

ECE 65: Components & Circuits Lab

Lecture 2

Operational Amplifier (op-amp)

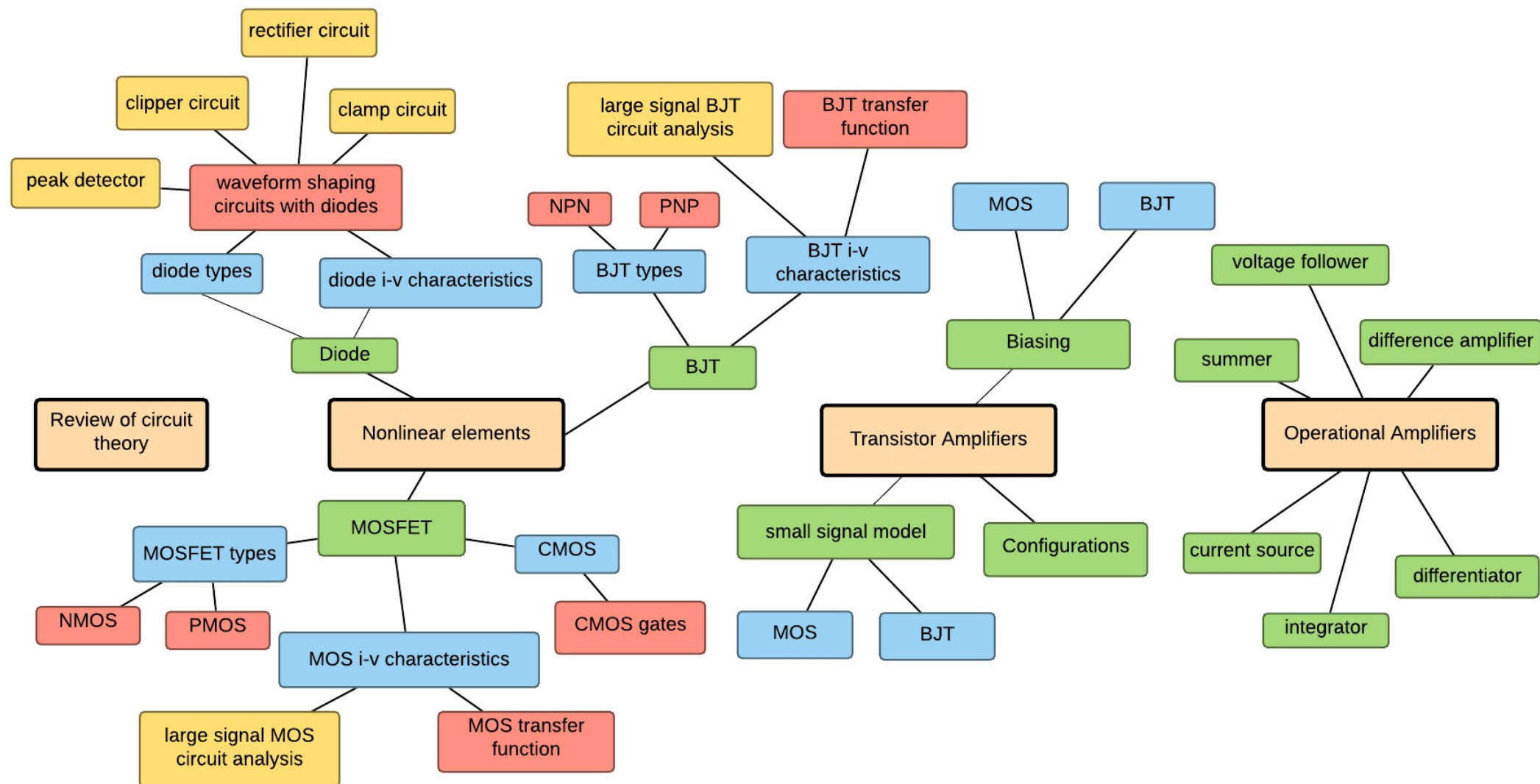
Reference notes: sections 7.1, 7.2

Sedra & Smith (7th Ed): sections 2-2.3

Saharnaz Baghdadchi

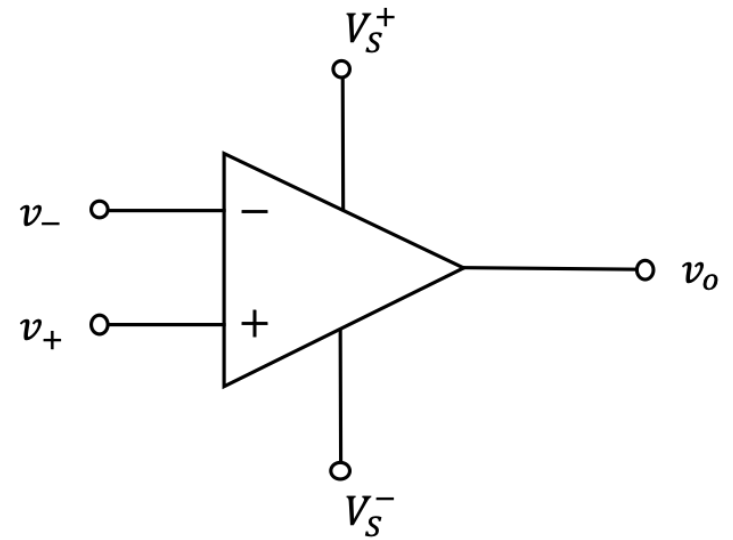
Course map

7. Operational amplifiers



Operational Amplifiers

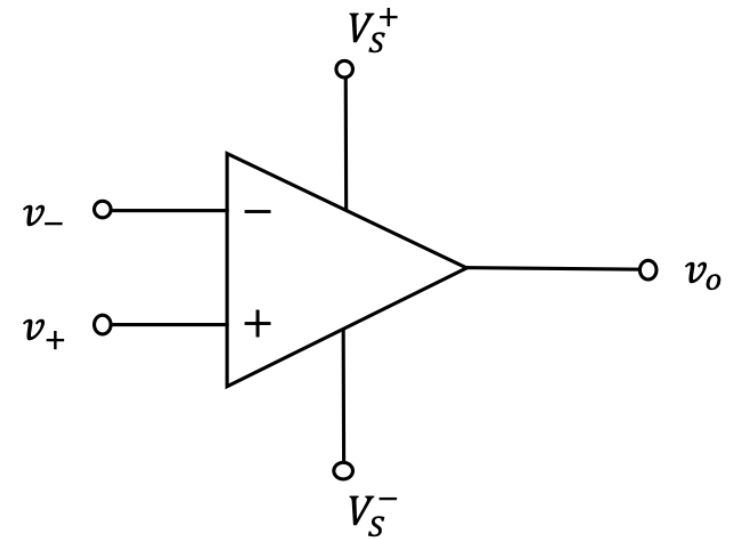
Operational amplifiers (op-amps) are general purpose voltage amplifiers.



Operational Amplifiers

Operational amplifiers (op-amps) are general purpose voltage amplifiers.

They are constructed such that they amplify the voltage difference between the two input signals.



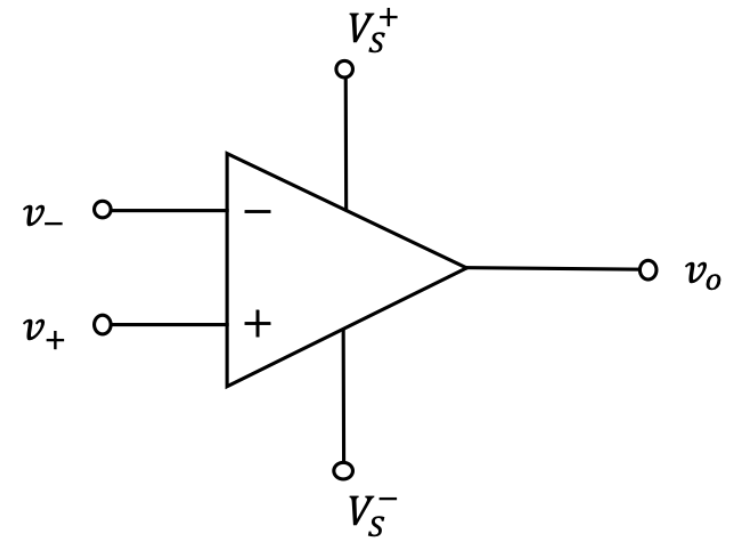
$$v_o = A(v_+ - v_-) = Av_d$$

open-loop voltage gain

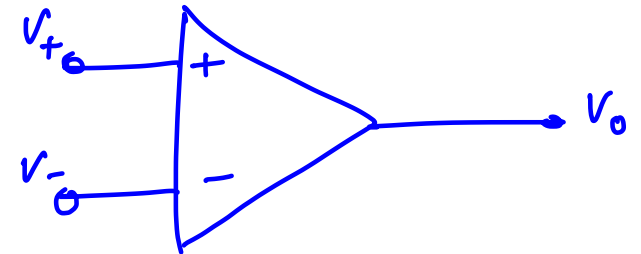
Operational Amplifiers

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$$v_o = A(v_+ - v_-) = Av_d$$

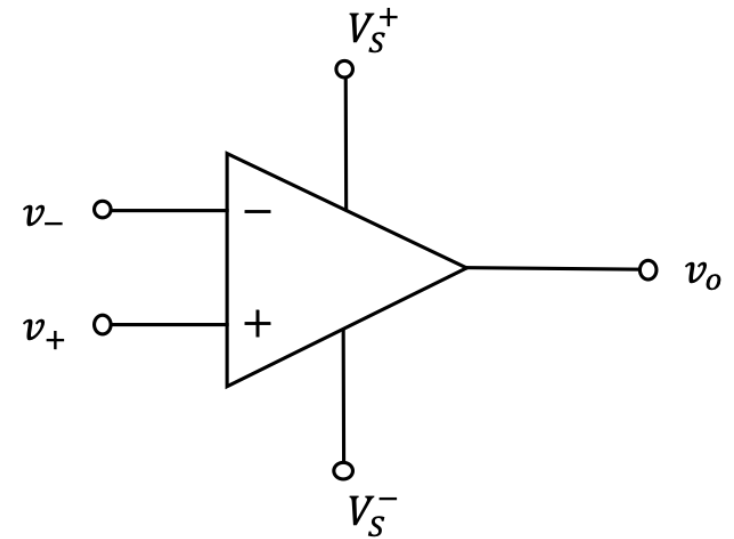


The $-$ and $+$ terminals are called the inverting and non-inverting terminals, respectively.

Operational Amplifiers

Operational amplifiers (op-amps) are general purpose voltage amplifiers.

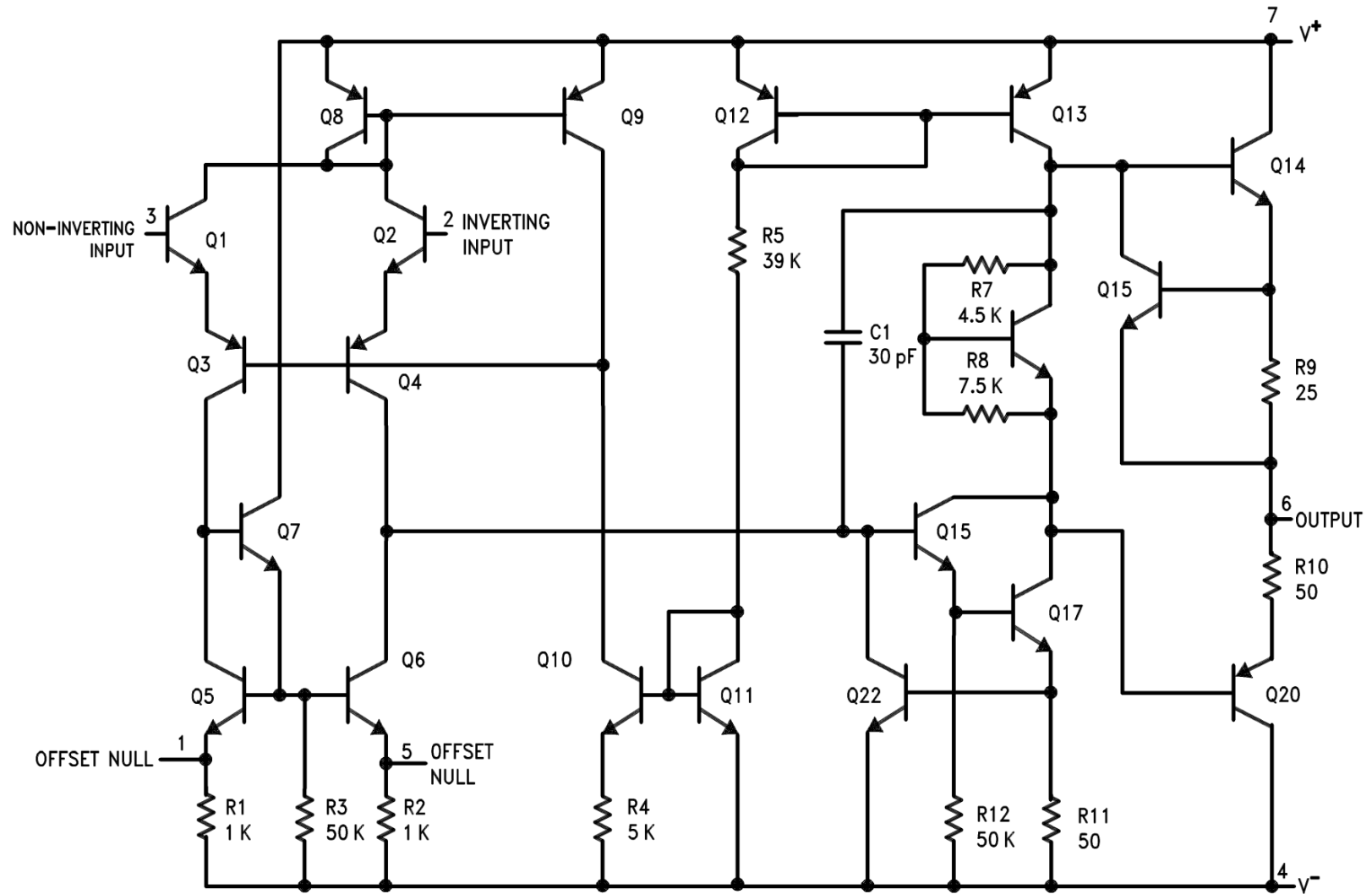
They are constructed such that they amplify the voltage difference between the two input signals.



$$v_o = A(v_+ - v_-) = Av_d$$

They have a very large gain. Typically, $A \sim 10^5$ to 10^7 .

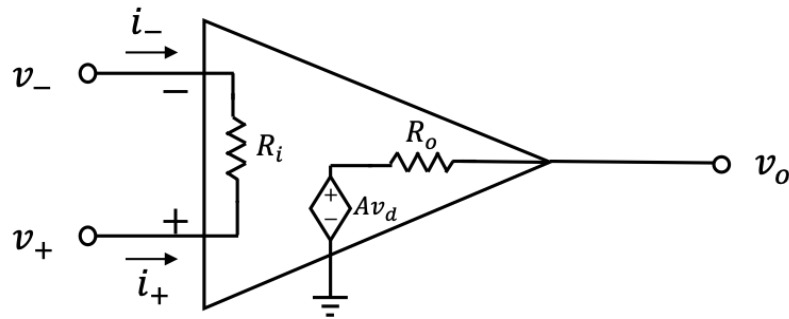
LM 741 op-amp



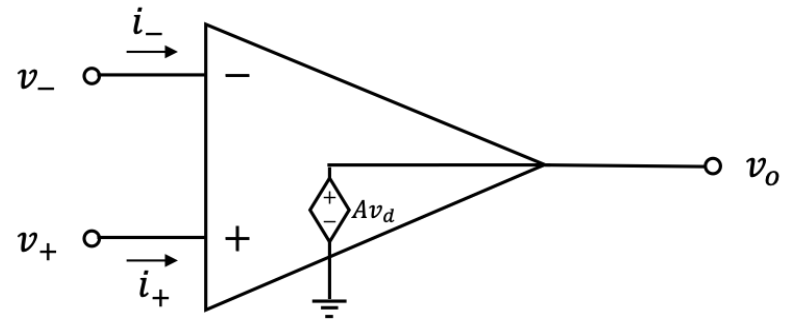
LM 741 op-amp (ti.com)

OpAmp models

Linear model



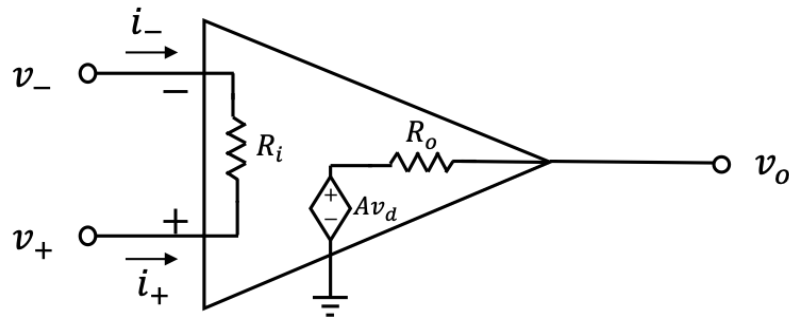
Ideal model



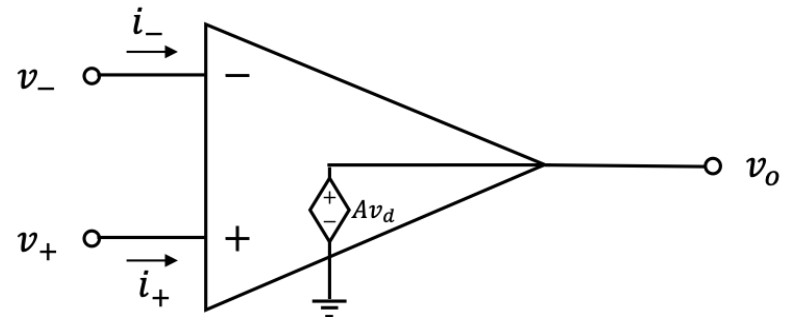
In op-amps, the input resistance, R_i , is very large, and the output resistance, R_o , is very small.

OpAmp models

Linear model



Ideal model

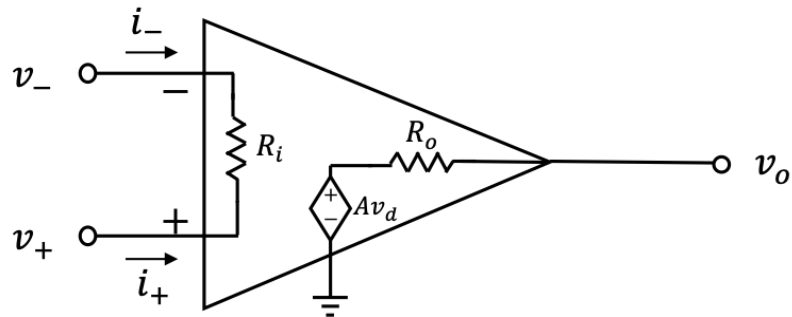


Because the input impedance of the op-amps is very large, the input current to the op-amp is very small.

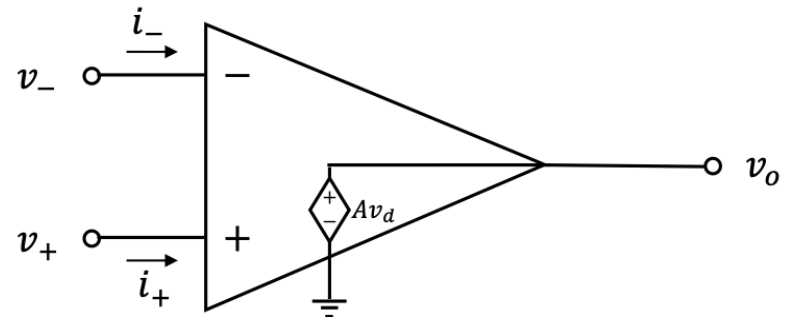
$$i_- \approx i_+ \approx 0$$

OpAmp models

Linear model



Ideal model

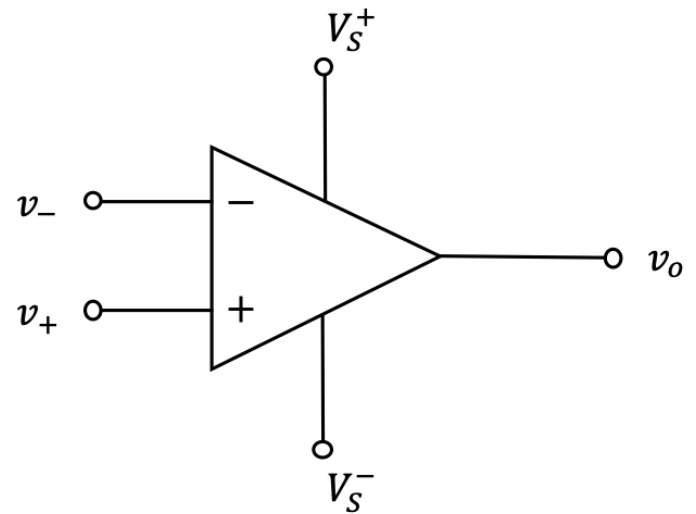


In the **ideal op-amp model**, $R_i = \infty$, $R_o = 0$, $i_- = i_+ = 0$

Output voltage and power supplies

The output voltage of an op-amp is limited by the power supplies used to power up the op-amp chip.

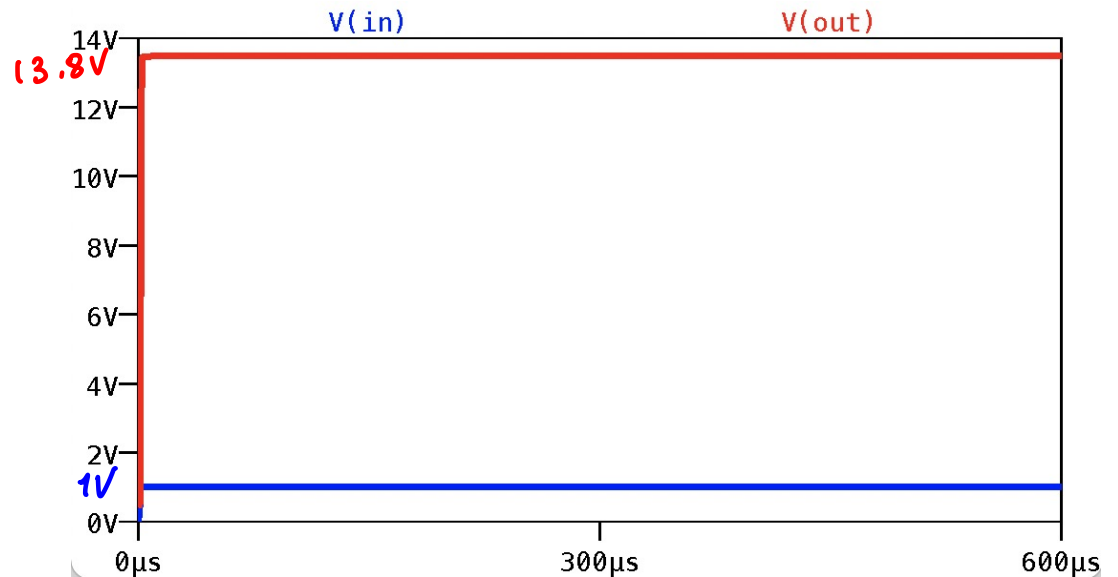
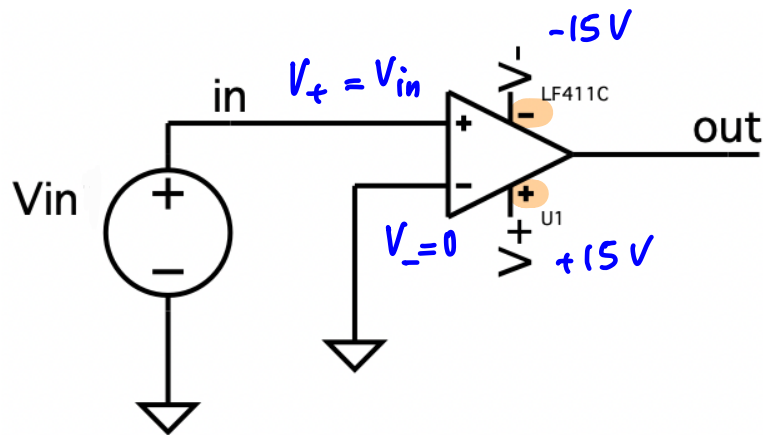
$$V_{S^-} < V_o < V_{S^+}$$



Open-loop operation of op-amps (no feedback)

$$A = 10^5$$

$$V_o = A (V_+ - V_-) = 10^5 (V_{in} - 0) = 10^5 \times V_{in}$$



$V_{o\max} = 13.8\text{ V}$, here.

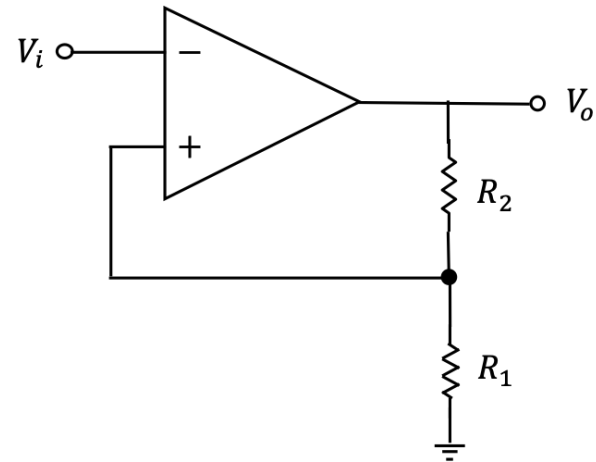
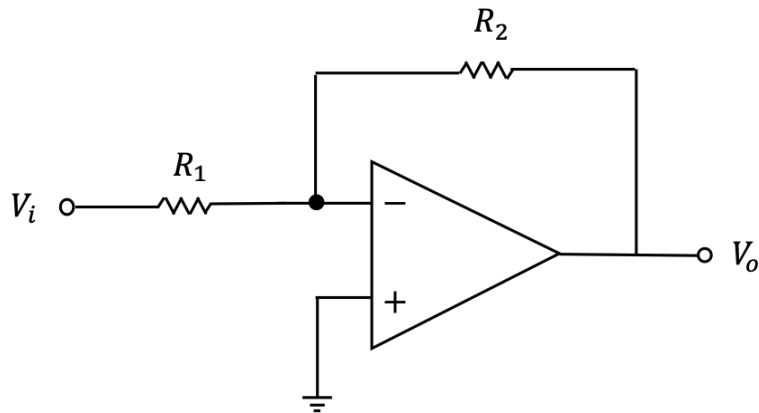
$$V_o = 10^5 V_{in} \rightarrow V_{in\max} = \frac{V_{o\max}}{10^5} = \frac{13.8\text{ V}}{10^5} = 13.8 \times 10^{-5} \text{ V} = 138 \times 10^{-6} \text{ V} = 138 \mu\text{V}$$

In open-loop configuration, op-amp cannot amplify input voltages greater than a few micro volts. It cannot be used as a voltage amplifier.

Feedback:

the concept, negative and positive feedback

- In circuits with feedback, a portion of the output signal is fed back to the circuit input.



- There are two types of feedback: Negative and Positive

Feedback:

the concept, negative and positive feedback

Negative feedback: In circuits with negative feedback, as the output increases, the input will decrease, and vice versa, such that the output signal would reach the desired stable level.

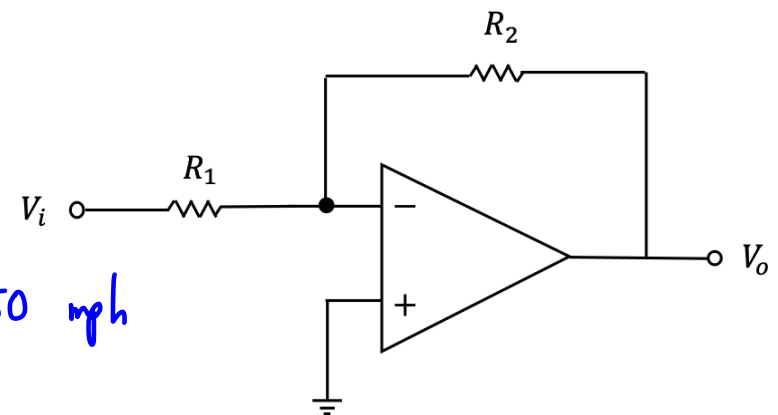
desired output : speed of 50 mph

if output \nearrow 55 mph

input $\downarrow \implies$ output $\downarrow \longrightarrow$ output : 50 mph

if output \downarrow 45 mph

input $\nearrow \implies$ output $\nearrow \longrightarrow$ output : 50 mph



Feedback:

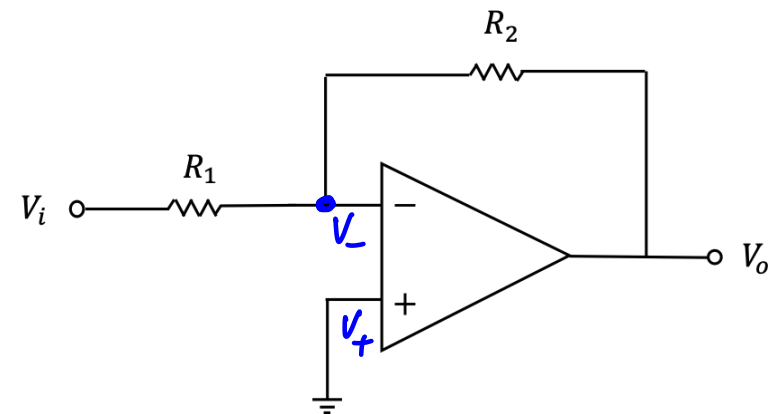
the concept, negative and positive feedback

Negative feedback: In circuits with negative feedback, as the output increases, the input will decrease, and vice versa, such that the output signal would reach the desired stable level.

$$V_o = A V_d$$

$$V_d = V_+ - V_-$$

$$V_- = \frac{R_2}{R_1 + R_2} V_i + \frac{R_1}{R_1 + R_2} V_o$$



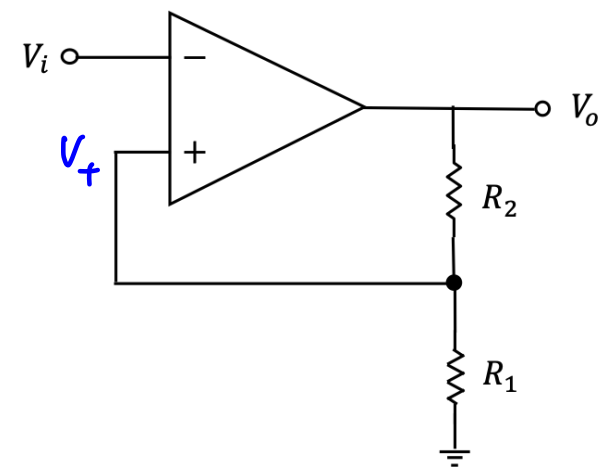
Feedback:

the concept, negative and positive feedback

Positive feedback: In circuits with positive feedback, when the output increases, the input will also increase, and vice versa. The output of circuits with positive feedback is always at its limits.

$$V_+ = \frac{R_1}{R_1 + R_2} V_o$$

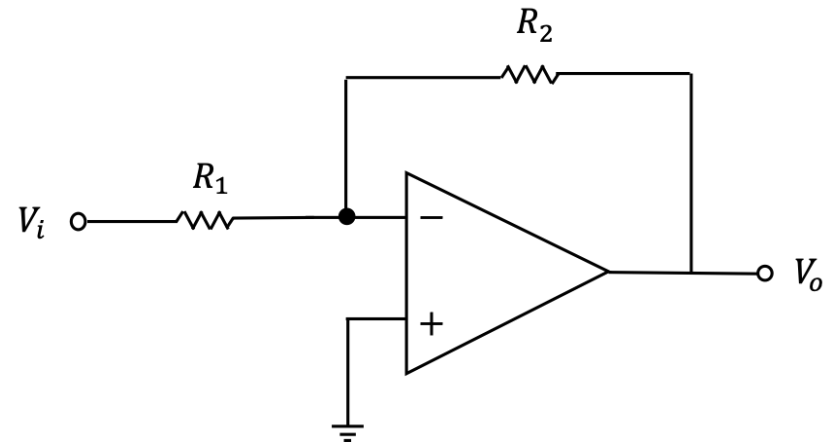
$$V_o = A (V_+ - V_-) = A (V_+ - V_i)$$



Solving op-amp circuits – example 1

Comprehensive solution

Find $\frac{v_o}{v_i}$ in the following op-amp circuit assuming an ideal op-amp.



Solving op-amp circuits – example 1

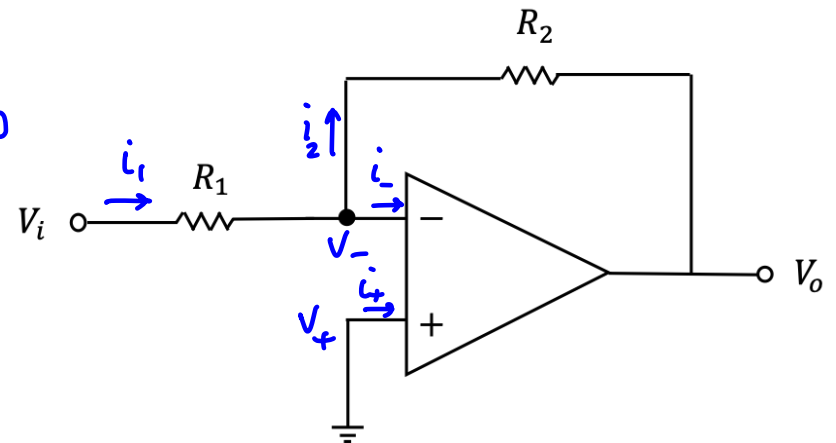
Comprehensive solution

Find $\frac{v_o}{v_i}$ in the following op-amp circuit assuming an ideal op-amp.

assume an ideal op-amp: $i_+ = i_- = 0$

$$V_+ = 0$$

$$V_o = A(V_+ - V_-) \rightarrow V_o = -AV_-$$



KCL at the inverting input node:

$$i_1 = i_2 + i_- \quad , \quad i_- = 0 \quad \rightarrow \quad i_1 = i_2$$

$$i_1 = \frac{v_i - v_-}{R_1} \quad , \quad i_2 = \frac{v_- - v_o}{R_2}$$

Solving op-amp circuits – example 1

Comprehensive solution

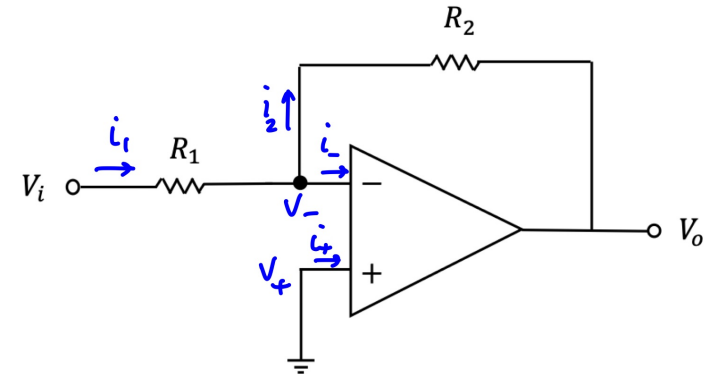
$$i_1 = \frac{V_i - V_-}{R_1}, \quad i_2 = \frac{V_- - V_o}{R_2}$$

$$i_1 = i_2 \rightarrow \frac{V_i - V_-}{R_1} = \frac{V_- - V_o}{R_2}$$

$$\left(-\frac{1}{R_1} - \frac{1}{R_2} \right) V_- = -\frac{1}{R_1} V_i - \frac{1}{R_2} V_o$$

$$-\left(\frac{R_1 + R_2}{R_1 R_2} \right) V_- = -\frac{1}{R_1} V_i - \frac{1}{R_2} V_o$$

$$\left(\frac{R_1 + R_2}{R_1 R_2} \right) V_- = \frac{1}{R_1} V_i + \frac{1}{R_2} V_o$$



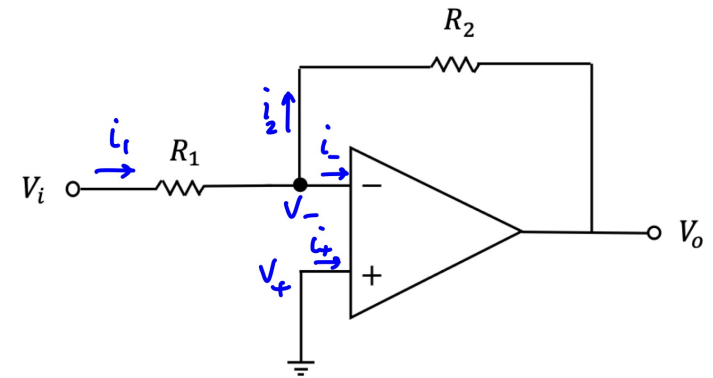
Solving op-amp circuits – example 1

Comprehensive solution

$$\left(\frac{R_1 + R_2}{R_1 R_2} \right) V_- = \frac{1}{R_1} V_i + \frac{1}{R_2} V_o$$

$$V_- = \frac{R_1 R_2}{R_1 + R_2} \left(\frac{1}{R_1} V_i + \frac{1}{R_2} V_o \right)$$

$$V_- = \left(\frac{R_2}{R_1 + R_2} \right) V_i + \left(\frac{R_1}{R_1 + R_2} \right) V_o$$



Solving op-amp circuits – example 1

Comprehensive solution

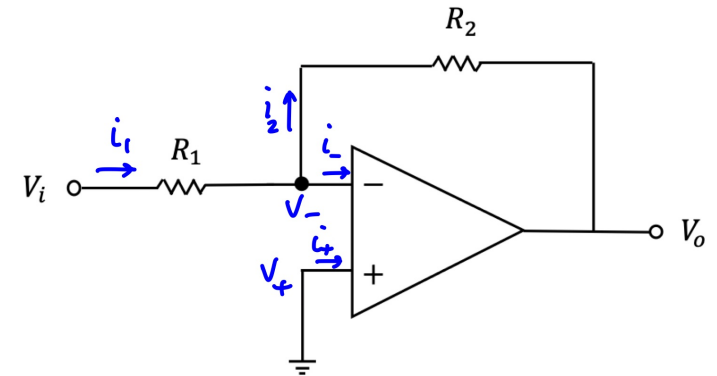
$$V_- = \left(\frac{R_2}{R_1 + R_2} \right) V_i + \left(\frac{R_1}{R_1 + R_2} \right) V_o$$

$$V_o = -A V_-$$

$$V_o = -A \left[\left(\frac{R_2}{R_1 + R_2} \right) V_i + \left(\frac{R_1}{R_1 + R_2} \right) V_o \right]$$

$$V_o + \left(\frac{A R_1}{R_1 + R_2} \right) V_o = - \left(A \frac{R_2}{R_1 + R_2} \right) V_i$$

$$\left[1 + \left(\frac{A R_1}{R_1 + R_2} \right) \right] V_o = - \left(A \frac{R_2}{R_1 + R_2} \right) V_i$$



Solving op-amp circuits – example 1

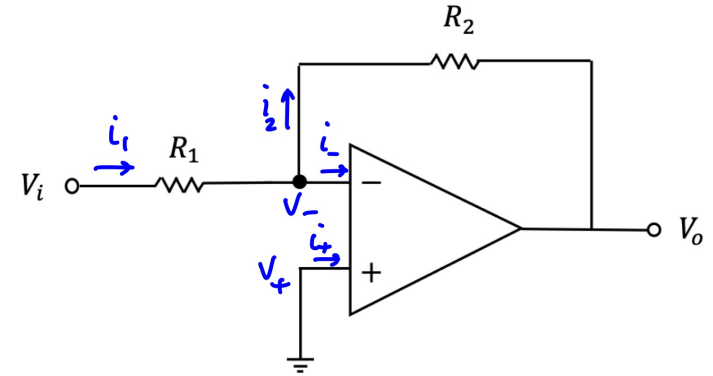
Comprehensive solution

$$\left[1 + \left(\frac{A R_1}{R_1 + R_2} \right) \right] V_o = - \left(A \frac{R_2}{R_1 + R_2} \right) V_i$$

define $B = \frac{R_1}{R_1 + R_2}$

$$\rightarrow \frac{R_2}{R_1 + R_2} = \frac{R_2}{R_1} \times \frac{R_1}{R_1 + R_2} = \frac{R_2}{R_1} \times B$$

$$(1 + AB) V_o = - \frac{R_2}{R_1} AB V_i$$



Solving op-amp circuits – example 1

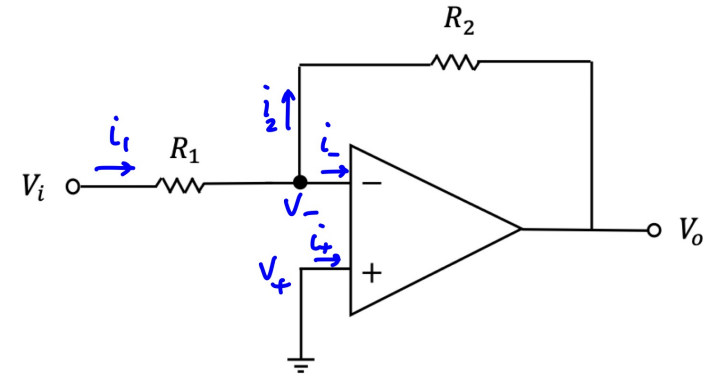
Comprehensive solution

$$B = \frac{R_1}{R_1 + R_2}$$

$$\frac{1}{AB} \times (1 + AB) V_o = \frac{1}{AB} \times -\frac{R_2}{R_1} AB V_i$$

$$\left(\frac{1}{AB} + 1 \right) V_o = -\frac{R_2}{R_1} V_i$$

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{AB}}$$

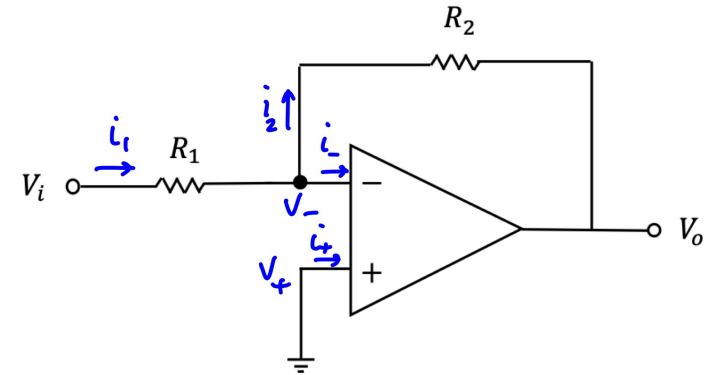


Solving op-amp circuits – example 1

Comprehensive solution

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{AB}}$$

$$B = \frac{R_1}{R_1 + R_2}$$



Example numbers : $R_1 = 1\text{ k}\Omega$, $R_2 = 9\text{ k}\Omega$, $A = 10^5$

$$B = \frac{1\text{ k}\Omega}{1\text{ k}\Omega + 9\text{ k}\Omega} = 0.1$$

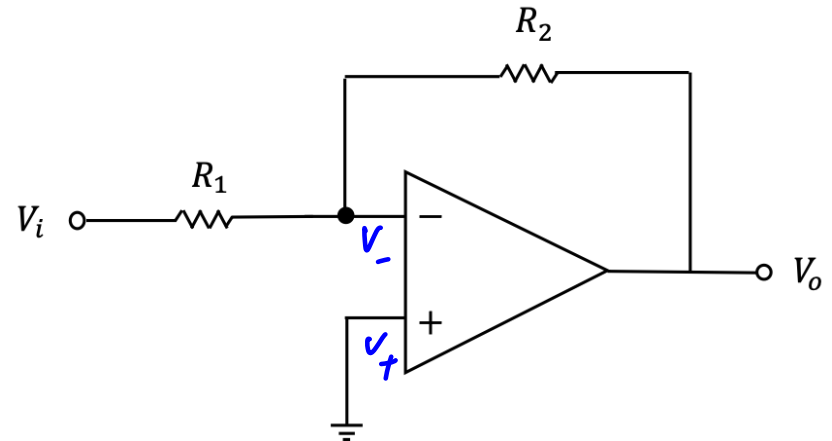
$$\frac{V_o}{V_i} = -\frac{9\text{ k}\Omega}{1\text{ k}\Omega} \times \frac{1}{1 + \frac{1}{10^5 \times 0.1}} = -9 \times \frac{1}{\underbrace{1 + 10^{-4}}_{\approx 1}} \approx -9 \frac{\text{V}}{\text{V}}$$

virtual short principle in op-amp circuits with negative feedback

$v_o \approx$ a finite value

$$v_o = A v_d \longrightarrow v_d = \frac{v_o}{A} \approx 0$$

$$\Rightarrow v_+ \approx v_-$$

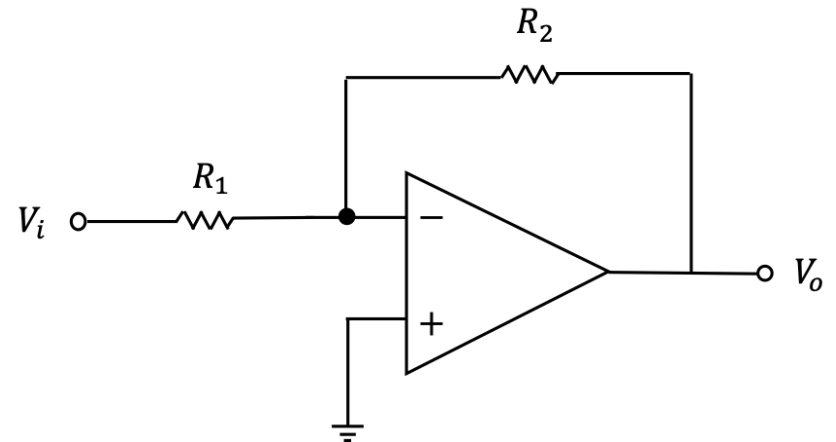


In op-amps with negative feedback and large open-loop gain, the op-amp adjusts its output voltage such that $v_d \approx 0$.

Solving op-amp circuits – example 1

Approximate solution

Find $\frac{v_o}{v_i}$ in the following op-amp circuit assuming an ideal op-amp.



Solving op-amp circuits – example 1

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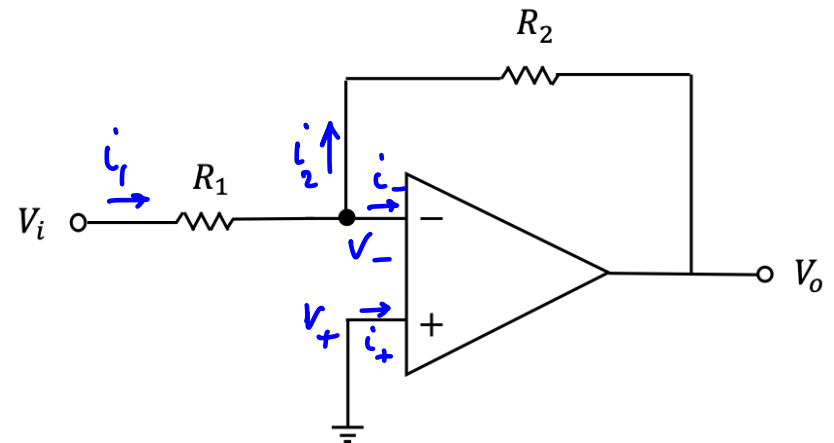
ideal op-amp : $i_+ = i_- = 0$
There is negative feedback : $v_+ \approx v_-$

$$v_+ = 0 \rightarrow v_- = 0$$

KCL at the inverting terminal : $i_1 = i_2 + i_- = i_2$

$$i_1 = i_2 \Rightarrow \frac{v_i - v_-}{R_1} = \frac{v_- - v_o}{R_2} ;$$

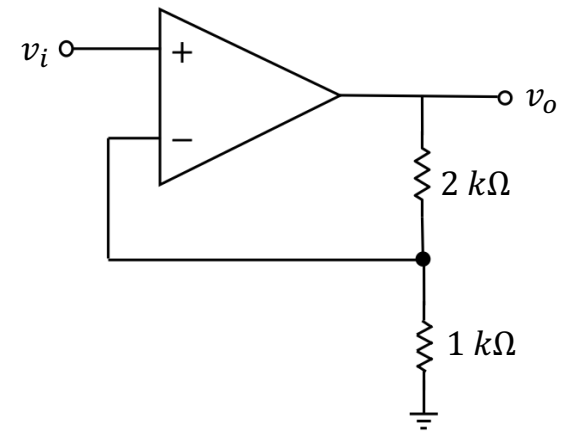
$$v_- = 0 \rightarrow \frac{v_i - 0}{R_1} = \frac{0 - v_o}{R_2} \Rightarrow \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$



Lecture 2 reading quiz.

In the following amplifier circuit, the input signal is $v_i(t) = 1.5 \sin(2\pi \times 10^3 t) \text{ V}$

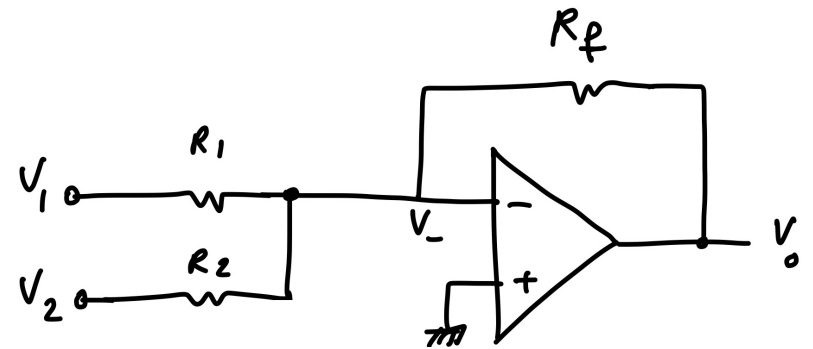
Which one of the options could be the output signal, $v_o(t)$?



Discussion question 1. (weighted summer)

Design the following op-amp circuit to achieve the weighted sum of input 1 and input 2 at the output. It is required that $v_o = -(v_1 + 5v_2)$.

Assume an ideal op-amp.



Discussion question 2. (non-inverting summer)

Using the structure of a non-inverting amplifier, design an op-amp circuit to achieve $v_o = 6v_1 + 4v_2$.

Assume an ideal op-amp.

Discussion question 3.

What is v_o/v_i in this op-amp circuit? Assume an ideal op-amp.

