Operational Amplifiers

or Op Amps for short
Objective of Lecture

- Describe how an ideal operational amplifier (op amp) behaves.
- Define voltage gain, current gain, transresistance gain, and transconductance gain.
- Explain the operation of an ideal op amp in a voltage comparator and inverting amplifier circuit.
  - Show the effect of using a real op amp.
Op Amps Applications

- Audio amplifiers
  - Speakers and microphone circuits in cell phones, computers, mpg players, boom boxes, etc.
- Instrumentation amplifiers
  - Biomedical systems including heart monitors and oxygen sensors.
- Power amplifiers
- Analog computers
  - Combination of integrators, differentiators, summing amplifiers, and multipliers
Symbols for Ideal and Real Op Amps

OpAmp

uA741

LM111

LM324
Terminals on an Op Amp

- Non-inverting Input terminal
- Inverting input terminal
- Positive power supply (Positive rail)
- Output terminal
- Negative power supply (Negative rail)
Op Amp Equivalent Circuit

\[ v_d = v_2 - v_1 \]

A is the open-loop voltage gain

Voltage controlled voltage source
## Typical Op Amp Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Typical Ranges</th>
<th>Ideal Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-Loop Voltage Gain</td>
<td>A</td>
<td>$10^5$ to $10^8$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>Ri</td>
<td>$10^5$ to $10^{13}$ $\Omega$</td>
<td>$\infty$ $\Omega$</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>Ro</td>
<td>10 to 100 $\Omega$</td>
<td>0 $\Omega$</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>Vcc/V+</td>
<td>5 to 30 V</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>-Vcc/V-</td>
<td>-30V to 0V</td>
<td>N/A</td>
</tr>
</tbody>
</table>
How to Find These Values

- Component Datasheets
  - Many manufacturers have made these freely available on the internet
  - Example: LM 324 Operational Amplifier
LM124/LM224/LM324/LM2902
Low Power Quad Operational Amplifiers

General Description
The LM124 series consists of four independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage.

Application areas include transducer amplifiers, DC gain blocks and all the conventional op amp circuits which now can be more easily implemented in single power supply systems. For example, the LM124 series can be directly operated off of the standard +5V power supply voltage which is used in digital systems and will easily provide the required interface electronics without requiring the additional ±15V power supplies.

Unique Characteristics
- In the linear mode the input common-mode voltage range includes ground and the output voltage can also swing to within ±0.2 V of the supply terminals.

Advantages
- Eliminates need for dual supplies
- Four internally compensated op amps in a single package
- Allows direct sensing near GND and V_OUT also goes to GND
- Compatible with all forms of logic
- Power drain suitable for battery operation

Features
- Internally frequency compensated for unity gain
- Large DC voltage gain 100 dB
- Wide bandwidth (unity gain) 1 MHz (temperature compensated)
- Wide power supply range:
  - Single supply 3V to 32V
  - Dual supplies ±1.5V to ±16V
- Very low supply current drain (700 µA)—essentially independent of supply voltage
- Low input biasing current, 45 pA
dB

- Decibels

Since $P = \frac{V^2}{R}$

$$10 \log \left( \frac{P}{P_{\text{ref}}} \right) \text{ or } 20 \log \left( \frac{V}{V_{\text{ref}}} \right)$$

In this case:

$$20 \log \left( \frac{V_o}{V_{\text{in}}} \right) = 20 \log (A) = 100$$

$A = 10^5 = 100,000$
### Electrical Characteristics

V* = +5.0V, (Note 7), unless otherwise stated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conditions</th>
<th>LM124A</th>
<th>LM224A</th>
<th>LM324A</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Offset Voltage</td>
<td>(Note 8) T_A = 25°C</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>mV</td>
</tr>
<tr>
<td>Input Bias Current (Note 9)</td>
<td>I_{IN(+) or I_{IN(-)}, V_{CM} = 0V, T_A = 25°C}</td>
<td>20</td>
<td>50</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Input Offset Current</td>
<td>I_{IN(+) or I_{IN(-)}, V_{CM} = 0V, T_A = 25°C}</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>Input Common-Mode Voltage Range</td>
<td>(Note 10) V* = 30V, (LM2902, V* = 26V), T_A = 25°C</td>
<td>0</td>
<td>V*&lt;1.5</td>
<td>0</td>
<td>V*&lt;1.5</td>
</tr>
<tr>
<td>Supply Current</td>
<td>Over Full Temperature Range R_L = ∞ On All Op Amps V* = 30V (LM2902 V* = 26V) V* = 5V</td>
<td>1.5</td>
<td>3</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>Large Signal Voltage Gain</td>
<td>V* = 15V, R_L ≥ 2kΩ, (V_O = 1V to 11V), T_A = 25°C</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Common-Mode</td>
<td>DC, V_{CM} = 0V to V* – 1.5V,</td>
<td>70</td>
<td>85</td>
<td>70</td>
<td>85</td>
</tr>
</tbody>
</table>

www.national.com
Large Signal Voltage Gain = A

- Typical
  - $A = 100 \text{ V/mV} = 100\text{V}/0.001\text{V} = 100,000$

- Minimum
  - $A = 25 \text{ V/mV} = 25 \text{V}/0.001\text{V} = 25,000$
Caution – A is Frequency Dependent

Modifying Gain in Pspice OpAmp

- Place part in a circuit
- Double click on component
- Enter a new value for the part attribute called GAIN
OrCAD Schematics
Open Circuit Output Voltage

\[ v_o = A \, v_d \]

- Ideal Op Amp

\[ v_o = \infty \, (v_d) \]
Open Circuit Output Voltage

- Real Op Amp

<table>
<thead>
<tr>
<th></th>
<th>Voltage Range</th>
<th>Output Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Saturation</td>
<td>$A v_d &gt; V^+$</td>
<td>$v_o \sim V^+$</td>
</tr>
<tr>
<td>Linear Region</td>
<td>$V^- &lt; A v_d &lt; V^+$</td>
<td>$v_o = A v_d$</td>
</tr>
<tr>
<td>Negative Saturation</td>
<td>$A v_d &lt; V^-$</td>
<td>$v_o \sim V^-$</td>
</tr>
</tbody>
</table>

The voltage produced by the dependent voltage source inside the op amp is limited by the voltage applied to the positive and negative rails.
Voltage Transfer Characteristic

Range where we operate the op amp as an amplifier.

slope = $A v_d$
Ideal Op Amp

Because $R_i$ is equal to $\infty \Omega$, the voltage across $R_i$ is $0V$.

$v_1 = v_2$

$v_d = 0 V$

$i_1 = 0$

$i_2 = 0$
Almost Ideal Op Amp

- $R_i = \infty \ \Omega$
  - Therefore, $i_1 = i_2 = 0 \ A$
- $R_o = 0 \ \Omega$
- Usually, $v_d = 0V$ so $v_1 = v_2$
  - The op amp forces the voltage at the inverting input terminal to be equal to the voltage at the noninverting input terminal if there is some component connecting the output terminal to the inverting input terminal.
- Op amp circuits are limited to $V^- < v_o < V^+$.
  - The output voltage is allowed to be as positive or as negative as needed to force $v_d = 0V$ up to those limits.
Example #1: Voltage Comparator

Note that the inverting input and non-inverting input terminals have rotated in this schematic.
Example #1 (con’t)

- The internal circuitry in the op amp tries to force the voltage at the inverting input to be equal to the non-inverting input.
  - As we will see shortly, a number of op amp circuits have a resistor between the output terminal and the inverting input terminals to allow the output voltage to influence the value of the voltage at the inverting input terminal.
Example #1: Voltage Comparator

When $V_s$ is equal to 0V, $V_o = 0V$.
When $V_s$ is smaller than 0V, $V_o = V^+$.
When $V_s$ is larger than 0V, $V_o = V^-$.
Electronic Response

- Given how an op amp functions, what do you expect $V_o$ to be if $v_2 = 5V$ when:
  1. $V_s = 0V$?
  2. $V_s = 5V$?
  3. $V_s = 6V$?
Example #2: Closed Loop Gain

\[ i_2 = 0 \]

\[ v_1 = v_2 \]

\[ i_1 = 0 \]

\[ i_f \]
Example #2 (con’t)

For an almost ideal op amp, \( R_i = \infty \Omega \) and \( R_o = 0 \Omega \). The output voltage will never reach \( V^+ \) or \( V^- \).
Example #2 (con’t)

The op amp outputs a voltage $V_0$ such that $V_1 = V_2$. 

Virtual ground
Example #2 (con’t)
Example #2: Closed Loop Gain

\[ v_1 = 0V \]
\[ V_S = R_1 i_s \]
\[ v_o = -R_f i_f \]
\[ i_s = i_f = i \]
\[ v_o / V_s = -R_f / R_1 \]
\[ A_V = -R_f / R_1 \]

This circuit is known as an inverting amplifier.
Types of Gain
# Types of Closed Loop Gain

<table>
<thead>
<tr>
<th>Gain</th>
<th>Variable Name</th>
<th>Equation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Gain</td>
<td>$A_V$</td>
<td>$v_o/v_s$</td>
<td>None or V/V</td>
</tr>
<tr>
<td>Current Gain</td>
<td>$A_I$</td>
<td>$i_o/i_s$</td>
<td>None or A/A</td>
</tr>
<tr>
<td>Transresistance Gain</td>
<td>$A_R$</td>
<td>$v_o/i_s$</td>
<td>V/A or Ω</td>
</tr>
<tr>
<td>Transconductance Gain</td>
<td>$A_G$</td>
<td>$i_o/v_s$</td>
<td>A/V or Ω⁻¹</td>
</tr>
</tbody>
</table>
Example #3: Closed Loop Gain with Real Op Amp
Example #3 (con’t)

\[ i_s = i_1 + i_f \]
\[ i = i_f \]
\[ -i_1 = i_2 \]
\[ v_d = v_2 - v_1 = R_i (-i_1) = R_i (i_2) \]
\[ V_o = A v_d - R_o(-i) \]
\[ V_s = R_1(i_s) - v_d \]
\[ V_s = R_1(i_s) + R_f(i_f) + V_o \]

\[ \frac{V_o}{V_s} = (-R_f/R_1)\{A\beta/[1 +A\beta]\}, \text{ where } \beta = R_1/(R_1+R_f) \]
Summary

- The output of an ideal op amp is a voltage from a dependent voltage source that attempts to force the voltage at the inverting input terminal to equal the voltage at the non-inverting input terminal.
  - Almost ideal op amp: Output voltage limited to the range between $V^+$ and $V^-$.
- Ideal op amp is assumed to have $R_i = \infty \Omega$ and $R_o = 0 \Omega$.
  - Almost ideal op amp: $v_d = 0$ V and the current flowing into the output terminal of the op amp is as much as required to force $v_1 = v_2$ when $V^+ < v_o < V^-$. 
- Operation of an op amp was used in the analysis of voltage comparator and inverting amplifier circuits.
  - Effect of $R_i < \infty \Omega$ and $R_o > 0 \Omega$ was shown.