ECE 65: Components & Circuits Lab

Lecture 2

Operational Amplifier (op-amp)

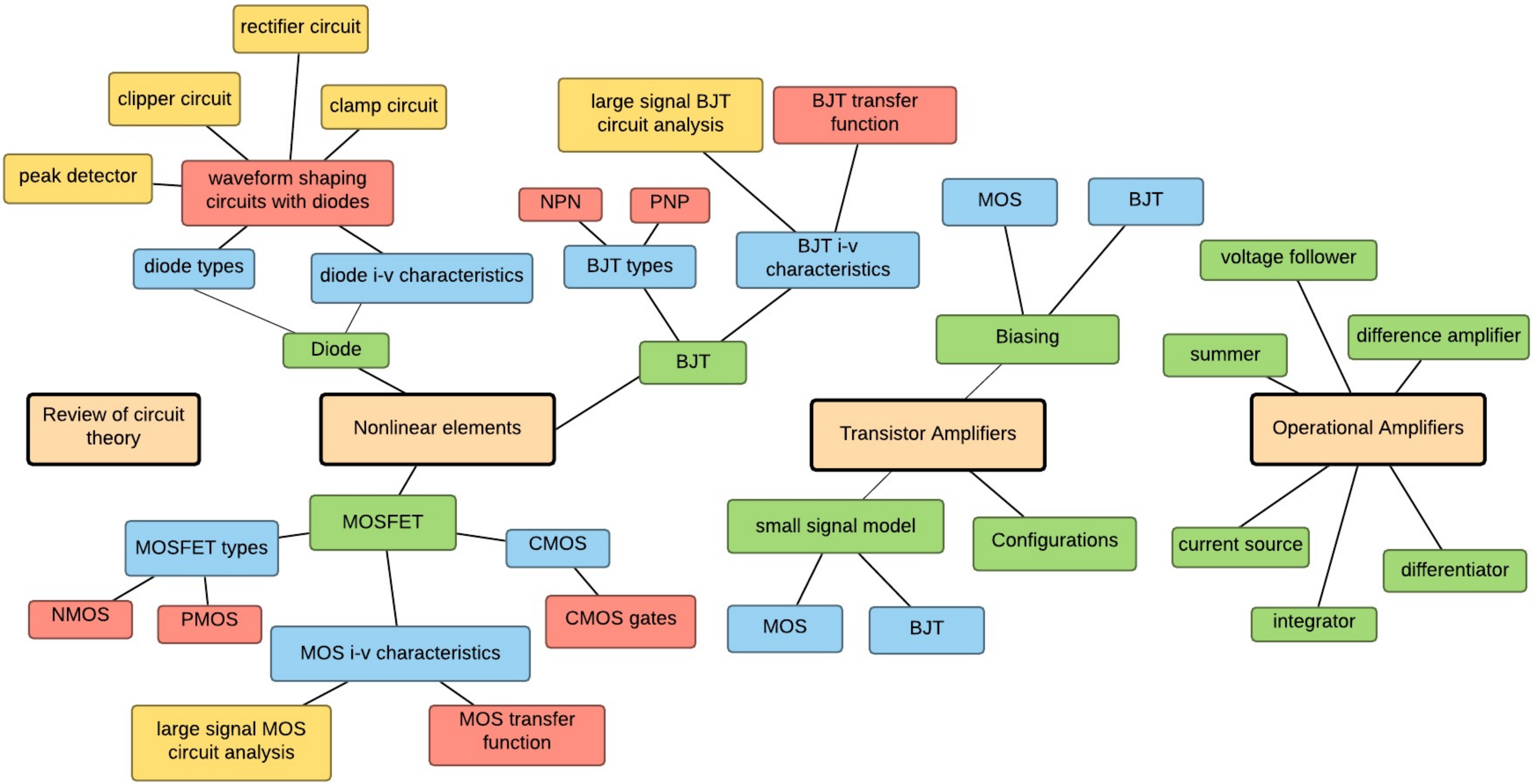
Reference notes: sections 7.1, 7.2

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

Saharnaz Baghdadchi

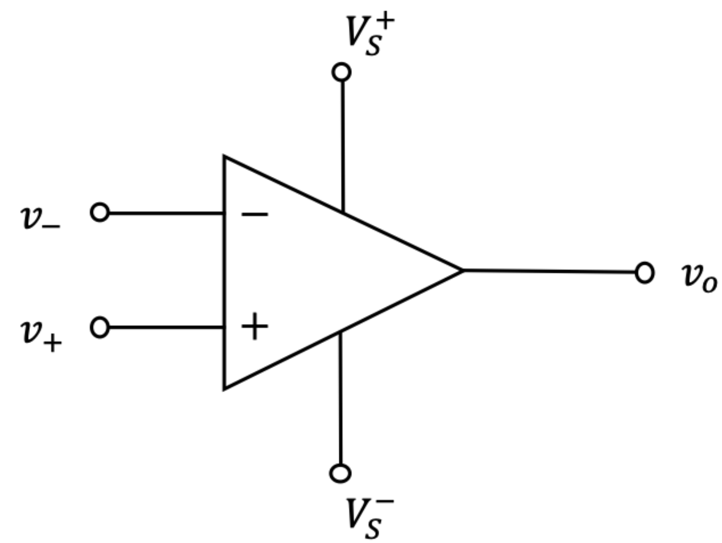
Course map

7. Operational amplifiers



Operational Amplifiers

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



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

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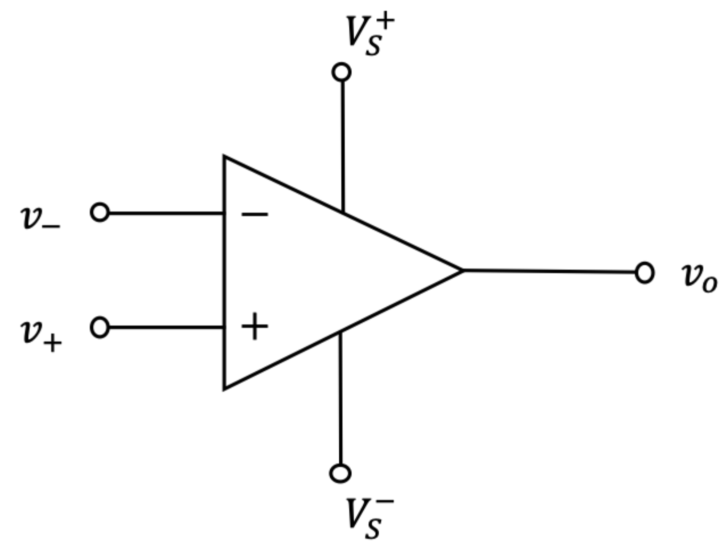

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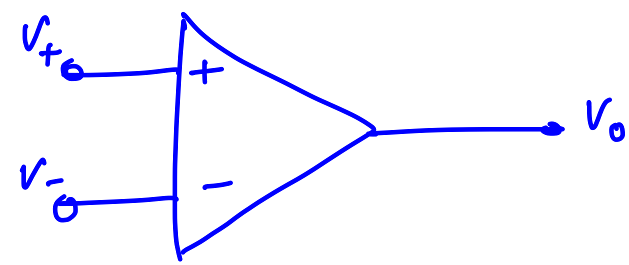

The $-$ and $+$ terminals are called the inverting and non-inverting terminals, respectively.

Operational Amplifiers

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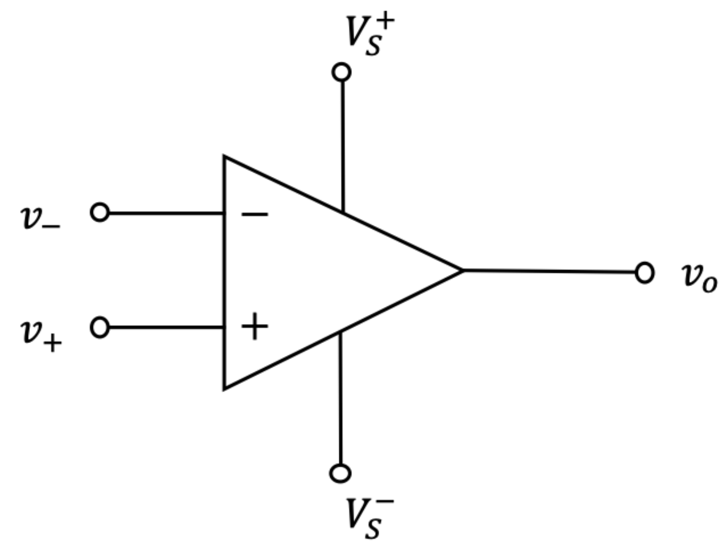
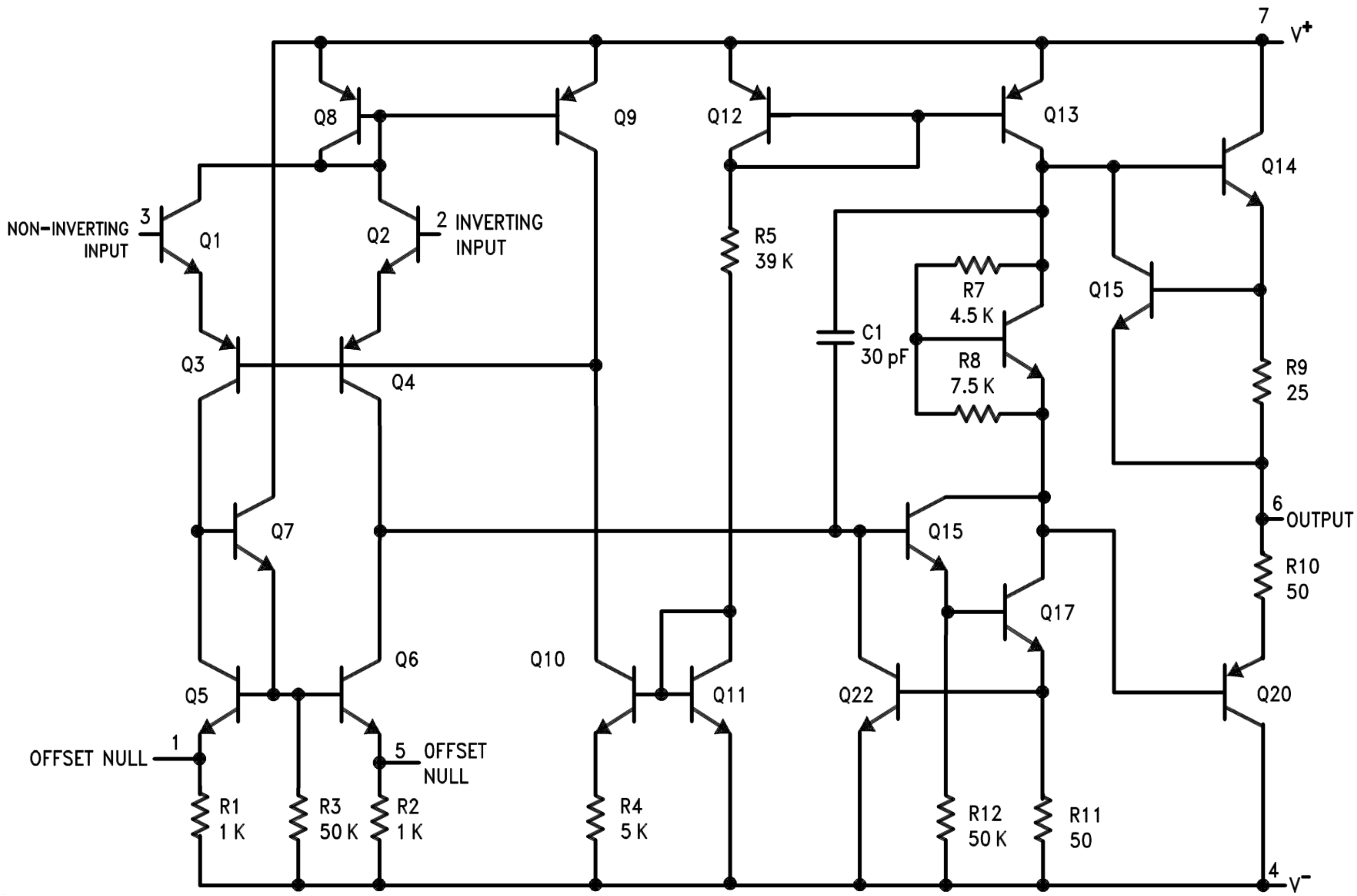


They are constructed such that they amplify the voltage difference between the two input signals.

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

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

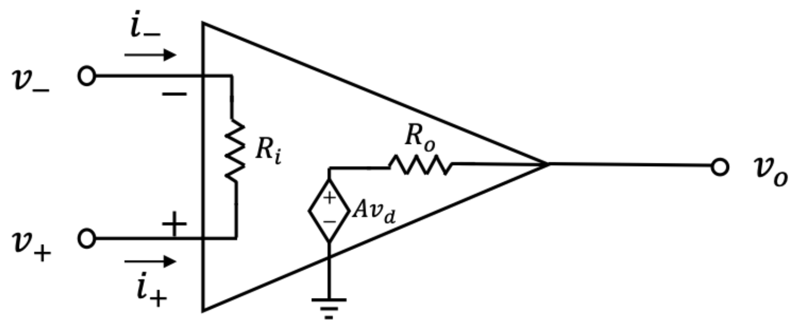
LM 741 op-amp



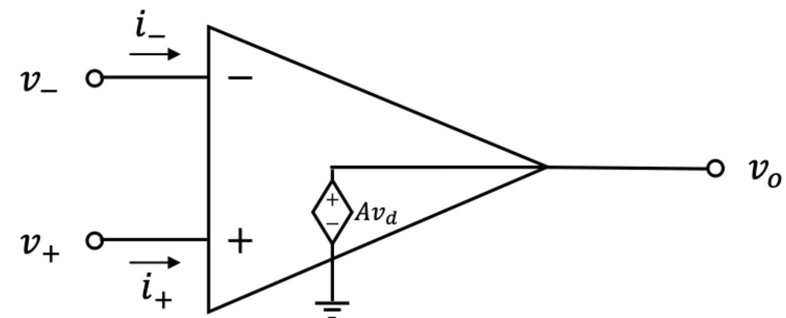
LM 741 op-amp (ti.com)

OpAmp models

Linear model



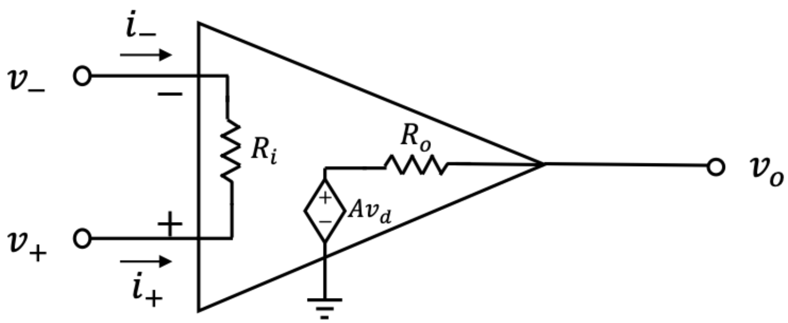
Ideal model



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

OpAmp models

Linear model



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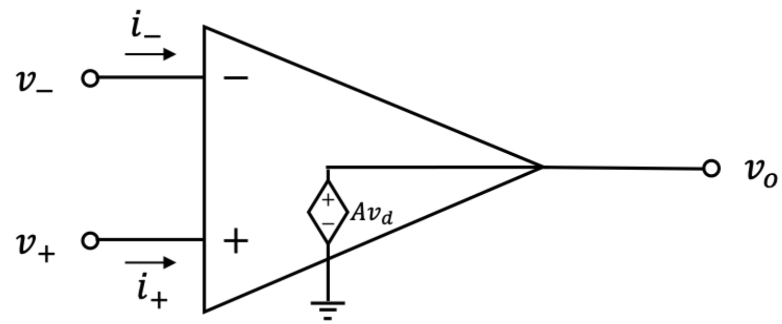
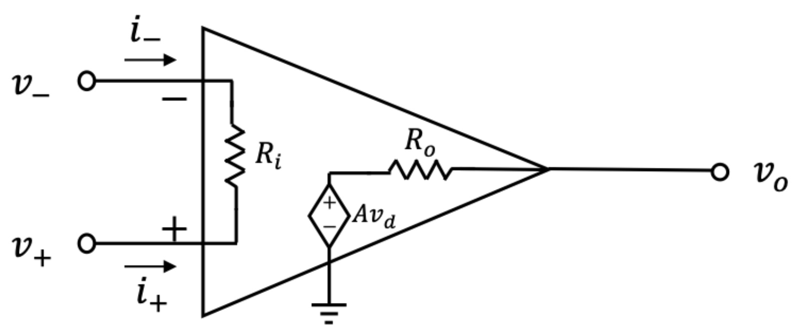


Because the input impedance of the op-amps is very large, the input current to the op-amp is very small.

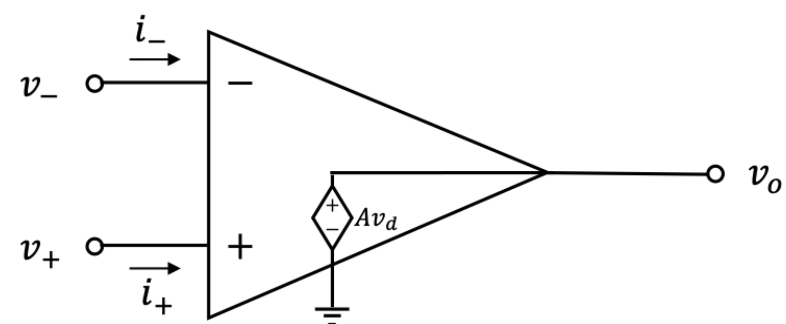
$$i_- \approx i_+ \approx 0$$

OpAmp models

Linear model



Ideal model

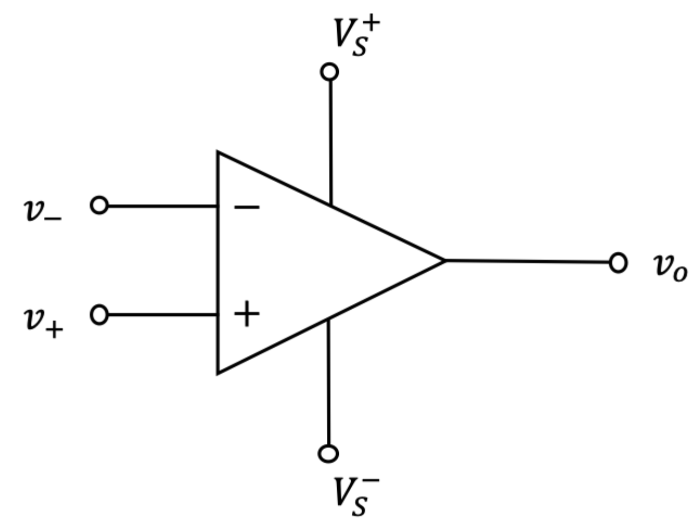


In the **ideal op-amp model**, $R_i = \infty$, $R_o = 0$, $i_- = i_+ = 0$

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.

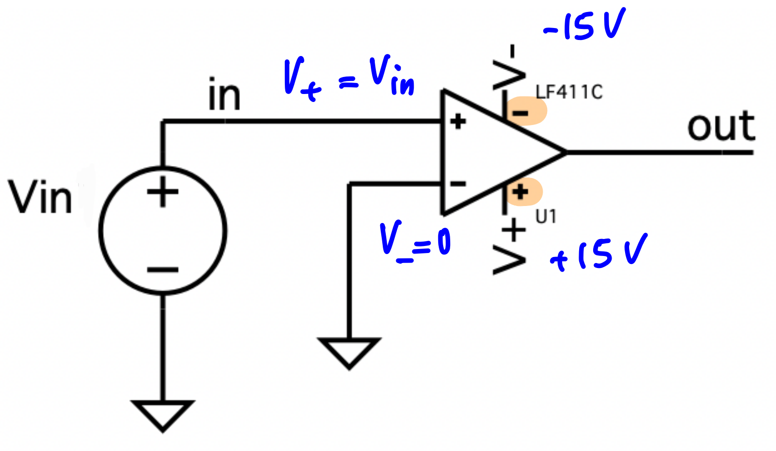
$$V_{S^-} < V_o < V_{S^+}$$

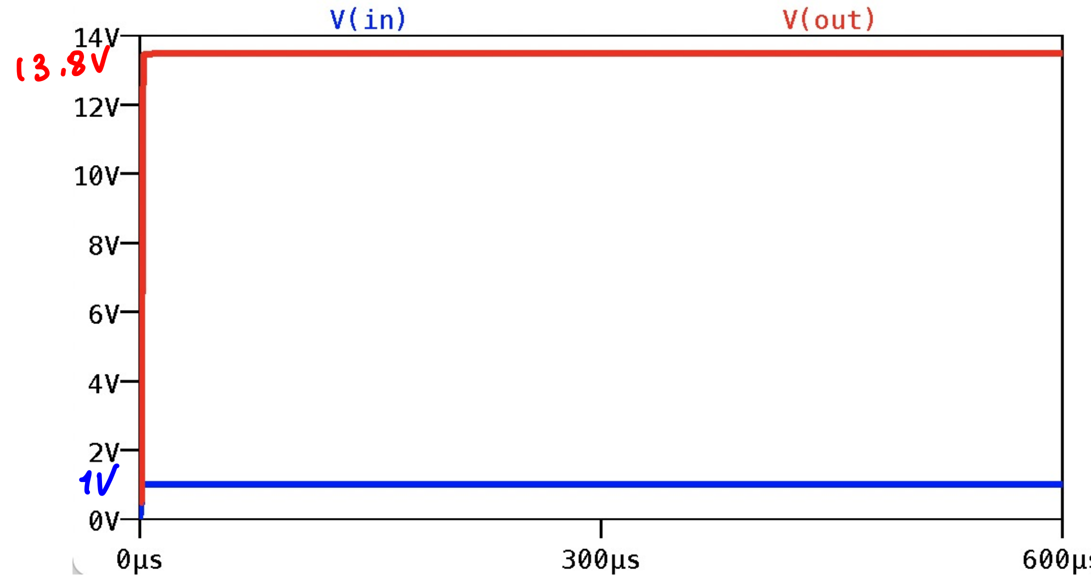


Open-loop operation of op-amps (no feedback)

$A = 10^5$

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





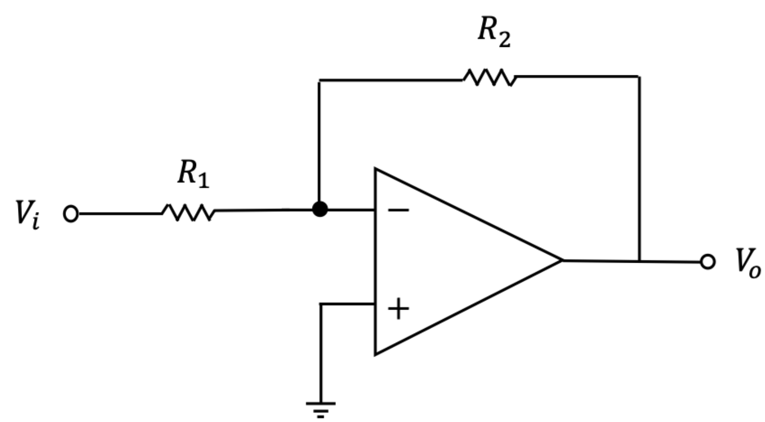
$V_{omax} = 13.8\,V$, here.

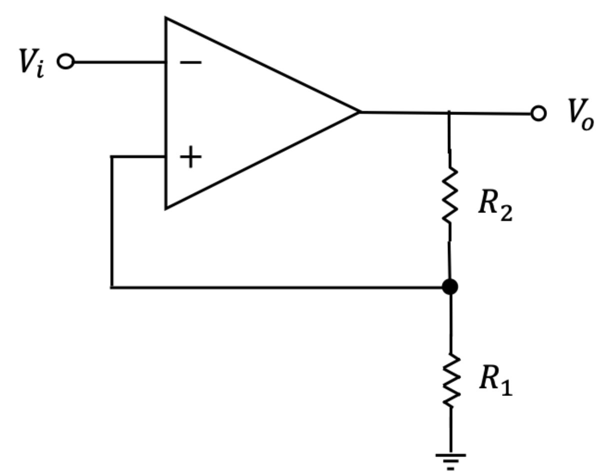
$V_o = 10^5 V_{in} \longrightarrow V_{inmax} = \frac{V_{omax}}{10^5} = \frac{13.8V}{10^5} = 13.8\,V \times 10^{-5} = 138 \times 10^{-6}\,V = 138\,\mu V$

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

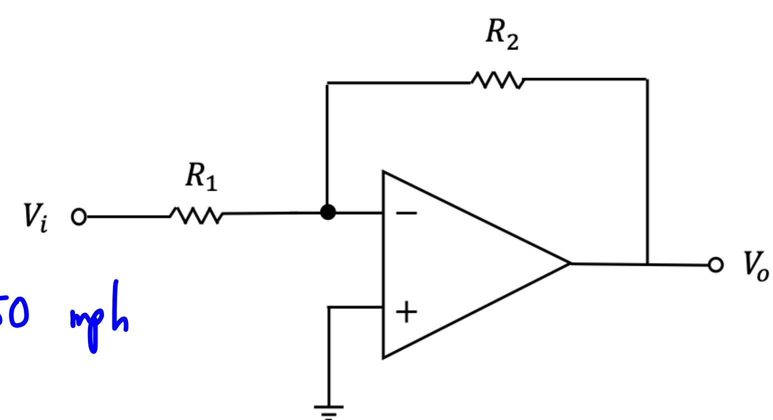
Feedback:
the concept, negative and positive feedback

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 ↗ 55 mph

input ↓ $\Longrightarrow$ output ↙ $\longrightarrow$ output : 50 mph



if output ↙ 45 mph

input ↗ $\Longrightarrow$ output ↗ $\longrightarrow$ output : 50 mph

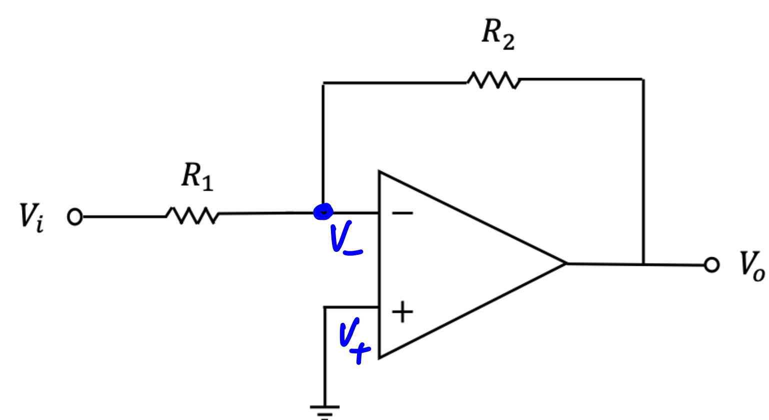
Feedback:
the concept, negative and positive feedback

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.

$V_o = A V_d$

$V_d = V_+ - V_-$

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

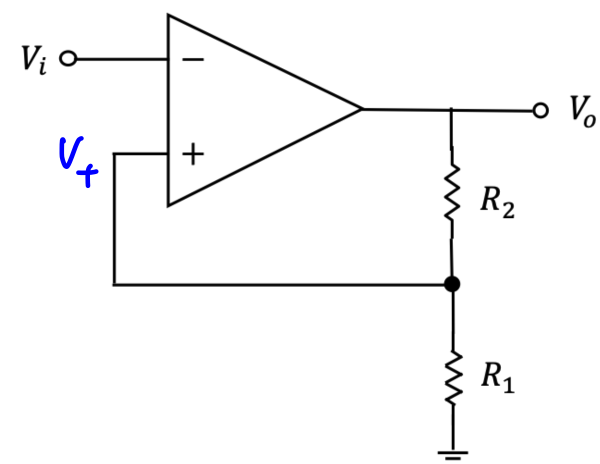


Feedback:
the concept, negative and positive feedback

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.

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

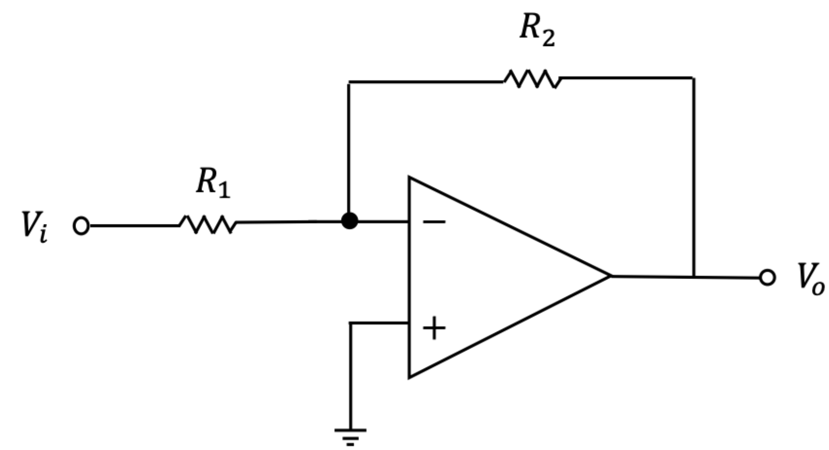
$$V_o = A(V_+ - V_-) = A(V_+ - V_i)$$



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.



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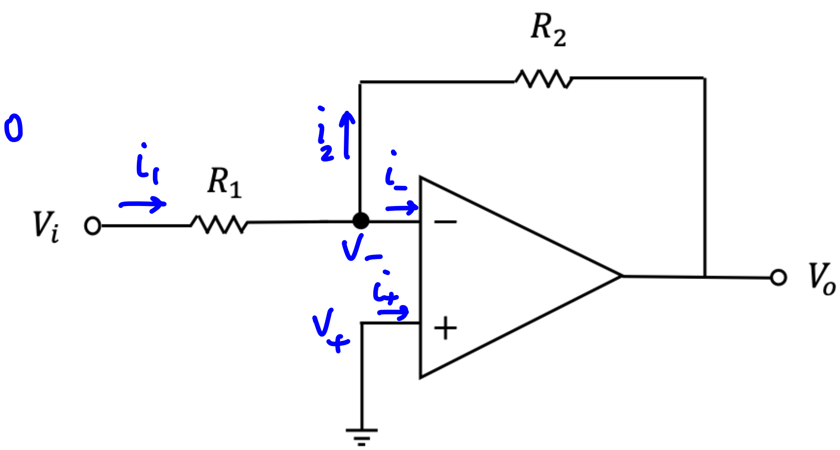


assume an ideal op-amp: $i_+ = i_- = 0$

$V_+ = 0$

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

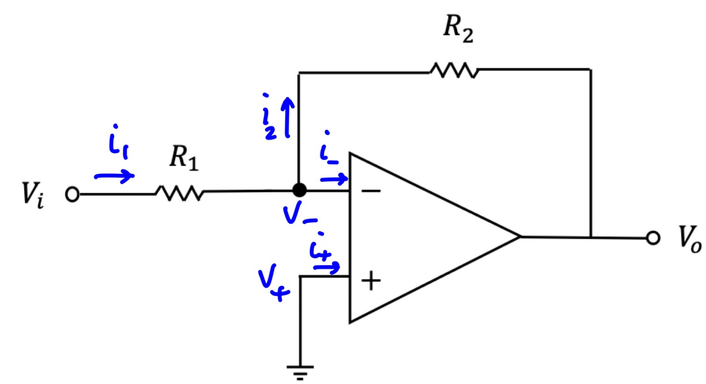
KCL at the inverting input node:

$i_1 = i_2 + i_-$, $i_- = 0 \longrightarrow i_1 = i_2$

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

Solving op-amp circuits – example 1

Comprehensive solution



$$i_1 = \frac{V_i - V_-}{R_1} \quad , \quad i_2 = \frac{V_- - V_0}{R_2}$$

$$i_1 = i_2 \longrightarrow \frac{V_i - V_-}{R_1} = \frac{V_- - V_0}{R_2}$$

$$\left(\frac{-1}{R_1} - \frac{1}{R_2} \right) V_- = \frac{-1}{R_1} V_i - \frac{1}{R_2} V_0$$

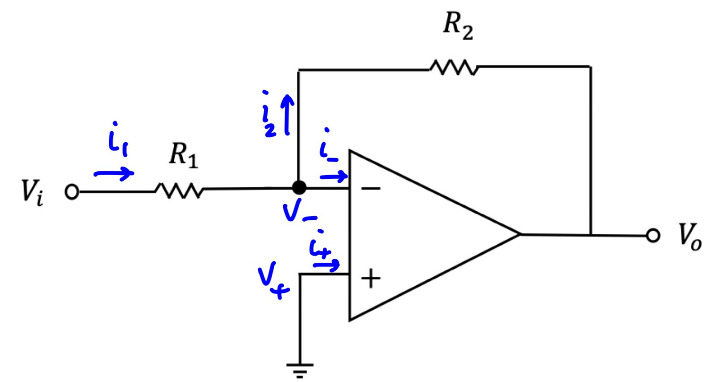
$$-\left(\frac{R_1 + R_2}{R_1 R_2} \right) V_- = -\frac{1}{R_1} V_i - \frac{1}{R_2} V_0$$

$$\left(\frac{R_1 + R_2}{R_1 R_2} \right) V_- = \frac{1}{R_1} V_i + \frac{1}{R_2} V_0$$

Solving op-amp circuits – example 1

Comprehensive solution

$$\left(\frac{R_1+R_2}{R_1 R_2}\right)V_- = \frac{1}{R_1}V_i + \frac{1}{R_2}V_0$$

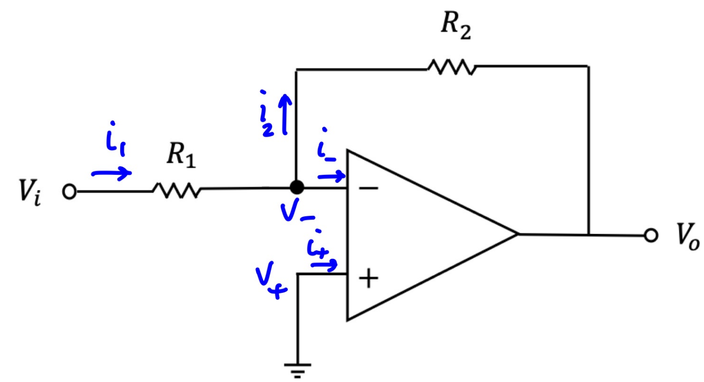


$$V_- = \frac{R_1 R_2}{R_1+R_2}\left(\frac{1}{R_1}V_i + \frac{1}{R_2}V_0\right)$$

$$\boxed{V_- = \left(\frac{R_2}{R_1+R_2}\right)V_i + \left(\frac{R_1}{R_1+R_2}\right)V_0}$$

Solving op-amp circuits – example 1

Comprehensive solution



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

$$\boxed{V_o = -A V_-}$$

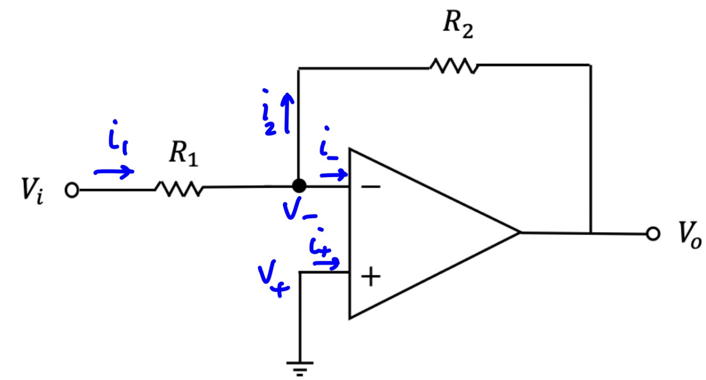
$$V_o = -A\left[\left(\frac{R_2}{R_1+R_2}\right) V_i + \left(\frac{R_1}{R_1+R_2}\right) V_o\right]$$

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

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

Solving op-amp circuits – example 1

Comprehensive solution



$$\left[1+\left(\frac{A R_1}{R_1+R_2}\right)\right] V_0 = -\left(A \frac{R_2}{R_1+R_2}\right) V_i$$

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

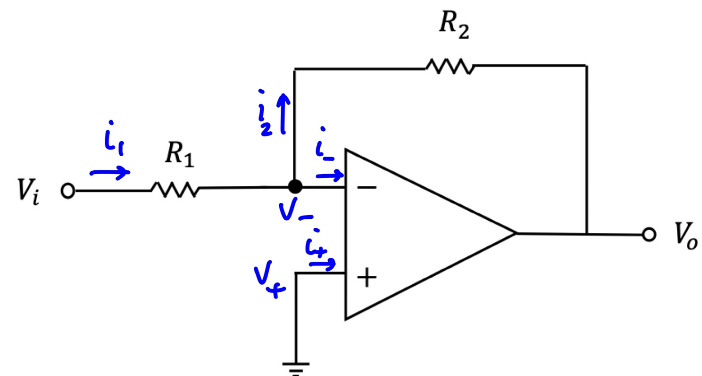
$$\rightarrow \frac{R_2}{R_1+R_2} = \frac{R_2}{R_1} \times \frac{R_1}{R_1+R_2} = \frac{R_2}{R_1} \times B$$

$$(1+AB)\, V_0 = -\frac{R_2}{R_1} AB\, V_i$$

Solving op-amp circuits – example 1

Comprehensive solution

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



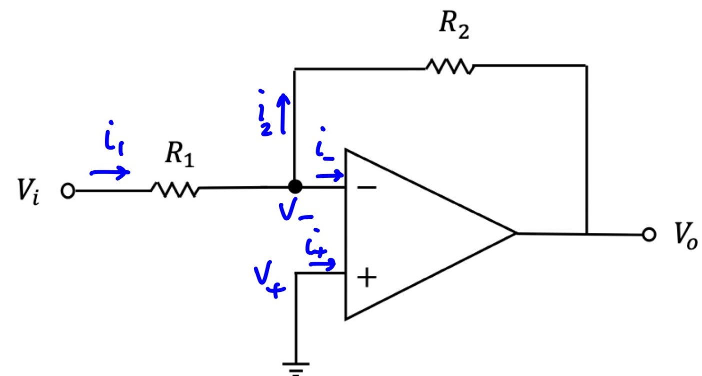
$$\frac{1}{AB} \times \left(1 + AB\right) V_o = \frac{1}{AB} \times -\frac{R_2}{R_1} AB \; V_i$$

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

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

Solving op-amp circuits – example 1

Comprehensive solution



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

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

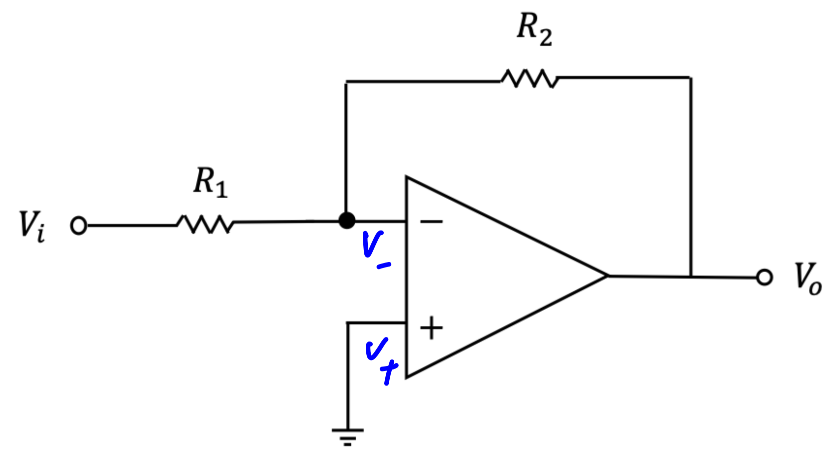
Example numbers : $R_1 = 1\,k\Omega$, $R_2 = 9\,k\Omega$, $A = 10^5$

$$\beta = \frac{1\,k\Omega}{1\,k\Omega + 9\,k\Omega} = 0.1$$

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

virtual short principle in op-amp circuits with negative feedback

$v_o \approx$ a finite value



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

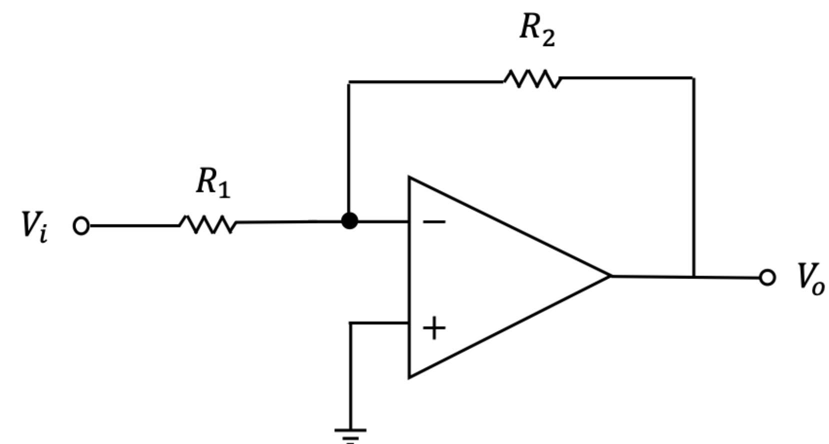
$$\Rightarrow v_+ \approx v_-$$

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.



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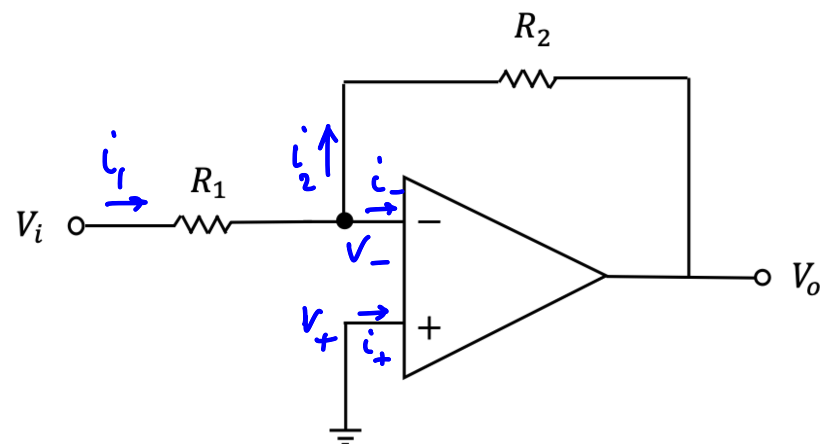


ideal op-amp : $i_+ = i_- = 0$

There is negative feedback : $V_+ \approx V_-$

$V_+ = 0 \longrightarrow V_- = 0$

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

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

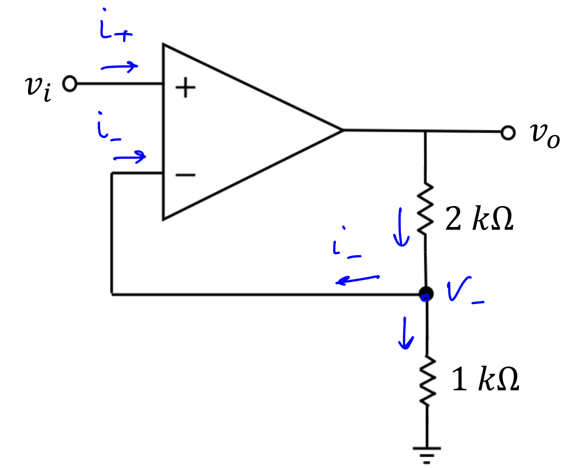
$V_- = 0 \longrightarrow \frac{V_i - 0}{R_1} = \frac{0 - V_o}{R_2} \Longrightarrow \frac{V_o}{V_i} = \frac{-R_2}{R_1}$

Lecture 2 reading quiz.

In the following amplifier circuit, the input signal is $v_i(t) = 1.5\sin(2\pi \times 10^3 t)\ V$.
Which one of the options could be the output signal, $v_o(t)$?

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

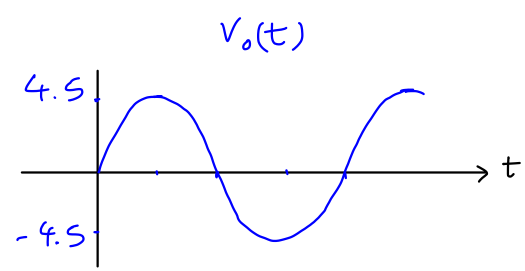
negative feedback : $V_+ = V_-$



$V_+ = V_i \longrightarrow V_- = V_+ = V_i$

KCL : $\dfrac{V_-}{1k} + i_- = \dfrac{V_o - V_-}{2k} \longrightarrow \dfrac{V_-}{1k\Omega} = \dfrac{V_o - V_-}{2k}$

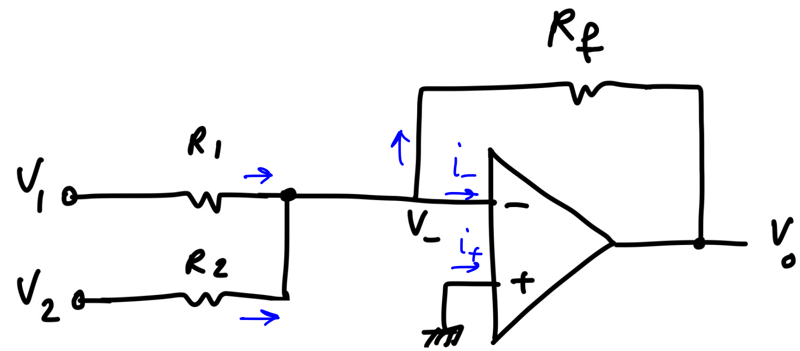
$\rightarrow V_o = 2\left(1 + \frac{1}{2}\right) V_- = 3\ V_- \longrightarrow V_o = 3\ V_i$



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.



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

negative feedback: $V_+ = V_-$

KCL at the inverting input terminal: $\dfrac{V_1 - V_-}{R_1} + \dfrac{V_2 - V_-}{R_2} = \dfrac{V_- - V_o}{R_f} + i_-$

$V_- = V_+ = 0 \longrightarrow \dfrac{V_1 - 0}{R_1} + \dfrac{V_2 - 0}{R_2} = \dfrac{0 - V_o}{R_f} \Longrightarrow V_o = \left(\dfrac{-R_f}{R_1}\right) V_1 + \left(\dfrac{-R_f}{R_2}\right) V_2$

$V_o = -V_1 - 5V_2 \Longrightarrow \dfrac{R_f}{R_1} = 1$ and $\dfrac{R_f}{R_2} = 5$, we can choose

$R_f = 5\,k\Omega$

$R_1 = 5\,k\Omega$

$R_2 = 1\,k\Omega$