Final.

Op-Amp.
Semiconductor physics.
Diode.

Diode Aplication.
transistor.
transistor Aplication

Alexander-Sadiku
Fundamentals of Electric Circuits

Chapter 5
Operational Amplifier

Operational Amplifier - Chapter 5

5.1 What is an Op Amp?

5.2 Ideal Op Amp

5.3 Configuration of Op Amp

5.4 Cascaded Op Amp

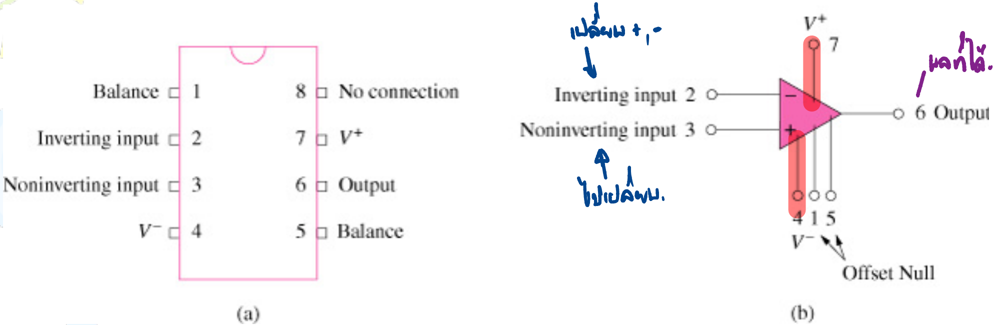
5.5 Application

– Digital-to Analog Converter

5.1 What is an Op Amp (1)

- It is an electronic unit that behaves like a voltage-controlled voltage source.
- It is an active circuit element designed to perform mathematical operations of ***addition***, ***subtraction***, ***multiplication***, ***division***, ***differentiation*** and ***integration***.
- The ability of the op amp to perform these mathematical operations is the reason it is called an operational amplifier. It is also the reason for the widespread use of op amps in analog design.

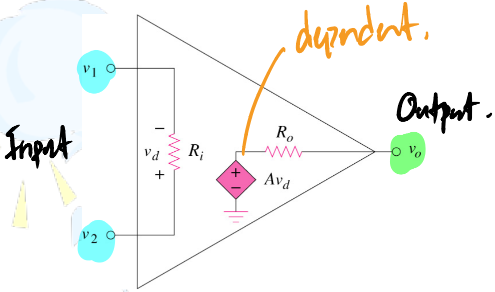
5.1 What is an Op Amp (2)



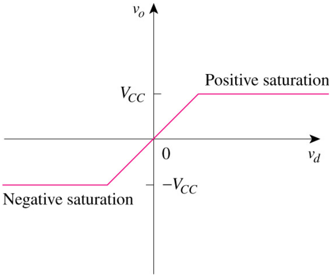
A typical op amp: (a) pin configuration, (b) circuit symbol

5.1 What is an Op Amp (3)

The equivalent circuit
Of the non-ideal op amp



Op Amp output:
vo as a function of Vd



$$vd = v2 - v1; \quad vo = Avd = A(v2 - v1)$$

5.1 What is an Op Amp (4)

Typical ranges for op amp parameters

Parameter	Typical range	Ideal values
Open-loop gain, A	10^5 to 10^8 Ω	∞ Ω
Input resistance, Ri	10^5 to 10^{15} Ω	∞ Ω
Output resistance, Ro	10 to 100 Ω	0 Ω
Supply voltage, VCC	5 to 24 V	

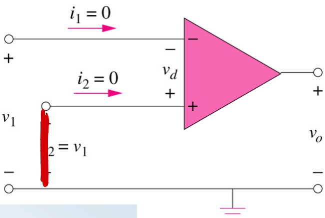
5.2 Ideal Op Amp (1)

An ideal op amp has the following characteristics:

① No current flow. in input.

1. Infinite open-loop gain, A ≈ ∞
2. Infinite input resistance, Ri ≈ ∞
3. Zero output resistance, Ro ≈ 0

$v_d = v_2 - v_1 = 0$



$\boxed{i_1 = 0, \qquad i_2 = 0}$

$\boxed{v_1 = v_2}$

An **ideal op amp** is an amplifier with infinite open-loop gain, infinite input resistance, and zero output resistance.

www.falstad.com.

5.2 Ideal Op Amp (2)

Example 1:

Determine the value of *io.*

KCL.

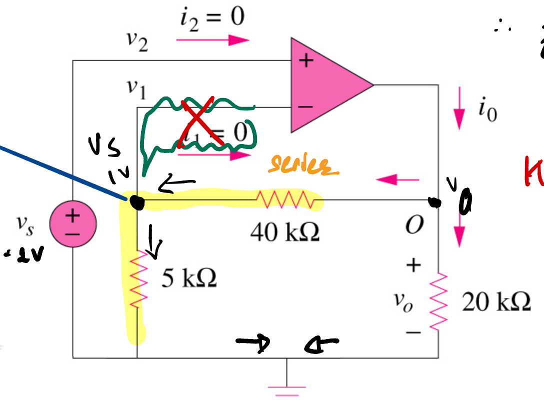
$$\frac{V_o}{20k} + \frac{V_o - 1}{40k} = i_o$$

$$\therefore \frac{9}{20k} + \frac{8}{40k} = i_o$$

$\therefore i_o = 0.65$ mA.

$$\frac{V_o - 1}{40} = \frac{1}{5}$$

$\therefore V_o = 9$ V.



KCL.

*Refer to in-class illustration, textbook

Ans: 0.65mA

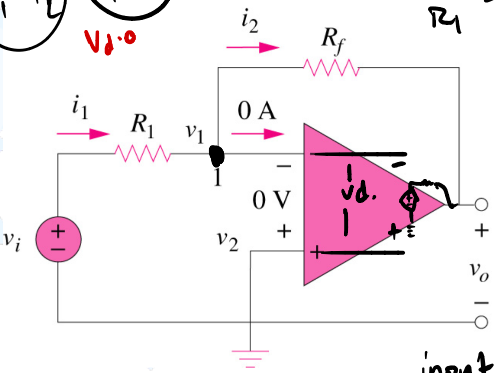
5.3 Configuration of Op amp (1)

- Inverting amplifier reverses the polarity of the input signal while amplifying it

$i_1 = i_2$ $\quad$ $v_1 = v_d$

$V_d = 0$

$$\frac{v_s - \cancel{v_1}^{\,0}}{R_1} = \frac{\cancel{v_1}^{\,0} - v_o}{R_f} \rightarrow \frac{v_o}{v_s} = -\frac{R_f}{R_1}$$



$$v_o = -\frac{R_f}{R_1} v_i$$

input		output
−V	→	+V
+V		−V

5.3 Configuration of Op amp (2)

Example 2

Refer to the op amp below. If vi = 0.5V, calculate: (a) the output voltage, vo and (b) the current in the 10k□ resistor.

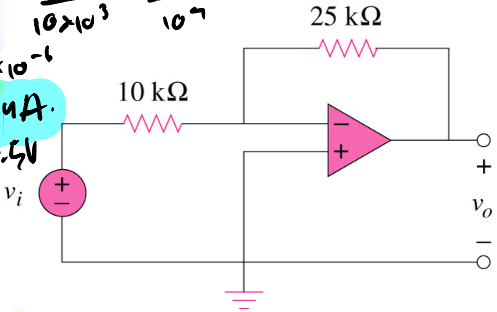
find V_o , find i_1.

$I_1 = \frac{V}{R} = \frac{0.5}{10\times10^3} = \frac{5\times10^{-1}}{10^4} = 5\times10^{-5}$

$= 50\times10^{-6}$

$= 50\,uA.$

0.5V



$V_o = -\frac{25k}{10k} \cdot 0.5$

$V_o = -1.25V.$

Ans:

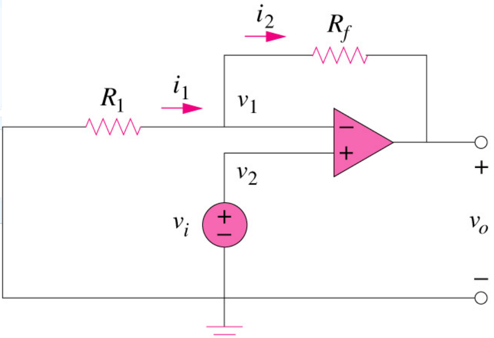
(a) -1.25V; (b) 50μA

*Refer to in-class illustration, textbook

5.3 Configuration of Op amp (3)

- Non-inverting amplifier is designed to produce positive voltage gain

input on +

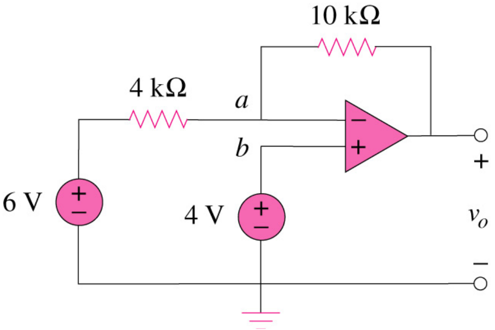


$$v_o = \left(1 + \frac{R_f}{R_1}\right)$$

5.3 Configuration of Op amp (4)

Example 3

For the op amp shown below, calculate the output voltage *vo*.

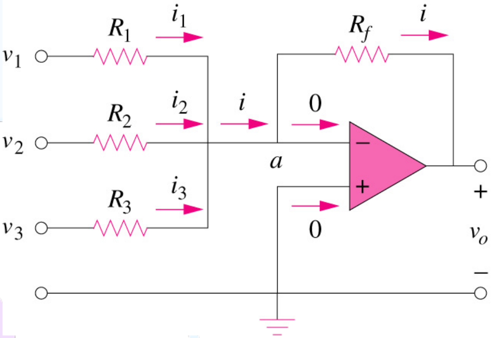


*Refer to in-class illustration, textbook

Ans: -1V

5.3 Configuration of Op amp (5)

- Summing Amplifier is an op amp circuit that combines several inputs and produces an output that is the weighted sum of the inputs.

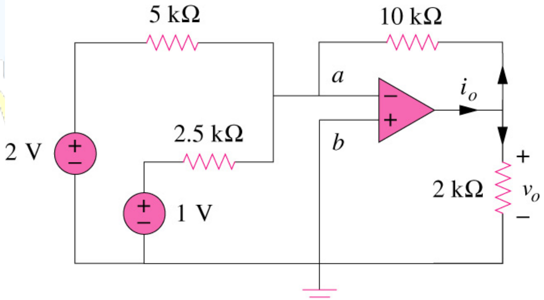


$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$

5.3 Configuration of Op amp (6)

Example 4

Calculate *vo* and *io* in the op amp circuit shown below.

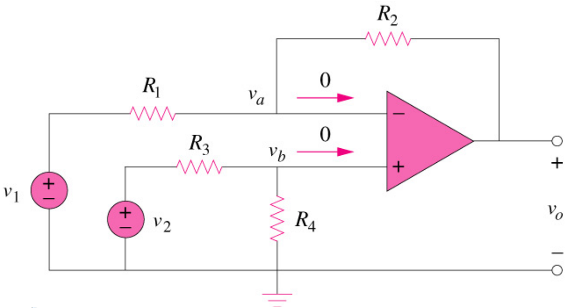


*Refer to in-class illustration, textbook

Ans: -8V, -4.8mA

5.3 Configuration of Op amp (7)

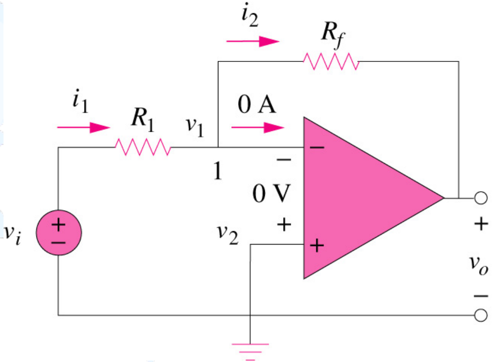
- Difference amplifier is a device that amplifies the difference between two inputs but rejects any signals common to the two inputs.



$$v_o = \frac{R_2(1+R_1/R_2)}{R_1(1+R_3/R_4)}v_2 - \frac{R_2}{R_1}v_1 \Rightarrow v_o = v_2 - v_1 \text{ , if } \frac{R_2}{R_1} = \frac{R_3}{R_4} = 1$$

5.3 Configuration of Op amp (1)

- Inverting amplifier reverses the polarity of the input signal while amplifying it

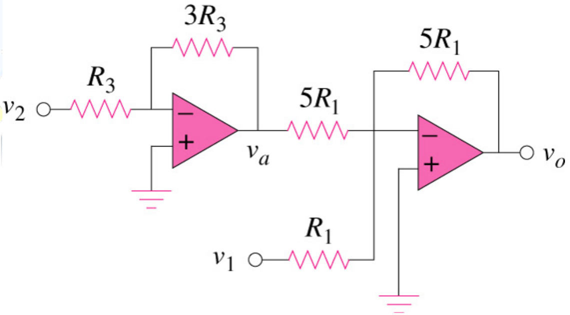


$$v_o = -\frac{R_f}{R_1} v_i$$

5.3 Configuration of Op amp (6)

Example 5

Determine R1, R2, R3 and R4 so that vo = -5v1+3v2 for the circuit shown below.



Ans:

R1 = 10kΩ

R2 = 50kΩ

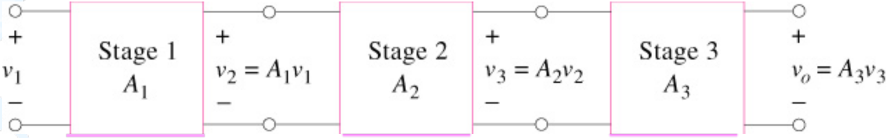
R3 = 20kΩ

R4 = 20kΩ

*Refer to in-class illustration, textbook

5.4 Cascaded Op Amp (1)

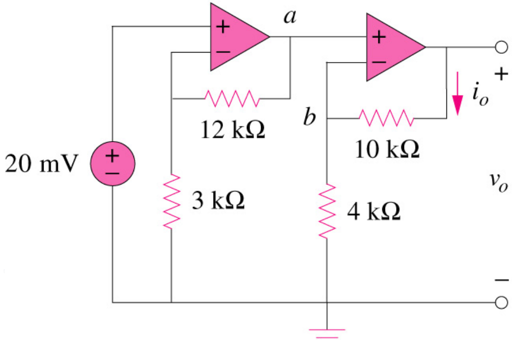
- It is a head-to-tail arrangement of two or more op amp circuits such that the output to one is the input of the next.



5.4 Cascaded Op Amp (2)

Example 6

Find vo and io in the circuit shown below.



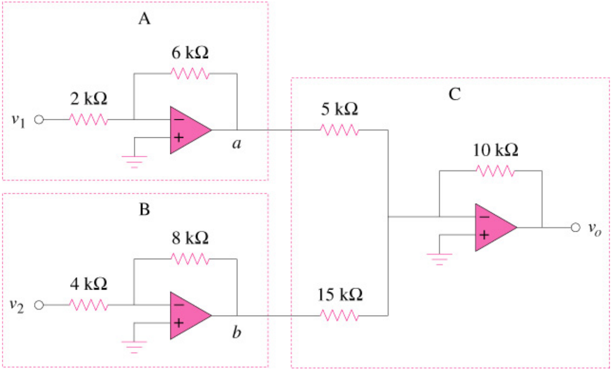
*Refer to in-class illustration, textbook

Ans: 350mV, 25μA

5.4 Cascaded Op Amp (3)

Example 7

If $v1 = 1V$ and $v2 = 2V$, find vo in the op amp circuit shown below.



*Refer to in-class illustration, textbook

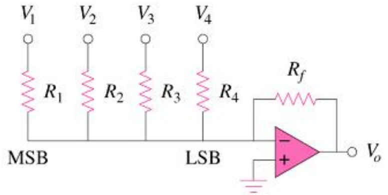
Ans: 8.667 V

5.5 Application (1)

- Digital-to Analog Converter (DAC) : it is a device which transforms digital signals into analog form.

Four-bit DCA: (a) block diagram (b) binary weighted ladder type

(a)



(b)

$$-V_0 = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \frac{R_f}{R_4}V_4$$

where

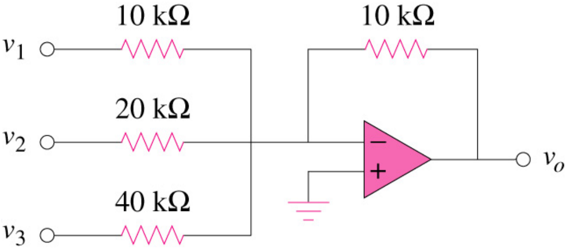
V1 – MSB, V4 – LSB

V1 to V4 are either 0 or 1 V

5.5 Application(2)

Example 8

For the circuit shown below, calculate vo if v1= 0V,v2=1V and v3 = 1V.

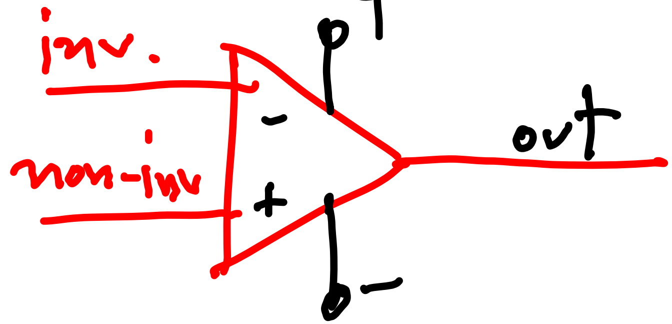


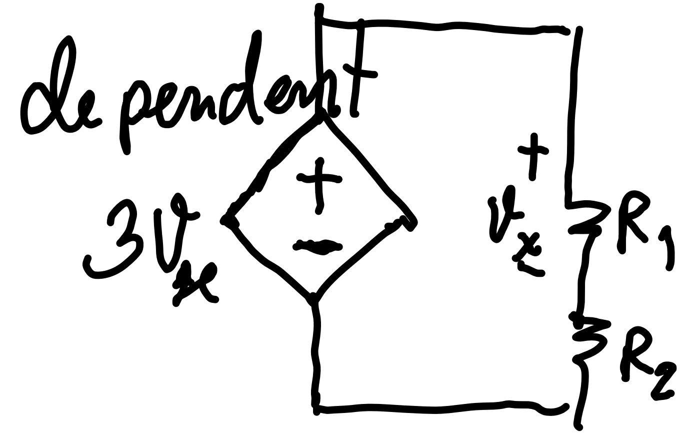
*Refer to in-class illustration, textbook

Ans:-0.75V

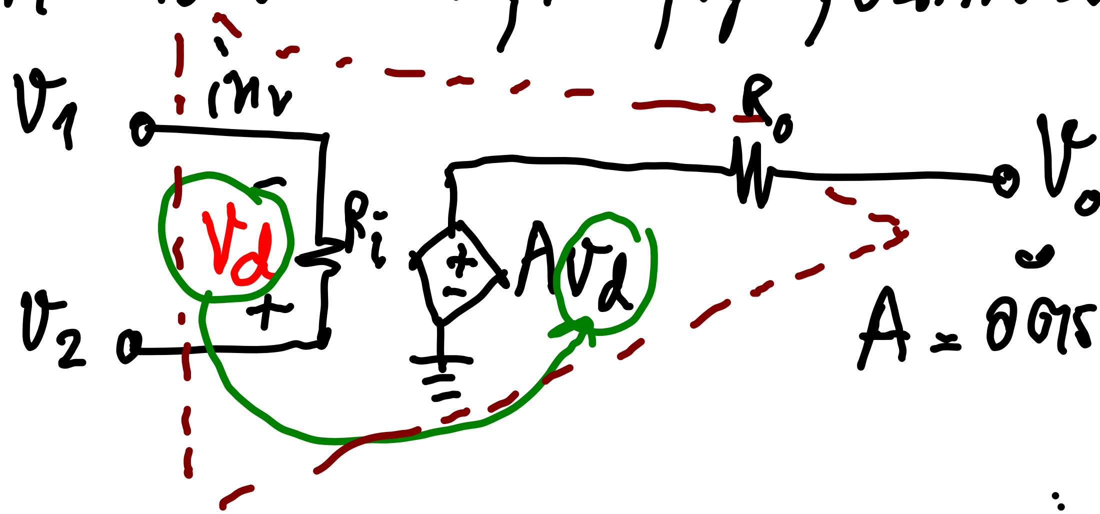
Op-amp

-





- Voltage-controlled voltage source
- ได้ถูกออกแบบมาใช้งานทางด้านการคำนวณทางคณิตศาสตร์ เช่น บวก, ลบ, คูณ, อินทิเกรต, diff.



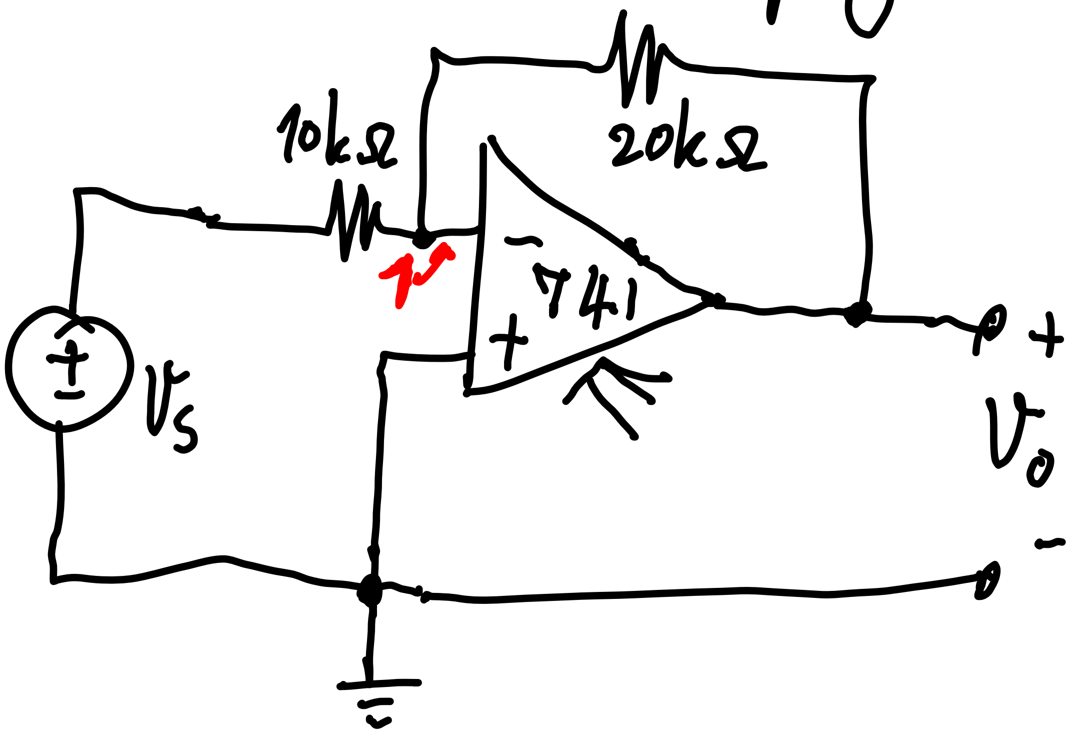
A = อัตราขยาย.

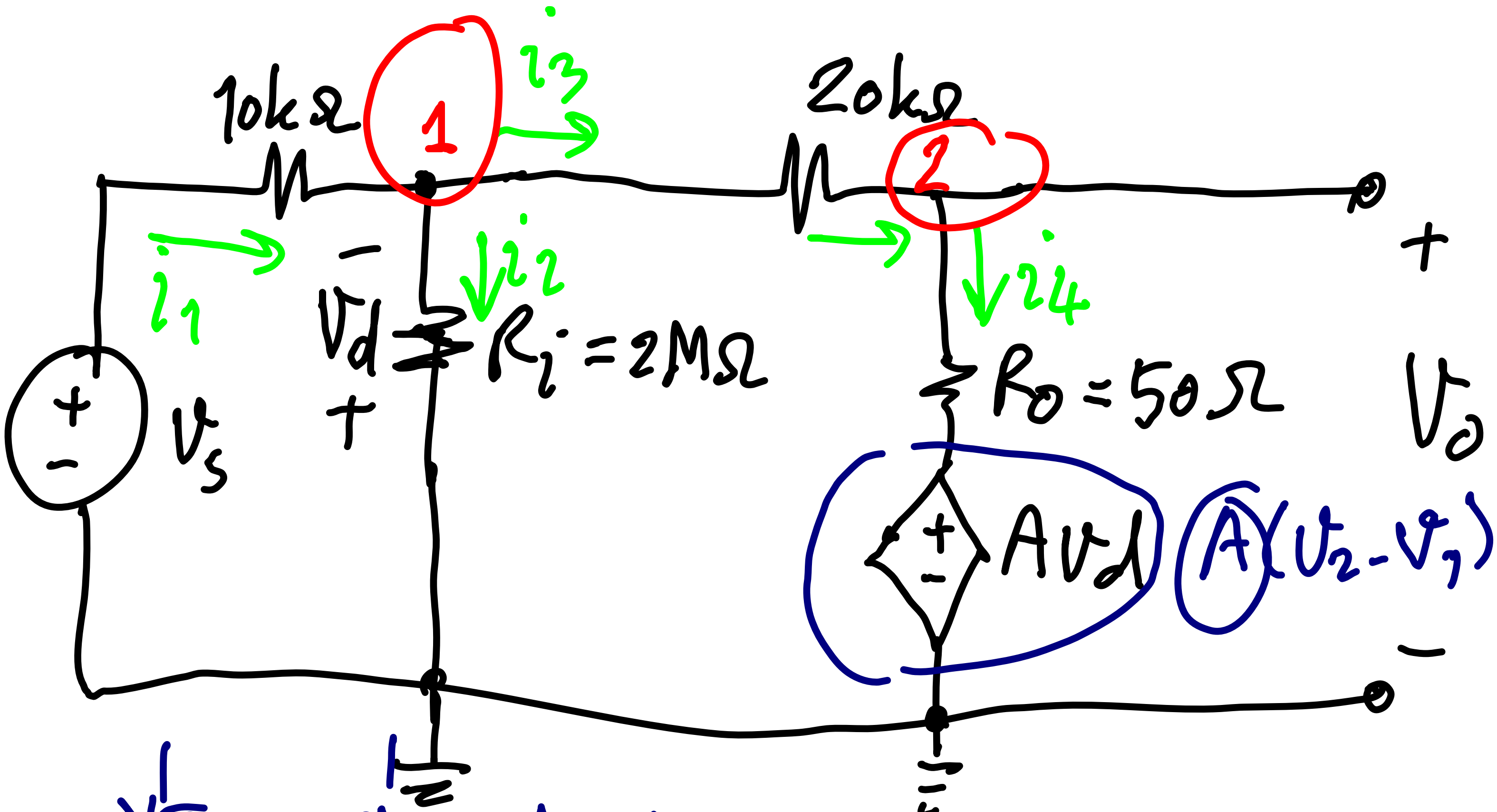
$v_d = v_2 - v_1$ และ $v_o = Av_d = A(v_2 - v_1)$ ※

ซึ่ง A ถูกเรียกว่า open-loop voltage gain

Parameters	ranges	Ideal value
A (อัตราการขยาย)	10^5 ถึง 10^8	∞
R_i (input Resistance)	10^6 ถึง 10^{13}	$\infty\ \Omega$
R_o (Output Resistance)	10 ถึง 100	$0\ \Omega$

Ex Op-Amp 741 มี open-loop gain (A) 2×10^5 มีความต้านทานอินพุท $2\,M\Omega$ มีความต้านทานเอาท์พุท $50\,\Omega$ จงหา close-loop gain V_o/V_s





ที่โหนดที่ 1 KCL

$$i_1 = i_2 + i_3 \Rightarrow \frac{v_s - v_1}{10k\Omega} = \frac{v_1}{R_i = 2M\Omega} + \frac{v_1 - v_2}{20k\Omega}$$

คูณด้วย 2×10^6 ทั้งสองข้าง

$$200v_s - 200v_1 = v_1 + 100v_1 - 100v_2$$

$$200v_s = 301v_1 - 100v_2$$

$$v_1 = \frac{200v_s + 100v_2}{301 \approx 300} = \frac{2v_s + v_2}{3}$$

ที่โหนดที่ 2

$$\frac{v_1 - v_2}{20\,k\Omega} = \frac{v_2 - A_{vd}}{50}$$

$$v_d = -v_1$$

จาก $A = 2\times10^5$ และ $v_d = -v_1$

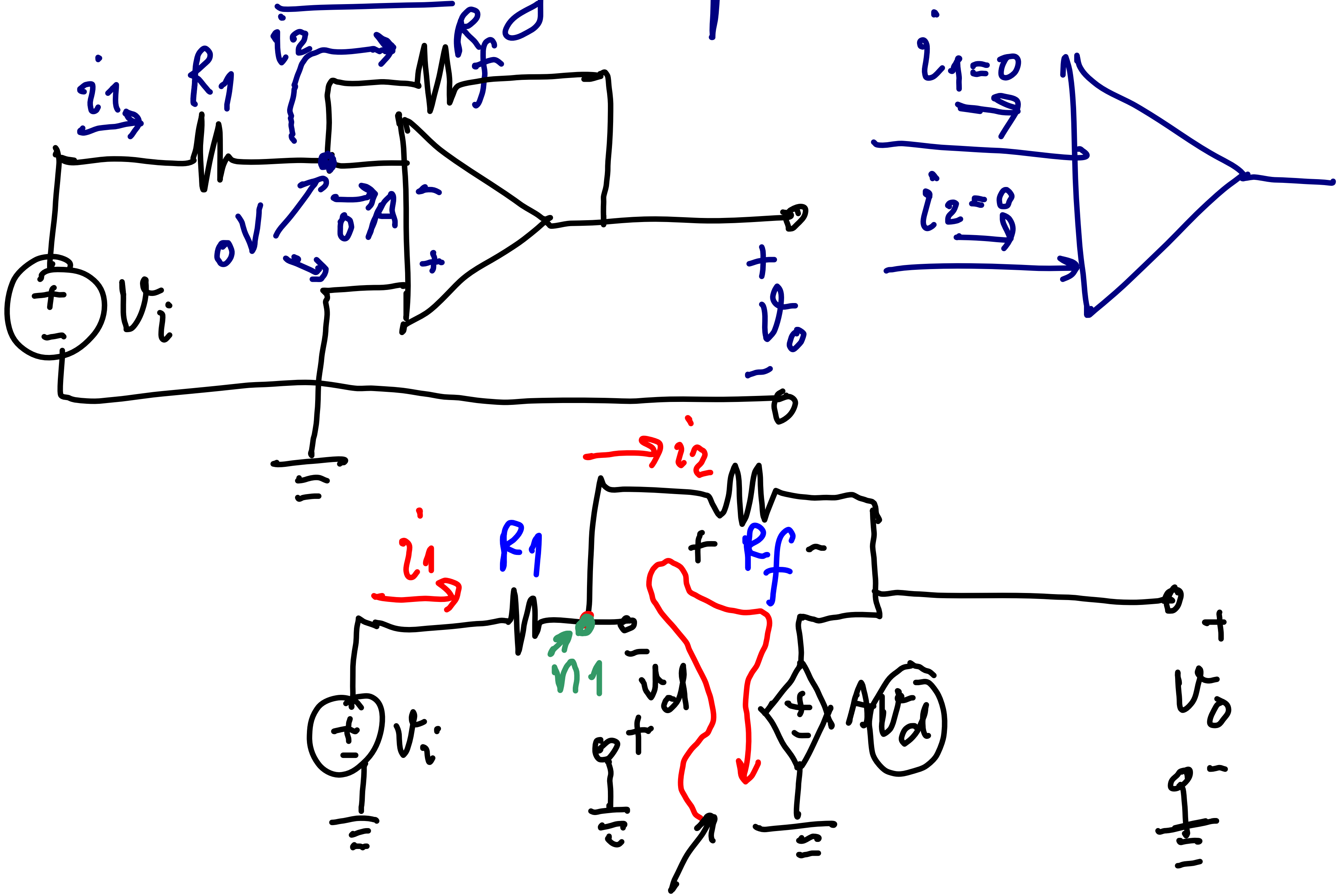
$$\frac{v_1 - v_2}{20\,k\Omega} = \frac{v_2 + 2\times10^5 v_1}{50}$$

แทน $v_1 = \frac{2}{3}v_s + \frac{v_2}{3}$

$$-53.33\times10^6 v_s = 26.66\times10^6 \underbrace{v_2}_{v_o}$$

$$\boxed{\frac{v_2}{v_s} = -2} \Rightarrow \text{close loop gain}$$

Inverting Amplifier



เขียน KCL ที่โหนด ทา จะได้ว่า

$$i_1 = i_2$$

$$\frac{v_i + \cancel{v_d}^{\,0}}{R_1} = \frac{-\cancel{v_d}^{\,0} - v_o}{R_f} \qquad \text{———} \quad (1)$$

เนื่องจาก $v_d = 0$

$$\frac{v_1}{R_1} = -\frac{v_o}{R_f}$$

$$\boxed{\frac{v_o}{v_1} = -\frac{R_f}{R_1}}$$

※ ไม่ใช่ศูนย์

แบบที่ 2 (inverting)

$$\frac{V_i + V_d}{R_1} = \frac{-V_d - V_o}{R_f} \quad \text{———} \quad 2$$

$$i_2 = \frac{-V_d - V_o}{R_f} \quad \text{———} \quad 3$$

$$3 \rightarrow 2 \Rightarrow \frac{V_i + V_d}{R_1} = i_2 \quad \text{———} \quad 4$$

เขียนสมการ KVL ในลูปจะได้

$$+V_d + i_2 R_f + AV_d = 0 \quad \text{—} \quad 5$$

นำ 4 แทนใน 5

$$V_d + \frac{V_i + V_d}{R_1} \times R_f + AV_d = 0 \quad \text{—— } 6$$

จาก $AV_d = V_o$

$$V_d = \frac{V_o}{A} \quad \text{—— } 7$$

นำ 7 แทน 6

$$\frac{V_o}{A} + \left(\frac{V_i}{R_1} + \frac{V_o}{AR_1}\right)R_f + \cancel{A}\frac{V_o}{\cancel{A}} = 0 \quad \text{—— } 8$$

$$\frac{V_o}{A} + \frac{V_i R_f}{R_1} + \frac{V_o R_f}{AR_1} + V_o = 0 \quad \text{—— } 9$$

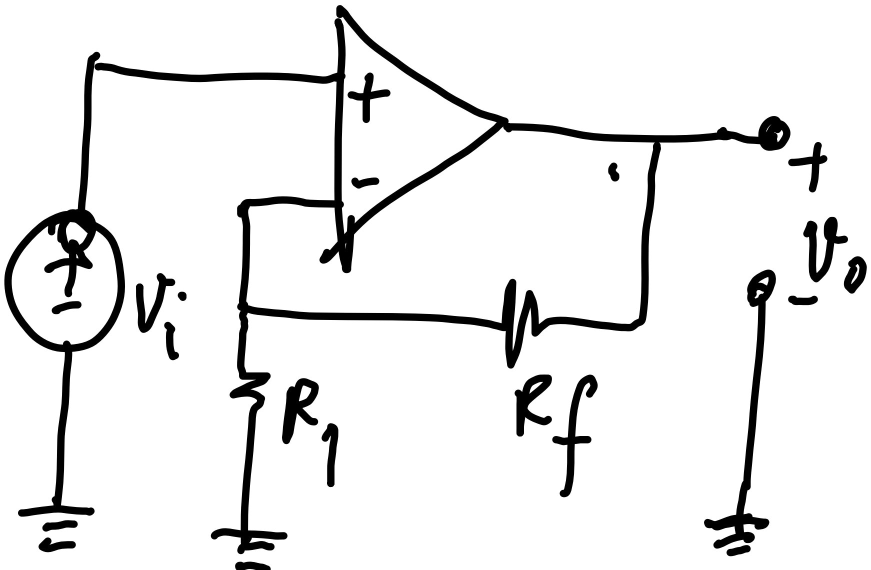
$$V_0\left(1+\frac{1}{A}+\frac{R_f}{AR_1}\right) = -V_i\frac{R_f}{R_1}$$

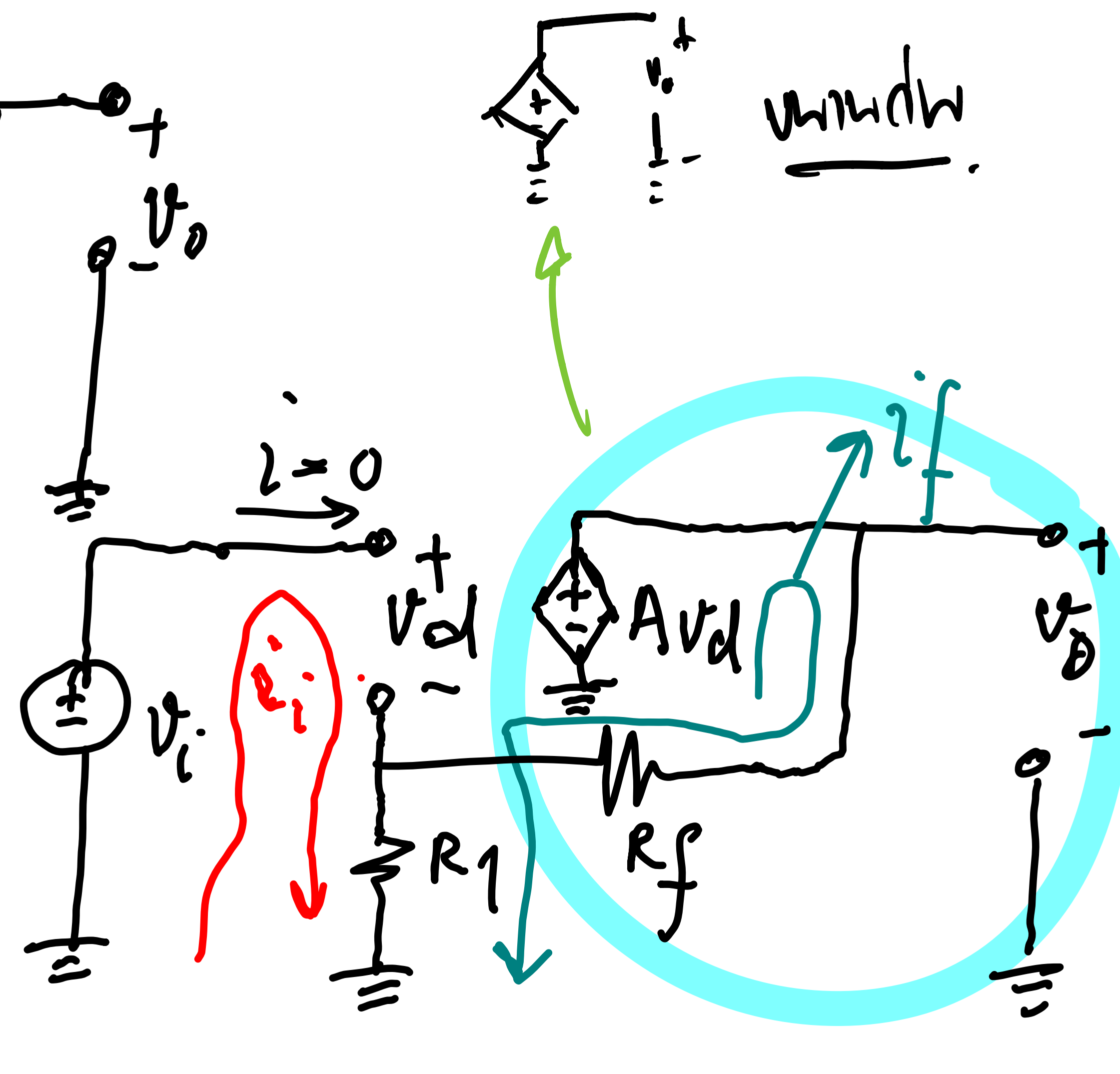
$$\frac{V_0}{V_i} = \frac{-R_f/R_1}{\left(1+\cancelto{0}{\frac{1}{A}}+\cancelto{0}{\frac{R_f}{AR_1}}\right)}$$

$$\therefore \qquad A \gg \infty$$

$$\boxed{\frac{V_0}{V_i} = -\frac{R_f}{R_1}}$$

Non-inverting Amplifier





จากรูปใช้ KVL ที่ loop (i_i) จะได้

$$-V_i + V_d + \cancel{i_i R_1}^{\,0} + i_f R_1 = 0 \quad \text{——} \quad (1)$$

$\therefore \quad i_i = 0$ ↳ Law (1) $i_1 = 0$

ที่ loop (i_f)

$V_o = V_{ad}$

กระแสเข้าเป็น 0

$$-V_o + i_f R_f + i_f R_1 + \cancel{i_i R_1}^{\,0} = 0 \quad \text{——} \quad (2)$$

$$\therefore \quad V_o = i_f (R_f + R_1) \quad \text{——} \quad (3)$$

จาก (1) $\quad i_f = \dfrac{V_i - V_d}{R_1} \quad \text{——} \quad (4)$

นำ ④ ไปแทนใน ③

$$v_o = \left(\frac{v_i - v_d}{R_1}\right)(R_f + R_1)$$

$$v_o = \frac{v_i}{R_1}(R_f + R_1) - \frac{v_d}{R_1}(R_f + R_1)$$

เนื่องจาก $v_d = \frac{v_o}{A}$

$$v_o = \frac{v_i(R_f + R_1)}{R_1} - \frac{v_o}{A}\frac{(R_f + R_1)}{R_1}$$

$$V_o\left(1+\frac{R_f+R_1}{AR_1}\right) = V_i\,\frac{(R_f+R_1)}{R_1}$$

DAC
Digital Analog Converter

$$\frac{V_o}{V_i} = \frac{(R_f+R_1)}{R_1} \Big/ \left(1+\cancel{\frac{R_f+R_1}{AR_1}}^{\,0}\right)$$

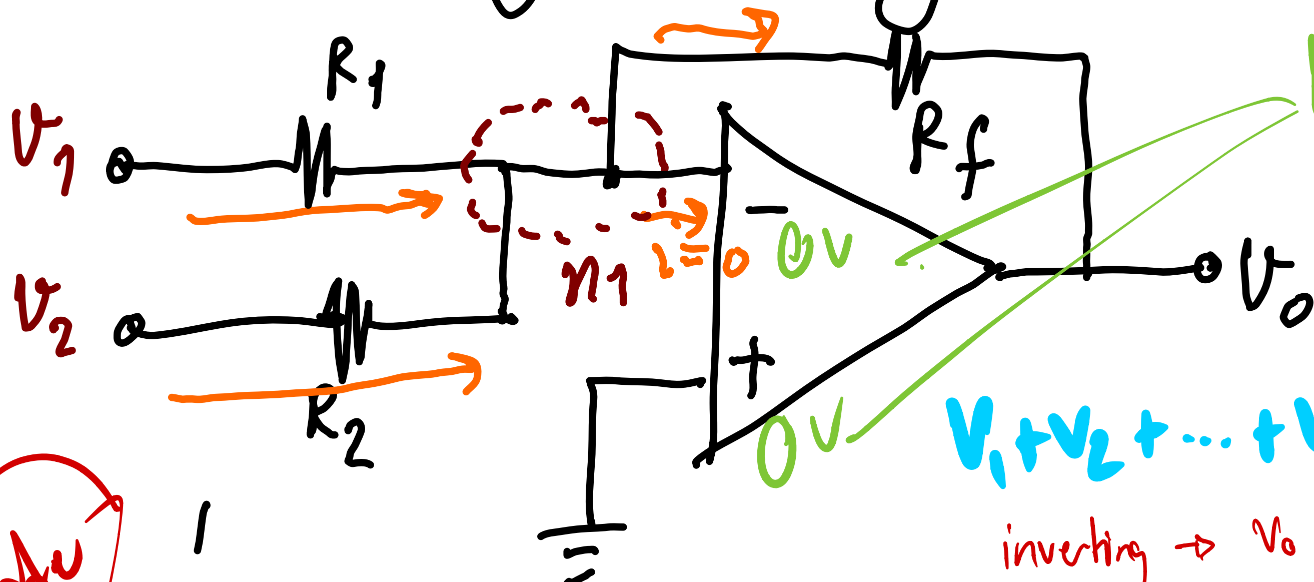
$\therefore A \gg$

$$\boxed{\frac{V_o}{V_i} = 1+\frac{R_f}{R_1}}$$

ต้องการขยายเพิ่ม.
ก็ เพิ่ม Rf

ค่ตราการ
ขยาย.

Inverting Summing Amplifier



$V_1 = 0 \Rightarrow V_2 = 0$

$V_1 + V_2 + \dots + V_n = V_o$

inverting $\Rightarrow V_o = -(V_1 + \dots + V_n)$

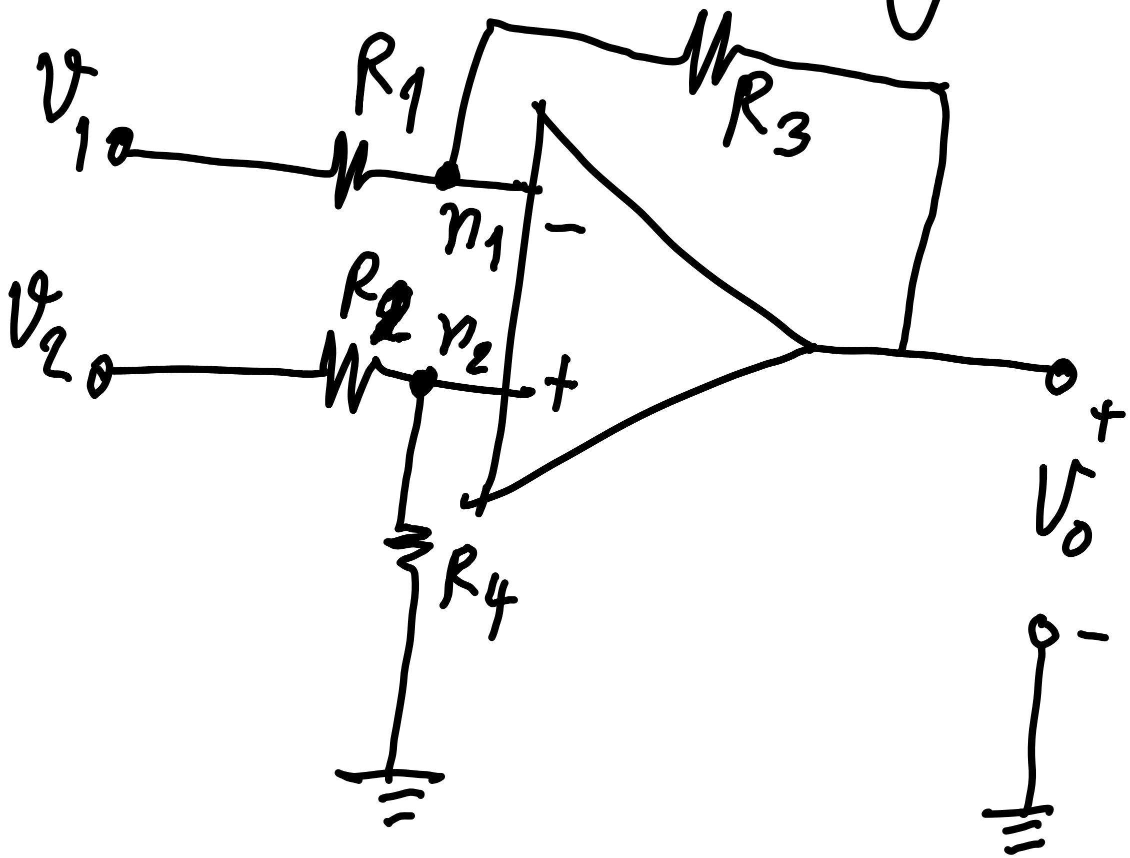
node analysis

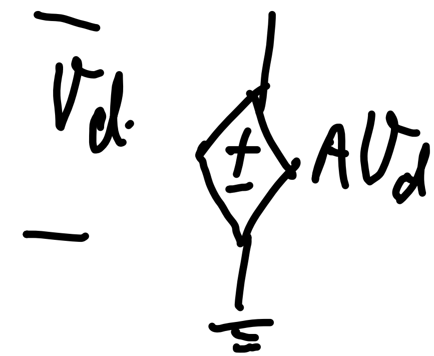
ที่ node n_1 (KCL) ($V_d \approx 0$)

$$\frac{V_1 - 0}{R_1} + \frac{V_2 - 0}{R_2} = \frac{0 - V_o}{R_f}$$

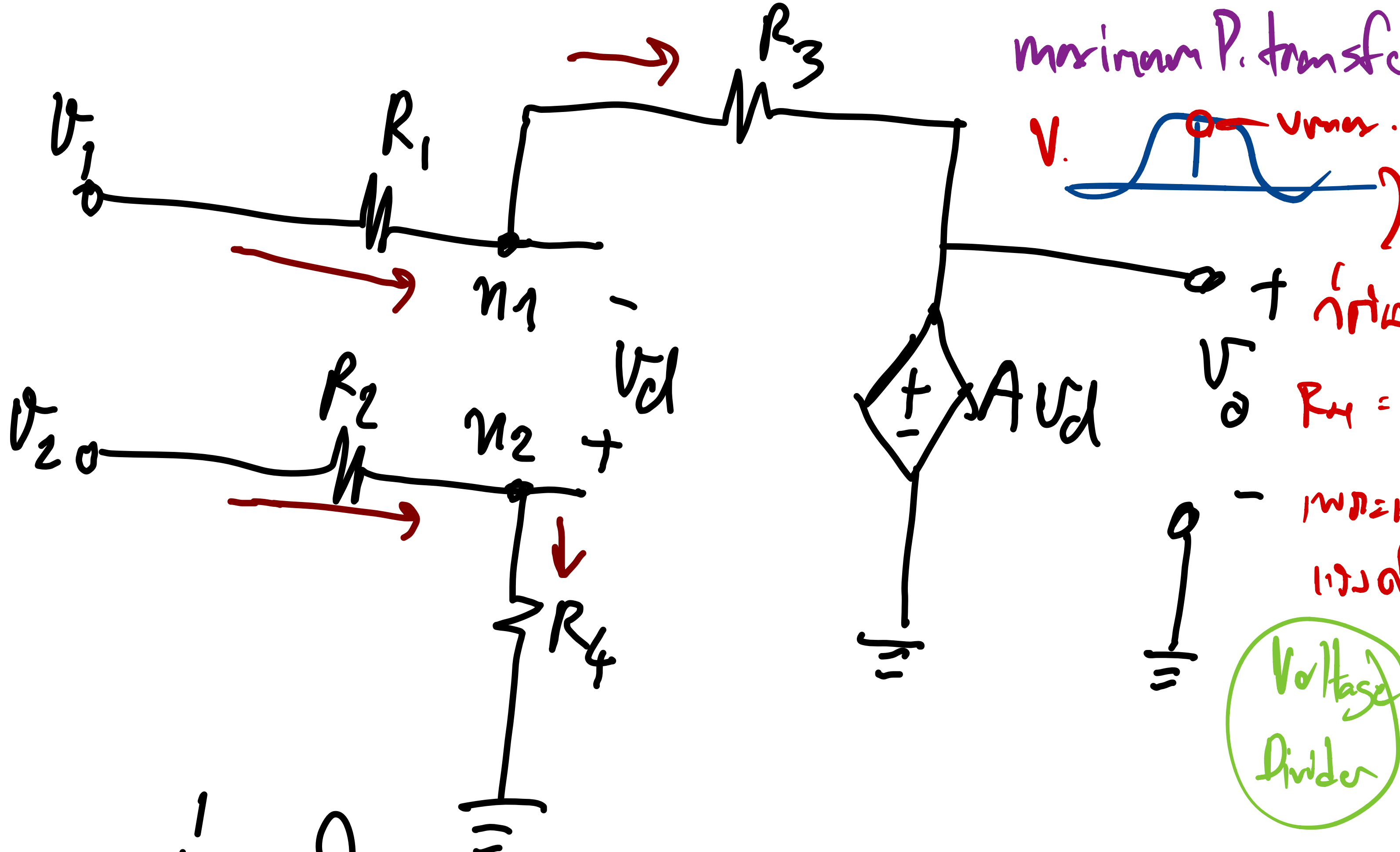
$$\frac{V_1}{R_1} + \frac{V_2}{R_2} = \frac{-V_o}{R_f} \Rightarrow V_o = -\left(\frac{V_1 R_f}{R_1} + \frac{V_2 R_f}{R_2}\right)$$

Subtracting Amplifier





maximum P. transfer



ค่าสูงเปิด

$R_{th} = R_1$

เพราะฉะนั้น

แรงดันเท่ากัน.

Voltage Divider

ที่ n_1 ใช้ KCL

$$\frac{v_1 - v_{n1}}{R_1} = \frac{v_{n1} - v_o}{R_3} \quad \text{--- (1)}$$

ที่ n_2

$$v_{n2} = v_2 \times R_4 / (R_2 + R_4) \quad \text{--- (2)}$$

เนื่องจาก $v_{n_1} = v_{n_2}$ แทนใน (1) Law no. 2 $V_1 = V_2$

$\therefore V_{n_1} = V_{n_2}$

$$\frac{v_1}{R_1} - v_{n_1}\left(\frac{1}{R_1} + \frac{1}{R_3}\right) + \frac{v_o}{R_3} = 0 \quad \text{—— (3)}$$

แทน v_{n_1} ด้วย $v_{n_2} = \frac{v_2 \cdot R_4}{R_2 + R_4}$

$$\frac{v_1}{R_1} - \left(\frac{v_2 \times R_4}{R_2 + R_4}\right)\left(\frac{1}{R_1} + \frac{1}{R_3}\right) + \frac{v_o}{R_3} = 0 \quad \text{—— (4)}$$

$$\frac{v_1}{R_1} - v_2\left(\frac{R_4}{R_1(R_2 + R_4)} + \frac{R_4}{R_3(R_2 + R_4)}\right) + \frac{v_o}{R_3} = 0 \quad \text{—— (5)}$$

ถ้าให้ $\frac{R_3}{R_1} = \frac{R_4}{R_2} = n$

$$R_3 = nR_1 \text{ และ } R_4 = nR_2 \quad \text{—— (6)}$$

(6) แทนใน (5).

$$\frac{V_1}{R_1} - V_2\left(\frac{nR_2}{R_1(R_2+nR_2)} + \frac{nR_2}{R_3(R_2+nR_2)}\right) + \frac{V_0}{R_3} = 0 \quad \text{--- (7)}$$

$$\frac{V_1}{R_1} - \frac{V_2}{R_1}\left(\frac{\cancel{n}}{\cancel{(1+n)}}\right)\left(\frac{\cancel{1+n}}{\cancel{n}}\right) + \frac{V_0}{R_3} = 0$$

$$\frac{V_1 - V_2}{R_1} + \frac{V_0}{R_3} = 0$$

$$V_0 = (V_2 - V_1)\underbrace{\frac{R_3}{R_1}}_{n}$$

∴ ถ้าให้ $R_3 = R_1$

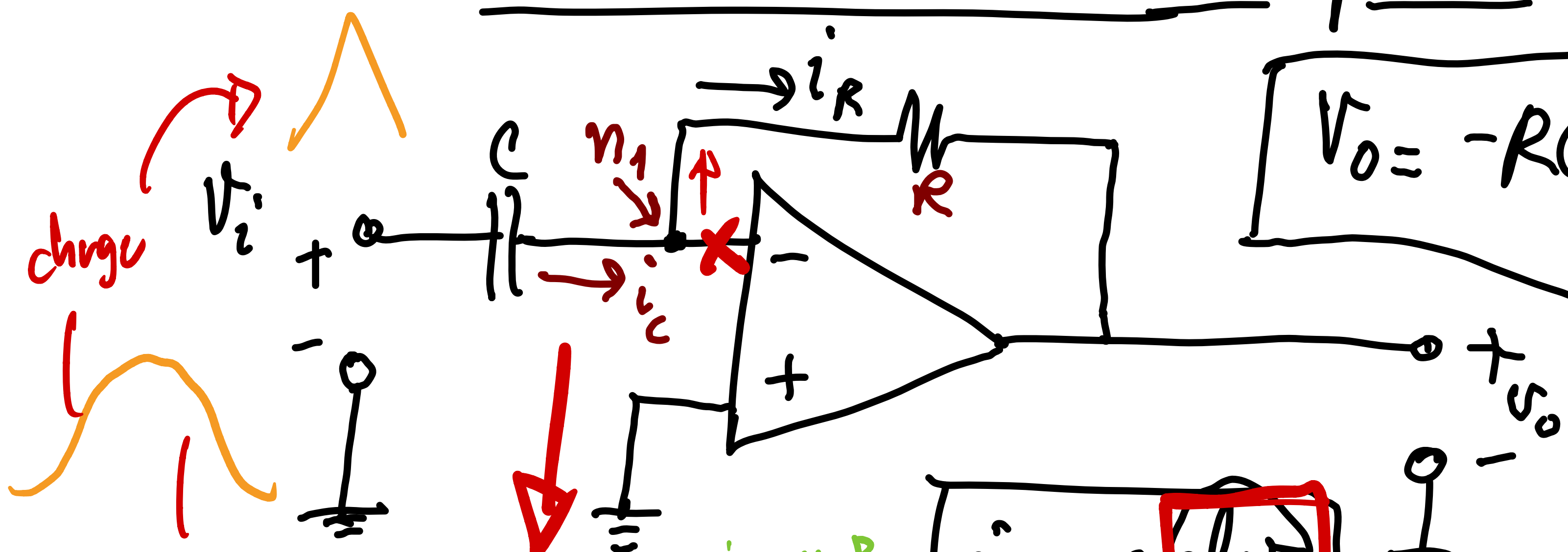
$$\boxed{V_0 = V_2 - V_1}$$ ※

พิสูจน์

Capa in DC

noeg change

Differentiator Amplifier



$$\boxed{V_o = -RC\frac{dv_i}{dt}}$$

$$\boxed{i_C = C\frac{dv_i}{dt}} \rightarrow s$$

Cinverse R.

$i_C = i_R$

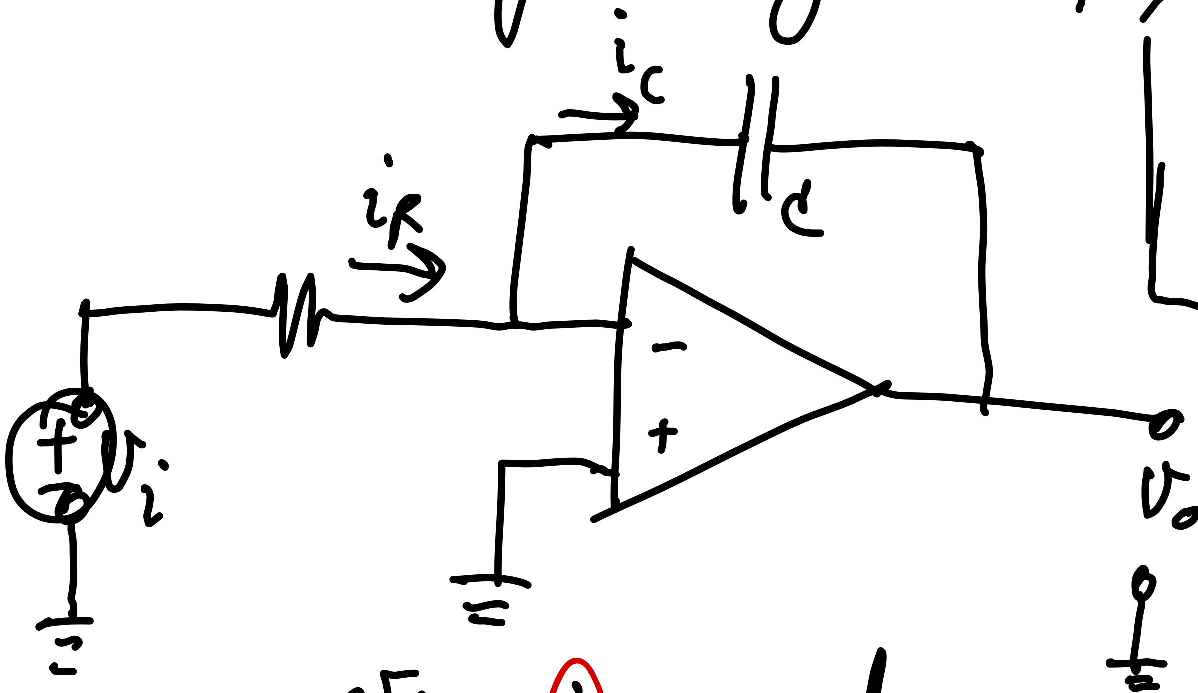
diff.

$$(V_i - V_{n_1})sC = \frac{V_{n_1} - V_o}{R} \quad \text{—— (1)}$$

แทน $V_{n_1} = 0 \Rightarrow V_i sC = -\frac{V_o}{R} = C\frac{dv_i}{dt} = \frac{-V_o}{R}$

$\therefore V_o = RC\frac{dv_i}{dt}$

Integrating Amplifier



$$\boxed{V_o = \frac{-1}{RC}\int v_i\,dt}$$

$$\frac{V_i}{R} = i_c = -C\frac{dv_o}{dt}$$

$= i_R.$

$$v_o = -\frac{v_i\,dt}{R*C}$$

$$\therefore \frac{v_i}{R} = -\frac{c\,dv_c}{dt}$$

$$\therefore v_o = \frac{\int v_i\,dt}{-RC}$$