Schematic of Op Amp

While op amp is complex in detail, there are really only three critical connections to understand its implementation in a circuit.

- Inverting Input (-)
- Non-inverting input (+)
- Output

Important Fundamentals

Important basic properties of an Op Amp
- High input impedance
- Low output impedance
- Large gain (10^4 to 10^6)
- Wide unity gain bandwidth
- Negligible output when inputs are equal

An Ideal Op Amp

- High input impedance
- Low output impedance
- Large gain
- Wide unity gain bandwidth
- Negligible output when inputs are equal

Basic operating principles:
- It draws negligible current into its inputs.
- It will do whatever it can to make the difference between the inputs 0.
- It is an active device which drives its output from its power supply. Its response is limited by what its power supply can deliver.
The Inputs

The notation on the inputs has nothing to do with the polarity of the signal but instead indicates the phase relationship between an input signal and the output signal.

Open Loop Configuration

No feedback (see later on).

\[ V_{\text{output}} = \beta(V_+ - V_-) \]

Gain \( \beta = 10^6 \)

When the input voltage difference is 15 \( \mu \text{V} \), the output is 15 V (the gain is \( 10^6 \)). 15 V is the maximum the op amp supply voltage can produce.

Frequency Response of Op Amp

Note how the extremely high gain is applicable only at very low frequencies. The gain decreases as the frequency increases.

Closed Loop Configuration

Op amps are employed most often when the output signal is fed back into one of the inputs through some passive electronic device.
**Voltage Follower**

This configuration uses negative feedback: the output is connected to the inverting input.

\[ \beta(V_+ - V_-) = V_{out} \]

but \( V_{out} = V_- \)

so \( \beta(V_+ - V_-) = V_{out} \)

\[ \beta V_+ = V_{out} + \beta V_{out} \]

\[ \beta V_+ = (1 + \beta)V_{out} \]

But \( \beta \) is huge \((10^6)\) so

\[ \therefore V_{out} = V_+ \]

The purpose of a voltage follower is to buffer a delicate investigation system from a demanding measurement system.

The op amp draws negligible input current (thereby not disturbing the investigated system) while delivering significant output current (to meet the demands of the measurement system) in such a way that the output voltage is the same as the input voltage.

**Current Amplifier**

This configuration will convert a small input current into an output voltage that can be easily measured.

\[ \beta I_{input} = I_{feedback} \]

or

\[ V_{input} = \frac{R_{feedback}}{R_{input}} V_{out} \]

The output voltage is scaled to the input voltage by the ratio of the two resistors. The gain of the circuit is now controlled by the resistor values and not the inherent op amp open loop gain. If \( R_i \) is larger than \( R_{in} \), we have an amplifier, \( R_i \) is less than \( R_{in} \), we have an attenuator.

**Voltage Amplifier**

Perhaps the most widely used op amp configuration is that of a voltage amplifier.

\[ V_{input} = \frac{R_{feedback}}{R_{input}} V_{out} \]

The input resistor controls the magnitude of the current and the capacitor controls the total charge that can be accumulated. These regulate the temporal behaviour of the device.

**Integrator**

The input current demands a matching feedback current which is delivered by the op amp by changing the output voltage. This current charges the capacitor. The input resistor controls the magnitude of the current and the capacitor controls the total charge that can be accumulated. These regulate the temporal behaviour of the device.

\[ \frac{dq}{dt} = i_{in} = -C_f \frac{dV_0}{dt} \]

\[ \frac{dV_0}{R_{in}} = -C_f \frac{dV_0}{dt} \]

\[ dV_0 = \frac{V_{in}}{R_{in} C_f} \]

\[ \int_0^t dV_0 = \frac{1}{R_{in} C_f} \int_0^t V_{in}(t) \, dt \]

If \( i_{input} = 1 \mu A \) and \( R_{feedback} = 100 k\Omega \) then \( V_{output} = 0.1 V = 100 mV \)

The reset switch discharges the capacitor and prepares the circuit for another charging cycle.
**Differentiator**

By switching the positions of the capacitor and the input resistor of the integrator, we obtain a differential response for the output voltage.

\[ V_{\text{output}}(t) = -R_c C_i \frac{dV_{\text{input}}(t)}{dt} \]

The output voltage is large when the rate of change of the input voltage is large. This circuit can be used for detecting "spikes" in a signal that need to be identified or guarded against or eliminated.

**Logarithmic Amplifier**

Many chemical properties have an exponential response (think of pH for example). This circuit nicely linearizes such a response.

\[ V_{\text{output}} = -\log(V_{\text{input}}/R_{\text{input}}) \]

By switching the diode and resistor, we can make an antilogarithmic (exponential) amplifier. Circuits are more commonly made using a transistor instead of a diode.

**Comparator**

The open circuit configuration has one important use. It forms a comparator that answers the question "Is the input voltage greater than or less than a given reference voltage?"

Because of the huge open loop gain of the op amp, the output voltage is driven to the power supply limits (±15 V) whenever the input exceeds or remains below the reference voltage.

When \( V_{\text{input}} \) is on the inverting input, \( V_{\text{output}} \) assumes the reverse sign; a non-inverting comparator can be formed by switching the input and reference.

This circuit turns a sine wave into a square wave. Often finds use as a trigger circuit.

Charge a capacitor and feed it back to the reference input. Circuit "remembers" peak value.

**Summing Amplifier**

We can run several voltages in parallel to produce a summing effect at the output.

If \( R_1 = R_2 = R_3 = R \) then
\[ V_{\text{output}} = -R_f \left[ \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right] \]

If \( R_1 = R_2 = R_3 = 3R \) then
\[ V_{\text{output}} = -\left[ \frac{1}{3} \right] \left[ \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right] \]
Multiplying Amplifier
By combining a summing circuit with logarithmic and antilogarithmic circuits, we can multiply two voltages together.

Difference Amplifier
This circuitry can determine the difference between two voltages. If \( R_1 = R_2 \) and \( R_3 = R_6 \) then \( V_{output} = \frac{R_2}{R_1}(V_2 - V_1) \). If \( R_1 = R_2 = R_3 = R_6 \) then \( V_{output} = (V_2 - V_1) \).

Dividing Amplifier
By combining a difference amplifier with log/antilog circuits we can divide two voltages.

Instrumentation Amplifier
This is a high precision, very stable difference amplifier which is at the core of most modern instrumental measurements. Very high CMRR, Fixed precision, internal gain, Always used as difference amp.

\[
V_0 = \left( \frac{R_3}{R_4} \right) \left( \frac{R_1 + 2R_3}{R_1} \right) (V_2 - V_1)
\]
when \( R_2 = R_3 ; R_4 = R_5 ; R_6 = R_7 \).
Example: A Spectrometer
A simple spectrometer can be built around an op amp. A photodiode can be used as a transducer; its resistance changes when light impinges on it. Resistance is inversely proportional to the power of the impinging light source.

\[
V_{\text{output}} = -(R_{\text{ref}}/R_{\text{sample}}) V_{\text{source}} \\
V_{\text{output}} = k(P_{\text{sample}}/P_{\text{ref}}) - V_{\text{source}}
\]

Example: Conductance Cell
This is a commonly used detector in devices such as HPLC, ion chromatography and some titrations. In this instrument, note the presence of a standard resistor to regularly calibrate the instrument. The variable resistor can change the gain to cover a larger range of possible cell conductances.

\[
V_{\text{output}} = V_{\text{source}} - R_{\text{variable}}/R_{\text{calibration}}
\]

Example: Thermocouple
Thermocouples are used in pairs and the voltage difference is related to the temperature. A difference amplifier is perfect for this job.

\[
V_{\text{output}} = (V_{\text{test}} - V_{\text{ref}}) - (R_{\text{t}}/R_{\text{in}})
\]