# ESC201T : Introduction to Electronics

## Lecture 30: Operational Amplifier Circuits-2

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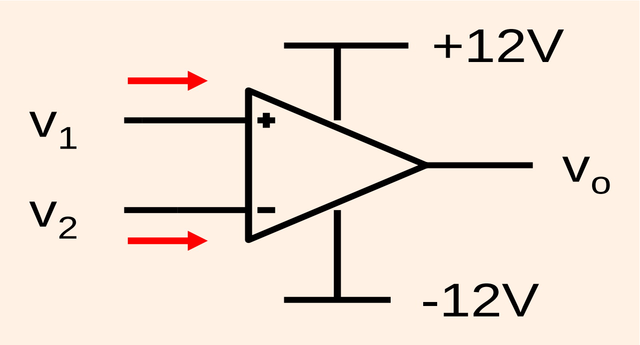
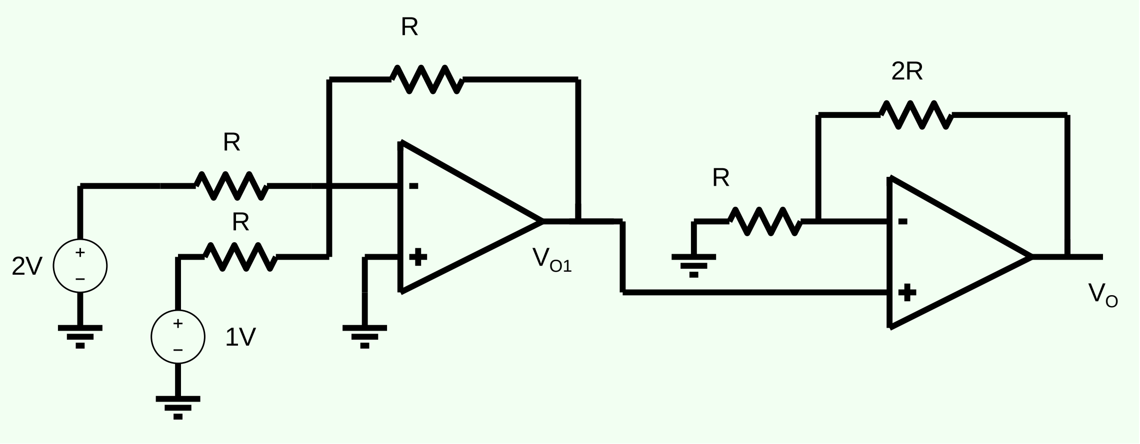
# Important properties for analyzing ideal opamp circuits under negative feedback



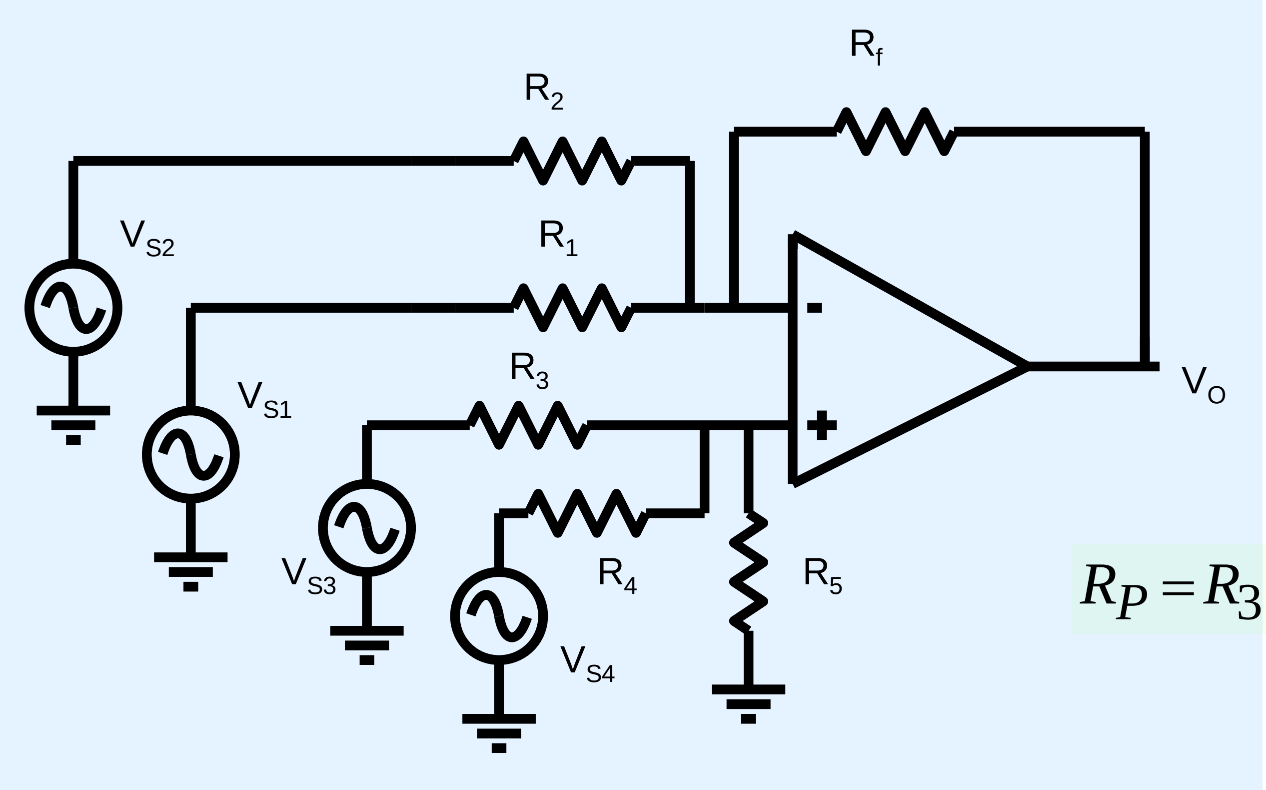

1. $v_1 = v_2$

2. $i_1 = i_2 = 0$




One stage does not load the preceding stage due to very small output impedance of the opamp

# Adder/Subtractor

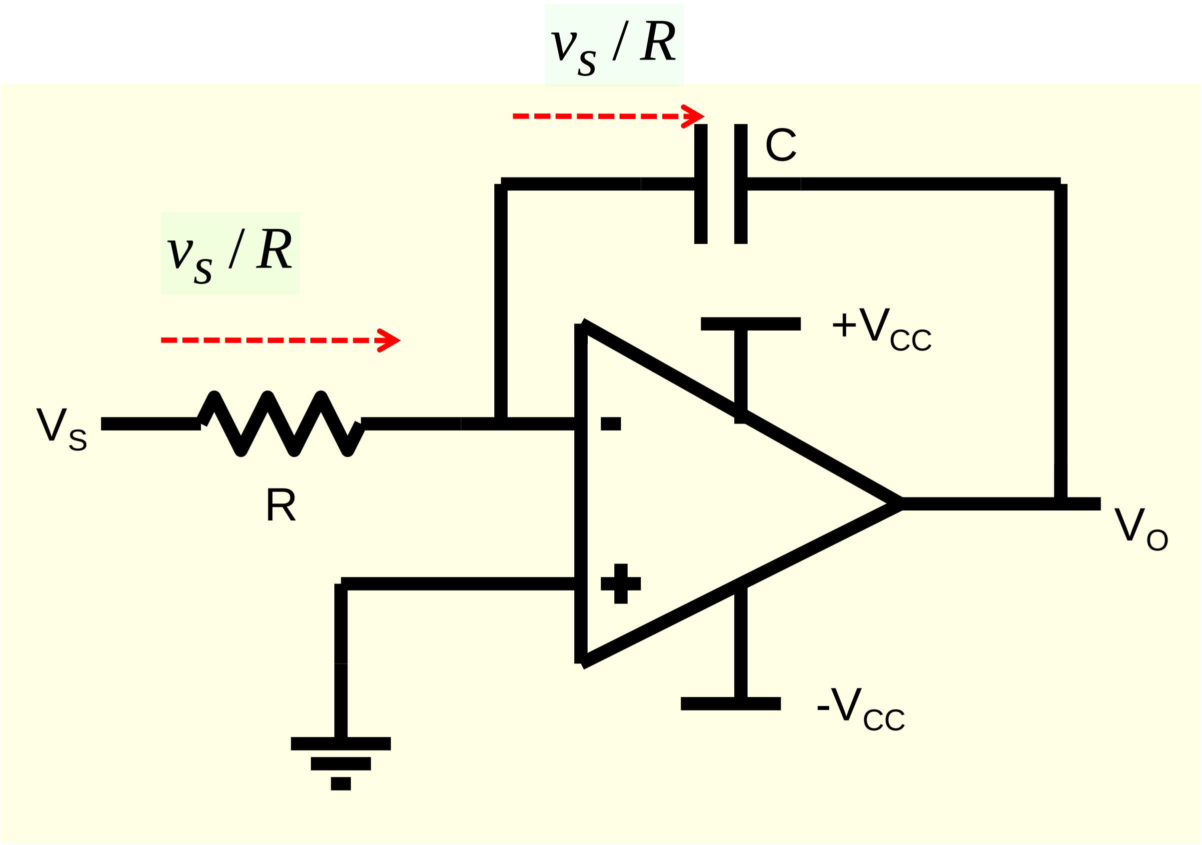



$$R_P = R_3 \| R_4 \| R_5$$

$$v_o = -(\frac{R_f}{R_1})v_{s1} + -(\frac{R_f}{R_2})v_{s2} + v_{s3}\frac{R_P}{R_3} \times (1 + \frac{R_f}{R_1 \| R_2})$$

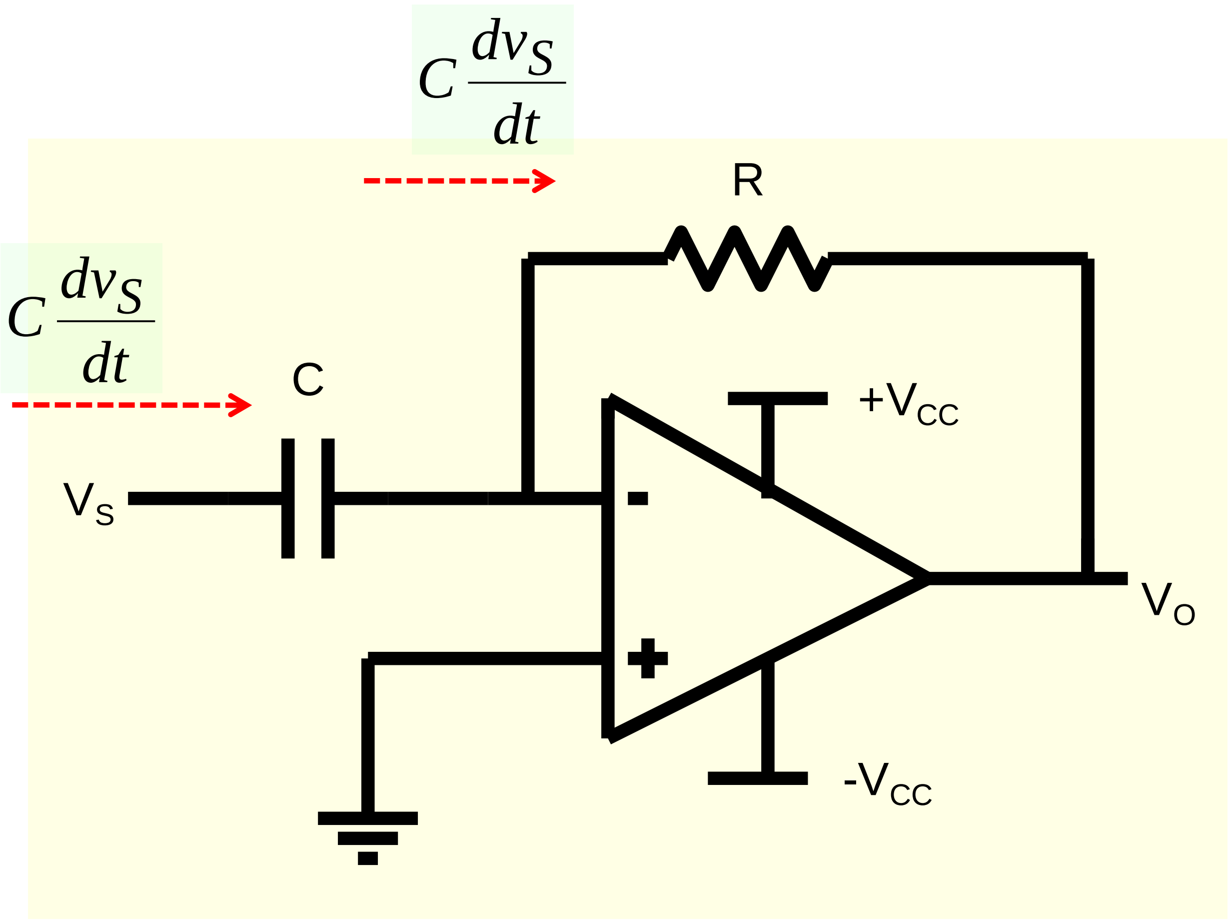
$$+ \quad v_{s4}\frac{R_P}{R_4} \times (1 + \frac{R_f}{R_1 \| R_2})$$

# Integrator



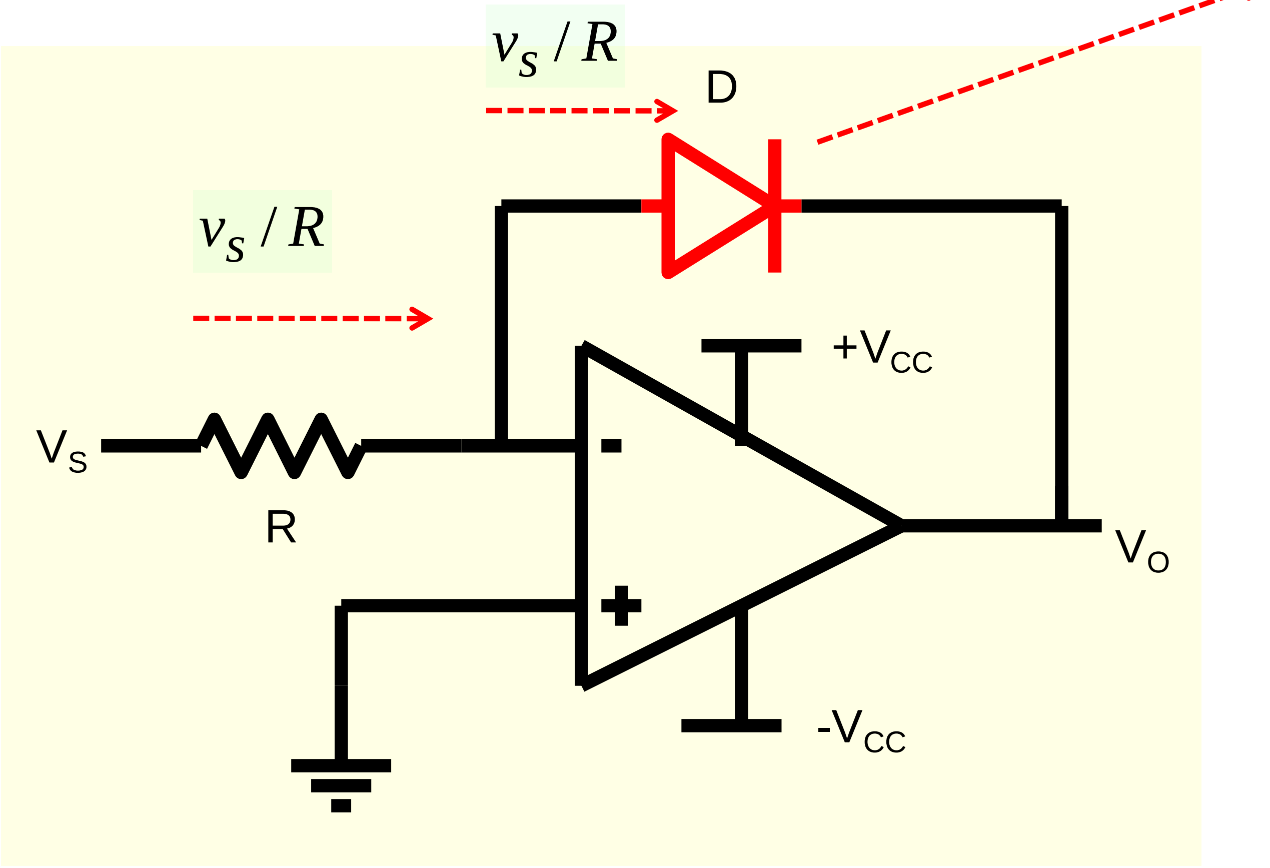

$$\frac{V_S}{R} = -C\frac{dV_O}{dt} \Rightarrow V_O(t) = -\frac{1}{RC}\int V_S dt$$

# Differentiator




$$-\frac{V_O}{R} = C\frac{dV_S}{dt} \Rightarrow V_O(t) = -RC\frac{dV_S}{dt}$$

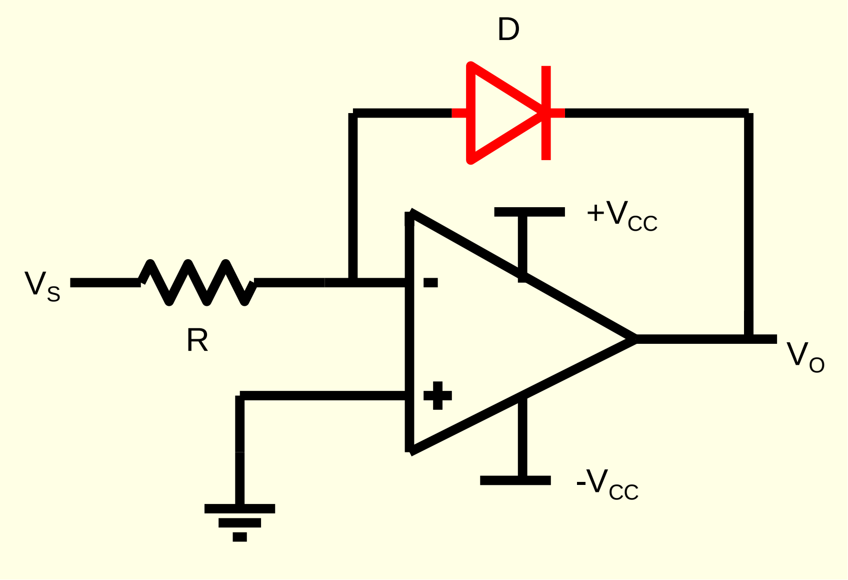
# Log Amplifier




$$I = I_S\left(e^{\frac{V}{V_T}} - 1\right)$$

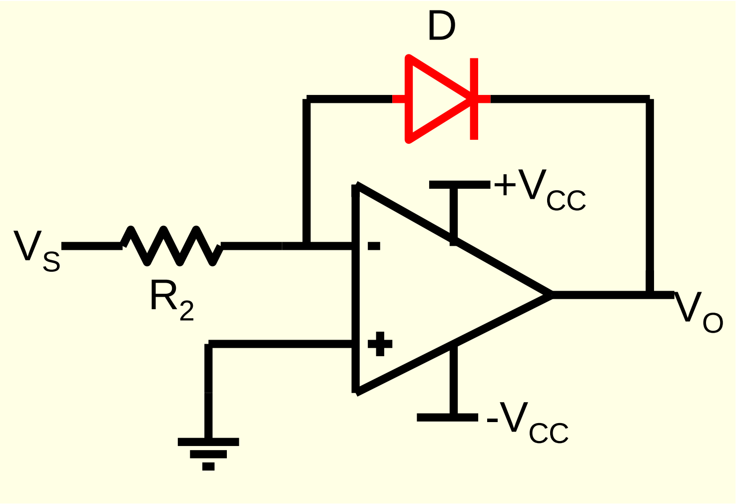
$$\frac{V_S}{R} = I_S\left(e^{-\frac{V_O}{V_T}} - 1\right) \Rightarrow -V_O = V_T \times \ln\left(1 + \frac{V_S}{RI_S}\right) \cong V_T \times \ln\left(\frac{V_S}{RI_S}\right)$$

# Temperature Sensor ?

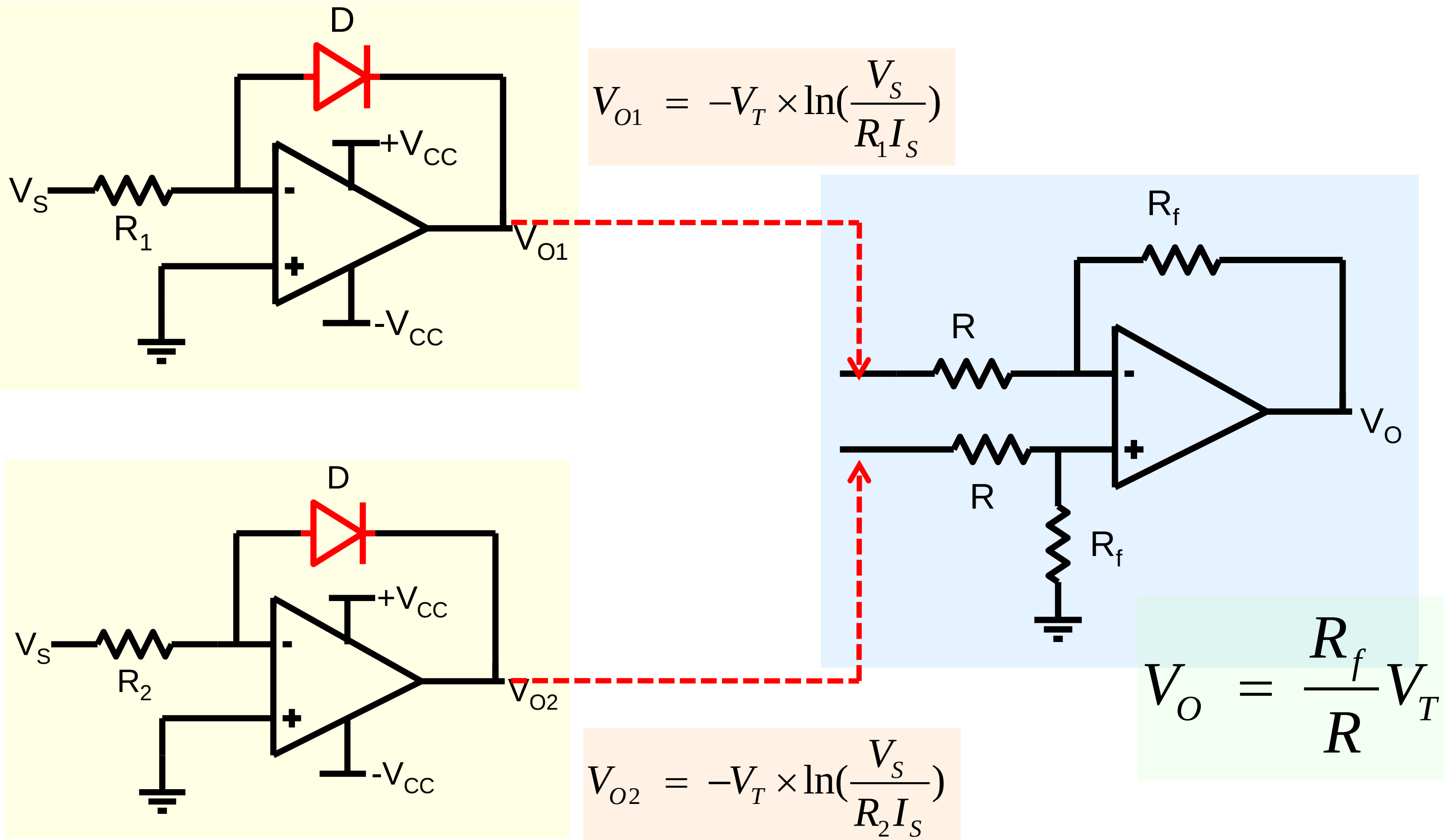



$$V_O = -V_T \times \ln(\frac{V_S}{RI_S}); \; V_T = \frac{k_B T}{q}$$

But $I_S$ is a function of temperature as well.



$$V_O = -V_T \times \ln(\frac{V_S}{R_2 I_S})$$




$$V_{O1} = -V_T \times \ln\left(\frac{V_S}{R_1 I_S}\right)$$

$$V_{O2} = -V_T \times \ln\left(\frac{V_S}{R_2 I_S}\right)$$

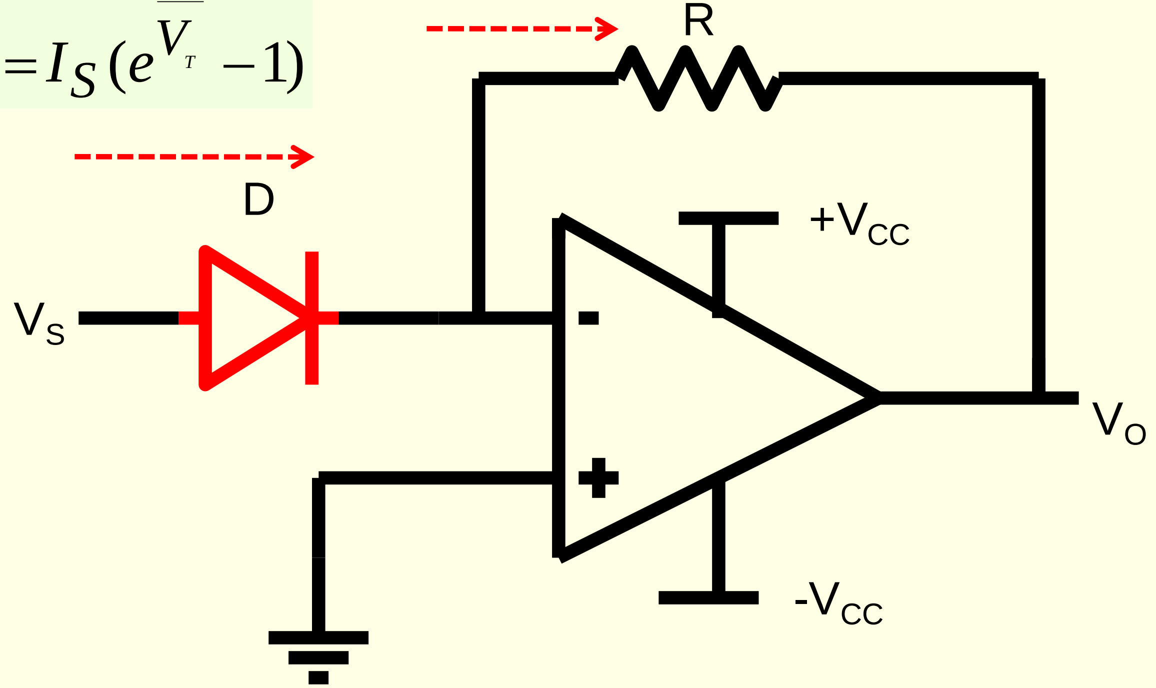
$$V_O = \frac{R_f}{R} V_T \times \ln\left(\frac{R_2}{R_1}\right)$$

Output voltage is directly proportional to temperature

# AntiLog Amplifier

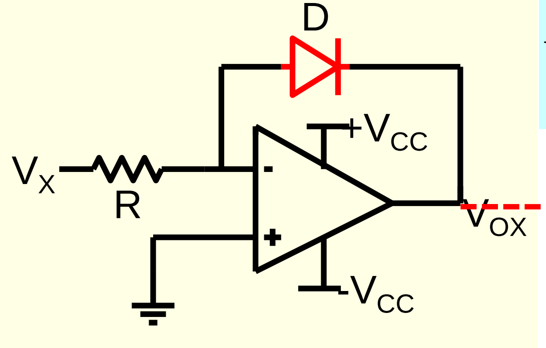
$$I = I_S\left(e^{\frac{V_s}{V_T}} - 1\right)$$

$$I = I_S\left(e^{\frac{V_s}{V_T}} - 1\right)$$

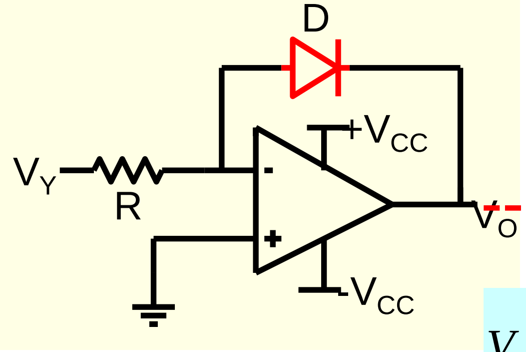



$$-\frac{V_O}{R} = I_S\left(e^{\frac{V_S}{V_T}} - 1\right) \Rightarrow V_O = -RI_S\left(e^{\frac{V_S}{V_T}} - 1\right) \cong -RI_S \times e^{\frac{V_S}{V_T}}$$

# Multiplier



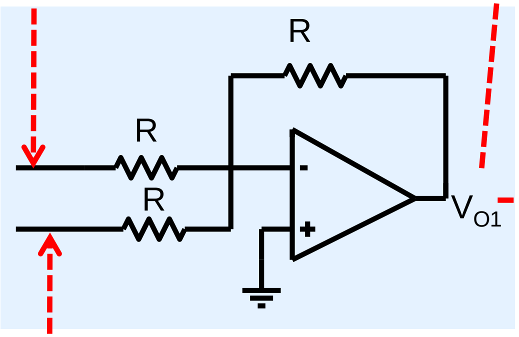

$$V_{OX} = -V_T \times \ln(\frac{V_X}{RI_S})$$

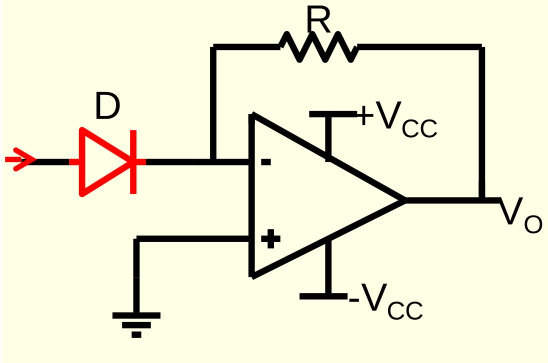



$$V_{OY} = -V_T \times \ln(\frac{V_Y}{RI_S})$$

$$V_{O1} = V_T \times (\ln(\frac{V_X}{RI_S}) + \ln(\frac{V_Y}{RI_S}))$$

$$V_{O1} = V_T \times \ln(\frac{V_X V_Y}{R^2 I_S^2})$$



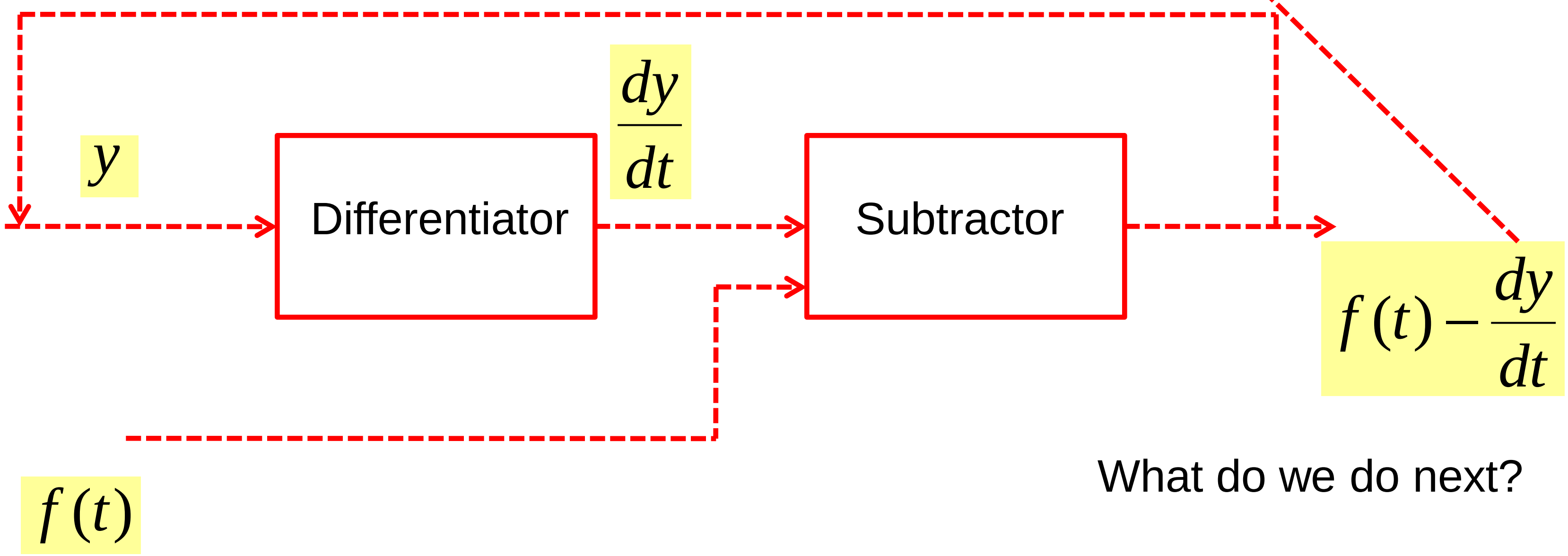




$$V_O \cong -RI_S \times e^{\frac{V_{O1}}{V_T}} = -\frac{V_X V_Y}{RI_S}$$

# Solving Differential Equations?

$$\frac{dy}{dt} + y = f(t)$$

$$y = f(t) - \frac{dy}{dt}$$




What do we do next?

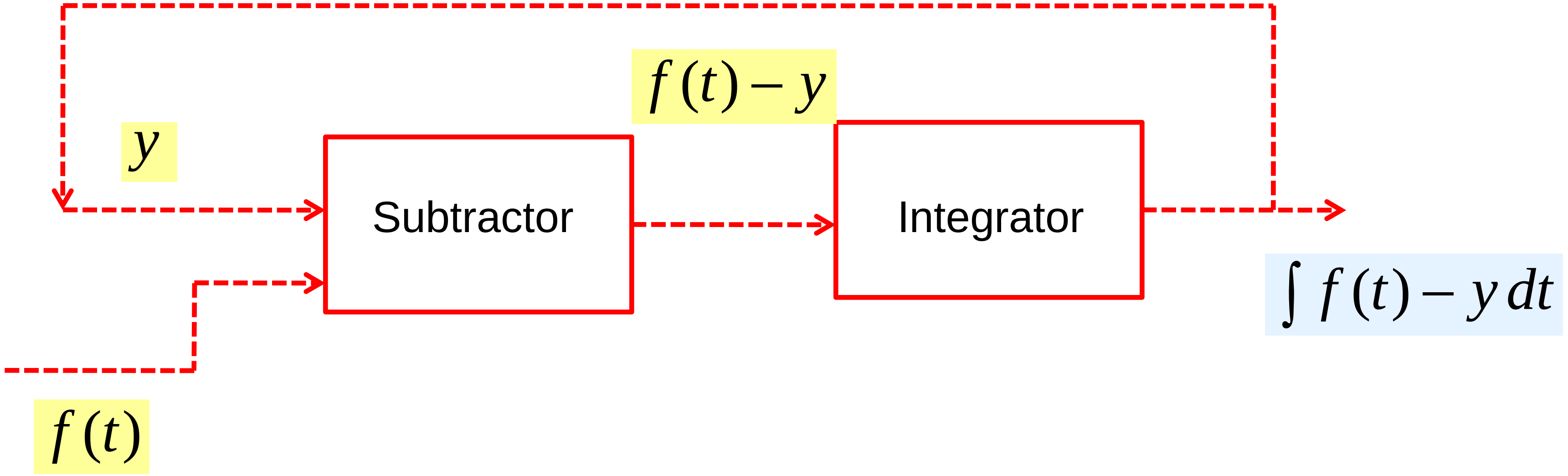
Where do we get y from?

Integrators are preferred over Differentiators because they are less sensitive to noise

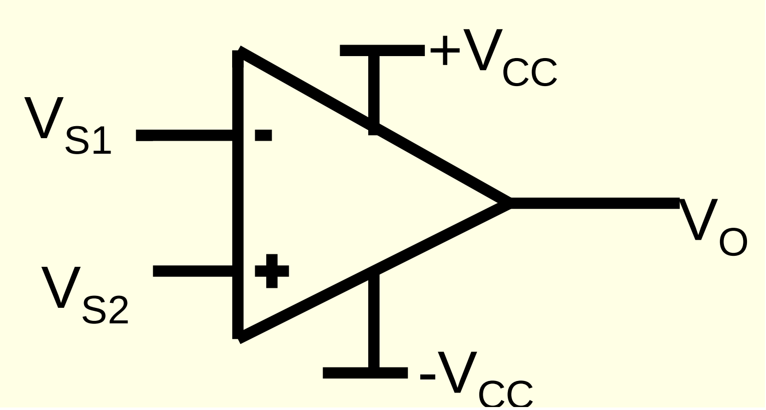
$$\frac{dy}{dt} + y = f(t)$$

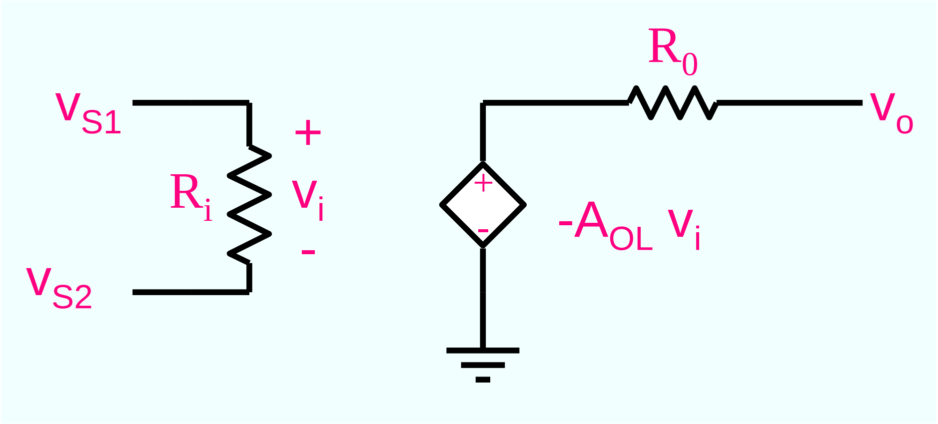
$$\frac{dy}{dt} = f(t) - y \Rightarrow$$

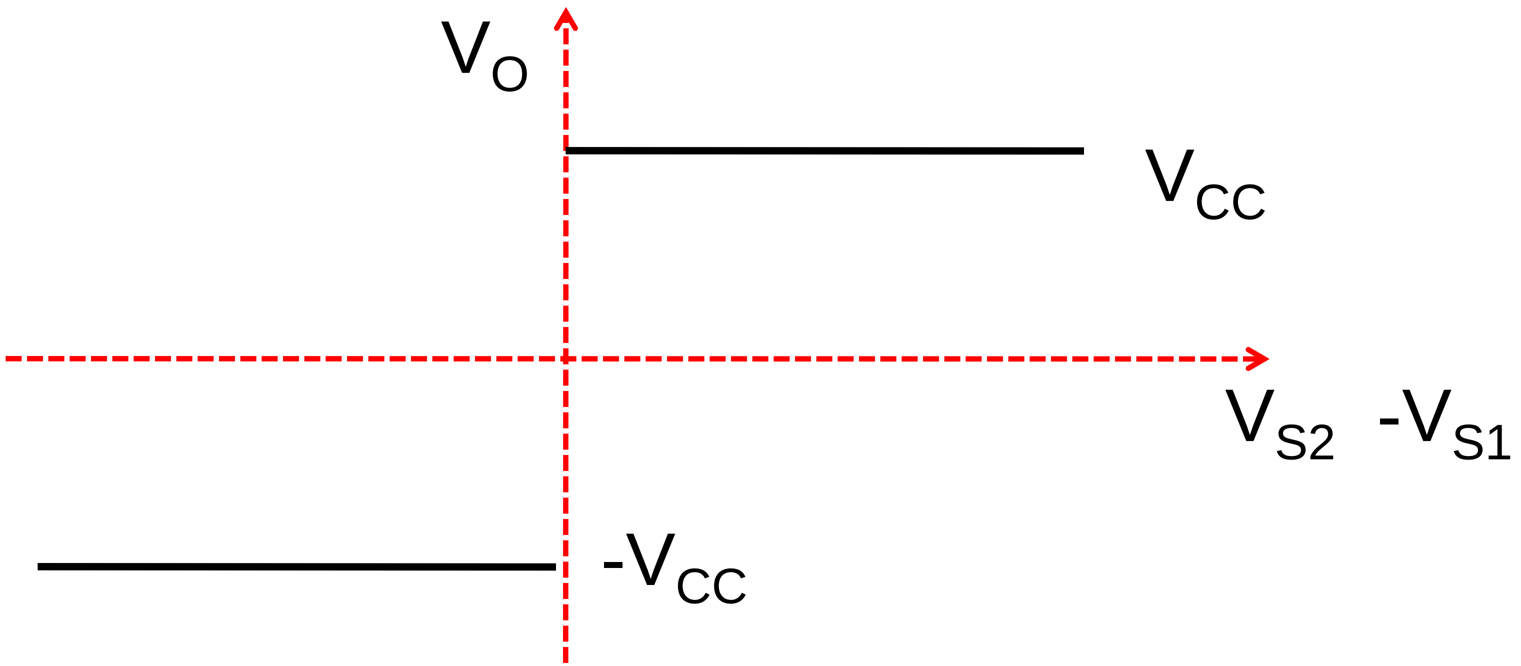
$$y = \int f(t) - y\, dt$$

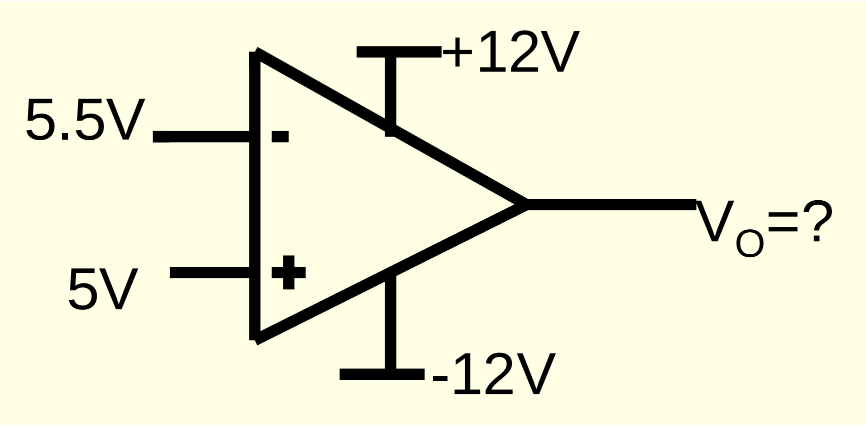


# Comparator: Opamp under open Loop condition

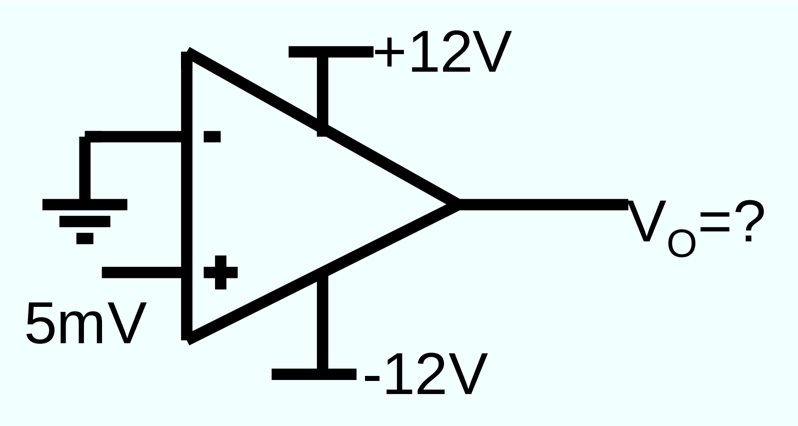




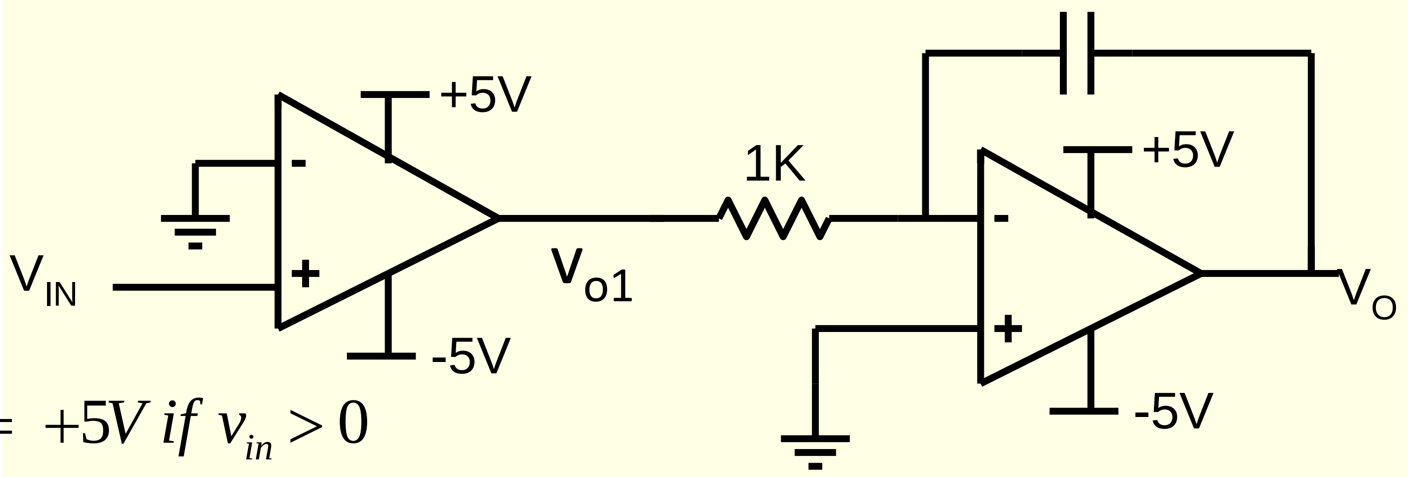

**~ -12V**



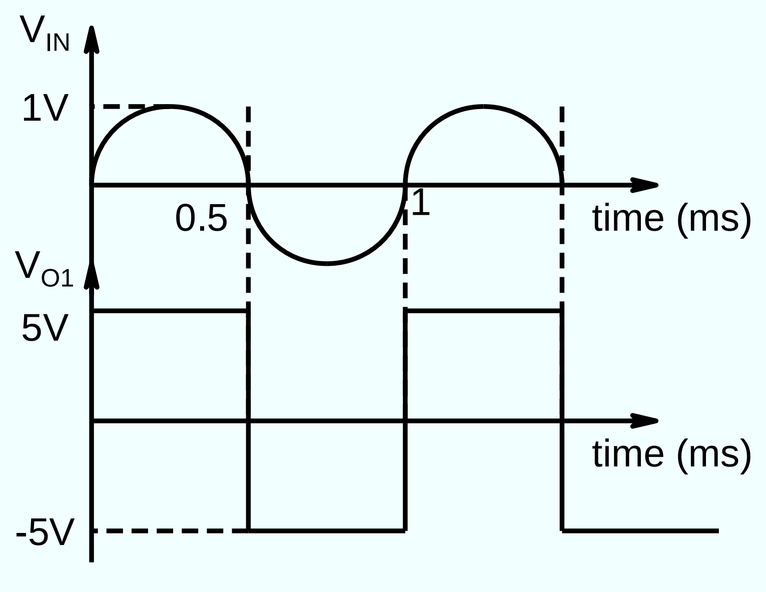

**~ +12V**

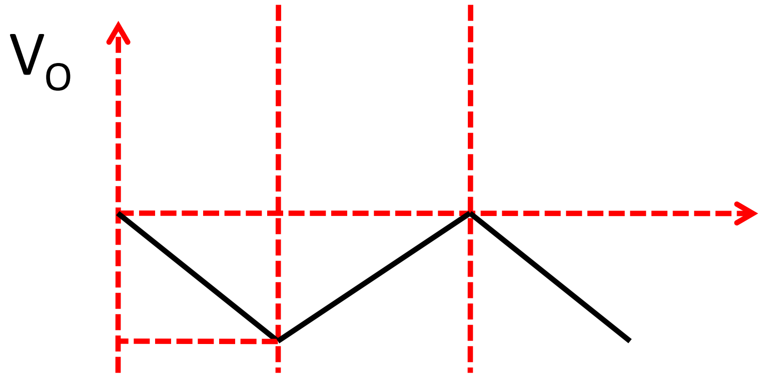
# Example

$$v_{in} = 1V\, Sin(2\pi\, ft);\;\; f = 1KHz$$

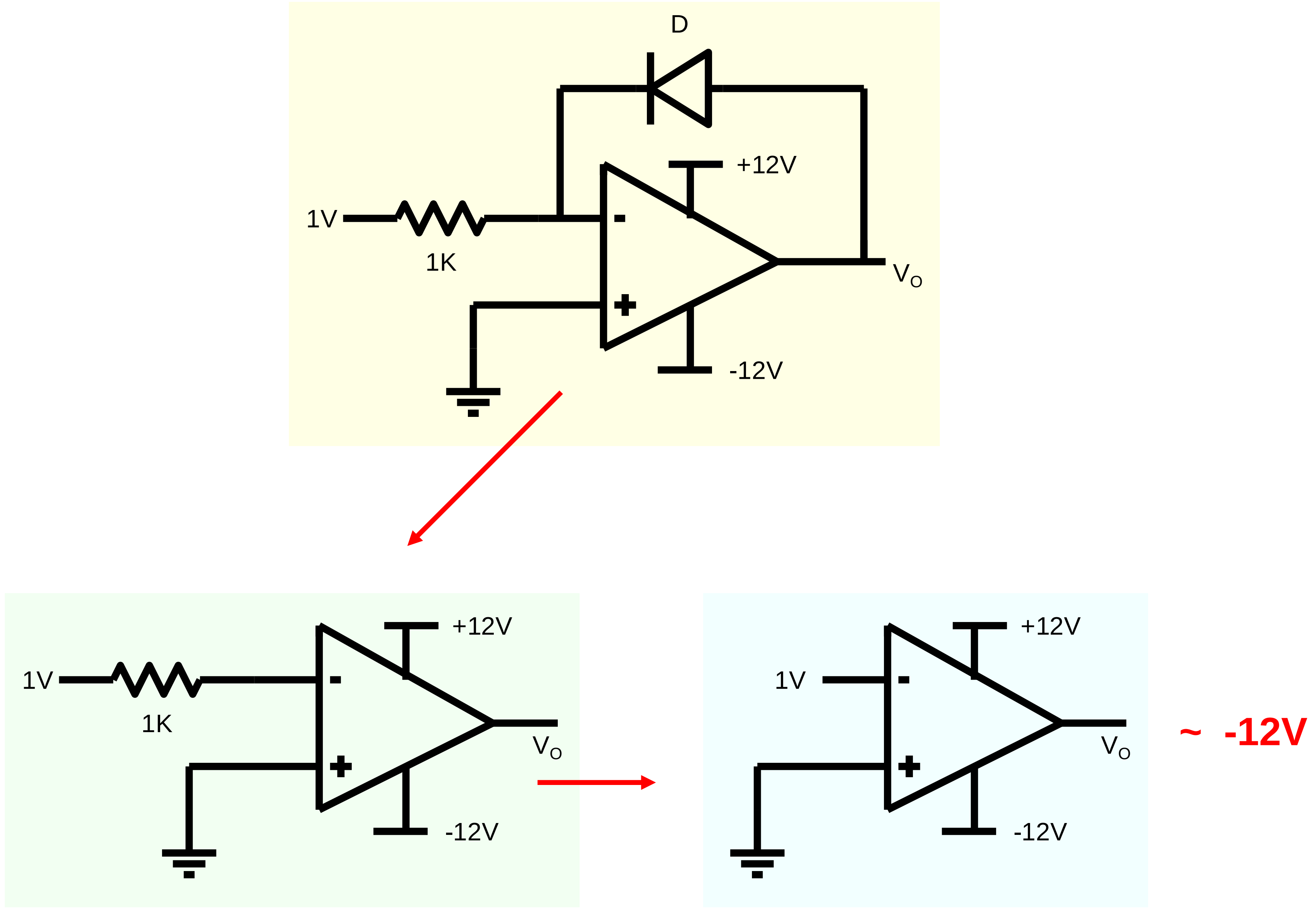



$$V_{O1} = +5V \text{ if } v_{in} > 0$$
$$= -5V \text{ if } v_{in} < 0$$

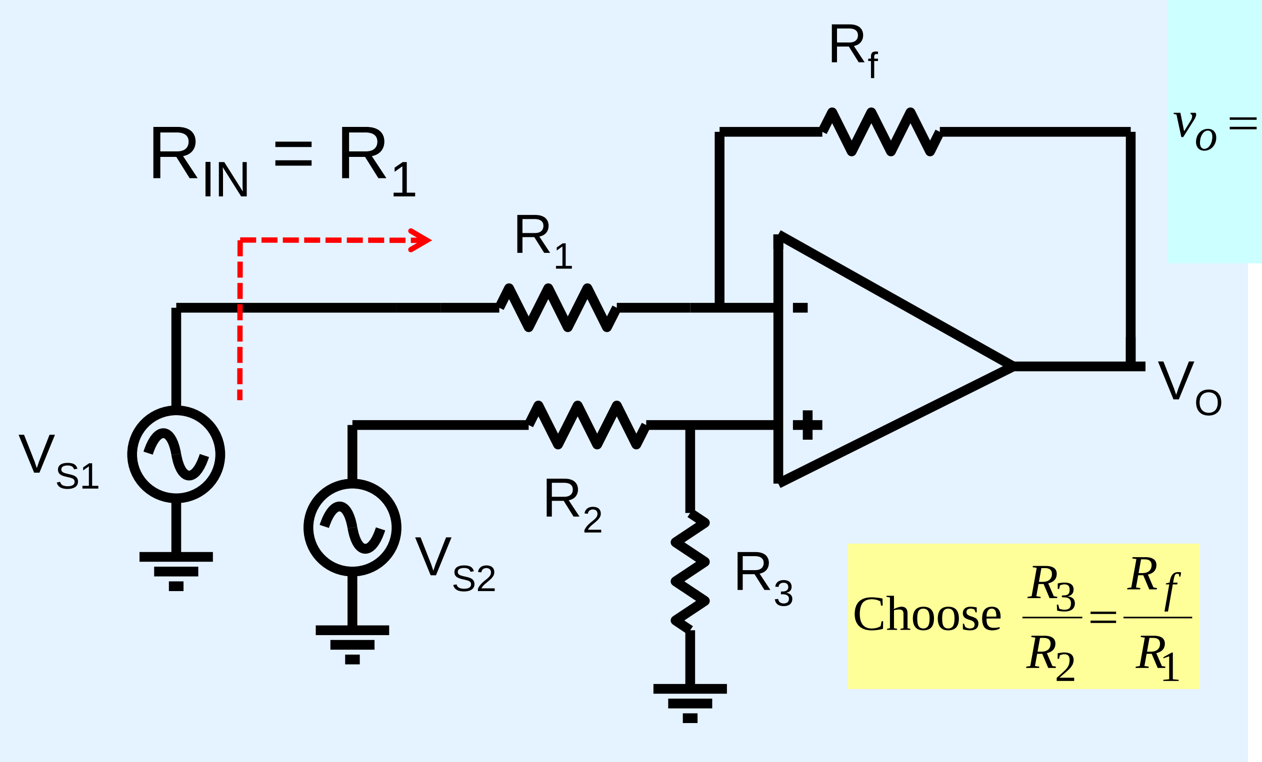


# Example



# Difference Amplifier




$$v_o = v_{s2}\frac{\frac{R_3}{R_2}}{(1+\frac{R_3}{R_2})}(1+\frac{R_f}{R_1}) - (\frac{R_f}{R_1})v_{s1}$$

Choose $\frac{R_3}{R_2} = \frac{R_f}{R_1}$

$$v_o = \frac{R_f}{R_1}(v_{s2} - v_{s1})$$

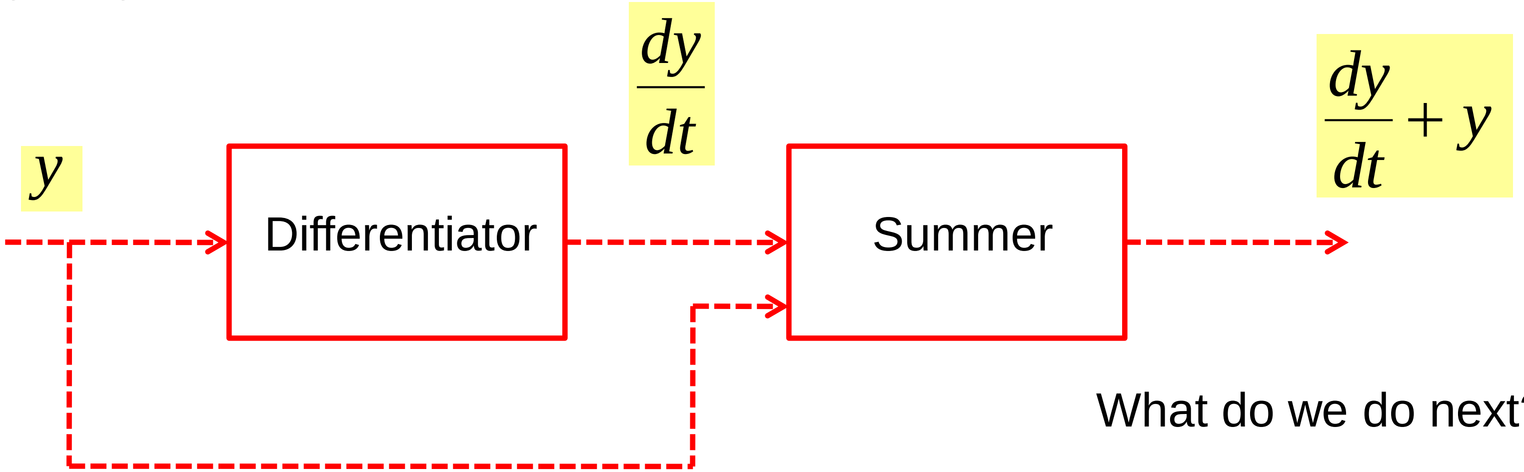
A drawback is that input resistance is relatively Lower

To change gain, we have to change two resistors and a slight mismatch can drastically reduce common mode rejection ratio

# Solving Differential Equations?

$$\frac{dy}{dt} + y = f(t)$$

Let us try and solve this equation using opamp circuit blocks that we are familiar with




What do we do next?

Where do we get y from?

# Solving Differential Equations?

$$\frac{dy}{dt} + y = f(t)$$

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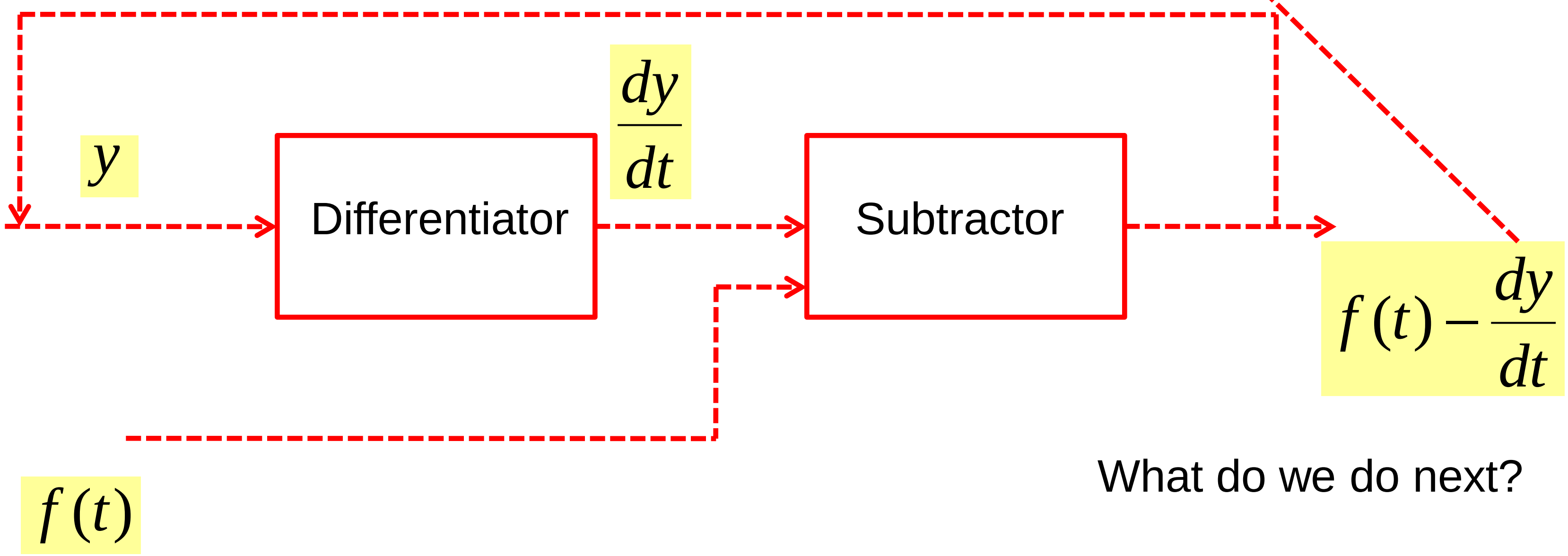


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$$\frac{dy}{dt} + y = f(t)$$

$$\frac{dy}{dt} = f(t) - y \Rightarrow$$

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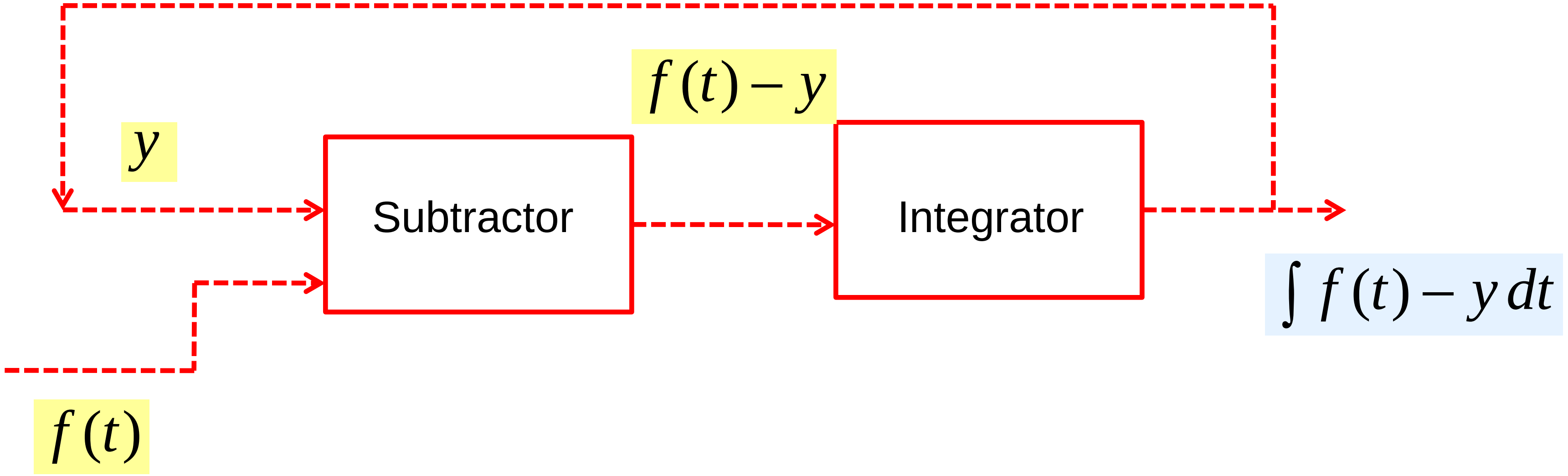
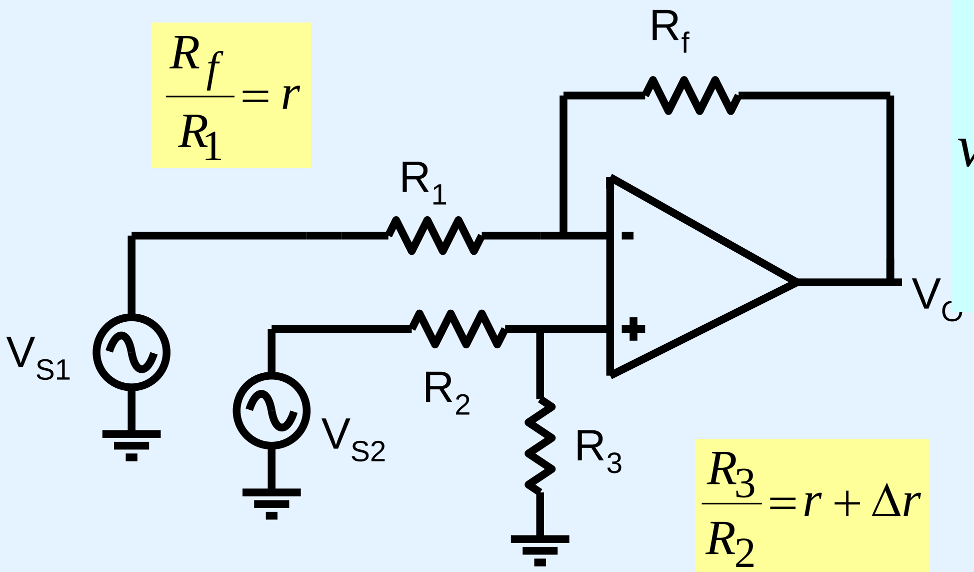


# Effect Of Mismatches




$$\frac{R_f}{R_1} = r$$

$$\frac{R_3}{R_2} = r + \Delta r$$

$$v_o = v_{s2}\frac{\frac{R_3}{R_2}}{(1+\frac{R_3}{R_2})}(1+\frac{R_f}{R_1}) - (\frac{R_f}{R_1})v_{s1}$$

$$v_o \cong (v_{s2} - v_{s1})r + v_{s2}\frac{\Delta r}{1+r}$$

Error term

$$v_{id} = v_{S2} - v_{S1}$$

$$v_{ic} = \frac{v_{S1} + v_{S2}}{2}$$

$$v_{S2} = 0.5v_{id} + v_{ic}$$

$$v_o = A_d v_{id} + A_{cm} v_{ic}$$

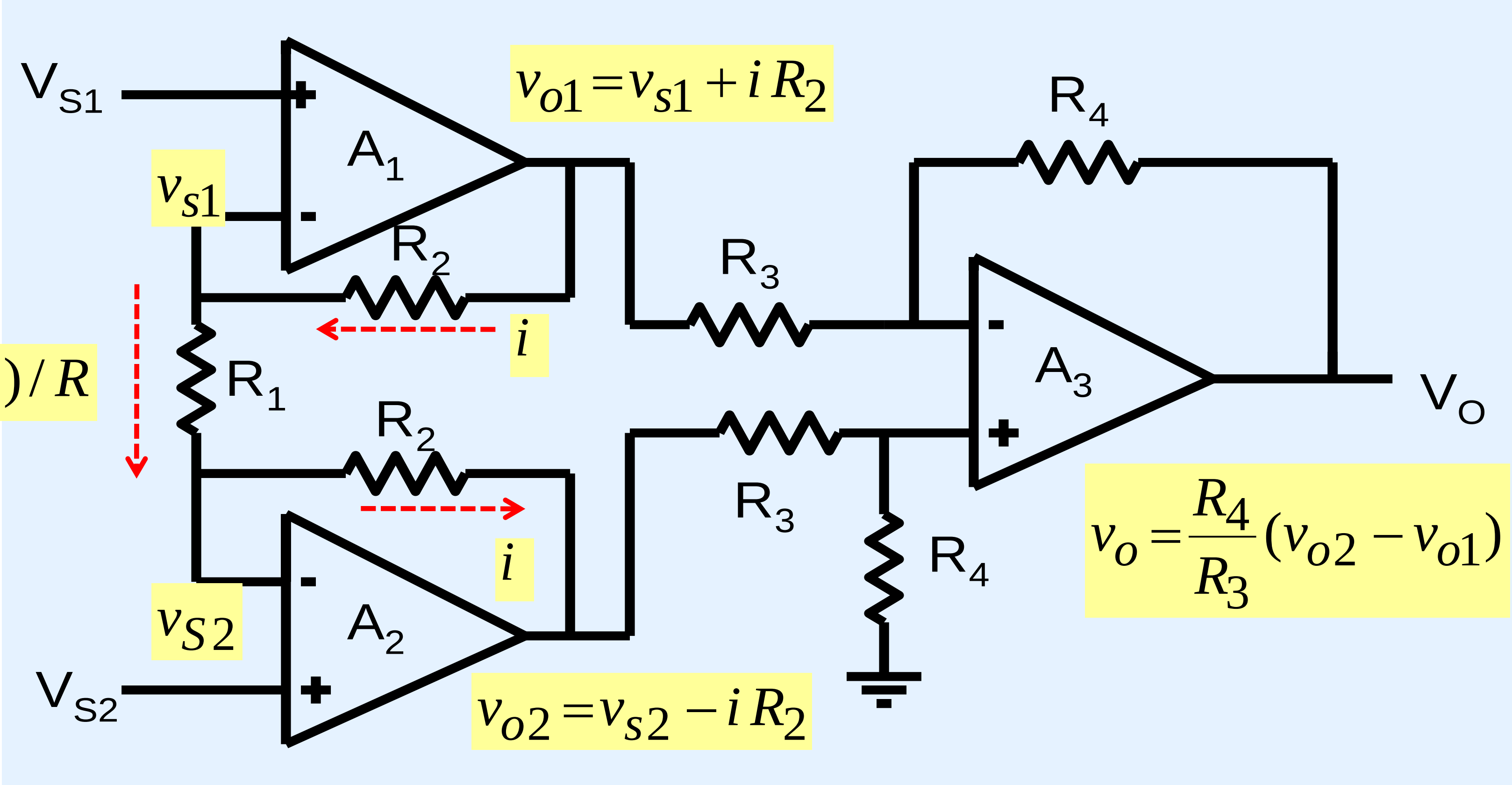
$$A_{dm} = r$$

$$A_{cm} = \frac{\Delta r}{1+r}$$

**Common mode gain and CMRR depend on mismatches**

# Instrumentation Amplifier

$$i = (v_{s1} - v_{s2}) / R$$




$$v_o = \frac{R_4}{R_3} \times (1 + \frac{2R_2}{R_1}) \times (v_{s2} - v_{S1})$$

Very high input Resistance

Can change one resistor $R_1$ and change gain

# ESC102 : Introduction to Electronics

## HW10: Solution

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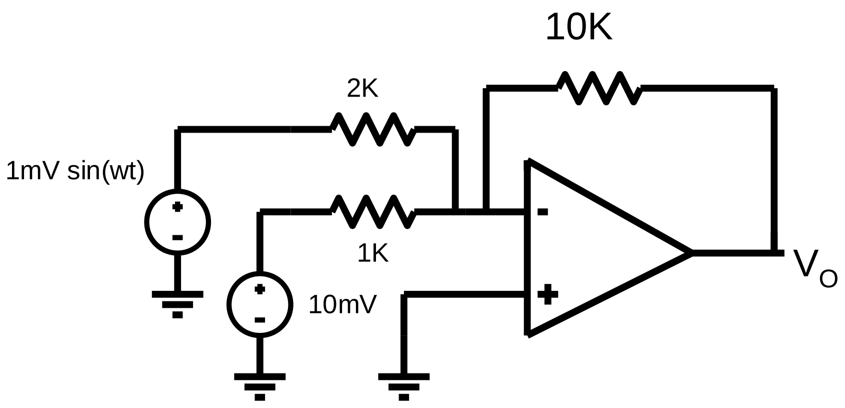
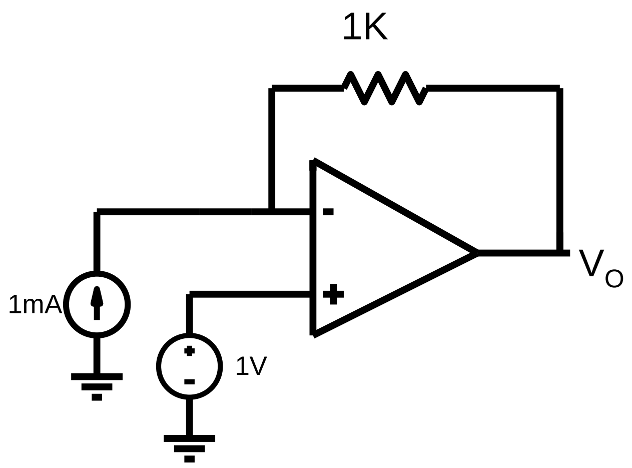
Q.1 Determine the output of the ideal opamp circuits shown below

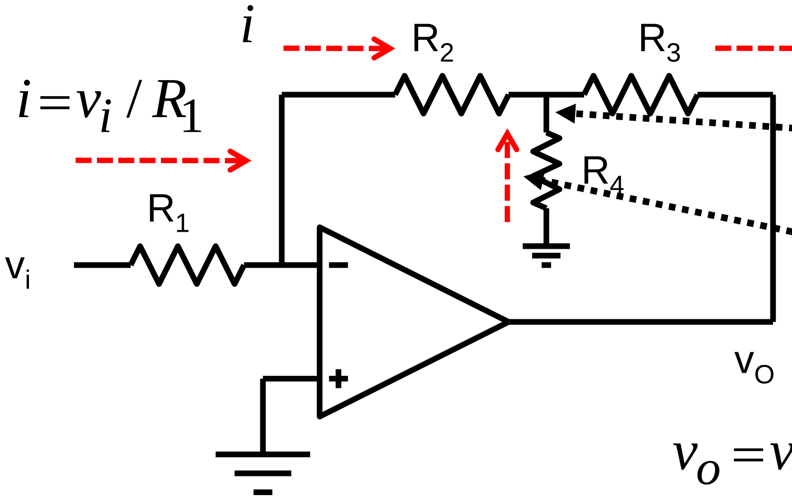



$$v_O = -\{\frac{10K}{1K}\times 10mV + \frac{10K}{2K}\times 1mV\sin(\omega t)\}$$
$$= -\{0.1 + 5\times 10^{-3}\sin(\omega t)\}$$




$$v_+ = v_- = 1V$$

$$\frac{1 - v_O}{1K} = 1mA \qquad v_O = 0V$$




$$i = v_i / R_1$$

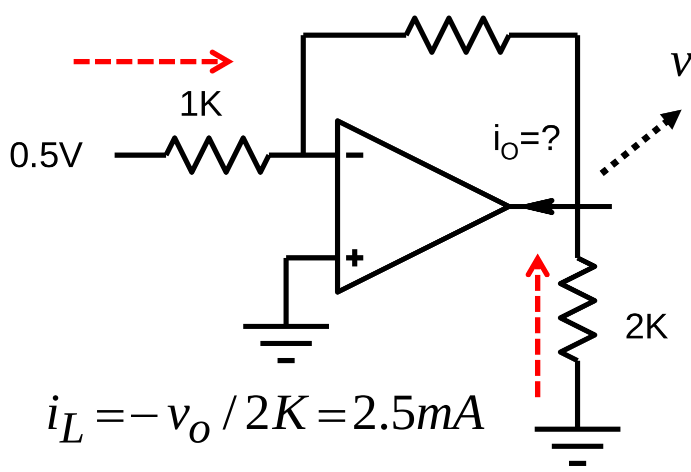
$$i_o = i + i_x$$

$$v_x = -iR_2 = -R_2 / R_1 v_i$$

$$i_x = -v_x / R_4$$

$$v_o = v_x - i_o R_3$$

$$v_o = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)v_i$$




$$i_s = 0.5mA$$

$$i_s = 0.5 / 1K = 0.5mA$$

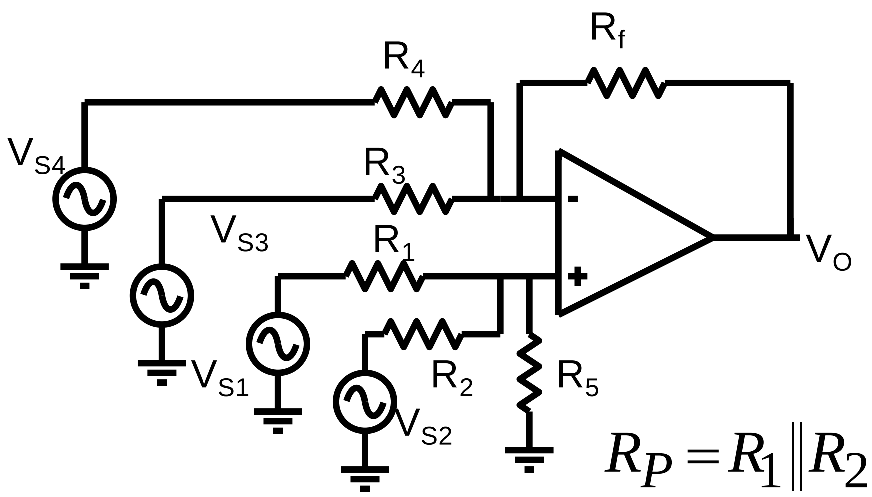
$$v_o = -i_s \times 10K = -5V$$

$$i_o = i_S + i_L = 3mA$$

$$i_L = -v_o / 2K = 2.5mA$$

Q.2 Design an opamp circuit that would generate the following output voltage where Vs1, Vs2, Vs3 and Vs4 are input voltages

$$V_O = 2v_{s1} + 4v_{s2} - 8v_{s3} - 10v_{s4}$$




$$R_P = R_1 \| R_2 \| R_5$$

$$v_o = -\left(\frac{R_f}{R_3}\right)v_{s3} - -\left(\frac{R_f}{R_4}\right)v_{s4} + \left(1 + \frac{R_f}{R_3\|R_4}\right) \times \frac{R_P}{R_1} v_{s1} + \left(1 + \frac{R_f}{R_3\|R_4}\right) \times \frac{R_P}{R_2} v_{s2}$$

Choose : $R_f = 10K \quad \Rightarrow R_3 = 1.25K \quad \Rightarrow R_4 = 1K$

$$\Rightarrow \frac{R_P}{R_1} = 0.105 \qquad \Rightarrow \frac{R_P}{R_2} = 0.211 \qquad \Rightarrow \frac{R_1}{R_2} = 2$$

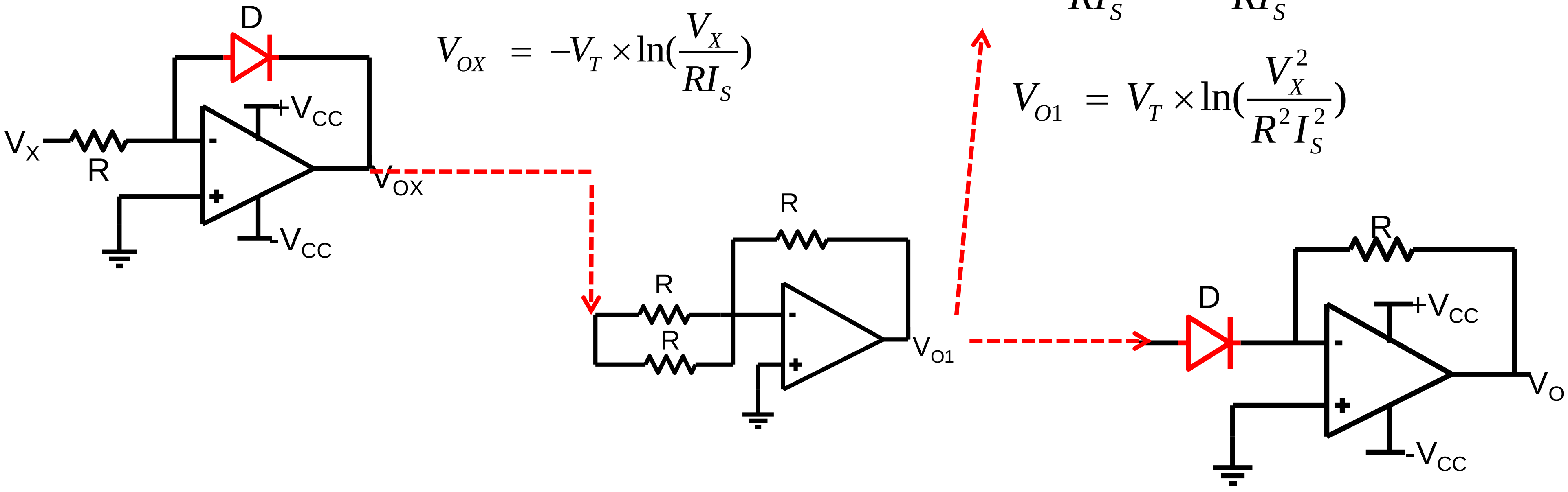
Choose : $R_2 = 1K \quad \Rightarrow R_1 = 2K \quad \Rightarrow R_P = 0.211K \quad \Rightarrow R_5 = 0.308K$

Q.3 Design an opamp circuit that can produce $V_O = K \times V_{IN}^2$ where Vin is the input voltage.

$$V_{O1} = V_T \times (\ln(\frac{V_X}{RI_S}) + \ln(\frac{V_X}{RI_S}))$$

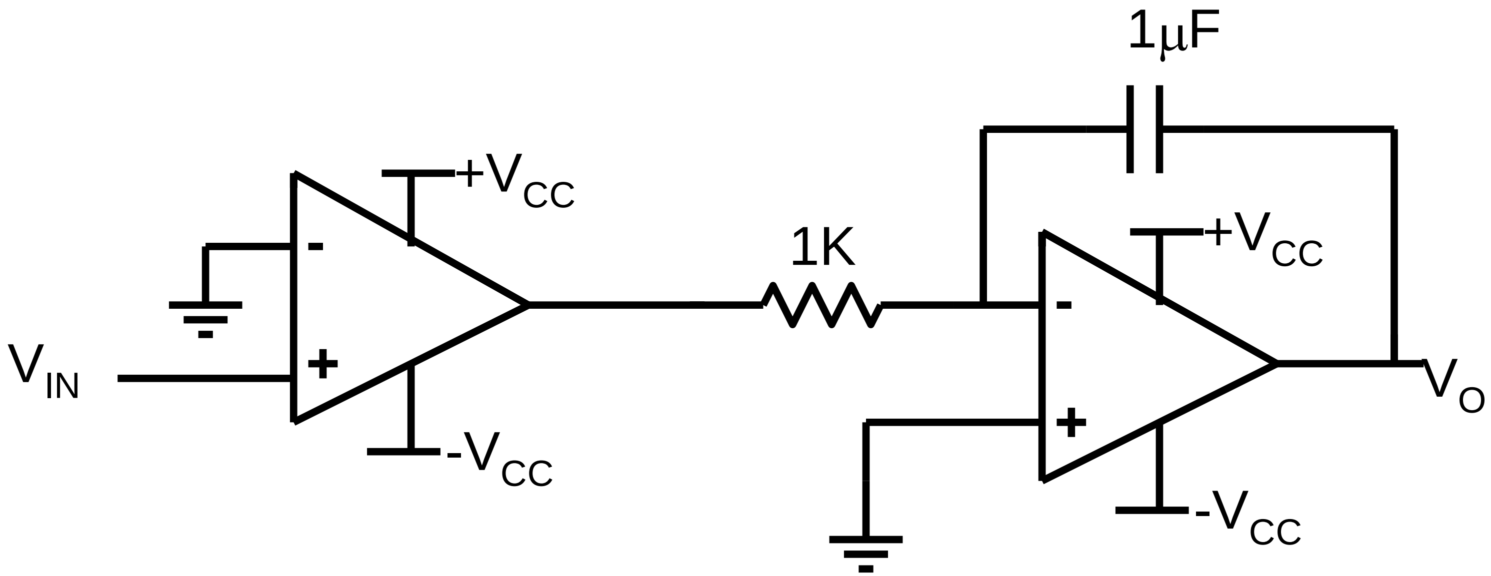
$$V_{OX} = -V_T \times \ln(\frac{V_X}{RI_S})$$

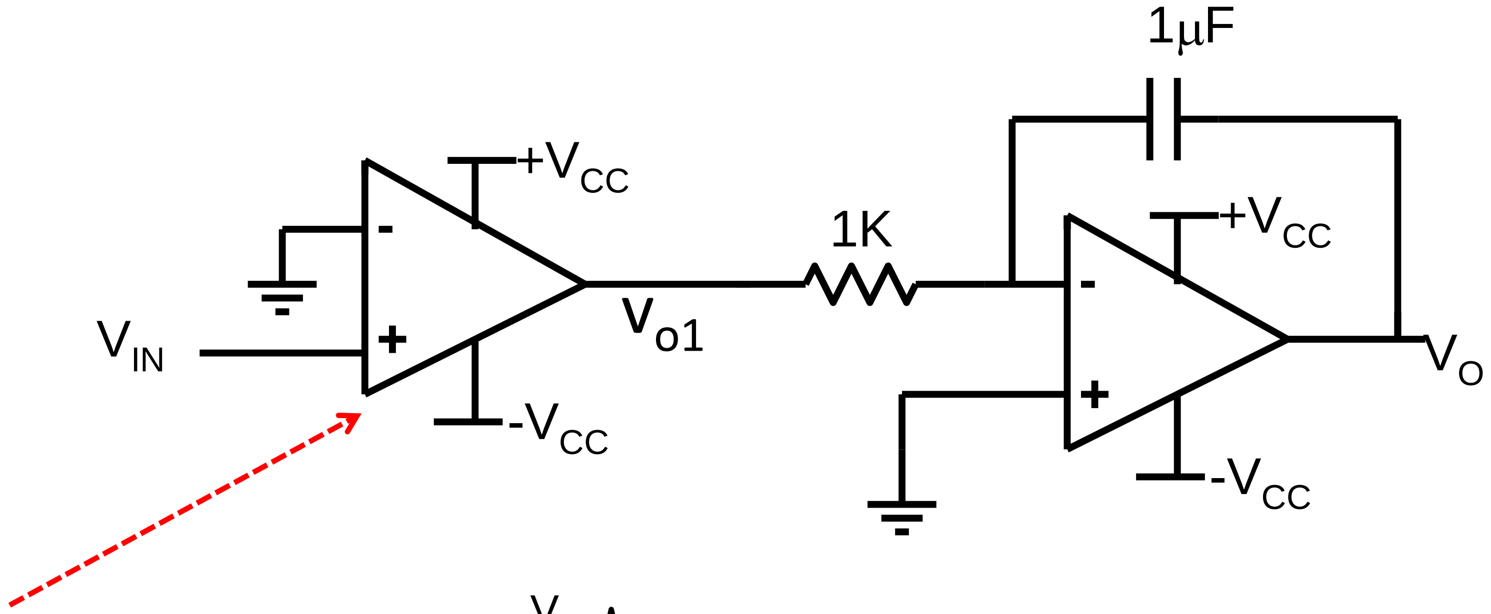
$$V_{O1} = V_T \times \ln(\frac{V_X^2}{R^2 I_S^2})$$




$$V_O \cong -RI_S \times e^{\frac{V_{O1}}{V_T}} = -\frac{V_X^2}{RI_S}$$

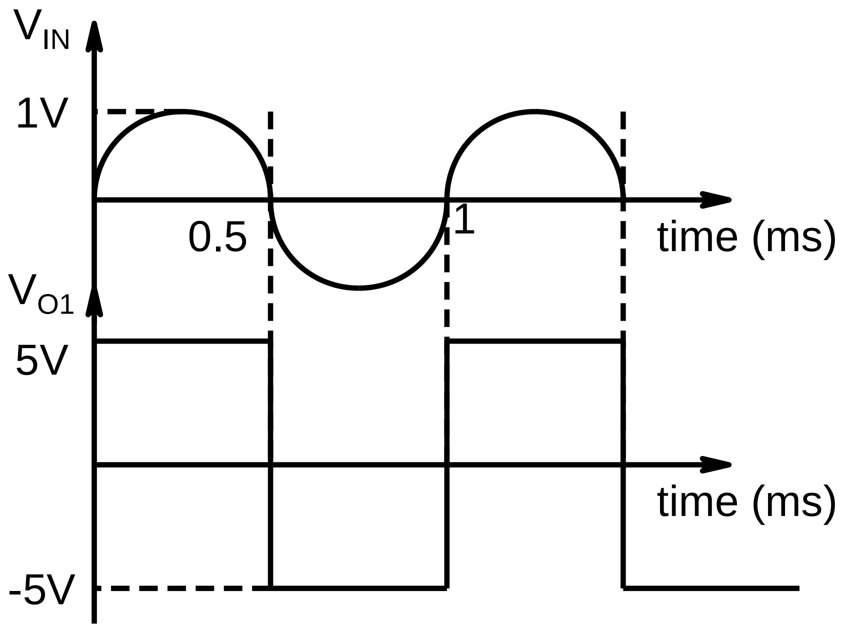
Q.4 Sketch the output voltage of the circuit shown below for $V_{in} = 1V\ Sin(2\pi ft);\ f = 1KHz$ and supply voltages of $\pm 5V$

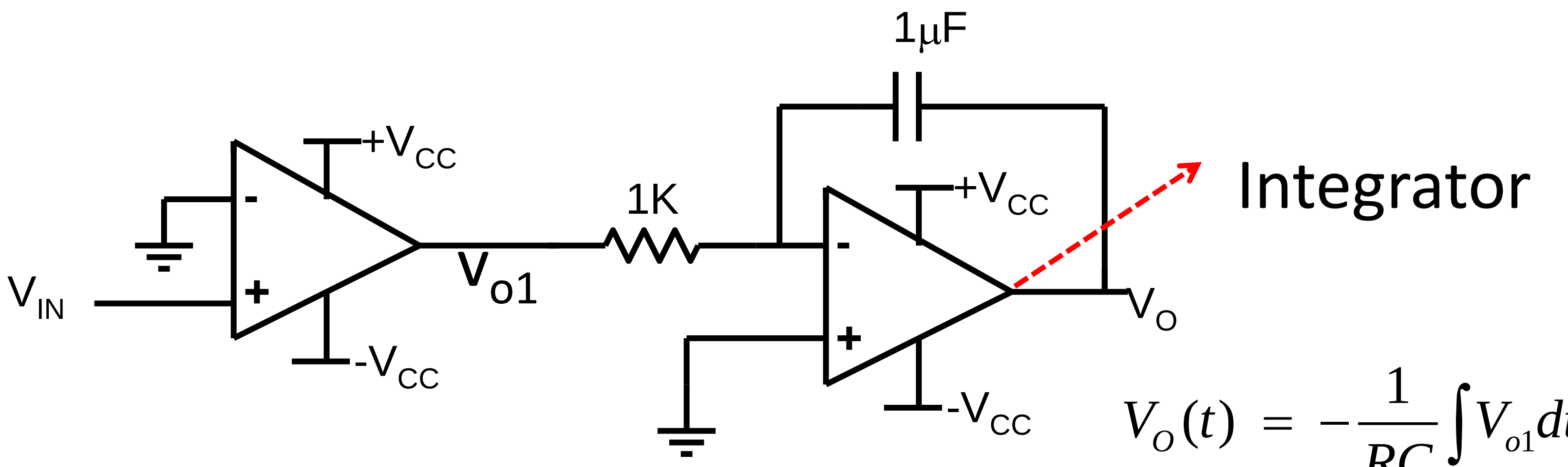




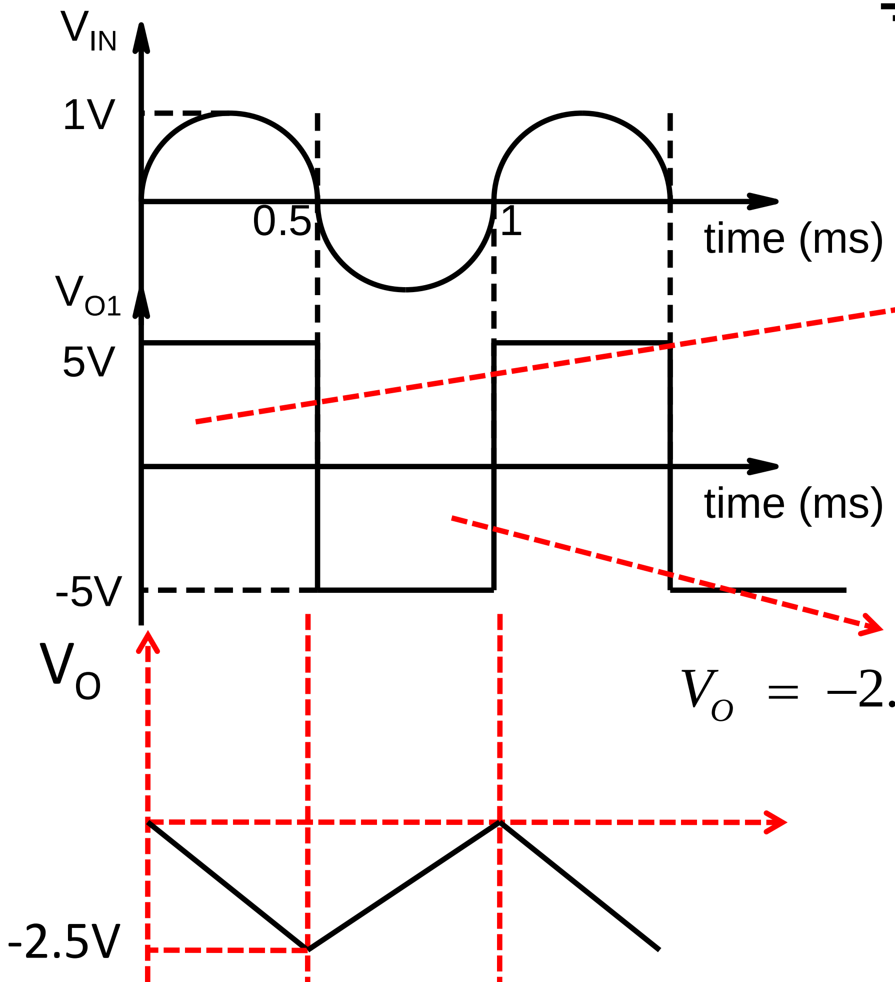

comparator

$$\begin{aligned} V_{O1} &= +5V \; if \; v_{in} > 0 \\ &= -5V \; if \; v_{in} < 0 \end{aligned}$$





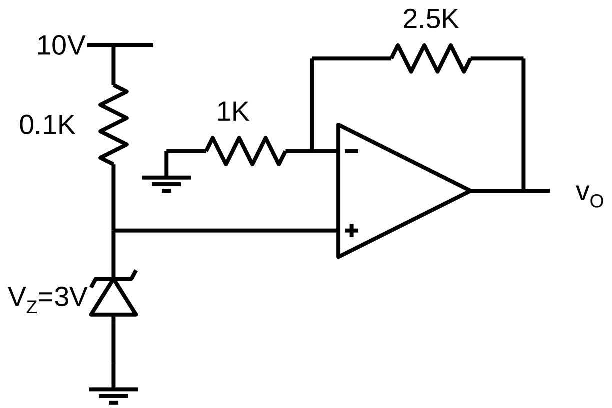

$$V_O(t) = -\frac{1}{RC}\int V_{o1}dt$$
$$= -10^3\int V_{o1}dt$$

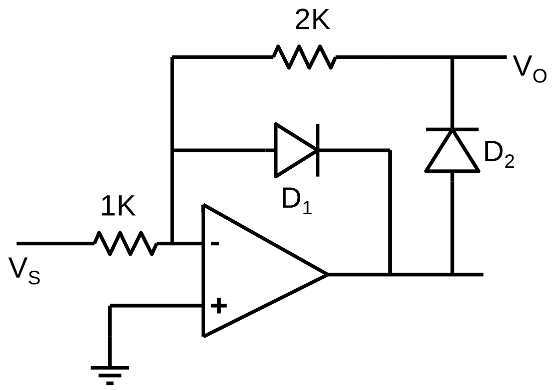


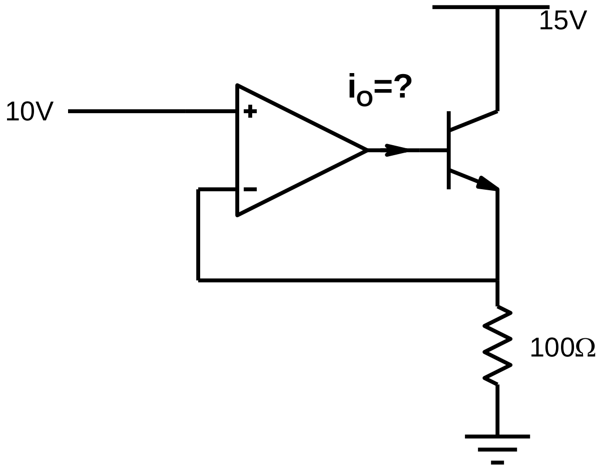

$$V_O = -5\times10^3\times t \;\; for\; 0\le t\le 0.5ms$$

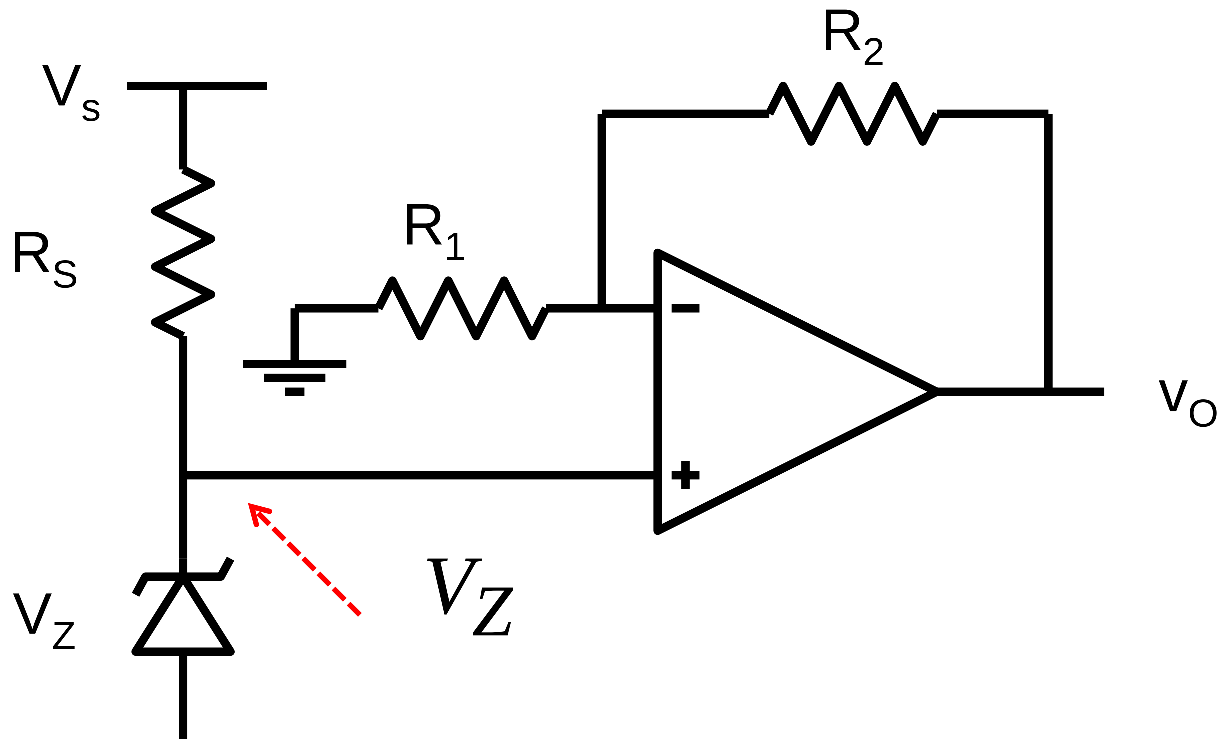
$$V_O = -2.5+5\times10^3\times(t-0.5ms) \;\; for\; 0.5ms\le t\le 1ms$$

Q.5 Determine the output for the ideal opamp circuits shown below. For the circuit on the right assume that diodes have cut-in voltage of 0.7V. Analyze the circuit for Vs = 1V and Vs = -1V. For the transistor assume a current gain of 100. What is the usefulness of each of the circuits?



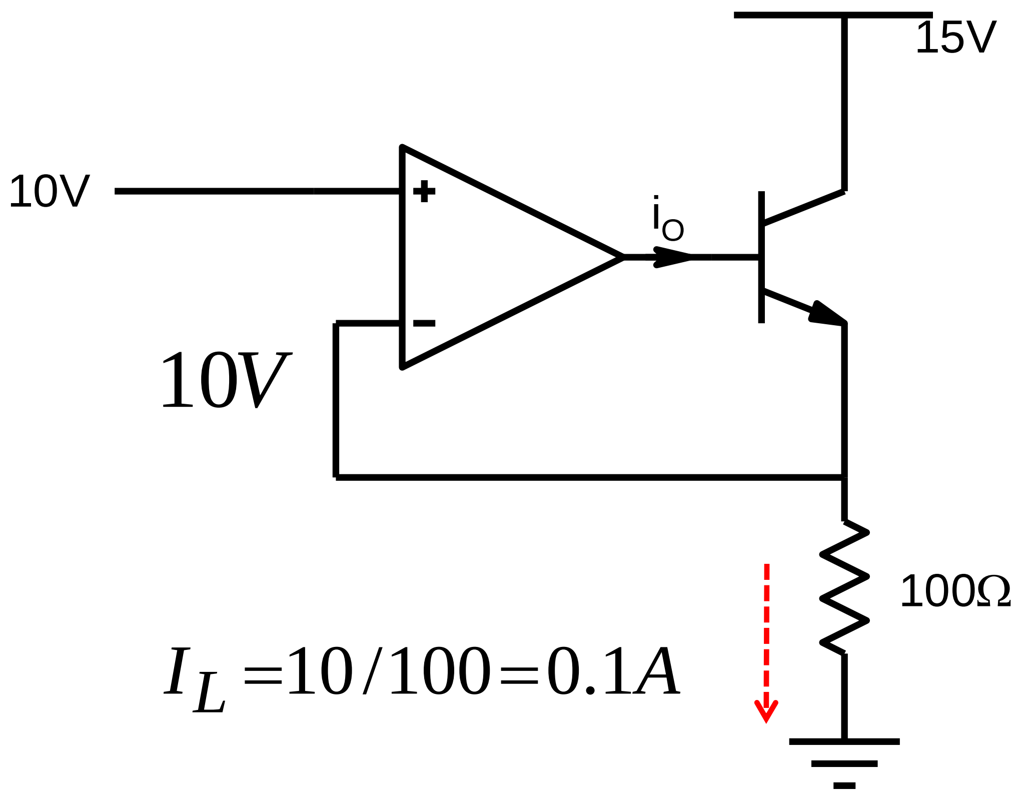






This is a non-inverting amplifier with $V_Z$ as input

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

The circuit produces a constant output voltage Vo even though supply voltage may vary and thus acts like a voltage regulator.

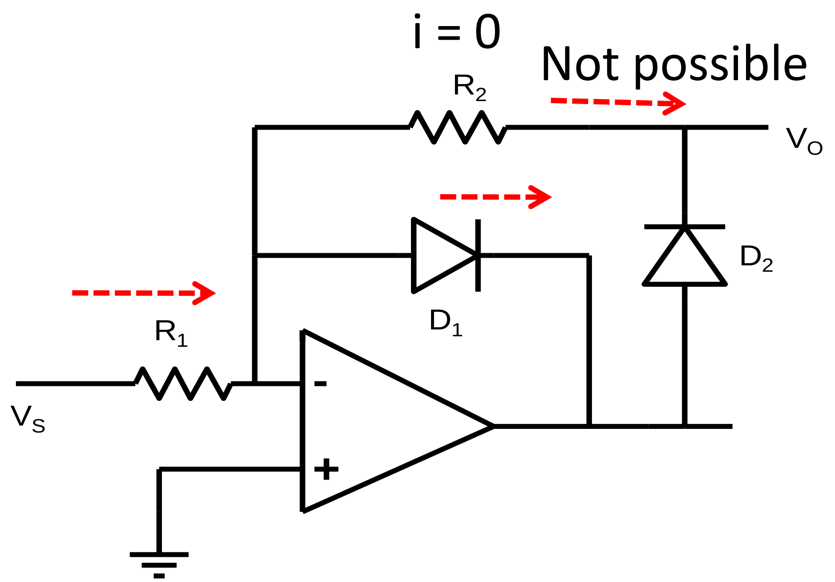



$$I_L = 10/100 = 0.1A$$

$$I_o = I_B = \frac{I_E}{\beta + 1} = 0.99mA$$

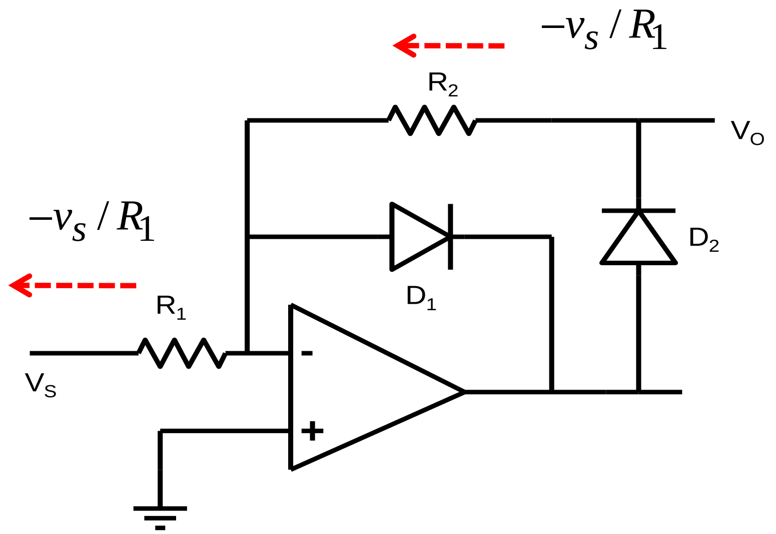
The circuit can supply load current that is much larger than opamp output current

$V_S > 0$




$V_O = 0$

$V_S < 0$




$$\frac{v_O}{v_S} = -\frac{R_2}{R_1}$$

The circuit acts like a rectifier