**OPAMPS** (Operational Amplifiers)

An **OPAMP** is a circuit (usually an IC) that acts as a voltage-controlled voltage source.

We can do with OPAMPS as well as making microphone amplifiers.

![Non-ideal OPAMP model](image)

The controlling voltage is a differential voltage across $V_1 + V_2$

$V_d = V_2 - V_1$

- Open loop gain $(A_{op} > 1 \times 10^6)$ (we almost never use it open loop)

$A_{op} = A_{d} = A(V_2 - V_1)$

- So open loop gain is the gain of the opamp without any external feedback voltage gain from output to input.

Modern OPAMPS are in many ways nearly ideal.

- $R_i = 1 - 10 T \Omega$ ($T = 1 \times 10^{12}$)
- $A = 2 - 4 \times 10^6$
- $R_o < 10 \Omega$

"Ideal" can be applied to many other parameters:

- noise, distortion, input offset voltage, bandwidth, PSRR, etc.

- We will stick to $R_i$, $A$, $R_o$

Inputs applied to the "-" terminal will appear with the opposite polarity at the output

A basic idea of how output moves with input change

Inputs applied to the non-inverting "+" input will appear with the same polarity at the output.
Why is $\infty$ input resistance & $\phi$ output resistance such a big deal? Imagine a source driving an amplifier and that amplifier driving a load in the non-ideal case.

\[
\text{INPUT: } V_2 - V_1 = V_s \left( \frac{-R_i}{R_s + R_i} \right) \quad \text{VOLTAGE DIVIDERS}
\]

\[
\text{OUTPUT: } V_{\text{out}} = A(V_2 - V_1) \left( \frac{R_L}{R_L + R_o} \right) \quad \text{if } R_i \to \infty + R_o \to 0, \text{ we have a much better situation.}
\]

\[
\frac{A_v}{V_s} = A \left( \frac{-R_i}{R_s + R_i} \right) \left( \frac{R_L}{R_L + R_o} \right) \quad \text{gain becomes dependent upon the source resistance & load resistance.}
\]

* Ideally we want our voltage amplifiers to minimize ($R_i \to \infty, I_{in} \to 0$) input resistive 'loading' so the full source output voltage is available to the amplifier.

* Also we want the voltage amplifier output to be immune to low values of load resistance, allowing the full gain of the amplifier to be used. ($R_o \to \phi$)
For our work we will assume ideal opamps.

Ideal opamps will have the following characteristics when operating close to loop:

- \( i_1 = i_2 = 0 \) (zero input current \( \Rightarrow R_e = \infty \))
- \( V_o = V_2 - V_1 = 0 \) (close loop)
  thus \( V_1 = V_2 \)
- \( R_o = \infty \)
- \( A = \infty \) (infinite voltage gain)

This greatly simplifies analysis!

Why can we assume \( V_1 = V_2 \) ?

- The amplifier cannot force this!
- We enforce this action via negative feedback (output to inverting input)

This path makes it close loop feedback ratio of \( V_o/V_i \) now insensitive to \( A \).

\[
V_o = A_v o (V_2 - V_1)
\]

Open loop only

If \( V_{in} \) goes up \( V_{out} \) goes up until \( V_1 = V_{in} \). Then \( V_{out} \) stops. Equilibrium.

If \( V_{in} \) goes negative \( V_{out} \) goes downward until \( V_{out} = V_1 \).

* Negative feedback makes the opamp output to move in such a way to force the input terminals to the same voltage. That is why we can say \( V_1 = V_2 \)!

Another reason:
Also, the output voltage cannot exceed the supply voltage. If the voltage between the terminals exceed \( \pm 4 \mu V \), the amplifier will be "against the rails" (clipping). We must stay in the linear region.

For our circuits, we assume operation in the linear region.
INVERTING AMPLIFIER

Find the circuit gain \( Av = \frac{V_o}{V_i} \) and the equation for \( V_o \)

KCL @ inverting terminal: \( \frac{V_i - V_1}{R_1} - \frac{V_2 - V_o}{R_f} = 0 \)

because \( I_1 = I_2 = 0 \)

\( R_1(V_1 - V_0) - R_f(V_i - V_1) = 0 \) and since \( V_2 = V_2 = 0 \)

\( -R_1V_0 - R_fV_i = 0 \)

\( \frac{V_o}{V_i} = -\frac{R_f}{R_1} \)

\( \frac{-R_f}{R_1} \) is the circuit voltage gain \( Av \) where \( Av = \frac{\Delta V_o}{\Delta V_i} \)

Output voltage out of phase 180° with the input: \( V_o = -V_i \frac{R_f}{R_1} \)

- The minus sign indicates that the amplifier induces a 180° phase change.
- The gain is seen to be dependent only upon the external components.
- Input resistance to the amplifier is \( R_1 \). This may limit the usefulness in high gain situations where \( R_1 \) may be small.
- Gain of the amplifier is relatively independent of \( V_o \).
- Node \( V_1 \) is often called the "virtual ground". It is kept at OV while not being connected to ground.
- Equivalent circuit from above:
NON-INVERTING AMPLIFIER

First equation for $V_0$:

KCL at $V_1$:

$$ \frac{V_0 - V_i}{R_F} = \frac{V_i}{R_1} $$

but $V_i = V_2 = V_i$ so

$$ \frac{V_0 - V_i}{R_F} = \frac{V_i}{R_1} $$

$$ R_1 (V_0 - V_i) = R_F V_i $$

$$ R_1 V_0 - R_1 V_i = R_F V_i $$

$$ R_1 V_0 = R_F V_i + R_1 V_i $$

$$ V_0 = V_i \left( \frac{R_F + R_1}{R_1} \right) = \frac{V_i (1 + \frac{R_F}{R_1})}{R_1} $$

Gain Equation ($A_v$):

$$ A_v = \left(1 + \frac{R_F}{R_1}\right) $$

This amplifier has a very high input impedance.

Note if $R_1 \to \infty$ or $R_F \to 0$, $A_v = 1$, called (VOLTAGE FOLLOWER or UNITY GAIN BUFFER)

Voltage follower

Good as intermediate "buffer" amplifier. Current gain = $\infty$, Voltage gain = 1
**SUMMING AMPLIFIER (OPAMP)**

\[ \begin{align*}
    V_A & \rightarrow R_1 \rightarrow i_1 \\
    V_B & \rightarrow R_2 \rightarrow i_2 \\
    V_C & \rightarrow R_3 \rightarrow i_3 \\
    \text{RF} & \rightarrow i_f \\
\end{align*} \]

\[ \text{KCL at V}_1: \ i_1 + i_2 + i_3 = i_f \]

with \( i_1 = \frac{V_A - V_i}{R_1} \)

\( i_2 = \frac{V_B - V_i}{R_2} \)

\( i_3 = \frac{V_C - V_i}{R_3} \)

\[ i_f = \frac{V_A - V_0}{RF} \]

With feedback closed, \( V_i = 0 \) this results in the following:

\[ \frac{V_A}{R_1} + \frac{V_B}{R_2} + \frac{V_C}{R_3} = \frac{-V_0}{RF} \]

\[ V_0 = -\left(V_A \left(\frac{RF}{R_1}\right) + V_B \left(\frac{RF}{R_2}\right) + V_C \left(\frac{RF}{R_3}\right)\right) \]

- Output is a weighted sum of inputs
**DIFFERENCE AMPLIFIER - OPAMP**

\[ V_0 = -\left(\frac{R_F V_A - R_F V_B \left(\frac{R_3}{R_2+R_3}\right) - R_F V_E \left(\frac{R_2}{R_2+R_3}\right)}{R_1}\right) \]

\[ = -V_A \left(\frac{R_F}{R_1}\right) + V_B \frac{R_F R_3}{R_1 (R_2+R_3)} + V_E \frac{R_2}{R_1 (R_2+R_3)} \]

If \( \frac{R_1}{R_F} = \frac{R_2}{R_3} \), then \( V_0 = -\frac{R_F}{R_1} (V_B - V_A) \)

- This amplifier does not respond to common mode signals.
- "Common mode" = same signal on each input.
  Gives excellent noise rejection.
LMC660
CMOS Quad Operational Amplifier

General Description
The LMC660 CMOS Quad operational amplifier is ideal for operation from a single supply. It operates from +5V to +15.5V and features rail-to-rail output swing in addition to an input common-mode range that includes ground. Performance limitations that have plagued CMOS amplifiers in the past are not a problem with this design. Input $V_{\text{CM}}$, drift, and broadband noise as well as voltage gain into realistic loads (2 kΩ and 600Ω) are all equal to or better than widely accepted bipolar equivalents.

This chip is built with National’s advanced Double-Poly Silicon-Gate CMOS process.

See the LMC662 datasheet for a dual CMOS operational amplifier with these same features.

Features
- Rail-to-rail output swing
- Specified for 2 kΩ and 600Ω loads
- High voltage gain: 126 dB
- Low input offset voltage: 3 mV
- Low offset voltage drift: 1.3 µV/°C
- Ultra low input bias current: 2 fA
- Input common-mode range includes V–
- Operating range from +5V to +15.5V supply
- $I_{\text{SS}} = 375$ µA/amplifier; independent of V–
- Low distortion: 0.01% at 10 kHz
- Slew rate: 1.1 V/µs

Applications
- High-impedance buffer or preamplifier
- Precision current-to-voltage converter
- Long-term integrator
- Sample-and-Hold circuit
- Peak detector
- Medical instrumentation
- Industrial controls
- Automotive sensors

Connection Diagram

LMC660 Circuit Topology (Each Amplifier)
### DC Electrical Characteristics (Continued)

Unless otherwise specified, all limits guaranteed for $T_J = 25^\circ C$. **Boldface** limits apply at the temperature extremes. $V^* = 5V$, $V^- = 0V$, $V_{CM} = 1.5V$, $V_O = 2.5V$ and $R_L > 1\text{M}\Omega$ unless otherwise specified.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>Typ (Note 4)</th>
<th>LMC660AI Limit (Note 4)</th>
<th>LMC660C Limit (Note 4)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Swing</td>
<td>$V^* = 5V$</td>
<td>4.87</td>
<td>4.82</td>
<td>4.78</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>$R_L = 2 \text{k}\Omega$ to $V^*/2$</td>
<td>0.10</td>
<td>0.15</td>
<td>0.19</td>
<td>min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.17</td>
<td>0.21</td>
<td></td>
<td>max</td>
</tr>
<tr>
<td></td>
<td>$V^* = 5V$</td>
<td>4.61</td>
<td>4.41</td>
<td>4.27</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>$R_L = 600\Omega$ to $V^*/2$</td>
<td>0.30</td>
<td>0.50</td>
<td>0.63</td>
<td>min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.56</td>
<td>0.69</td>
<td></td>
<td>max</td>
</tr>
<tr>
<td></td>
<td>$V^* = 15V$</td>
<td>14.63</td>
<td>14.50</td>
<td>14.37</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>$R_L = 2 \text{k}\Omega$ to $V^*/2$</td>
<td>0.26</td>
<td>0.35</td>
<td>0.44</td>
<td>min</td>
</tr>
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<td></td>
<td>0.40</td>
<td>0.48</td>
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<td>max</td>
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<td></td>
<td>$V^* = 15V$</td>
<td>13.90</td>
<td>13.35</td>
<td>12.92</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>$R_L = 600\Omega$ to $V^*/2$</td>
<td>0.79</td>
<td>1.16</td>
<td>1.45</td>
<td>min</td>
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<td></td>
<td></td>
<td>1.32</td>
<td>1.58</td>
<td></td>
<td>max</td>
</tr>
<tr>
<td>Output Current</td>
<td>Sourcing, $V_O = 0V$</td>
<td>22</td>
<td>16</td>
<td>13</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>11</td>
<td></td>
<td>min</td>
</tr>
<tr>
<td></td>
<td>Sinking, $V_O = 5V$</td>
<td>21</td>
<td>16</td>
<td>13</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
<td>11</td>
<td></td>
<td>min</td>
</tr>
<tr>
<td>Output Current</td>
<td>Sourcing, $V_O = 0V$</td>
<td>40</td>
<td>28</td>
<td>23</td>
<td>mA</td>
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<td></td>
<td></td>
<td>25</td>
<td>21</td>
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<td>min</td>
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<td></td>
<td>Sinking, $V_O = 13V$ (Note 11)</td>
<td>39</td>
<td>28</td>
<td>23</td>
<td>mA</td>
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<td></td>
<td></td>
<td>24</td>
<td>20</td>
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<tr>
<td>Supply Current</td>
<td>All Four Amplifiers</td>
<td>1.5</td>
<td>2.2</td>
<td>2.7</td>
<td>mA</td>
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<td></td>
<td>$V_O = 1.5V$</td>
<td>2.6</td>
<td>2.9</td>
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<td>max</td>
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</table>

### AC Electrical Characteristics

Unless otherwise specified, all limits guaranteed for $T_J = 25^\circ C$. **Boldface** limits apply at the temperature extremes. $V^* = 5V$, $V^- = 0V$, $V_{CM} = 1.5V$, $V_O = 2.5V$ and $R_L > 1\text{M}\Omega$ unless otherwise specified.

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<th>LMC660C Limit (Note 4)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slew Rate</td>
<td>(Note 6)</td>
<td>1.1</td>
<td>0.8</td>
<td>0.8</td>
<td>V/\mu s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6</td>
<td>0.7</td>
<td></td>
<td>min</td>
</tr>
<tr>
<td>Gain-Bandwidth Product</td>
<td></td>
<td>1.4</td>
<td></td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Phase Margin</td>
<td></td>
<td>50</td>
<td></td>
<td></td>
<td>Deg</td>
</tr>
<tr>
<td>Gain Margin</td>
<td></td>
<td>17</td>
<td></td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>Amp-to-Amp Isolation</td>
<td>(Note 7)</td>
<td>130</td>
<td></td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>Input Referred Voltage Noise</td>
<td>$F = 1 \text{kHz}$</td>
<td>22</td>
<td></td>
<td></td>
<td>nV/\sqrt{Hz}</td>
</tr>
<tr>
<td>Input Referred Current Noise</td>
<td>$f = 1 \text{kHz}$</td>
<td>0.0002</td>
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<td></td>
<td>pA/\sqrt{Hz}</td>
</tr>
</tbody>
</table>
Typical Performance Characteristics

$V_{SB} = \pm 7.5V$, $T_A = 25^\circ C$ unless otherwise specified.

Supply Current vs. Supply Voltage

Offset Voltage

Input Bias Current

Output Characteristics Current Sinking

Output Characteristics Current Sourcing

Input Voltage Noise vs. Frequency