Operational Amplifiers

- Here we see two matched differential amps cascaded to form a basic OP-AMP.
- The differential pair cancel temperature drifts and common mode noise at the input.
- First built to perform math operations, analogue computers.
Differential Amplifiers

$V_{\text{OUT}} = A_V (V_1 - V_2)$

$+V_{cc}$ and $-V_{EE}$ bias the inputs and output to 0 volts.

Common mode noise refers to same sign pickup on $V_1$ and $V_2$.

The differential pair cancels common-mode signals in transistors $Q_1$ and $Q_2$ eg, temperature drifts, noise, etc.
LM741

Dual-In-Line or S.O. Package

- Offset Null
- Verting Input
- Non-Inverting Input
- Output

Die
Bonding Wire
Resin mould
Leadframe
Ideal Op Amp

- Very high or Infinite open loop gain. $A_v \approx 100K$
- Very high or Infinite input impedance ~100MΩ.
- Very low or zero output impedance. ~1Ω
- Zero DC output voltage when inputs grounded.
Negative Feedback

- High gain amplifiers can become unstable in open loop configuration.
- A portion of the output $\beta$ can be feed back to the input to correct this situation.
- For $Av >> 1$ the closed loop gain $A_v^\beta = 1/\beta$

is only a function of the feedback loop and $\beta$ easily fixed.

\[
A_v = \frac{V_{out}}{V_{in}} \Rightarrow \frac{V_{out}}{V_{in} - \beta V_{in}} = \frac{(V_{out}/V_{in})}{1 - \beta(V_{out}/V_{in})} = \frac{A_v^\beta}{1 - \beta A_v^\beta}
\]

\[
A_v^\beta = \frac{A_v}{1 + \beta A_v} \Rightarrow A_v^\beta \approx \frac{1}{\beta} \quad \text{when} \quad A_v >> 1
\]
Voltage Follower

1. \( \Delta V_{+} = 0 \) no current flows no voltage drop!
2. \( V_{in} = V_A = V_{out} \)
3. Voltage Follower is used as an impedance matching device from a hi to low impedance devise. It also acts as a current booster or buffer amp.
Inverting Amp

1. \( V_+ = V_- = 0 \) (since no current flows thru \( Z_{\text{in}} \))
2. \( V_{\text{in}} - I R_1 = 0 \)
3. \( 0 - I R_2 = V_{\text{out}} \)
4. \( A_V^\beta = \frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{R_2}{R_1} \) (combining 2 and 3)
5. \( Z_{\text{in}} = R_1 \) (point-A at virtual ground).
   \( R_1 \) should be fixed and not too small!
Non-Inverting Amp

\[ V_{\text{out}} = V_{\text{in}} \left(1 + \frac{R_2}{R_1}\right) \]

1. \( V_A = V_{\text{in}} \) (No current flows thru \( Z_{\text{in}} \) so \( V_{+} = 0 \))
2. \( V_{\text{out}} - I R_2 = V_A = V_{\text{in}} \)
3. \( V_{\text{in}} - I R_1 = 0 \)
4. \( V_{\text{out}} = V_{\text{in}} \left(1 + \frac{R_2}{R_1}\right) \) combining 1,2
5. Input impedance = \( Z_{\text{in}} + R_1 \sim Z_{\text{in}} \)
Difference Amp

\[ V_{\text{out}} = (V_2 - V_1) \frac{R_F}{R_1} \]
Integrator/Differentiator

\[ V_{out} = -\frac{1}{RC} \int V_{in} \, dt \]

integrator

\[ V_{out} = -RC \frac{d}{dt} V_{in} \]

differentiator
• Inputs $V_1, V_2, V_3$ are summed with gain factor $R_i/R_F$ $i=1,2,3$. 

$$V_{\text{out}} = -(V_1/R_1 + V_2/R_2 + V_3/R_3)R_F$$
Frequency Response

We build an amplifier with gain of 1000, what will $f_{hi}$ be?

Ans.- Based on the graph:
$f_{hi} \sim (10^6 / \text{gain})$ Hz

$f_{hi} \sim (10^6 / \text{gain})$ Hz
Frequency Response (2)

With a voltage gain of 190, an amplifier will have that gain up to the frequency response of about 5.3 KHz below. Not very good for Hi-Fi reproduction! But if we were to reduce the voltage gain to just 20 then the frequency response would extend to 50 KHz. If we needed an amplifier to have a gain of 190 then we would be far better off to have two cascaded amplifier; each with a voltage gain of just 14. The total gain would then be a little over 190 and the frequency response would be flat to over 70KHz.

\[ f_{\text{max}} \sim (10^6 / \text{gain}) \]
An unwanted common mode noise signal $V_{CM}$ appears on inputs 1 and 2 with a weak transducer signal $V_S$.

The $V_{CM}$ is cancelled by the Difference Amp resulting in a noise-free $V_S$ signal.

$$V_{out} = A_v(V_{S+} - V_{S-}) + A_{CMRR}(V_{cm+} + V_{cm-})$$
INSRUMENATION AMPLIFIER
Instrumentation amplifiers are actually made up of 2 parts: a buffered amplifier XOP1, XOP2 and a basic differential amplifier XOP3. The differential amplifier part is often essential when measuring sensors. Why? A sensor produces a signal between its terminals. However, for some applications, neither terminal may be connected to the same ground potential as your measuring circuit. The terminals may be biased at a high potential or riding on a noise voltage. The differential amplifier rescues the signal by directly measuring the difference between the sensor’s terminals.

The buffered amplifier XOP1 and XOP2 not only provides gain, but provides impedance matching from a low Impedance transducer to the high impedance Differential amplifier stage XOP3.

SIGNAL GAIN
The instrumentation amp offers two useful functions: amplify the difference between inputs and reject the signal that’s common to the inputs. The latter is called Common Mode Rejection (CMR). The signal gain is accomplished by XOP1 and XOP2 while XOP3 typically forms a differential gain of 1. You can calculate the overall gain by

\[
\frac{V_o}{V_s} = \left(1 + 2 \frac{R_1}{R_2}\right) \frac{R_5}{R_4}
\]

where \(R_1=R_3\) and \(R_5/R_4 = R_7/R_6\).

http://www.ecircuitcenter.com/Circuits/instamp1/instamp1.htm
The common mode rejection ratio (cmrr) reflects the ability of the op-amp to reject noise common to both inputs.

\[ \text{cmrr} = \frac{A_v}{A_{\text{cmrr}}} = \text{Ndb} \]

Consider an amplifier with cmrr=80db and Av=180 gain. If a differential signal of +2mV, -2mV is applied along with an unwanted common mode signal of 10mV, what is the amplitude of each at the output?

\[ V_{\text{diff}} = 180 \times 4mV = 720mV \]

\[ A_{\text{CMRR}} = \text{Common mode gain} = \frac{A_v}{80\text{db}} = \frac{180}{10^4} = 0.018 \]

\[ V_{\text{cmrr}} = 0.018 \times 20mV = 0.36mV \]

\[ V_{\text{out}} = V_{\text{diff}} + V_{\text{cmrr}} = 720mV + 0.36mV \]
Analogue Computation

\[ \frac{d^2y}{dt^2} + k^2 y = 0 \]

\[ RC = 1 \]
\[ \frac{R_F}{R_1} = k^2 \]

\[ \ddot{y} + k^2 y \to 0 \]
**Analogue Computation**

\[
\ddot{y} + a\dot{y} + by + c = 0
\]

\[
\ddot{y} = -(a\dot{y} + by + c)
\]

\[V_{cc}\] \[+c\] \[+by\] \[+a\dot{y}\]

\[R_1\] \[R_2\] \[R_3\]

\[C\]

\[\text{Summing Integrator}\]

\[a = 1 / R_3C\]

\[b = 1 / R_2C\]

\[c = 1 / R_1C\]

\[\text{Integrator}\]

\[1 = 1 / R'C\]

\[\text{Inverter}\]

\[1 = R / R\]

\[V_{out}\]
1.8.1 Amplitude Distortion Basics

Amplitude distortion occurs in the transistor and is the result of operating the transistor over the nonlinear portion of the characteristics curve (Fig. 1-6). The usual remedy is to use a bias that places the operating point well within the linear portion, preferably at the center of the linear portion. In addition, the amplitude of the input signal must be small enough so that the positive and negative half-cycles do not drive the transistor beyond the linear portion. Generally, a low input signal and proper operating point (at the center of the linear portion) mean that gain must be sacrificed. To sum up, an overdriven amplifier (used to get maximum gain) almost always results in some amplitude distortion. A low-distortion amplifier generally requires at least two stages to get the same gain as an overdriven amplifier.

1.8.2 Frequency Distortion Basics

Frequency distortion occurs because the input signal rarely, if ever, is at a single frequency. Instead, the input signal usually contains components of several frequencies, making the signal waveform somewhat complex. The amplifier circuit is composed of resistors, capacitors (unless direct coupled), and possibly inductances (coils/transformers). Capacitors and inductances have reactance. Because reactance is a function of frequency, the different signal frequencies produce different reactances and attenuate the signal by different amounts. This produces distortion of the signal waveform from the original.

1.8.3 Phase Distortion Basics

When a signal flows through a capacitance or inductance, the signal is shifted in phase. The degree of this shift is a function of frequency. Because several frequencies are present simultaneously, several phase shifts occur, producing phase distortion. As in the case of frequency distortion, amplifier phase distortion can be minimized by proper design.
A **phase-shift oscillator** is a simple sine wave electronic oscillator. It contains an inverting amplifier, and a feedback filter consisting of an RC network which 'shifts' the phase by 180 degrees at the oscillation frequency.

The filter must be designed so that at frequencies above and below the oscillation frequency the signal is shifted by either more or less than 180 degrees. This results in constructive superposition for signals at the oscillation frequencies, and destructive superposition for all other frequencies.

The most common way of achieving this kind of filter is using three cascaded resistor-capacitor filters, which produce no phase shift at one end of the frequency scale, and a phase shift of 270 degrees at the other end. At the oscillation frequency each filter produces a phase shift of 60 degrees and the whole filter circuit produces a phase shift of 180 degrees.

**Op-Amp implementation**

One of the simplest implementations for this type of oscillator uses an operational amplifier (op-amp), three capacitors and four resistors, as shown in the diagram.

The mathematics for calculating the oscillation frequency and oscillation criterion for this circuit are surprisingly complex, due to each R-C stage loading the previous ones. The calculations are greatly simplified by setting all the resistors (except the negative feedback resistor) and all the capacitors to the same values. In the diagram, if $R_1 = R_2 = R_3 = R$, and $C_1 = C_2 = C_3 = C$, then:

$$f_{oscillation} = \frac{1}{2\pi RC \sqrt{6}}$$

and the oscillation criterion is:

$$R_{feedback} = 29 \cdot R$$

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1) **High gain for +feedback cancellation**

2) $180^\circ + 60^\circ + 60^\circ + 60^\circ = 360^\circ$

   - **Music Tremolo**
   - **Flasher**

Without the simplification of all the resistors and capacitors having the same value, the calculations become more complex:
Summary

(A) Inverting amp.

(B) Noninverting amp.

(C) Voltage follower.

(D) Summer.

(E) Integrator.

(F) Differential-input amp.