Operational Amplifiers (op amps) are important building blocks for amplifiers, unity-gain buffer and active filters. They come in small IC chips and can be very handy for various signal conditioning circuitry. Typical IC pin layout is similar to LM741 (DIP package) as shown in Fig.1.

Here are some tips in selecting op amps and constructing op amp circuits:

- Determine whether a single power supply or dual power supply is required for the given application. For example, OP741 or LM741 requires dual power supply of +/-15 V, while MCP-6001, TLV2774 or LM124 can be operated using a single power supply at low voltage such as 5 V. Therefore, the availability of the power supply is a major consideration.
- Single supply op amps sometimes are referred to as rail-to-rail op amps because their output voltage can be very close to the power rail. For example, LM124 can reach the ground rail, but cannot quite reach the Vcc rail, but it is relatively cheap. TLV2774 is more expensive, but can reach both rails very closely. In dual supply op amps such as 741, you can at most reach a couple volts below both of the rails before the internal transistors driven into saturation.
- Using single supply op amps (such as powered by 0 and 5V) requires simpler power supply, but usually requires more complex setup due to limited polarity at the output voltage. To solve this issue, virtual ground (middle of the two power rails) is usually added to handle the negative signal swing. As an example, an inverting amplifier circuit can be set up using virtual ground of $\frac{V_{cc}}{2}$ at “+” pin. It is compared to a same function circuit using a dual supply op amp in Fig.2. The output AC signal is the same, except in the case of single supply op amp with virtual ground, the output voltage is shifted with a $\frac{V_{cc}}{2}$ offset voltage.
Fig. 2  Inverting amplifier using (a) single supply op amp with virtual ground and (b) dual supply op amp

- Keep in mind that the output voltage signal cannot exceed the power supply (power rail) range. The output current of op amp should also be within the current limit. These limits are important when choosing the gain of amplifier and the output loads. Some op amps have built-in protection for over-current conditions such as OPA551, which is also designed to shut down under over-thermal conditions.
- To minimize noise, always put capacitors of 0.1uF and 10uF in parallel between the power pins of the op amp and the ground. Keep the caps as close to power pins as possible.
- If multiple op amps are required in a circuit, an op amp IC with dual or quad devices provides more compact setup. For example MCP-6004 contains 4 op amps and belongs to the same family as MCP-6001; LM124 and LM 324 family is designed to be a quad op amp package.

There are standard configurations for op amps based amplifiers and active filters. Based on the requirement, choose a proper configuration and component values to set the gain and corner frequency. For your reference, here are some of the most commonly used configurations. If the circuit is implemented using single supply op amp, then virtual ground could be introduced properly to handle the negative signal swing if needed.

(1) Inverting amplifier

- The output is 180° out of phase from the input signal.
- When putting multiple stages together, keep in mind that the input impedance of the inverting amplifier is $R_1$.
- It can be used to provide gain or scale down the input signal.
- Replace “+” of op amp with virtual ground if a single supply op amp is used.

\[
\frac{v_0}{v_i} = -\frac{R_f}{R_1}
\]

Fig. 3 Inverting amplifier configuration

(2) Non-inverting amplifier

- The output voltage is in phase with the input voltage.
- The gain is larger than 1, so this cannot be used for scaling down the signal.
- The input impedance of non-inverting amplifier is better than the inverting amplifier because the op amp “+” pin does not take current.
- Replace the left node of R_1 with virtual ground if a single supply op amp is used.

\[
\frac{v_0}{v_i} = 1 + \frac{R_f}{R_1}
\]

Fig. 4 Non-inverting amplifier configuration
(3) Unity-gain buffer

- This is a special case of non-inverting amplifier where $R_f = 0, R_1 = \infty$.
- The gain of the buffer is 1, and this is often used to isolate systems because of its infinite input impedance and zero output impedance. This can be useful in cascading systems that otherwise would affect or load each other.
- If a single supply op amp is used, add a virtual ground at “+” and AC couple the input signal so it is shifted up by $\frac{V_{\infty}}{2}$ at “+” node.

![Fig.5 Unity-gain buffer configuration](image)

(4) Instrumentation amplifier

- In applications where differential signal is desired (for example, to eliminate the common mode large noise), instrumentation amplifier can be very useful configuration. A1 and A2 creates unity-gain buffer for minimized input loading effect, and the difference amplifier in A3 allows for the output voltage to be related to difference of input voltages. The gain can be set by two different pairs of resistance ratios.

![Fig.6 Instrumentation amplifier configuration](image)

$$v_0 = \frac{R_2}{R_1} \left(1 + \frac{2R_3}{R_4}\right)(v_2 - v_1)$$

Fig.6 Instrumentation amplifier configuration
(5) First order low pass filter (LPF) and high pass filter (HPF)

- First order active filters are built from RC and OpAmp circuit. The inverting configuration can be used to create inverting LPF (a) or HPF (b) as shown, where the output voltage is 180° out of phase with the input at pass-band. The passband gain is determined by the ratio of resistors.

\[ H(j\omega) = \frac{V_o}{V_i} = \frac{-R_f/R_i}{1+j\omega R_f C_f} \]  
\[ H(j\omega) = \frac{V_o}{V_i} = \frac{-R_i}{1+j\omega R_i C_i} \]

Fig.7 Inverting first-order Low Pass Filter (LPF) and High Pass Filter (HPF)

- Non-inverting LPF (c) and HPF (d) can be constructed using a simple RC filter in combination of non-inverting amplifier as shown. The pass-band gain can be adjusted as that of non-inverting amplifier.

\[ H(j\omega) = \frac{V_o}{V_i} = \frac{-1}{1+j\omega R_1 C_1} \left( 1 + \frac{R_2}{R_3} \right) \]  
\[ H(j\omega) = \frac{V_o}{V_i} = \frac{j\omega R_1 C_1}{1+j\omega R_1 C_1} \left( 1 + \frac{R_2}{R_3} \right) \]

Fig.8 Non-inverting first order LPF and HPF

(6) Sallen-key configuration for 2nd order LPF and HPF

- Sallen-Key configuration is a commonly used to build 2nd order active filters. The same topology can be designed to build butterworth filters,
Tschebyscheff filters and Bessel filters, each optimized for different characteristics such as flatness in passbands, sharpness in cut off and linearity in phase.

- LFP and HFP Sallen-Key topology simply switch the relative R and C positions.
- This configuration in combination of 1\textsuperscript{st} order filters can be used in cascade to build higher order filters.

\[ H(j\omega) = \frac{V_0}{V_i} = \frac{1}{-\omega^2(R_1R_2C_1C_2 + j\omega(R_1+R_2)C_1) + 1} \]

Fig 9 2\textsuperscript{nd} order Sallen Key configuration LPF

Reference: