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Electronic Circuits and Applications

Lesson 10. Operational Amplifier

Learning Contents

1. Introduction
2. Inverting & Non-inverting Amplifier
3. Linear Op-Amp Applications
4. Bias Current and Bandwidth Limitations

Learning Goals

1. Explain basic concepts and definitions of an operational amplifier.
2. Explain fundamental circuits and applications using the operational amplifier.
3. Understand practical limitations of the operational amplifier.

1. Introduction

1.1. Ideal Op-Amp

1.2. Practical Op-Amp

1.3. Block Diagram of an Op-Amp

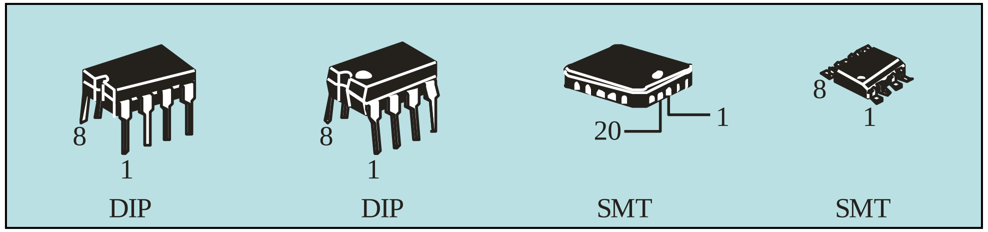
1.4. Signal Modes

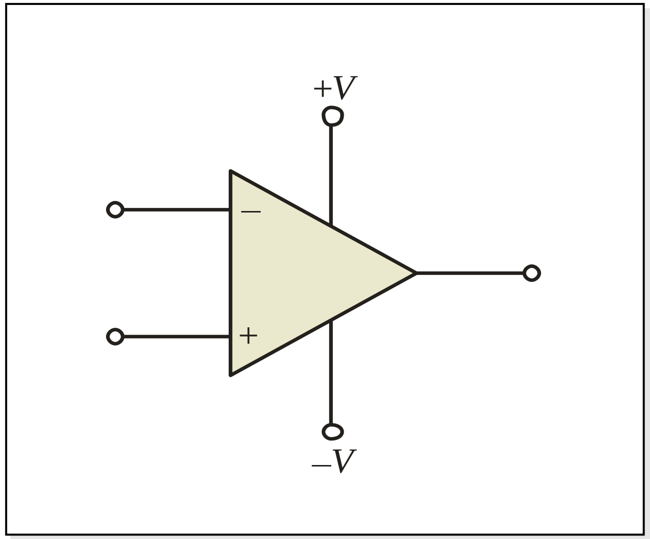
1.5. Parameters

1. Introduction

1.1. Ideal Op-Amp

- **Operational amplifiers (op-amps)** are very high gain dc coupled amplifiers with differential inputs.
- One of the inputs is called the inverting input (-); the other is called the noninverting input. Usually there is a single output.
- Most op-amps operate from plus and minus supply voltages, which may or may not be shown on the schematic symbol.

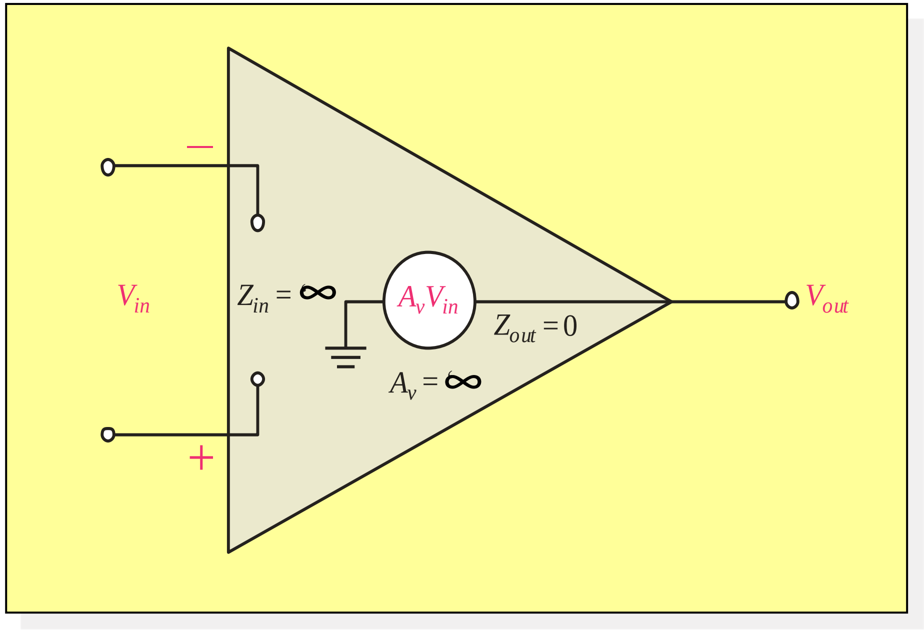




1. Introduction

1.1. Ideal Op-Amp

- Simplify analysis of op-amp circuits.
- Ideally, op-amps have *infinite voltage gain*, *infinite bandwidth*, *infinite input impedance* and *zero output impedance*.



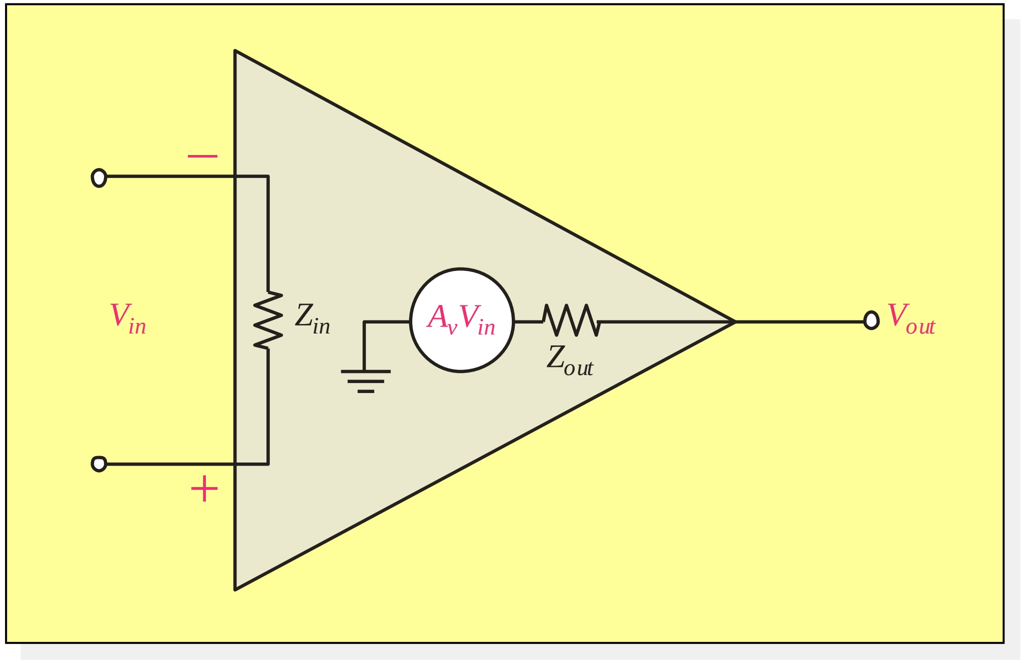
Basic operating principles

1. Negligible current into its inputs
2. Difference between the inputs 0.
3. Limited by what its power supply

1. Introduction

1.2. Practical Op-Amp

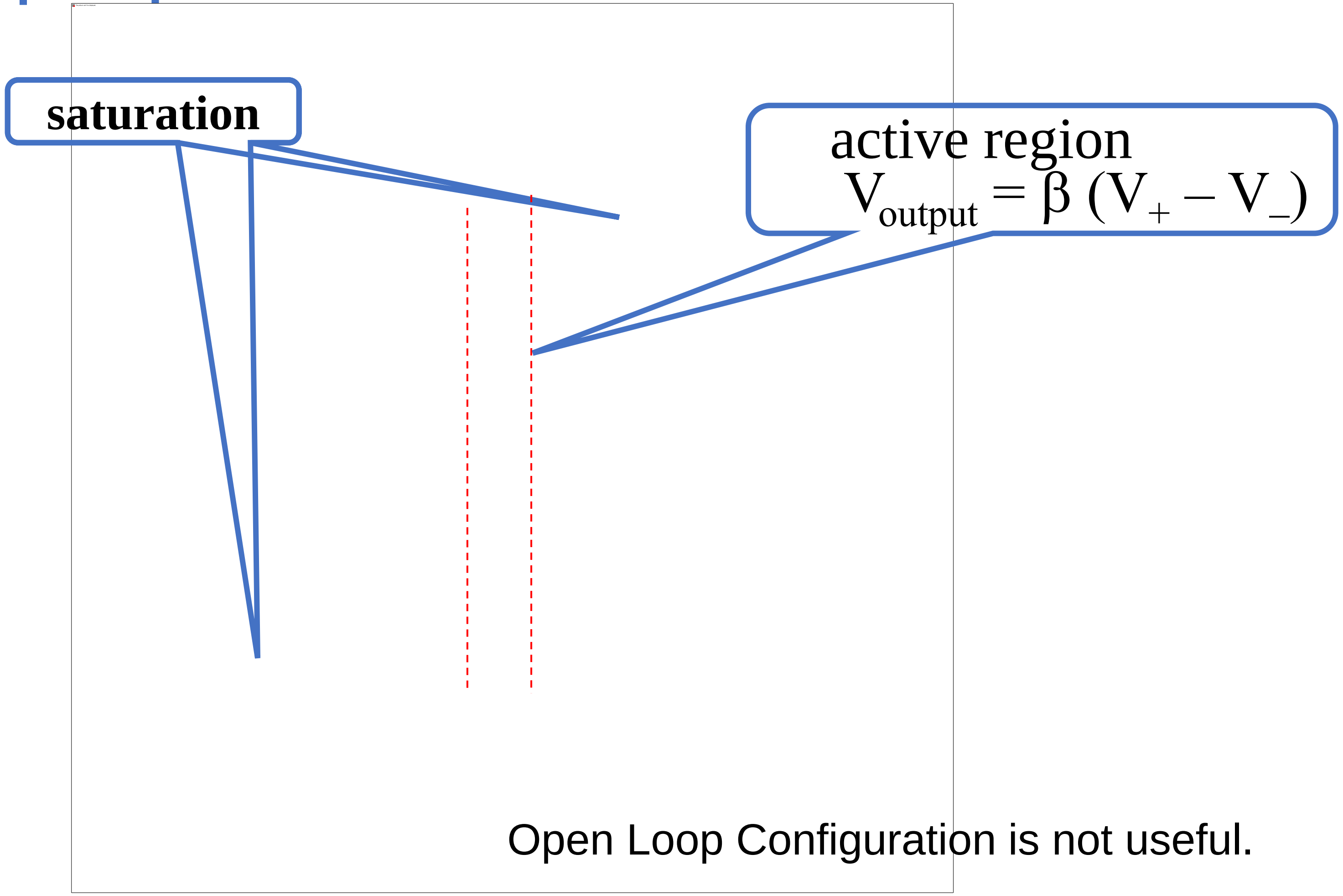
- Practical op-amps have characteristics that often can be treated as ideal for certain situations but can never actually attain ideal characteristics. In addition to finite gain, bandwidth, and input impedance, they have other limitations.



1. Introduction

1.2. Practical Op-Amp

Op Amp transfer characteristic curve



Open Loop Configuration is not useful.

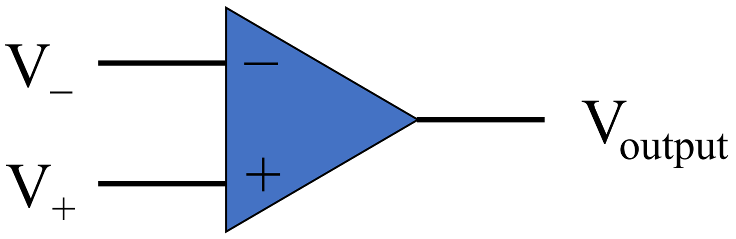
1. Introduction

1.2. Practical Op-Amp

Open Loop Configuration

$$V_{output} = A\,(V_+ - V_-)$$

Gain $A = 10^6$

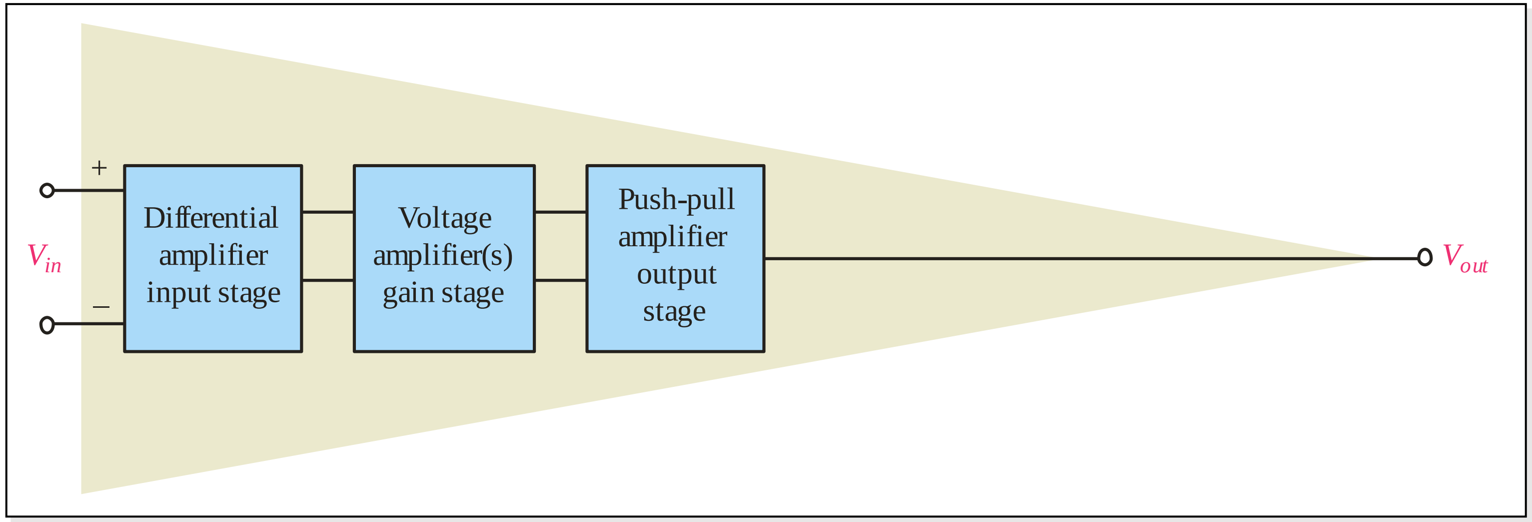


When input difference is 15 µV, the output is 15 V, the power supply maximum.

1. Introduction

1.3. Block Diagram of an Operational Amplifier

- Internally, the typical op-amp has ***a differential input***, ***a voltage amplifier***, and a ***push-pull output***. The differential amplifier amplifies the *difference* in the two inputs.



1. Introduction

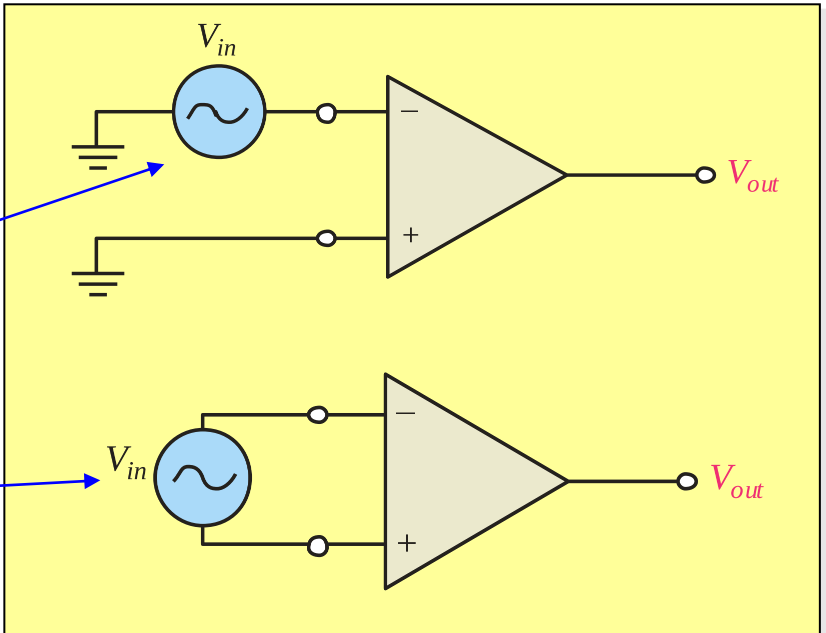
1.4. Signal Modes

- The input signal can be applied to an op-amp in <u>differential-mode</u> or in <u>*common-mode*</u>.

Differential-mode signals are applied either as

<u>single-ended</u> (one side on ground) or

<u>double-ended</u> (opposite phases on the inputs).



Differential signals

1. Introduction

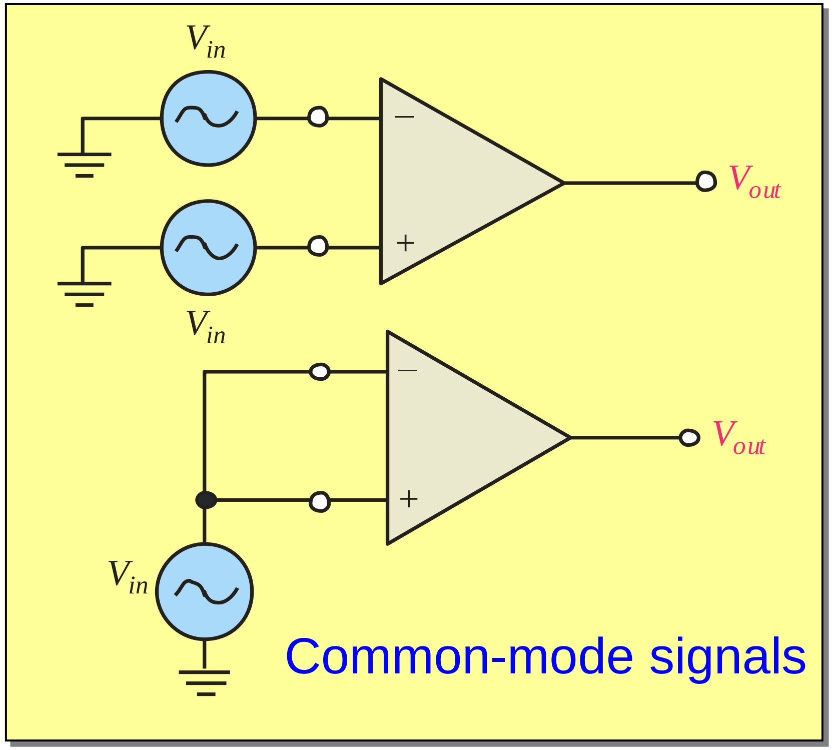
1.4. Signal Modes

- The input signal can be applied to an op-amp in differential-mode or in common-mode.

Common-mode signals are applied to both sides with the same phase on both.

Usually, common-mode signals are from unwanted sources, and affect both inputs in the same way.

The result is that they are essentially cancelled at the output.



1. Introduction

1.4. Signal Modes

Common-Mode Rejection Ratio

- The ability of an amplifier to amplify differential signals and reject common-mode signals is called the **common-mode rejection ratio (CMRR).**

CMRR is defined as $\mathbf{CMRR} = \frac{A_{ol}}{A_{cm}}$

where A_{ol} is the open-loop differential-gain
and A_{cm} is the common-mode gain

CMRR can also be expressed in decibels as $\mathbf{CMRR} = 20\log\left(\frac{A_{ol}}{A_{cm}}\right)$

1. Introduction

1.4. Signal Modes

Common-Mode Rejection Ratio

- **Example:**
  - What is CMRR in decibels for a typical 741C op-amp?
  - The typical open-loop differential gain for the 741C is 200,000 and the typical common-mode gain is 6.3.
- **Solution:**

$$\mathbf{CMRR} = 20\log\left(\frac{A_{ol}}{A_{cm}}\right)$$

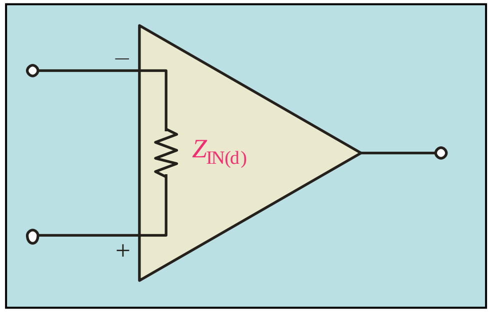
$$= 20\log\frac{200,000}{6.3} = 90\ \text{dB}$$

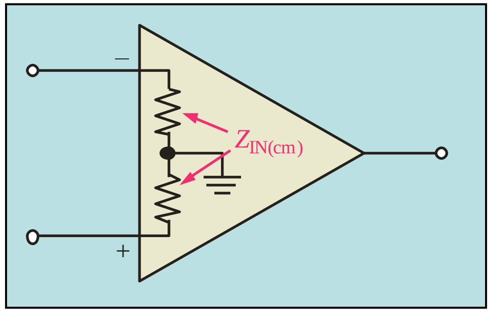
(The minimum specified CMRR is 70 dB)

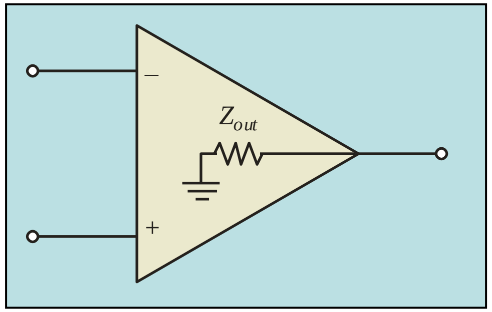
1. Introduction

1.5. Parameters

- $Z_{IN(d)}$: The **differential input impedance** is the total resistance between the inputs
- $Z_{IN(cm)}$: The **common-mode input impedance** is the resistance between each input and ground
- Z_{out}: The **output impedance** is the resistance viewed from the output of the circuit.



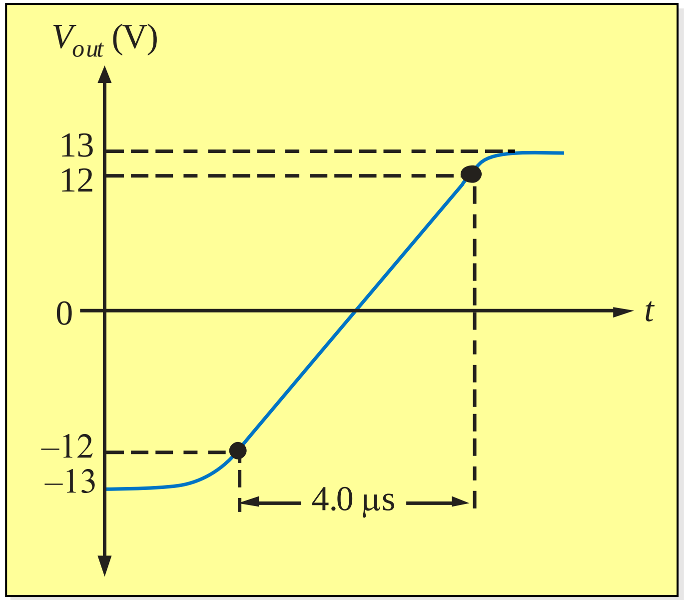




1. Introduction

1.5. Parameters

$$\text{Slew Rate} = \frac{\Delta V_{out}}{\Delta t}$$



- The **slew rate** is the maximum rate of change of the output voltage in response to a step input voltage

- **Example:** Determine the slew rate for the output response to a step input.

- **Solution:**

$$\text{Slew Rate} = \frac{\Delta V_{out}}{\Delta t} = \frac{(+12\text{ V}) - (-12\text{ V})}{4.0\ \mu\text{s}}$$

$$= 6\ \text{V}/\mu\text{s}$$

2. Inverting and Noninverting Amplifier

2.1. Negative Feedback

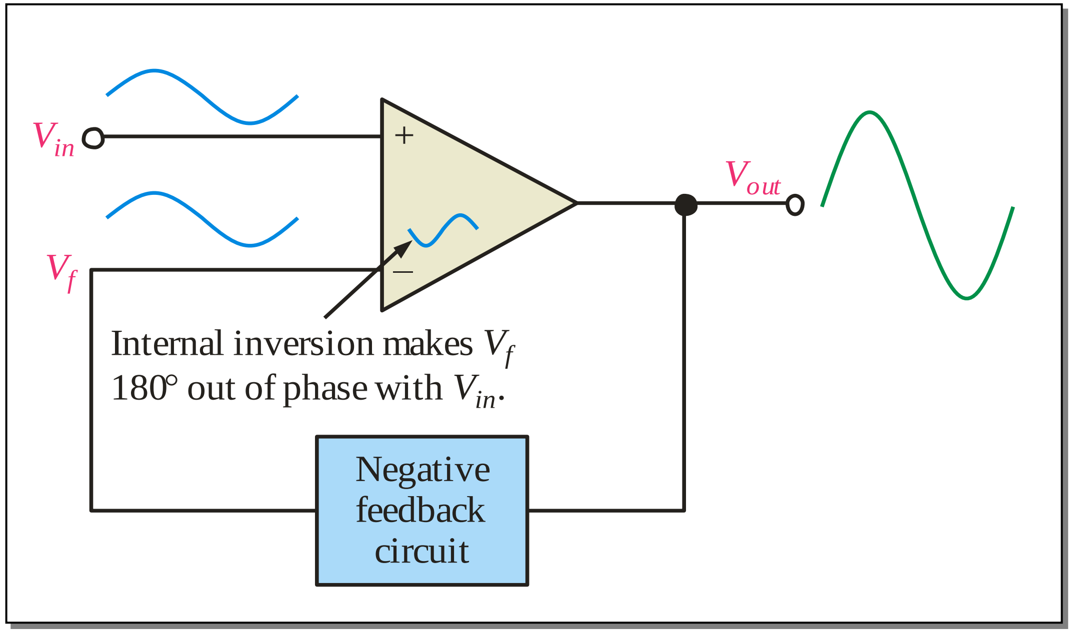
2.2. Noninverting Amplifier

2.3. Inverting Amplifier

2. Inverting and Noninverting Amplifier

2.1. Negative Feedback

- **Negative feedback** is the process of returning a portion of the output signal to the input with a phase angle that opposes the input signal.
- The advantage of negative feedback is that *<u>precise values of amplifier gain can be set</u>*. In addition, *<u>bandwidth and input/output impedances can be controlled</u>*.

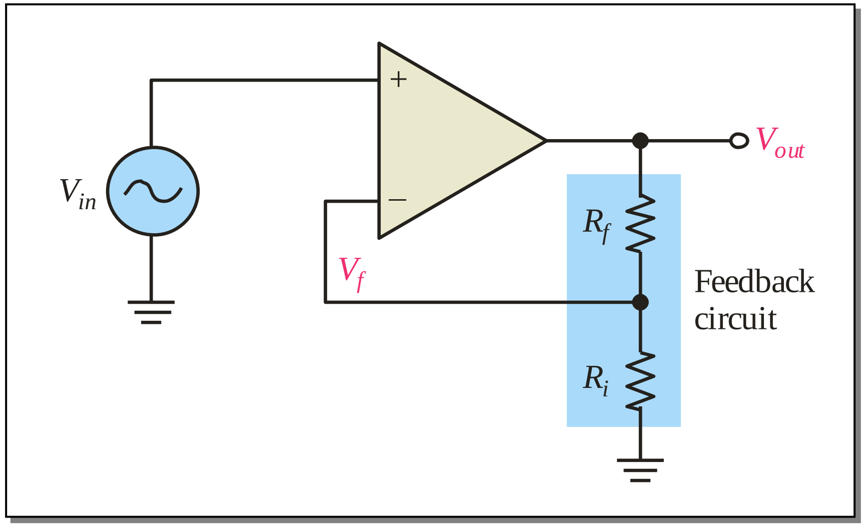


2. Inverting and Noninverting Amplifier

2.2. Noninverting Amplifier

- A **noninverting amplifier** is a configuration in which the signal is on the noninverting input and a portion of the output is returned to the inverting input.
- Feedback forces V_f to be equal to V_{in}, hence V_{in} is across R_i.
- The closed-loop gain of the noninverting amplifier is:

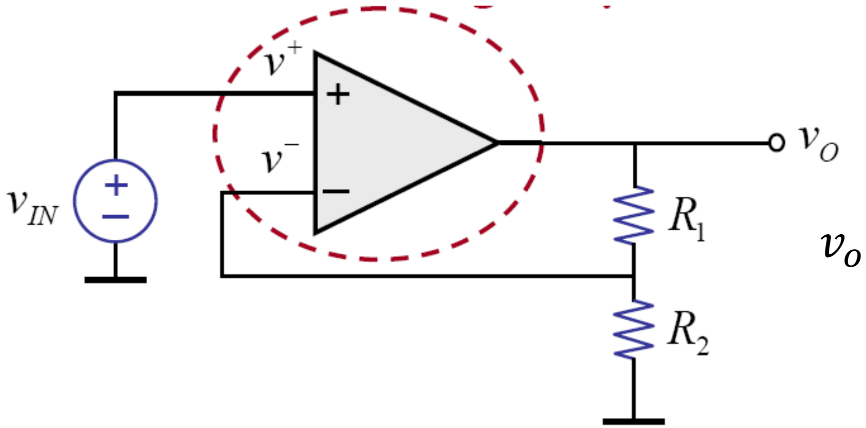
$$A_{cl(\mathrm{NI})} = 1 + \frac{R_f}{R_i}$$



Shall we prove it ?

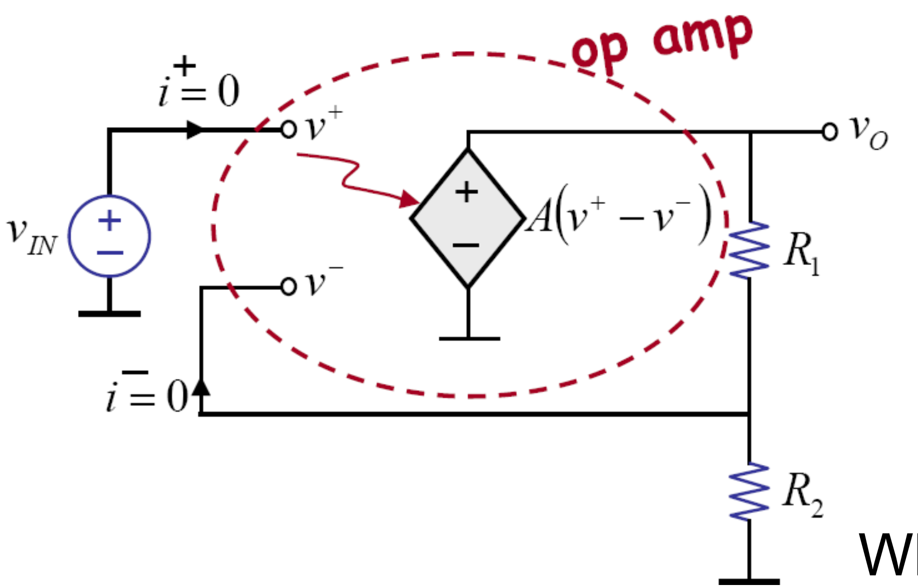
2. Inverting and Noninverting Amplifier

2.2. Noninverting Amplifier



$$v_o = A(v^+ - v^-) = A(v_{IN} - v_o \frac{R_2}{R_1 + R_2})$$

Equivalent circuit model

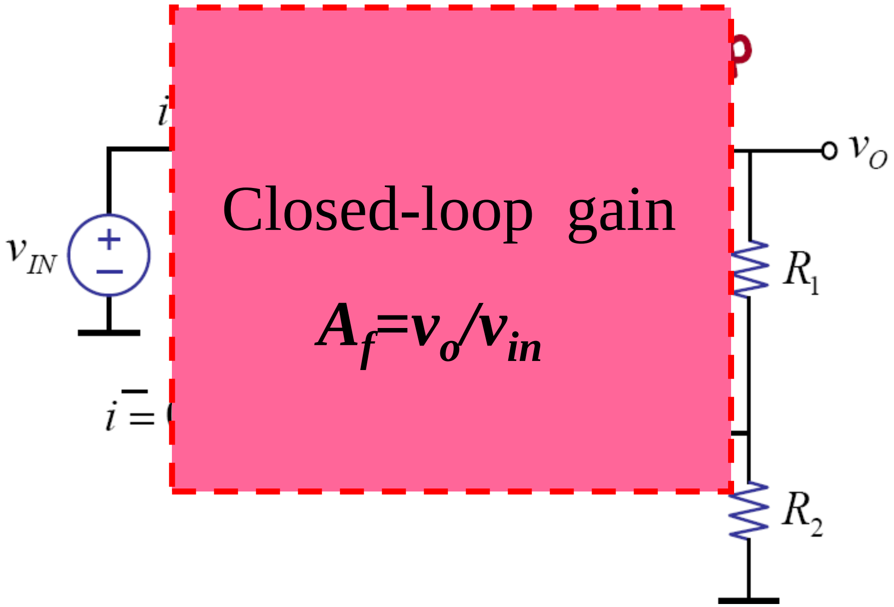


$$v_o = \frac{Av_{IN}}{1 + \dfrac{AR_2}{R_1 + R_2}}$$

What happens when "*A*" is very large?

2. Inverting and Noninverting Amplifier

2.2. Noninverting Amplifier



$$v_o = \frac{A v_{IN}}{1 + \dfrac{A R_2}{R_1 + R_2}}$$

$$\approx v_{IN} \frac{R_1 + R_2}{R_2} = A_f v_{IN}$$

Gain

$$A_f = \left(1 + \frac{R_1}{R_2}\right)$$

Closed-loop gain: determined by resistor ratio
insensitive to *A*, temperature

2. Inverting and Noninverting Amplifier

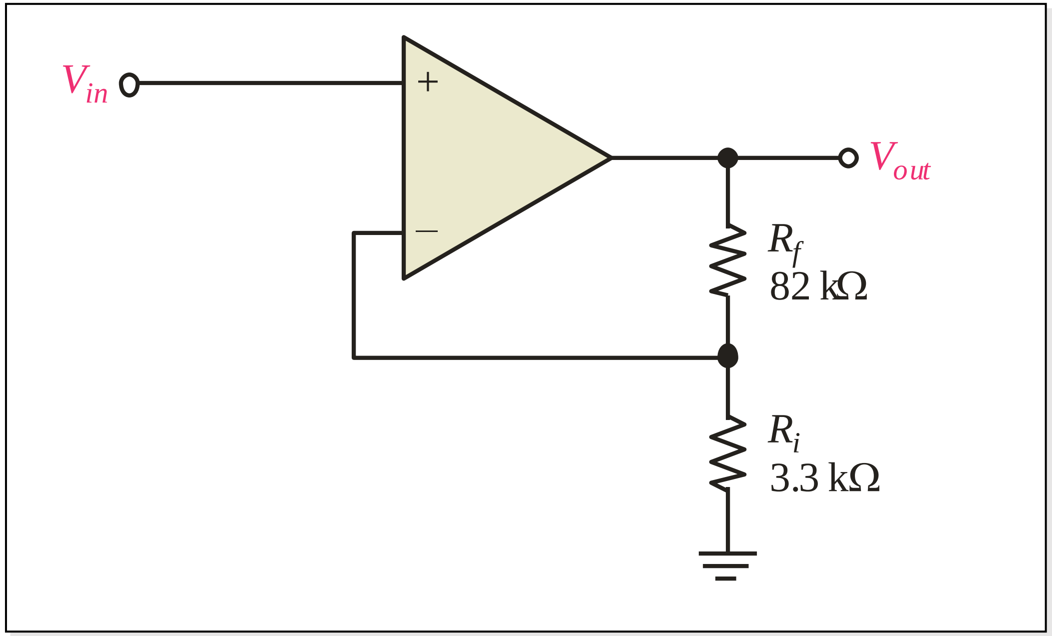
2.2. Noninverting Amplifier

- Example: Determine the gain of the noninverting amplifier shown.
- Solution:

$$A_{cl(\mathrm{NI})} = 1 + \frac{R_f}{R_i}$$

$$= 1 + \frac{82\ \mathrm{k\Omega}}{3.3\ \mathrm{k\Omega}}$$

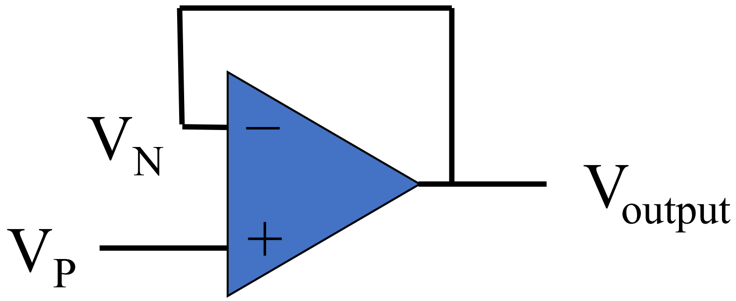
$$= 25.8$$



2. Inverting and Noninverting Amplifier

2.2. Noninverting Amplifier

- A special case of the inverting amplifier is when R_f =0 and $R_i = \infty$.
- Voltage Follower (unity gain buffer with a gain of 1)



$A(V_P - V_N) = V_o$

but $V_o = V_N$

so $A(V_P - V_o) = V_o$

$AV_P = V_o + AV_o$

$AV_P = (1 + A)V_o$

But A is huge (10^6)

$A \cong (1 + A)$

$V_P = V_o$

- Purpose: A voltage follower **buffers** a delicate investigation system from a demanding measurement system.

2. Inverting and Noninverting Amplifier

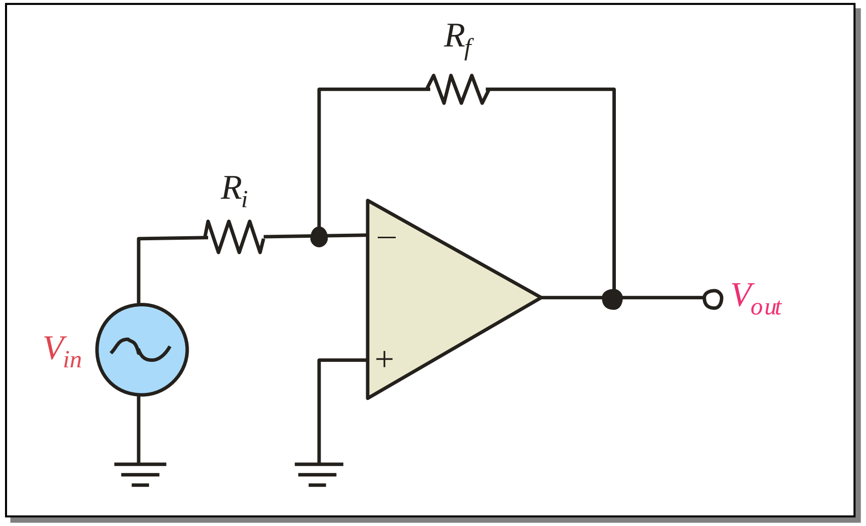
2.3. Inverting Amplifier

- An **inverting amplifier** is a configuration in which the noninverting input is grounded and the signal is applied through a resistor to the inverting input.

- Feedback forces the inputs to be nearly identical; hence the inverting input is very close to 0 V. The closed-loop gain of the inverting amplifier is

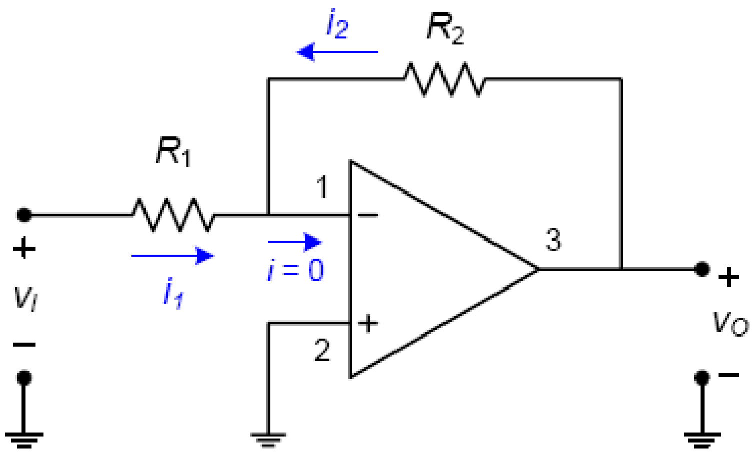
$$A_{cl(\mathrm{I})} = -\frac{R_f}{R_i}$$

0 V (virtual ground)



2. Inverting and Noninverting Amplifier

2.3. Inverting Amplifier



$$i_1 = \frac{v_i - v_-}{R_1} = \frac{v_i}{R_1}$$

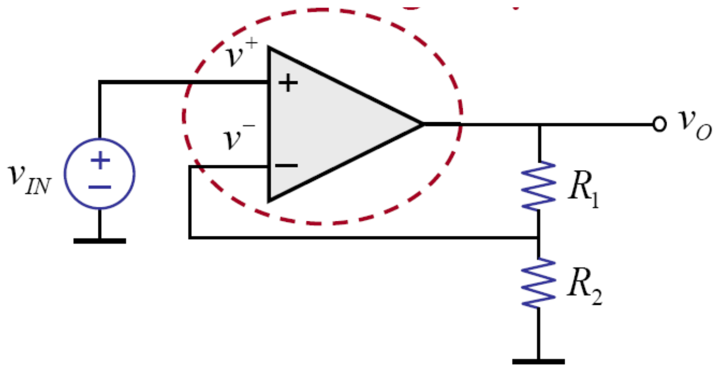
$$i_2 = \frac{v_o - v_-}{R_2} = \frac{v_o}{R_2}$$

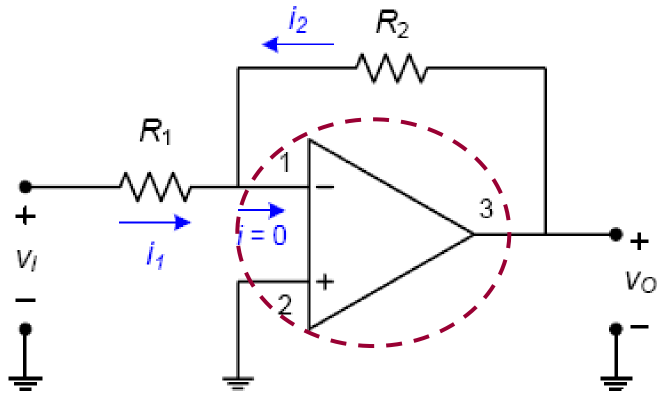
$$i = i_1 + i_2 = 0$$

$$\boxed{A_f = \frac{v_o}{v_i} = -\frac{R_2}{R_1}}$$

2. Inverting and Noninverting Amplifier

2.3. Inverting Amplifier





$$A_f = \frac{v_o}{v_i} = (1 + \frac{R_1}{R_2})$$

$$A_f = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

- We can adjust the closed-loop gain by changing the ratio of R_2 and $R_{1.}$
- We can make it arbitrarily large or small and with the desired accuracy depending on the accuracy of the resistors.
- The terminal 1 is a *virtual* ground since terminal 2 is grounded

2. Inverting and Noninverting Amplifier

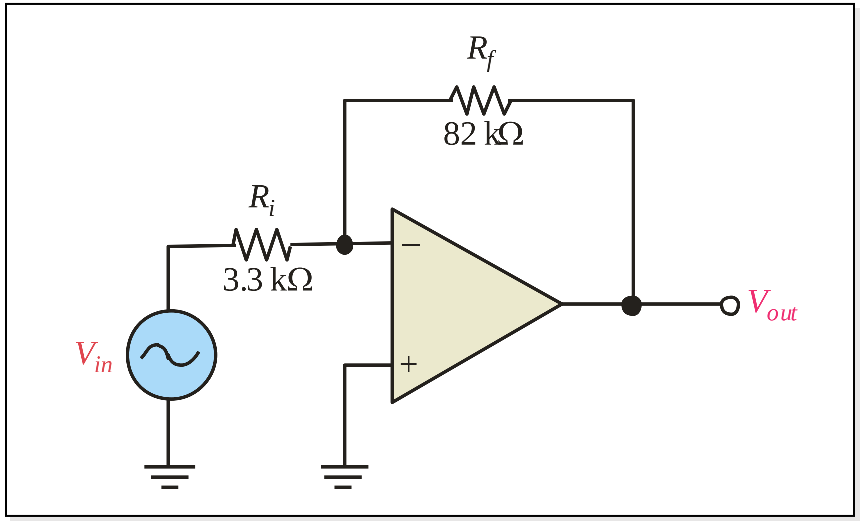
2.3. Inverting Amplifier

- Example: Determine the gain of the inverting amplifier shown.
- Solution:

$$A_{cl(\mathrm{I})} = -\frac{R_f}{R_i}$$

$$= -\frac{82\ \mathrm{k}\Omega}{3.3\ \mathrm{k}\Omega}$$

$$= -24.8$$



The minus sign indicates inversion.

3. Linear Op-Amp Applications

3.1. Summing & Averaging

3.2. Scaling Adder

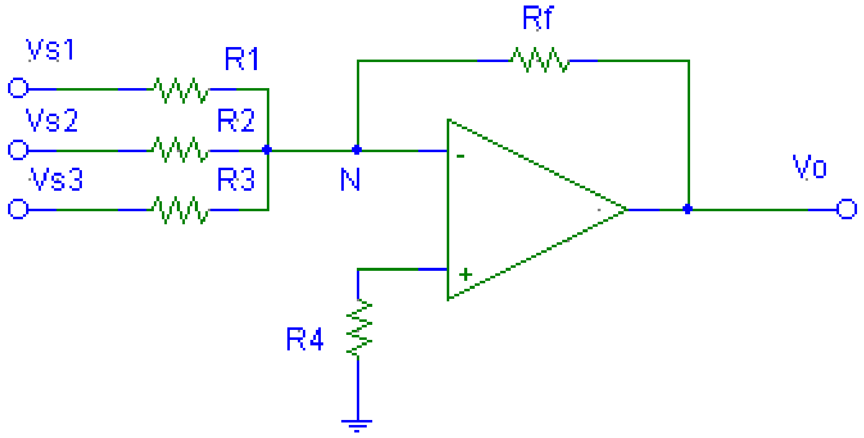
3.3. Subtracting

3.4 Practical Applications

3. Linear Op-Amp Applications

3.1. Summing & Averaging

Summing Amplifiers $v_o = k_1 v_{i1} + k_2 v_{i2} + \cdots\cdots k_n v_{in}$



For node N，

$$\frac{v_{S3}}{R_3} + \frac{v_{S2}}{R_2} + \frac{v_{S1}}{R_1} = -\frac{v_o}{R_f}$$

$$\Longrightarrow \quad v_o = -\left(\frac{R_f}{R_1} v_{S1} + \frac{R_f}{R_2} v_{S2} + \frac{R_f}{R_3} v_{S3}\right)$$

Let $R_1 = R_2 = R_3$

$$\longrightarrow \quad v_o = -\frac{R_f}{R_1}(v_{S1} + v_{S2} + v_{S3}) \xrightarrow{R_f = R_1} v_o = -(v_{S1} + v_{S2} + v_{S3})$$

$R_f / R = 1/3$ => Averaging

Summing

3. Linear Op-Amp Applications

3.1. Summing & Averaging

- **Example:** What is V_{OUT} if the input voltages are +5.0 V, -3.5 V and +4.2 V and all resistors = 10 kW?
- **Solution:** $V_{OUT} = -(V_{IN1} + V_{IN2} + V_{IN3})$

$$= -(+5.0\text{ V} - 3.5\text{ V} + 4.2\text{ V})$$

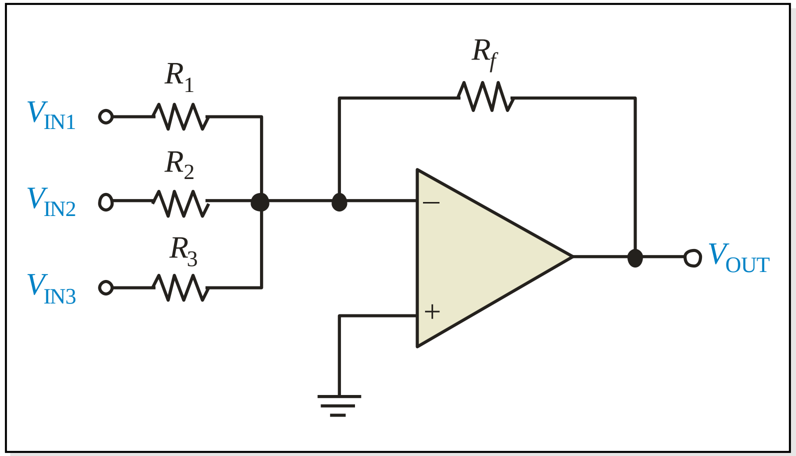
$$= -5.7\text{ V}$$

- **Example:** Assume $R_1 = R_2 = R_3 = 10$ kW and $R_f = 3.3$ kW?
- **Solution:**

$$V_{OUT} = -⅓(V_{IN1} + V_{IN2} + V_{IN3})$$

$$= -⅓(+5.0\text{ V} - 3.5\text{ V} + 4.2\text{ V})$$

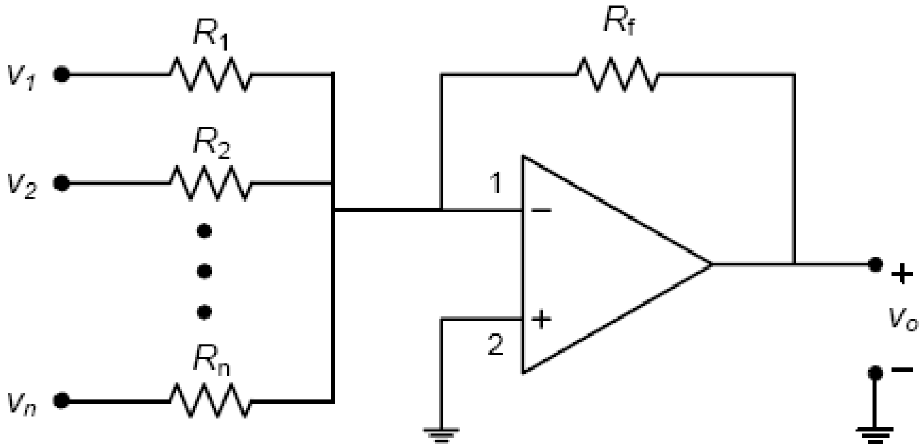
$$= -1.9\text{ V}$$



3. Linear Op-Amp Applications

3.2. Scaling Adder

Scaling Adder (Weighted Summer)



$$i_1 = \frac{v_1}{R_1}, i_2 = \frac{v_2}{R_2}, \cdots, i_n = \frac{v_n}{R_n}$$

$$i = i_1 + i_2 + \cdots + i_n$$

$$v_o = 0 - iR_f$$

$$v_o = -(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \cdots + \frac{R_f}{R_n}v_n)$$

3. Linear Op-Amp Applications

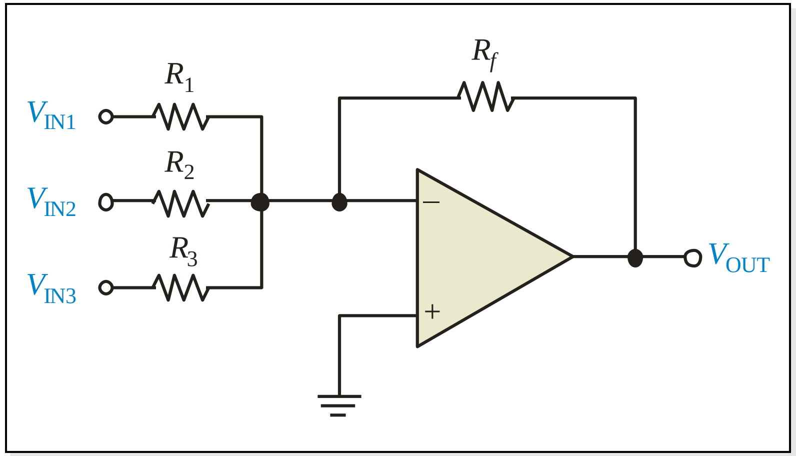
3.2. Scaling Adder

- **Example**: Assume you need to sum the inputs from three microphones. *The first two microphones require a gain of -2*, but the *third microphone requires a gain of -3*. What are the values of the input *Rs* (R_1, R_2, R_3) if R_f = 10 kΩ?

- **Solution**:

$$R_1 = R_2 = -\frac{R_f}{A_{v1}} = -\frac{10\ \text{k}\Omega}{-2} = 5.0\ \text{k}\Omega$$

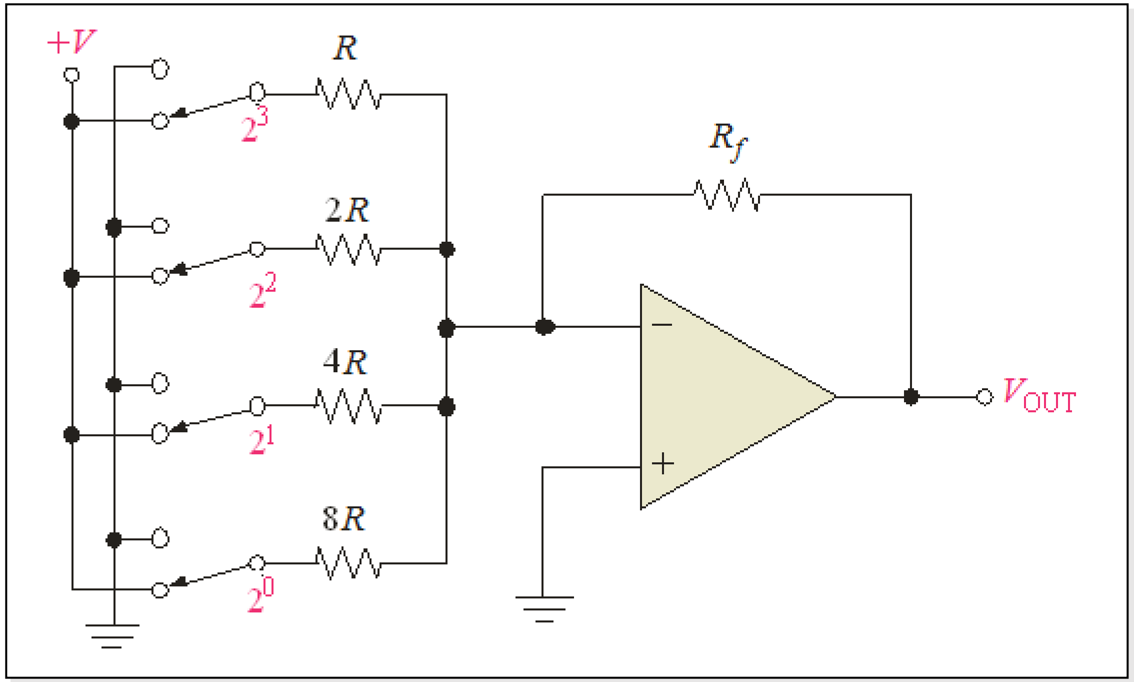
$$R_3 = -\frac{R_f}{A_{v3}} = -\frac{10\ \text{k}\Omega}{-3} = 3.3\ \text{k}\Omega$$



3. Linear Op-Amp Applications

3.2. Scaling Adder

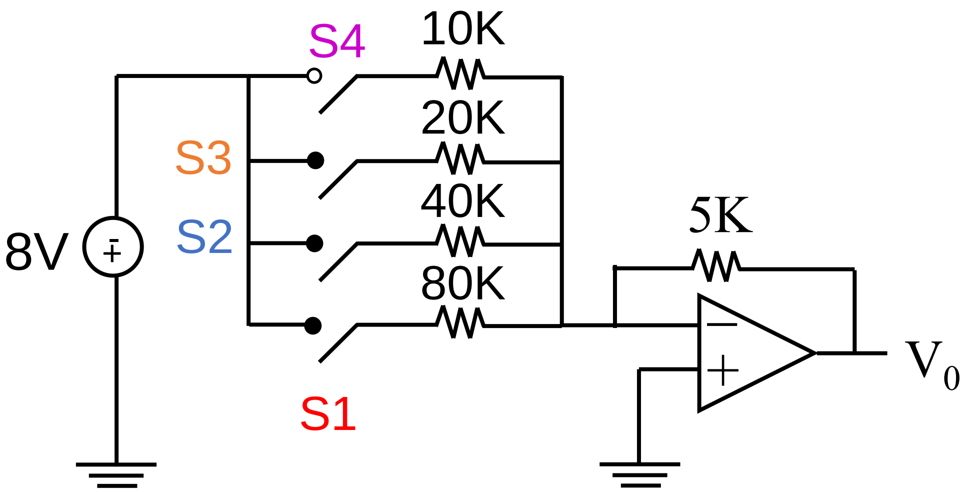
- An application of a **scaling adder** is the D/A converter circuit shown here. The resistors are inversely proportional to the binary column weights.
- Because of the precision required of resistors, the method is useful only for small DACs.



3. Linear Op-Amp Applications

3.2. Scaling Adder

"Weighted-adder D/A converter"



4-Bit D/A

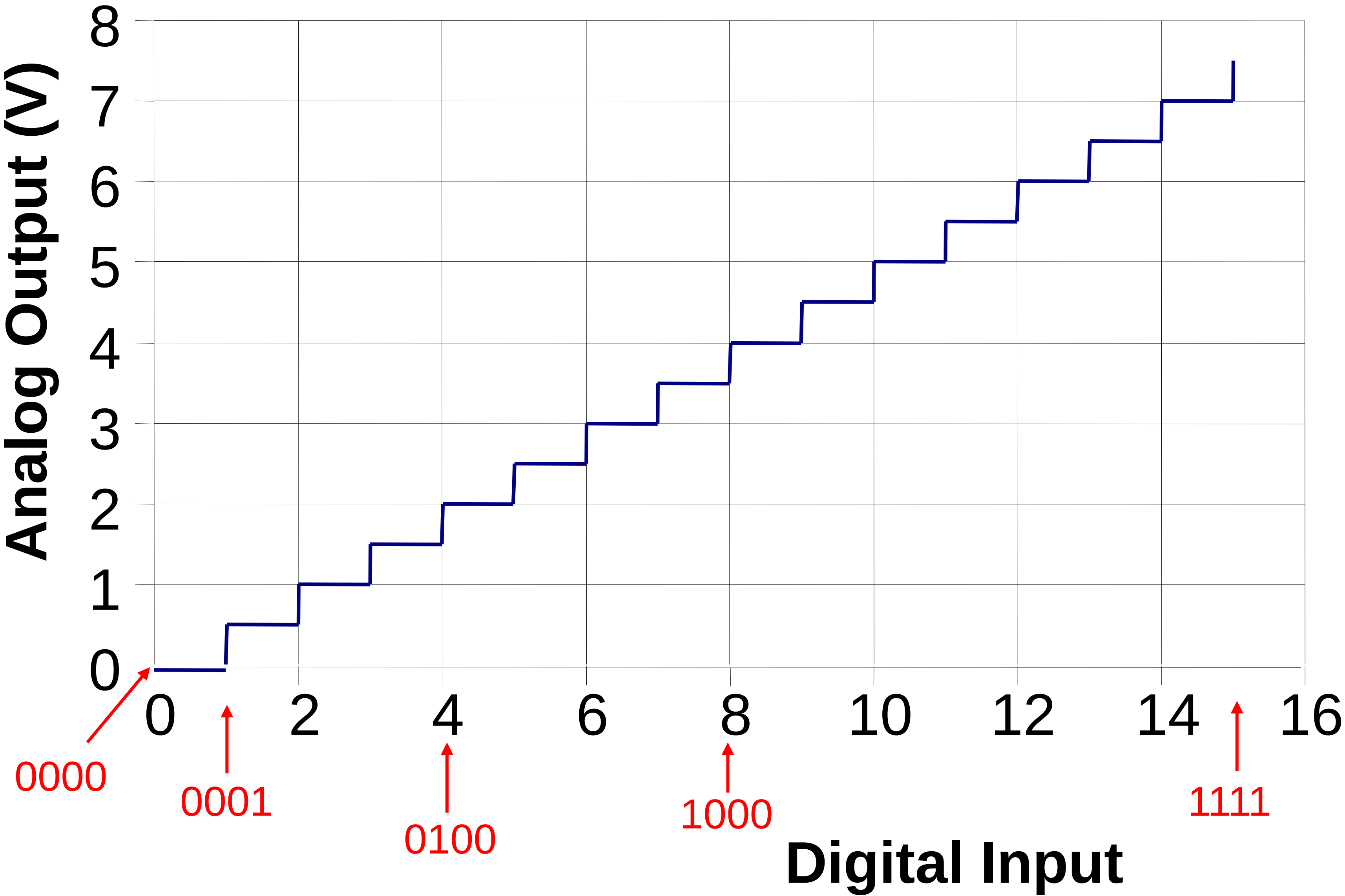
S1 closed if LSB =1
S2 " if next bit = 1
S3 " if " " = 1
S4 " if MSB = 1

Binary number	Analog output (volts)
0 0 0 0	0
0 0 0 1	.5
0 0 1 0	1
0 0 1 1	1.5
0 1 0 0	2
0 1 0 1	2.5
0 1 1 0	3
0 1 1 1	3.5
1 0 0 0	4
1 0 0 1	4.5
1 0 1 0	5
1 0 1 1	5.5
1 1 0 0	6
1 1 0 1	6.5
1 1 1 0	7
1 1 1 1	7.5

MSB LSB

3. Linear Op-Amp Applications

3.2. Scaling Adder

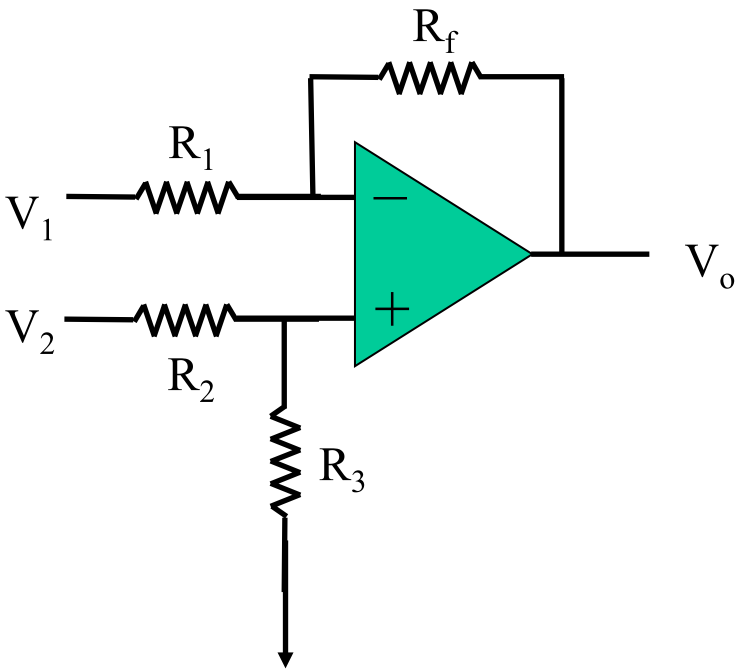


3. Linear Op-Amp Applications

3.3. Subtracting Amplifier

- With inverting and non-inverting amplifier, we can determine the difference between two voltages.

$$V_o = -\frac{R_f}{R_1}V_1 + (1+\frac{R_f}{R_1})\frac{R_3}{R_2+R_3}V_2$$



$R_1 = R_2$ and $R_f = R_3$, then

$V_o = [R_f/R_1]\ (V_2 - V_1)$

$R_1 = R_2 = R_f = R_3$, then

$V_o = (V_2 - V_1)$

3. Linear Op-Amp Applications

3.4. Practical Applications

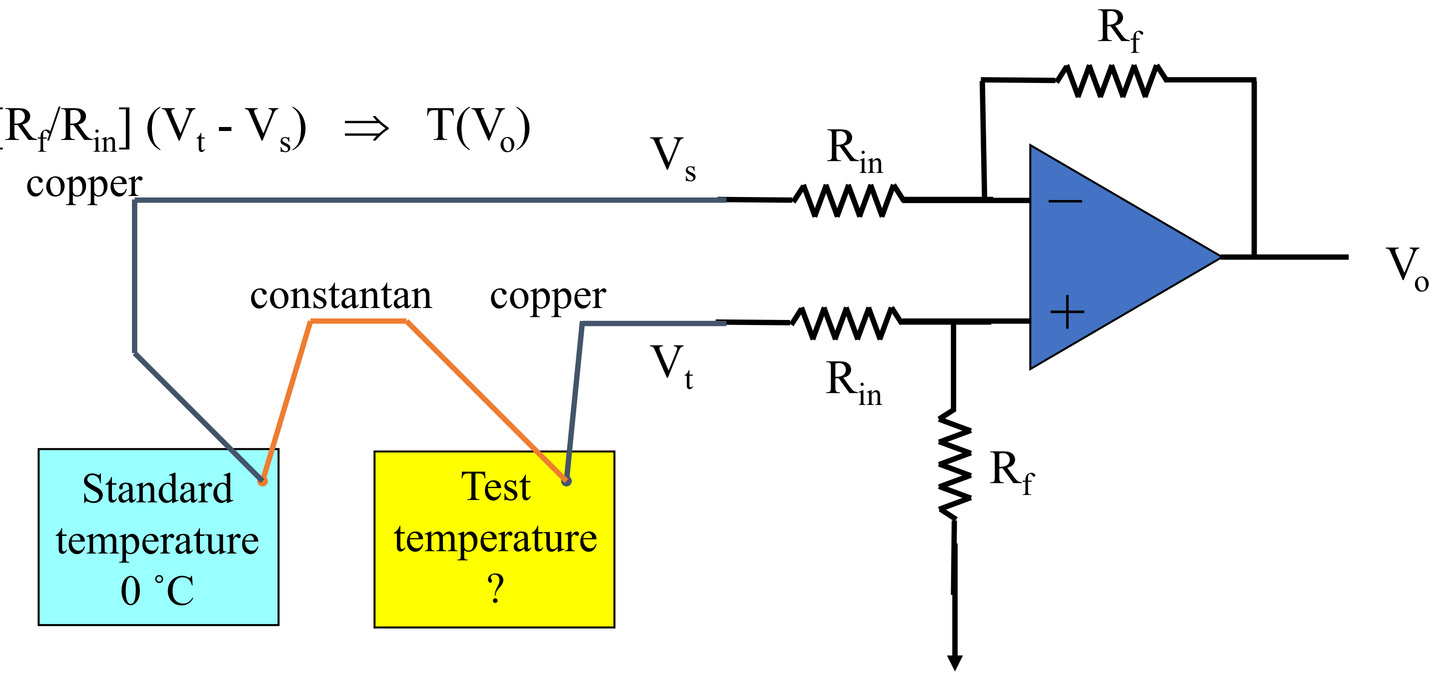
A Thermocouple

Thermocouples are used in pairs.

The voltage difference is related to the temperature.

A difference amplifier is perfect for this job.

$V_o = [R_f/R_{in}]\,(V_t - V_s) \;\Rightarrow\; T(V_o)$



3. Linear Op-Amp Applications

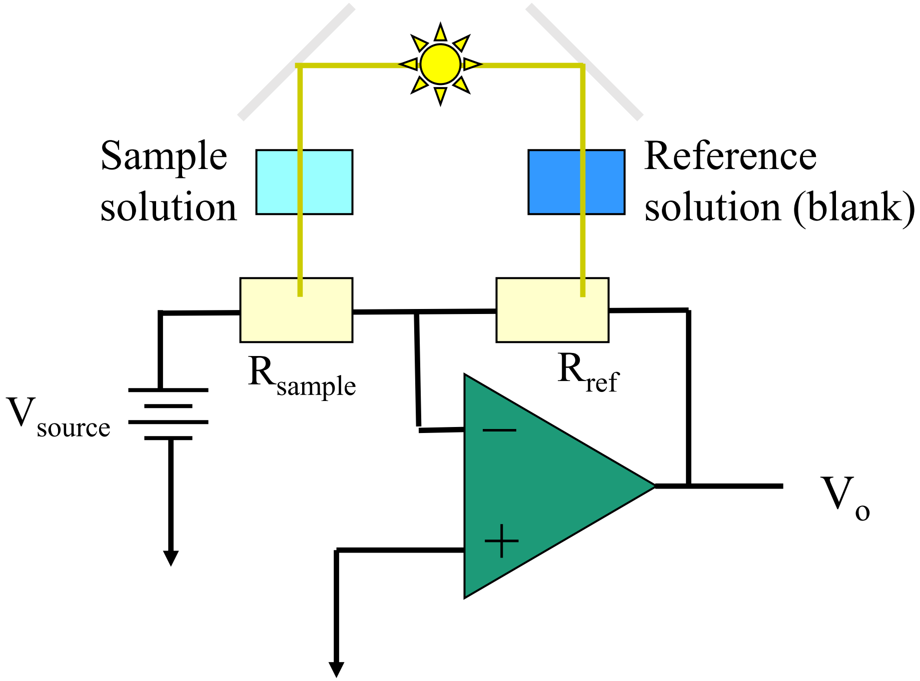
3.4. Practical Applications

A Spectrometer

- A photodiode can be used as a transducer;
- Its resistance changes when light impinges on it.
- Resistance is inversely proportional to the power of the impinging light source.

$$V_o = -(R_{ref}/R_{sample})\ V_{source}$$

$$V_o = k\ (P_{sample}/P_{ref})$$



4. Bias Current and Bandwidth Limitations

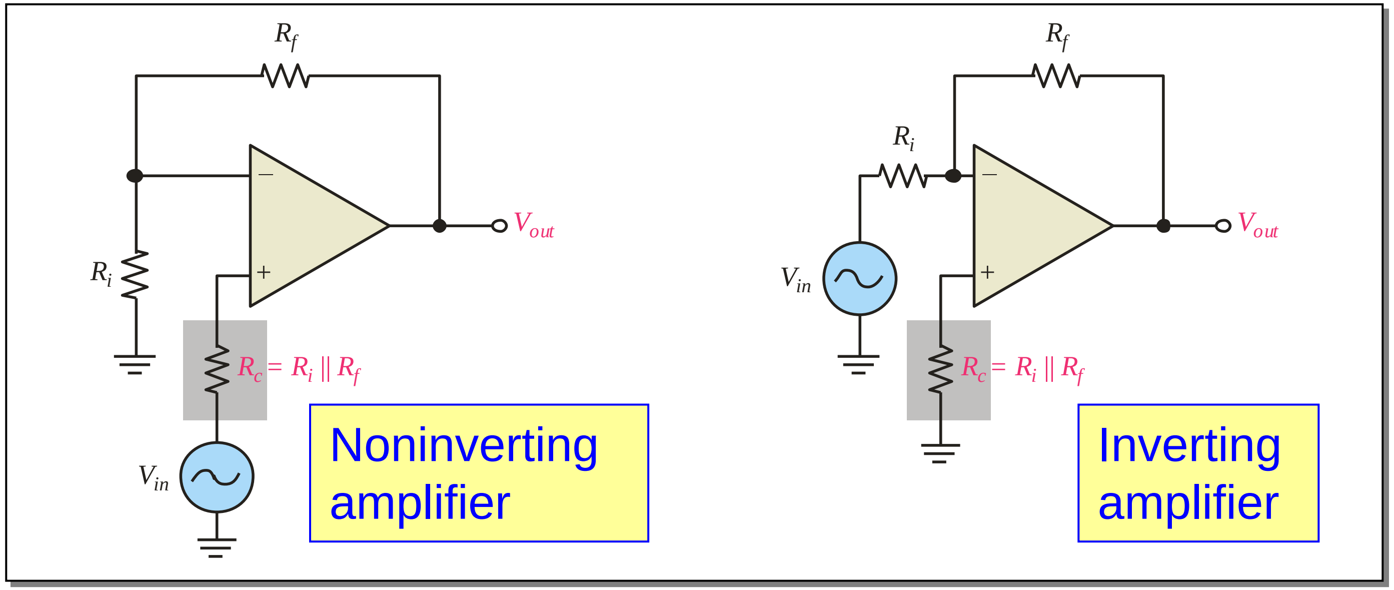
4.1. Bias Current Compensation

4.2. Bandwidth Limitations

4. Bias Current and Bandwidth Limitations

4.1. Bias Current Compensation

- For op-amps with a BJT input stage, bias current can create a small output error voltage.
- To compensate for this, a resistor equal to $R_i||R_f$ is added to one of the inputs.

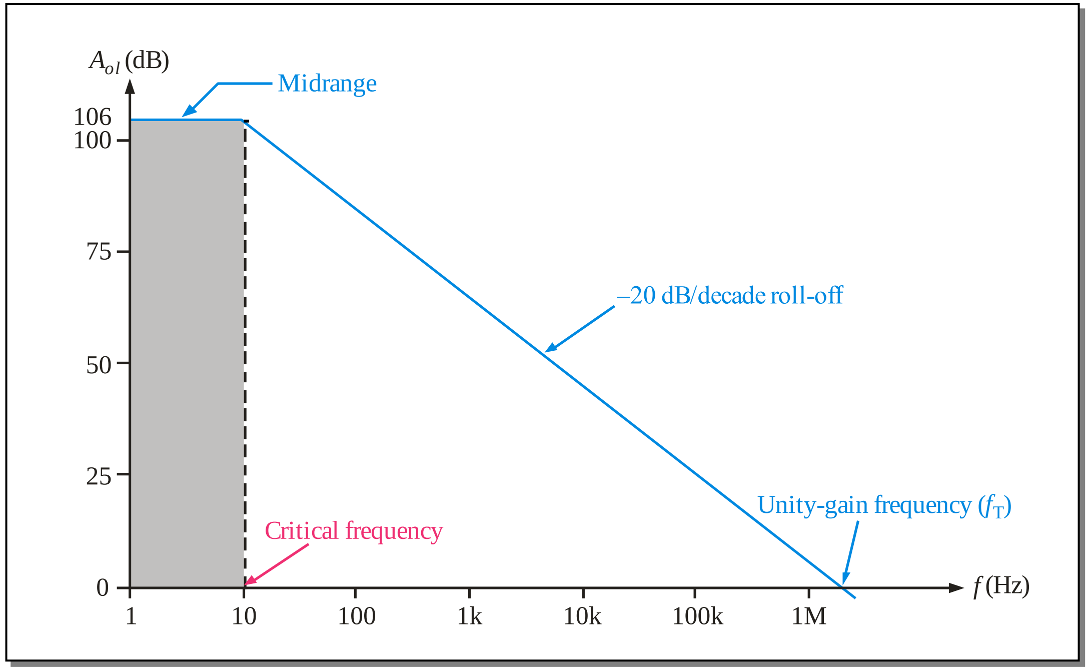


4. Bias Current and Bandwidth Limitations

4.2. Bandwidth Limitations

- Many op-amps have a roll off rate determined by a single low-pass *RC* circuit, *<u>giving a constant -20 dB/decade down to unity gain</u>*.

- Op-amps with this characteristic are called *<u>compensated op-amps</u>*.
- The blue line represents the open-loop frequency characteristic (Bode plot) for the op-amp.

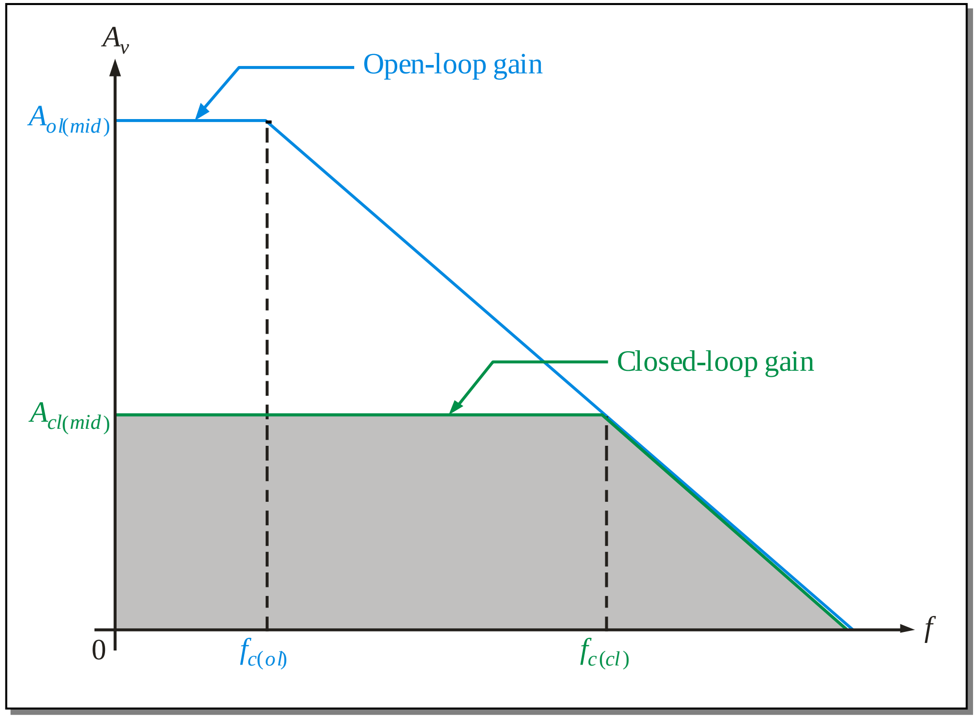


4. Bias Current and Bandwidth Limitations

4.2. Bandwidth Limitations

- For op-amps with a -20 dB/decade open-loop gain, the closed-loop critical frequency is given by $f_{c(cl)} = f_{c(ol)}(1 + BA_{ol(mid)})$

- The closed-loop critical frequency is higher than the open-loop critical frequency by the factor $(1 + BA_{ol(mid)})$. This means that you can *achieve a higher BW by accepting less gain*.
- For a compensated op-amp, $A_{cl}\, f_{(cl)} = A_{ol}\, f_{c(ol)} = f_T$



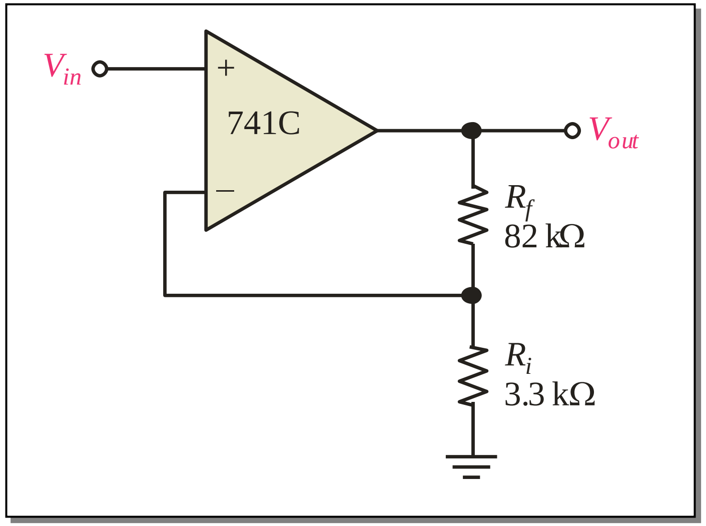
4. Bias Current and Bandwidth Limitations

4.2. Bandwidth Limitations

- The equation, $A_{cl}\, f_{(cl)} = A_{ol}\, f_{c(ol)}$ shows that the product of the gain and bandwidth are constant.
- *The gain-bandwidth product is also equal to the unity gain frequency*.
- That is $f_T = A_{cl}\, f_{c(cl)}$, where f_T is the unity-gain bandwidth.
- **Example**: The f_T for a 741C op amp is 1 MHz. What is the BW_{cl} for the amplifier?
- **Solution:**

$$A_{cl(NI)} = 1 + \frac{R_f}{R_i} = 1 + \frac{82\ \text{k}\Omega}{3.3\ \text{k}\Omega} = 25.8$$

$$BW_{cl} = \frac{f_T}{A_{cl}} = \frac{1\ \text{MHz}}{25.8} = 38.8\ \text{kHz}$$



Quiz 1.

Quiz Number	1	Quiz Type	OX	Example Select
Question	The ideal op-amp has			
Example	A. Zero input impedance and zero output impedance B. Zero input impedance and infinite output impedance C. Infinite input impedance and zero output impedance D. Infinite input impedance and infinite output impedance			
Answer	C			
Feedback				

Quiz 2.

<table>
<tr><td rowspan="2">Quiz Number</td><td rowspan="2">2</td><td rowspan="2">Quiz Type</td><td>OX</td><td>Example Select</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Question</td><td colspan="4">Given a noninverting amplifier with a gain of 10 and a gain-bandwidth product of 1.0 MHz, the expected high critical frequency is</td></tr>
<tr><td>Example</td><td colspan="4">A. 100 Hz
B. 1.0 kHz
C. 10 kHz
D. 100 kHz</td></tr>
<tr><td>Answer</td><td colspan="4">D</td></tr>
<tr><td>Feedback</td><td colspan="4"></td></tr>
</table>

Summary

1. **Operational amplifier**: A type of amplifier that has very high voltage gain, very high input impedance, very low output impedance and good rejection of common-mode signals.
2. **Differential mode**: A mode of op-amp operation in which two opposite-polarity signals voltages are applied to the two inputs (double-ended) or in which a signal is applied to one input and ground to the other input (single-ended).
3. **Common mode**: A condition characterized by the presence of the same signal on both inputs
4. **Open-loop voltage gain**: The voltage gain of an op-amp without external feedback.
5. **Negative feedback**: The process of returning a portion of the output signal to the input of an amplifier such that it is out of phase with the input.
6. **Closed-loop voltage gain**: The voltage gain of an op-amp with external feedback.
7. **Gain-bandwidth product**: A constant parameter which is always equal to the frequency at which the op-amp's open-loop gain is unity (1).

Next lesson guide...

Lesson 11: Op-Amp Applications (I)

Reference

[1] Electronics devices and Circuits theory – Robert Boylestad, Louis Nashelsky, Prentice Hall, 11th edition
[2] Fundamental of Microelectronics – Behzad Razavi, Wiley, Preview Edition 2006
[3] Electronics Fundamentals : Circuits, Devices, and Applications - Thomas L. Floyd, David. L. Buchla, Pearson, 8th Edition