplifier is an inverting Op-Amp circuit that produces an output that is proportional to the logarithm of the applied input. The output is given as

$$V_{out} = -nV_T \ln\left(\frac{V_{in}}{R_{in}I_S}\right) \quad (13)$$

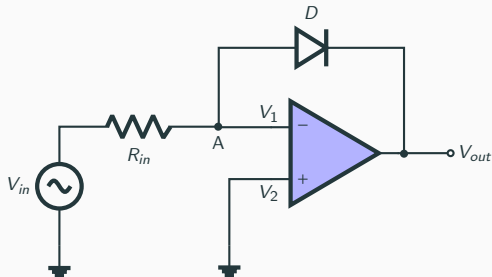


Figure 19: Logarithm Amplifier



Anti-Logarithm Amplifier

An anti-logarithm or exponential amplifier is an inverting Op-Amp circuit that produces an output that is proportional to the anti-logarithm of the applied input voltage. The output is given as

$$V_{out} = -R_F I_S \exp^{V_{in}/nV_T} \quad (14)$$

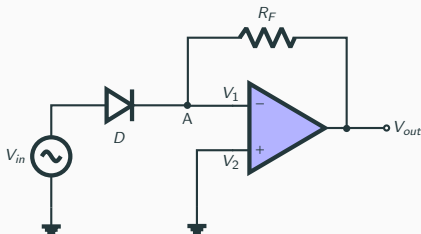


Figure 20: Anti-Logarithm Amplifier



Comparator

The Comparator is an open loop configuration that operates in the saturation region of the transfer characteristic plot of Figure 6. The open-loop Op-Amp Comparator behaves like a digital bistable device because it has two output states. The Comparator, can be termed inverting or non-inverting depending on the pin the **input voltage** is applied. Figure 21 is a non-inverting Comparator with a DC reference voltage V_{ref} .

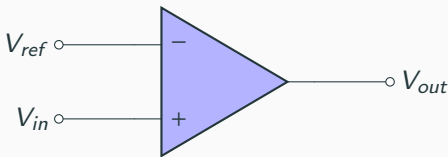


Figure 21: Comparator



Figure 22 describes the operation of the Comparator. The output is such that whenever $V_{in} > V_{ref}$ then the differential voltage $V_d = V_{in} - V_{ref}$ is positive so that the output swings to V_{CC} . However, if $V_{in} < V_{ref}$, the output switches to $-V_{EE}$.

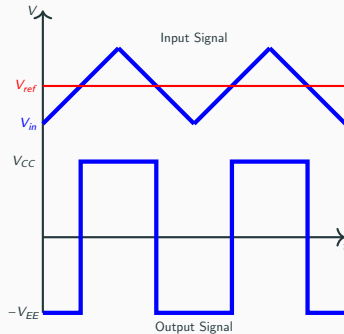


Figure 22: Non-inverting Comparator



Schmidt Trigger

The Schmidt Trigger is a Comparator circuit but with a positive feedback and used to convert any regular or irregular shaped input waveform into a square wave output voltage or pulse.

The Schmidt Trigger is an improved Comparator with two reference voltages (hysteresis), as such offers noise immunity. With the comparator, a noisy signal could create a *ping-pong* effect particularly if the noisy input voltage is around the one reference voltage. However, with the introduction of a second reference voltage a buffer region or hysteresis width is created.



Op-Amp Parameters

Op-Amp Parameters

- DC offset: The DC offset voltage is a measure of the symmetry of the Op-Amp circuit and represents the small DC voltage present at the output.
- Input Offset Voltage Drift: It measures the change in the input offset voltage for each degree Celsius change in temperature.
- Input Bias Current: The input bias current is the DC current required by the inverting and non-inverting input terminals of the amplifier to properly operate the first discrete internal stage of the Op-Amp circuitry. It is defined as the average of both input currents. Smaller input bias currents result in lower drift.
- Input Offset Current: This parameter represents the difference between the input bias currents of the differential amplifier's input terminals. Similar to the input offset voltage, it reflects the symmetry of the Op-Amp's internal circuit. A better symmetric internal circuit will have a smaller input offset current.



Recommendation:

See worked examples in reference material!

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