Operational Amplifier

- The Operational Amplifier (also: op amp, opamp, OPAMP) is a versatile building block of analog design.
- Op amps have been around since the 1940’s and are still very widely used today.
- The OPAMP has a differential-input and a singled-ended output (outputs can be differential too).
- The OPAMP amplifies the voltage difference between the inverting and non-inverting inputs.

![OPAMP schematic symbol](image)

**Figure:** OPAMP schematic symbol

- The schematic symbol may or may not have $V_{cc}$ and $V_{ee}$ pins shown depending upon the application.
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- The output voltage (unloaded) is the difference between the inputs multiplied by the OPAMP gain. \( V_o = AV_d = A(v_1 - v_2) \). This however is in the open loop (no feedback) situation.
- The gain \( A_d \) of the OPAMP is typically in excess of \( 10^6 \)! This value \( A_d \) is called the open-loop gain. The OPAMP is almost never used without negative feedback due to the extremely high gain.
- The OPAMP’s input resistance \( R_i \) is typically \( \geq 2 \times 10^9 \) ohms, and its output impedance \( R_o \) is typically \( \leq 25 \) ohms!
- Modern op amps very closely approximate an ideal differential amplifier.

![Diagram of OPAMP](image)

**Figure:** Non-ideal OPAMP model (Boyle Model)
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- The ”perfect” description on op amps can be applied to several parameters, but not all at once. You can optimize noise, distortion, input outset voltage, bandwidth, PSRR, CMRR, but not all at once.
- A brief sampling of near perfect op amp parameters:

<table>
<thead>
<tr>
<th>Part</th>
<th>Parameter</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMH6629</td>
<td>-3dB small signal BW = 1GHz</td>
<td>5.00$</td>
</tr>
<tr>
<td>OPA140</td>
<td>$R_{in} = 10^{12}$ (tera) ohms</td>
<td>3.00$</td>
</tr>
<tr>
<td>OPA209</td>
<td>PSRR=$0.055uV/V, G=4 \times 10^6$</td>
<td>2.00$</td>
</tr>
<tr>
<td>LT1115</td>
<td>THD= 0.002% into 600 ohm load</td>
<td>6.50$</td>
</tr>
</tbody>
</table>

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- Inputs applied to the "-" **inverting** terminal appear with the opposite polarity at the output.
- Inputs applied to the "+" **non-inverting** terminal appear with the same polarity at the output.

- How far the output and inputs can transition is limited by the power supply **rails**.
- A 100uV change at the inputs with a gain of $10^6$ would send the output to the supply rails, not 100V!
We will consider the op amp to be ideal:
- Infinite input impedance
- Zero output resistance
- Open loop gain is infinite

This implies:
- Input current at either input terminal is zero.
- Under closed loop conditions, \( V_1 = V_2 \), \( \Rightarrow \) both inputs will be at the same voltage. (super important!)

Why can we say that \( V_1 = V_2 \)? The amplifier cannot force this to happen by itself. We make this happen with negative feedback.

Let’s see how...
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- Resistor $R_f$ applies negative feedback to the op amp making the circuit operate *closed loop*. The value of $R_f$ does not matter in this case, as $R_{in} = \infty$.

Imagine if $V_i$ goes up a little. Then $V_o$ goes up until $V_1 = V_i$, then it stops. Equilibrium in a sense is reached. $V_i = V_o = V_1$.

- If $V_i$ goes down a little, $V_o$ goes down until it equals $V_i$ then it stops.

- Let’s look at some other op amp circuits.
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▶ We will now look at several op amp amplifier circuits. First up is the inverting amplifier. Let’s find the circuit gain $A_v = \frac{V_o}{V_i}$ and the equation for $V_o$.

▶ Writing KCL at the inverting terminal:

$$\frac{V_i - V_1}{R_1} - \frac{V_1 - V_o}{R_f} = 0$$

$R_1(V_1 - V_o) - R_f(V_i - V_1) = 0$ ; cross mult., and since $V_1 = V_2 = 0$

$-R_1 V_o - R_f V_i = 0$

$$\frac{V_o}{V_i} = -\frac{R_f}{R_1} ; \text{ the circuit voltage gain } A_v \text{ is: } -\frac{R_f}{R_1}$$

$$V_o = -V_i \left( \frac{R_f}{R_1} \right) ; \text{ output voltage has } -180^\circ \text{ phase shift}$$
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- Observations about the inverting amplifier:

  - The minus sign in the gain equation tells us that the amplifier exhibits a $-180^\circ$ phase shift.
  - The gain is seen to be independent of the open loop gain and is only dependent on external components.
  - Node $V_1$ is called the *virtual ground*. It is kept at 0V yet it is not connected to ground.
  - Amplifier input resistance is $R_1$.
  - Resistor $R_f$ cannot be arbitrarily small. The op amp must be able to drive the $V_1$ node without excessive loading.
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► The non-inverting amplifier:

Writing KCL at \( V_1 \) to find circuit gain and equation for \( V_o \):

\[
\frac{V_o - V_1}{R_f} = \frac{V_1}{R_1}; \quad KCL \ @ \ V_1, \ but \ V_1 = V_2 = V_i, \ so:
\]

\[
\frac{V_o - V_i}{R_f} = \frac{V_i}{R_1}
\]

\[
R_1(V_o - V_i) = R_f V_i
\]

\[
R_1 V_o - R_1 V_i = R_f V_i
\]

\[
R_1 V_o = R_f V_i + R_1 V_i
\]

\[
V_o = V_i \left( \frac{R_f + R_1}{R_1} \right) = V_i \left( 1 + \frac{R_f}{R_1} \right); \quad \text{and} \quad A_v = \left( 1 + \frac{R_f}{R_1} \right)
\]
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- Observations about the non-inverting amplifier:

- Amplifier input resistance is $\infty$.
- A positive gain equation tells us that the amplifier does not introduce a phase change.
- The gain is independent of open loop gain and dependent only on external components.
- There is no virtual ground. However, $V_1 = V_2$ as the loop is closed.
- Resistors $R_f$ and $R_1$ must still be chosen appropriately.
The degenerate case of the non-inverting amplifier is when $R_1 = \infty$ and $R_f = 0$. In this case $A_v = 1$. $R_f$ could be any practical value.

This is called a voltage follower or unity-gain buffer.

This amplifier has infinite power and current gain and unity voltage gain.
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The summing inverting amplifier:

Writing KCL at $V_1$ to find the equation for $V_o$:

$$i_f = i_1 + i_2 + i_3 ; \text{ where}$$

$$i_1 = \frac{V_a - V_1}{R_1}, \quad i_2 = \frac{V_b - V_1}{R_2}, \quad i_3 = \frac{V_c - V_1}{R_3}, \quad \text{and} \quad i_f = \frac{V_1 - V_o}{R_f}$$

In closed loop, $V_1 = 0$, which results in:

$$\frac{V_a}{R_1} + \frac{V_b}{R_2} + \frac{V_c}{R_3} = -\frac{V_o}{R_f} \quad \text{thus:}$$

$$V_o = - \left[ V_a \left( \frac{R_f}{R_1} \right) + V_b \left( \frac{R_f}{R_2} \right) + V_c \left( \frac{R_f}{R_3} \right) \right] ; \text{ a weighted sum of the inputs}$$
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- So far we have used a power supply with both positive and negative potentials. Sometimes, there is only a single polarity supply source. We will need extra components to implement *single-supply* circuits.
- The additional circuitry biases the op amp output to $0.5V_{cc}$. This allows for maximum input and output voltage swing for a given supply voltage.
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- $R_a$ and $R_b$ bias the non-inverting input to $V_{cc}/2$. Op amp inputs and outputs are all at $V_{cc}/2$!
- The input signal is capacitively coupled to the non-inverting input.
- Power supply noise rejection is missing. Noise on $V_{cc}$ will be coupled to the non-inverting input.
- If the op amp current consumption causes a change on $V_{cc}$, a feedback loop would be formed possibly causing instability or oscillations.

For AC signals, $V_{out} = V_{in}(1+(R_2/R_1))$, when $Xc1 << R_1$
Several bandwidth breakpoints have been created. The choice of the capacitors depends on the desired bandwidth of the amplifier.

\[ BW_1 = \frac{1}{2\pi (R_a || R_b) C_{in}} \; \text{; high-pass} \]

\[ BW_2 = \frac{1}{2\pi R_1 C_1} \; \text{; high-pass} \]

\[ BW_3 = \frac{1}{2\pi R_{load} C_{out}} \; \text{; high-pass} \]

With: \( R_a = R_b = 100K \), \( R_2 = 10K \), \( R_1 = 1K \), \( C_1 = C_2 = C_3 = 1uF \)

\( BW_1 = 3.18 \text{hz} \), \( BW_2 = 159 \text{hz} \) (dominant), \( BW_3 = 16 \text{hz} \)
.title opamp_single_supply.sp
.include LM358.subckt
Vin in gnd ac=1m ; for small signal response
Vcc vcc gnd 12v ; single supply
*.subckt LM358 IN+ IN- VCC VEE OUT ; LM358 pin order
XOPAMP in_pos in_neg vcc gnd opamp_out LM358 ; OPAMP
Cin in in_pos 1uF ; input coupling cap
Ra Vcc in_pos 100K ; biasing resistor
Rb in_pos gnd 100K ; biasing resistor
R1 in_neg cap_tie 1K ; gain setting resistor
C1 cap_tie gnd 1uF ; DC blocking cap
Rf opamp_out in_neg 10K ; gain setting resistor
Cout opamp_out out 1uF ; output coupling cap
Rload out gnd 10K ; lightly loaded
.control
.destroy all ; remove old plots
* printing and color options
.set hcopydevtype=pscript
.set hcopypscolor=true
.set color0=rgb:f/f/f
.set color1=rgb:0/0/0
* small signal analysis
. ac dec 10 1 meg ; 10 pts per decade, 1 hz-1 mhz
.plot 20* log10 (vm(out)/vm(in)) ylabel '20* log (v(out)/v(in))'
.endc
.end

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Figure: Gain of 10 op amp amplifier with all caps 1uF
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- Modifying the amplifier to decouple the tap point on the voltage divider restores some of the power supply noise rejection. The capacitor ($C_{byp}$) needs to be large enough to set the -3dB bandwidth low enough to be effective for the lowest frequencies anticipated to be on $V_{cc}$. A rule of thumb is for $R_a, R_b,$ and $C_{byp}$ to set a pole roughly $1/10$ the -3dB pole for $R1, C1$ or $C_{in}, R_{in}$.
- Gain resistors were changed to offset input bias current errors.

![Non-inverting op amp amplifier with decoupled bias](image)

**Figure:** Non-inverting op amp amplifier with decoupled bias
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- These same technique can be applied to the inverting amplifier.
- The input impedance is 5k ohms.
- Gain resistors were adjusted to offset input bias current errors.

Figure: Inverting op amp amplifier with decoupled bias
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- Split power rails can be synthesized by several means.
- One of the easiest is the TI TLE2426.

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**TLE2426, TLE2426Y**

**THE “RAIL SPLITTER”**

**PRECISION VIRTUAL GROUND**

<table>
<thead>
<tr>
<th>Description</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| 1/2 $V_I$ Virtual Ground for Analog Systems | Excellent Output Regulation
- $-45 \mu V$ Typ at $I_O = 0$ to $-10 mA$
- $+15 \mu V$ Typ at $I_O = 0$ to $+10 mA$

| Self-Contained 3-terminal TO-226AA Package | Low-Impedance Output . . . $0.0075 \Omega$ Typ |
| Micropower Operation . . . $170 \mu A$ Typ, $V_I = 5 V$ | Noise Reduction Pin (D, JG, and P Packages Only) |
| Wide $V_I$ Range . . . $4 V$ to $40 V$ | |
| High Output-Current Capability
  - Source . . . $20 mA$ Typ
  - Sink . . . $20 mA$ Typ | |

**description**

In signal-conditioning applications utilizing a single power source, a reference voltage equal to one-half the supply voltage is required for termination of all analog signal grounds. Texas Instruments presents a precision virtual ground whose output voltage is always equal to one-half the input voltage, the TLE2426 “rail splitter.”
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- You can also "roll your own" rail splitter with an op amp.
- This should look familiar!