Electronics
Operational Amplifier Basics

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Ideal Operational Amplifiers
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Basic Schematic Symbol
Showing power connections
Operational amplifier supply voltage rules
Equivalent circuit
Negative feedback

Ideal Operational Amplifiers
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inverting input
Ideal Operational Amplifiers

- Non-inverting input
- Inverting input
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- Non-inverting input
- Inverting input
- Output

Basic Schematic Symbol
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Ideal Operational Amplifiers

Output is proportional to the difference between the non-inverting and inverting inputs.
Output is proportional to the *difference* between the non-inverting and inverting inputs.

Active device; requires power to work, even though power connections often not shown.
Showing power connections
Showing power connections

\[ V_{supply}^+ \]

non-inverting input

inverting input

output
Showing power connections

\[ V_{\text{supply}^+} \]

non-inverting input

inverting input

\[ V_{\text{supply}^-} \]

output
Showing power connections

Supplies are usually not shown, but must be used.
Operational amplifier supply voltage rules
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\( V_{\text{supply}+} \) is the positive supply.
Operational amplifier supply voltage rules

$V_{\text{supply}^+}$ is the positive supply.

$V_{\text{supply}^-}$ is the negative supply.
Operational amplifier supply voltage rules

$V^{\text{supply}+}$ is the positive supply.

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The output of an op amp can’t go outside the supply voltages.
Operational amplifier supply voltage rules

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The output of an op amp can’t go outside the supply voltages. In fact, you usually can’t get closer than a volt or two from the supplies. These voltage limits are also called rails.

When an op amp hits one of the rails, its output can be called saturated, or we can say the op amp is in saturation.
In a dual supply op amp, typically the positive and negative supplies are similar, such as $\pm$12V.
In a **dual supply** op amp, typically the positive and negative supplies are similar, such as ±12V.

In a **single supply** op amp, often the negative supply is ground.
In a **dual supply** op amp, typically the positive and negative supplies are similar, such as ±12V.

In a **single supply** op amp, often the negative supply is ground.

→ **Single supply op amps** are an exception to the previous rule; you usually can usually get within a few millivolts of the negative supply.
Equivalent circuit
Equivalent circuit

\[ V_{in} \rightarrow \text{Operational amplifier} \rightarrow V_{out} \]
Operational amplifier equivalent circuit
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\[ R_{in} \approx \infty \]
Operational amplifier equivalent circuit

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\[ \Rightarrow R_{in} \approx M\Omega \text{ for real op amps} \]
Operational amplifier equivalent circuit

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\[ R_{out} \approx 0 \]
Operational amplifier equivalent circuit

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Operational amplifier equivalent circuit

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\[ A_v \approx \infty \]
Operational amplifier equivalent circuit

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\[ \rightarrow A_v \approx 10^4 \rightarrow 10^5 \text{ for real op amps} \]
Operational amplifier equivalent circuit

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\[ V_{out} = A_v (V_+ - V_-) \]
Negative feedback
Negative feedback

\[ V_{in} \]
Negative feedback

$V_{in}$

$V_{out}$
Negative feedback

\[ V_{in} \quad \beta \quad V_{out} \]
Op amps are rarely used in the *open-loop* configuration.
Op amps are rarely used in the open-loop configuration.
→ They usually use negative feedback.
Negative feedback

\[ \beta \in (0, 1) \quad \text{→ It is the proportion of the output fed back into the input} \]

If it goes into the inverting input, it is negative feedback.
If it goes into the non-inverting input, it is positive feedback.

\[ R_{in} \approx R_{in} (1 + \beta A) \]
\[ R_{out} \approx R_{out} (1 + \beta A) \]

Gain = \( \frac{1}{\beta} \); i.e. the output depends only on the feedback, not on the op amp characteristics.
Negative feedback

β is called the feedback factor, and $\beta \in (0, 1)$
Negative feedback

\[ \beta \text{ is called the feedback factor, and } \beta \in (0, 1) \]
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Negative feedback

$\beta$ is called the **feedback factor**, and $\beta \in (0, 1)$

→ It is the *proportion* of the output *fed back* into the input

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\[ R_{in} \approx R_{in} (1 + \beta A) \]
\[ R_{out} \approx \frac{R_{out}}{1 + \beta A} \]
Negative feedback

$\beta$ is called the **feedback factor**, and $\beta \in (0, 1)$

→ It is the *proportion* of the output *fed back* into the input

→ If it goes into the inverting input, it is *negative* feedback

→ If it goes into the non-inverting input, it is *positive* feedback

$R_{in} \approx R_{in} (1 + \beta A)$

$R_{out} \approx \frac{R_{out}}{(1+\beta A)}$

$gain = \frac{1}{\beta}$; i.e. the output depends only on the feedback, not on the op amp characteristics
You will virtually *never* use positive feedback!
You will virtually **never** use positive feedback! Note that all of the circuits that follow use negative feedback;
You will virtually never use positive feedback! Note that all of the circuits that follow use negative feedback; (i.e. feedback goes into the inverting input.)
Terminology
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Without feedback is called *open loop* configuration.
Terminology

Without feedback is called *open loop* configuration.
With feedback is called *closed loop* configuration.
Terminology

Without feedback is called *open loop* configuration.
With feedback is called *closed loop* configuration.
The gain without feedback is called *open loop* gain.
Terminology

Without feedback is called *open loop* configuration.
With feedback is called *closed loop* configuration.
The gain without feedback is called *open loop* gain.
The gain with feedback is called *closed loop* gain.
Analyzing Op Amp Circuits; ideal assumptions with closed loop circuits
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No current goes into op amp inputs
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Analyzing Op Amp Circuits; ideal assumptions with closed loop circuits

No current goes into op amp inputs

Inputs are *virtually equal*; i.e. inputs are at the same voltage

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→ i.e. *if the output is not at either of the rails*
Analyzing Op Amp Circuits; ideal assumptions with closed loop circuits

No current goes into op amp inputs.
Inputs are *virtually equal*; i.e. inputs are at the same voltage.
Frequency of input signal doesn’t matter.

**These assumptions only hold if the output is not saturated!**

→ i.e. *if the output is not at either of the rails*

Instead of thinking of the device as an amplifier, you can think the purpose of the device is to keep the inputs equal.
<table>
<thead>
<tr>
<th>Buffer circuit</th>
<th>Inverting amplifier circuit</th>
</tr>
</thead>
</table>

**Buffer (or voltage follower)**
Buffer (or voltage follower)
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\[ V_- = V_{out} \text{ and } V_+ = V_{in} \]
Buffer (or voltage follower)

\[ V_- = V_{out} \text{ and } V_+ = V_{in} \]

\[ V_- \approx V_+ \text{ (virtual equality)} \]
Buffer (or voltage follower)

\[ V_- = V_{out} \text{ and } V_+ = V_{in} \]

\[ V_- \approx V_+ \text{ (virtual equality)} \]

\[ \therefore V_{out} \approx V_{in} \]
Here’s a simulation.
With a large amplitude signal, you can see the rails.
This is a closer look at the positive rail.
This is a closer look at the negative rail.
Inverting amplifier

Many op amp circuits are based on this.
\[ V_+ = 0 \text{ (ground)} \]
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\[ I_f R_f = V_{out} - V_- \]
\[ V_+ = 0 \text{ (ground)} \]
\[ I_f R_f = V_{out} - V_- \]
\[ I_i R_i = V_- - V_{in} \]
$V_+ = 0$ (ground)

$I_f R_f = V_{out} - V_-$

$I_i R_i = V_- - V_{in}$

$V_- \approx V_+$ (virtual equality)
\[ V_+ = 0 \text{ (ground)} \]
\[ I_f R_f = V_{out} - V_- \]
\[ I_i R_i = V_- - V_{in} \]
\[ V_- \approx V_+ \text{ (virtual equality)} \]
\[ I_f = I_i \text{ (no current into inputs)} \]
\[ V_+ = 0 \text{ (ground)} \]
\[ I_f R_f = V_{out} - V_- \]
\[ I_i R_i = V_- - V_{in} \]
\[ V_- \approx V_+ \text{ (virtual equality)} \]
\[ I_f = I_i \text{ (no current into inputs)} \]
\[ \therefore \frac{V_{out} - 0}{R_f} = \frac{0 - V_{in}}{R_i} \]
$$V_+ = 0 \text{ (ground)}$$

$$I_f R_f = V_{out} - V_-$$

$$I_i R_i = V_- - V_{in}$$

$$V_- \approx V_+ \text{ (virtual equality)}$$

$$I_f = I_i \text{ (no current into inputs)}$$

$$\therefore \frac{V_{out} - 0}{R_f} = \frac{0 - V_{in}}{R_i}$$

$$\therefore V_{out} = -\frac{R_f}{R_i} V_{in}$$
Op amp circuit input resistance
Op amp circuit input resistance

Even though the input resistance of an op amp is very large, the input resistance of an op amp circuit may not be.
Op amp circuit input resistance

Even though the input resistance of an op amp is very large, the input resistance of an op amp circuit may not be.

\[ V_{in} \]
Op amp circuit input resistance

Even though the input resistance of an op amp is very large, the input resistance of an *op amp circuit* may not be.

\[ I \approx 0 \]

\[ V_{in} \]
Op amp circuit input resistance

Even though the input resistance of an op amp is very large, the input resistance of an *op amp circuit* may not be.

\[ I \approx 0 \]

\[ V_{in} \]

For the buffer circuit, since the signal goes directly into an op amp input, then the input resistance is very large.
For a circuit like the inverting amplifier, the input signal *doesn’t go directly* into the op amp input.
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\[
V_{in} \quad I_i \quad V_{out} \\
\downarrow \quad R_i \quad R_f \\
\downarrow \quad I_f \quad \Rightarrow \\
\downarrow \quad V_+ \approx V_- = 0
\]
For a circuit like the inverting amplifier, the input signal doesn’t go directly into the op amp input.

It looks more like this.
For a circuit like the inverting amplifier, the input signal *doesn’t* go directly into the op amp input.

\[
I_i = \frac{V_{in}}{R_i}
\]

It looks more like this.
For a circuit like the inverting amplifier, the input signal *doesn’t* go directly into the op amp input.

![Diagram](image)

It looks more like this.

The effective input resistance is $R_i$. 