Chapter 5

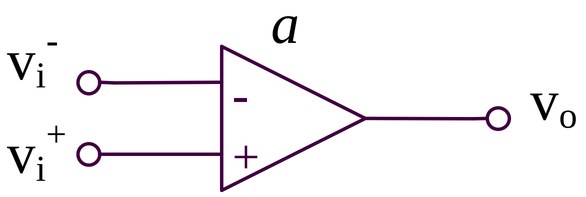
Operational amplifiers. Applications

5.1. Introduction

5.1. Introduction

It is an amplifier with:

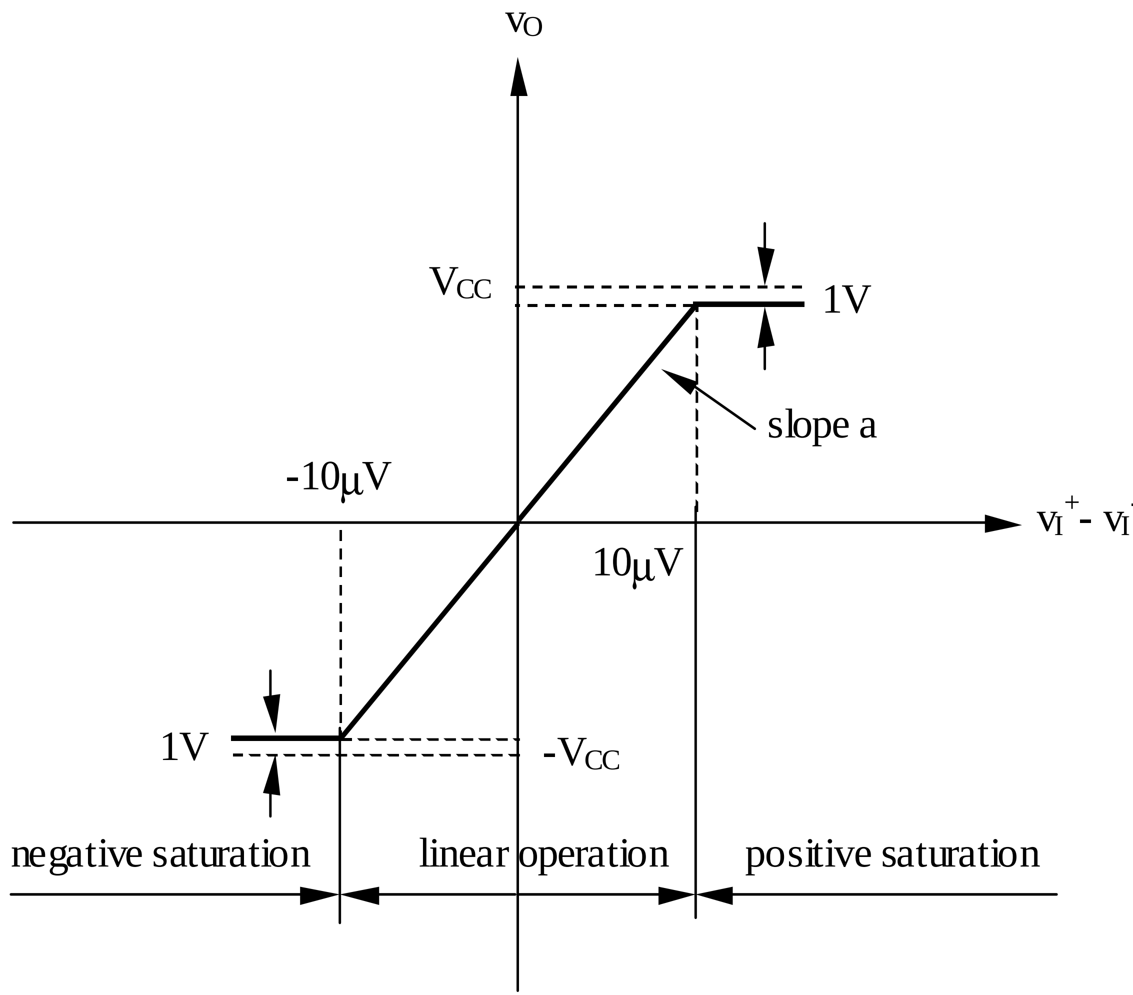
- high voltage gain (ideal ∞)
- large input impedance (ideal ∞)
- small output impedance (ideal 0)
- differential inputs and single output



$$v_O = a\left(v_i^+ - v_i^-\right)$$

Parameters	**Order of magnitude**
• voltage gain	$a_{v0} > 10^5$
• input offset voltage (DC voltage applied between the inputs for obtaining a null output voltage)	v_{IO} = 2-10 mV
• the input offset current	I_{IO} = 5nA - bipol. I_{IO} = 1pA - CMOS

Parameters	Order of magnitude
• input biasing currents	I_I = 80 nA - bipol. I_I = 10 pA - CMOS
• input impedance	R_i = 2MΩ $R_i \rightarrow \infty$ - CMOS
• common-mode input range	V_{CC} (V_{DD}) – 2V
• output voltage range	V_{CC} (V_{DD}) – 1V
• common-mode rejection ratio (differential voltage gain/ common-mode voltage gain)	CMRR = 80dB
• output impedance	R_O = 50Ω
• bandwidth (frequency for which the voltage gain without reaction is equal with 1)	f_T = 1MHz
• slew-rate (maximum slope of a transient response for a large signal input "rectangular" signal)	SR = 0.5V/μs



In linear region, $v_O = a\left(v_I^+ - v_I^-\right)$

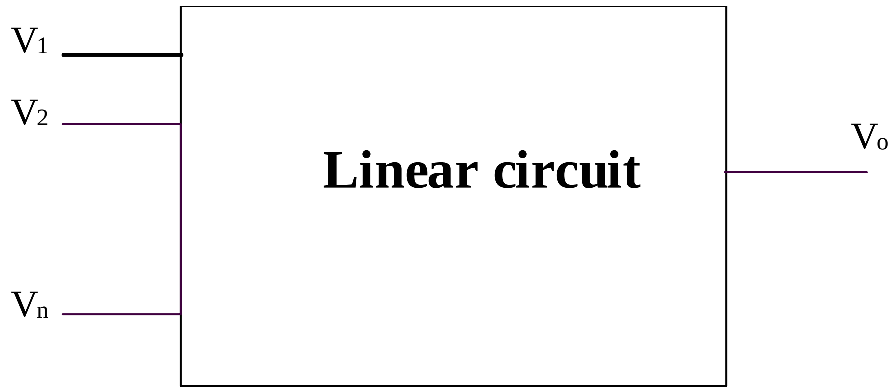
In negative saturation, $v_O \cong -\left(V_{CC} - 1V\right)$

In positive saturation, $v_O \cong V_{CC} - 1V$

5.2. Applications with operational amplifiers

5.2. Applications with operational amplifiers

Superposition theorem



$$V_o = V_o\Big|_{\substack{V_1 \neq 0 \\ V_2 = V_3 = \ldots V_n = 0}} + V_o\Big|_{\substack{V_2 \neq 0 \\ V_1 = V_3 = \ldots V_n = 0}} + \ldots + V_o\Big|_{\substack{V_n \neq 0 \\ V_1 = V_2 = \ldots V_{n-1} = 0}}$$

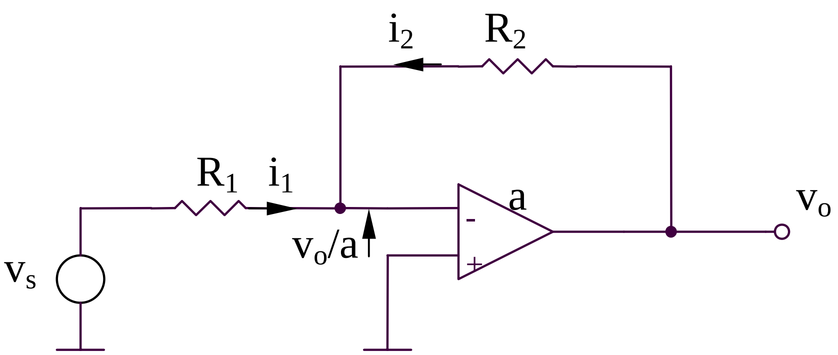
5.2. Applications with operational amplifiers

5.2.1. Ideal operational amplifier

An ideal operational amplifier is characterized in open loop by:
- infinite voltage gain
- infinite input impedance
- null output impedance

In consequence:
- the differential voltage between the two input pins is zero
- the input currents are zero

5.2.2. Inverting amplifier



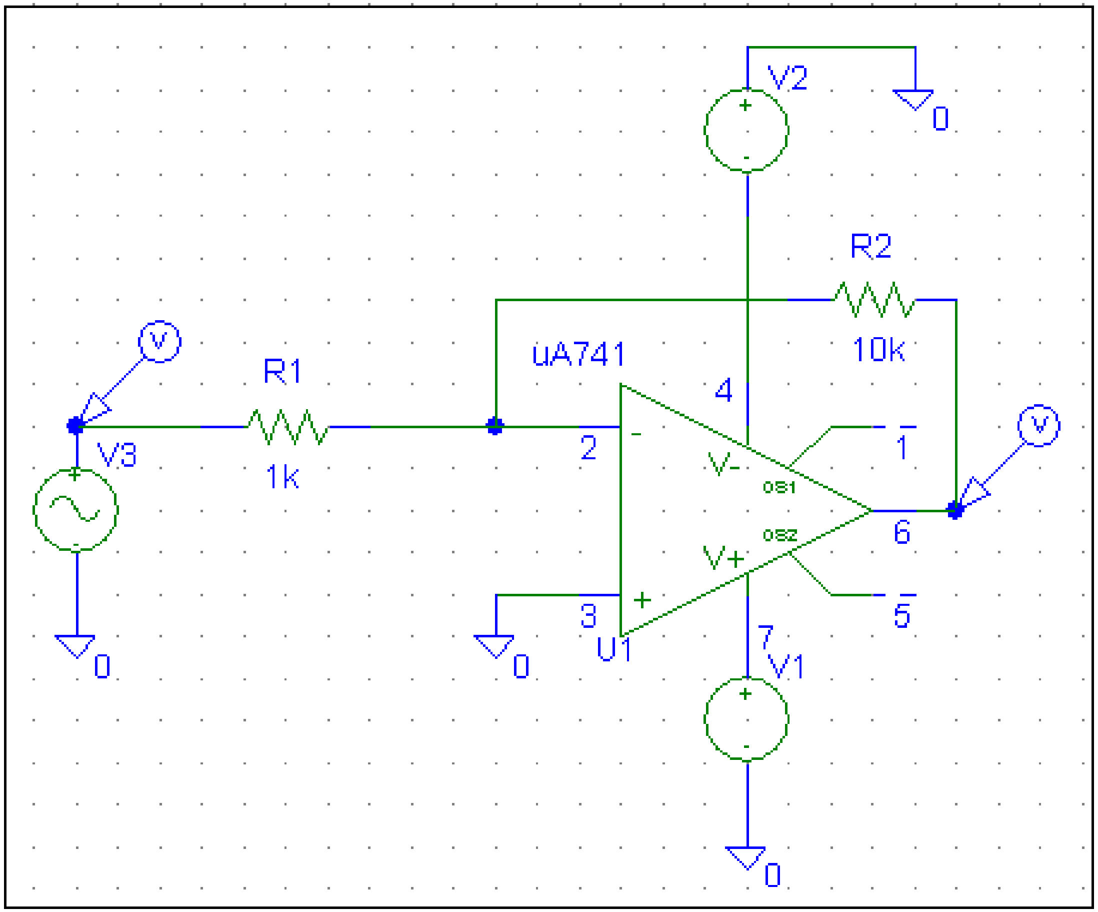
$$\frac{v_s + \frac{v_o}{a}}{R_1} + \frac{v_o + \frac{v_o}{a}}{R_2} = 0 \Rightarrow$$

$$\Rightarrow A = \frac{v_o}{v_s} = -\frac{R_2}{R_1} \frac{1}{1 + \frac{1}{a}\frac{R_1 + R_2}{R_1}} \to -\frac{R_2}{R_1}$$

SIMULATIONS for inverting amplifier

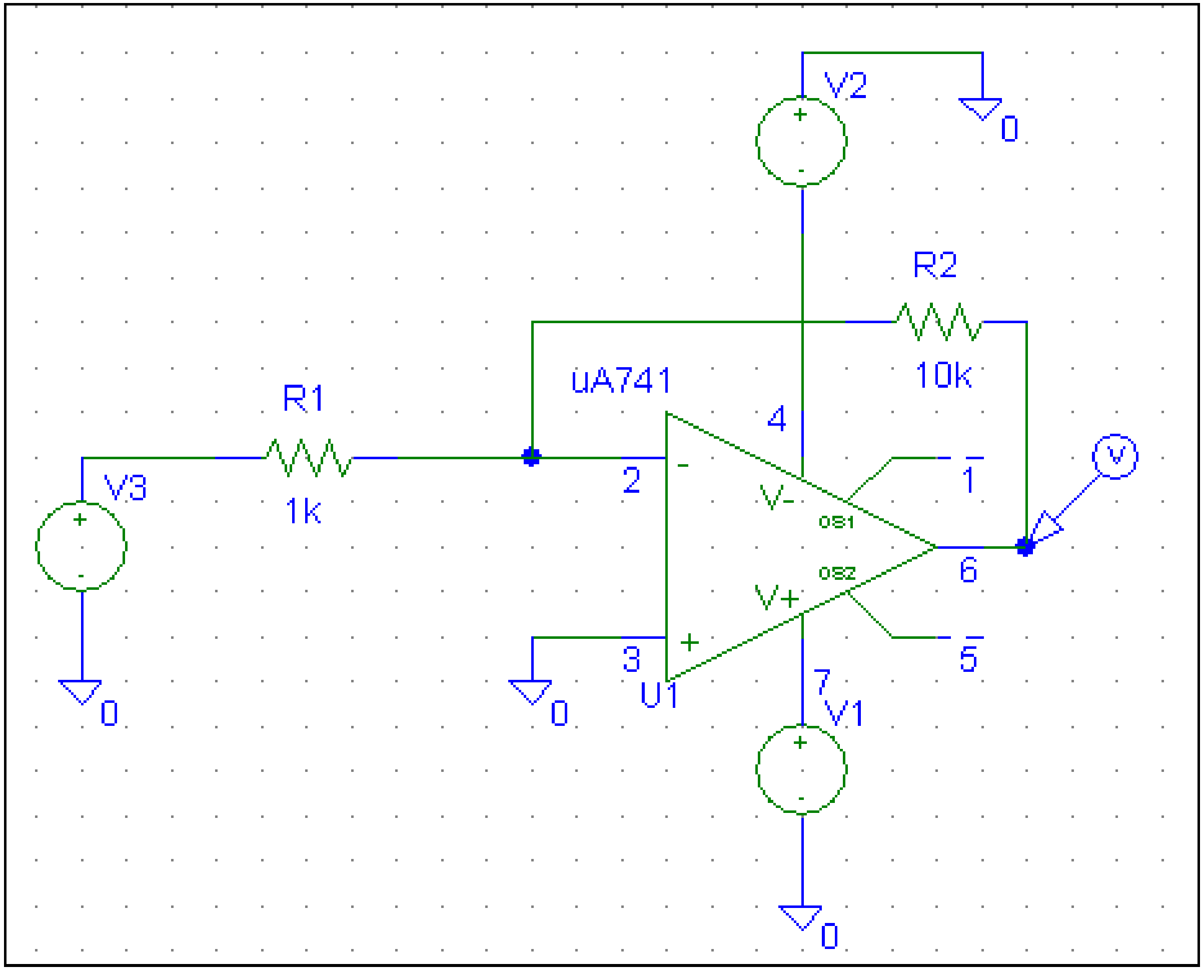
SIMULATIONS for inverting amplifier

SIM 5.1: V_3 (t), V_O (t)

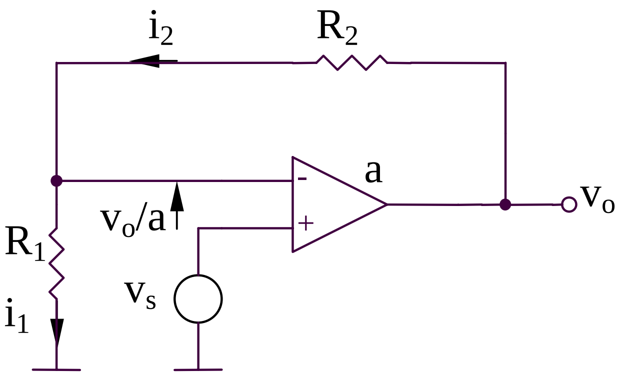


SIMULATIONS for inverting amplifier

SIM 5.2: V_O (V_3)



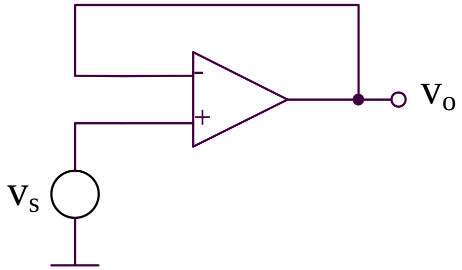
5.2.3. Non-inverting amplifier



$$\frac{v_s - \frac{v_o}{a}}{R_1} = \frac{v_o - \left(v_s - \frac{v_o}{a}\right)}{R_2} \Rightarrow$$

$$\Rightarrow A = \frac{v_o}{v_s} = \frac{R_1 + R_2}{R_1} \frac{1}{1 + \frac{R_1 + R_2}{aR_1}} \to 1 + \frac{R_2}{R_1}$$

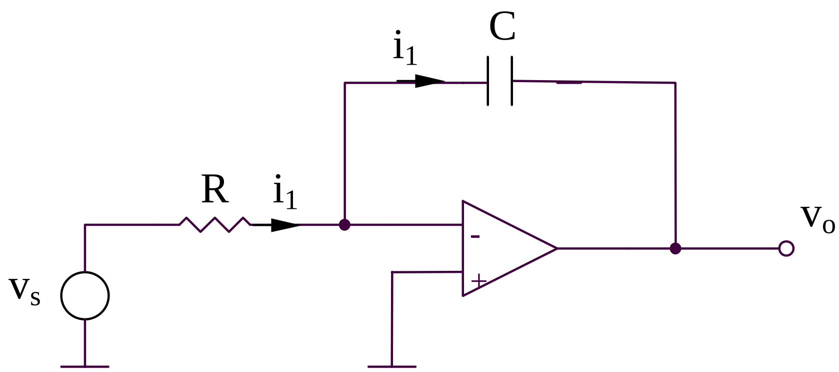
5.2.4. Follower circuit

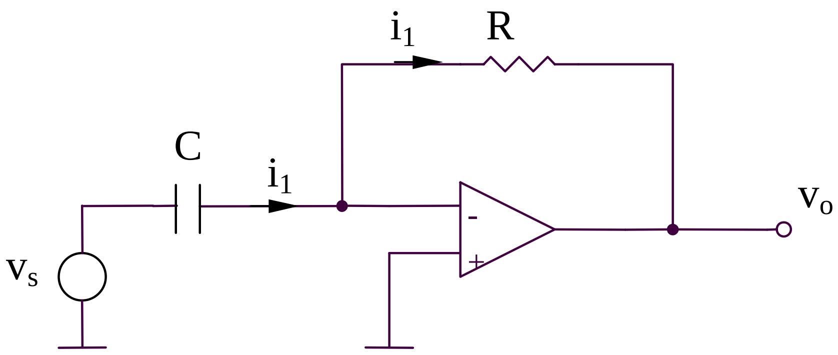


If the operational amplifier is ideal, the output voltage is identical with the input voltage:

$$v_O = v_s$$

5.2.5. Integrating and differentiating circuits





Integrating circuit

$$i_1 = \frac{v_s(t)}{R}$$

$$v_o = -\frac{1}{C}\int i_1(t)dt + v_o(0)$$

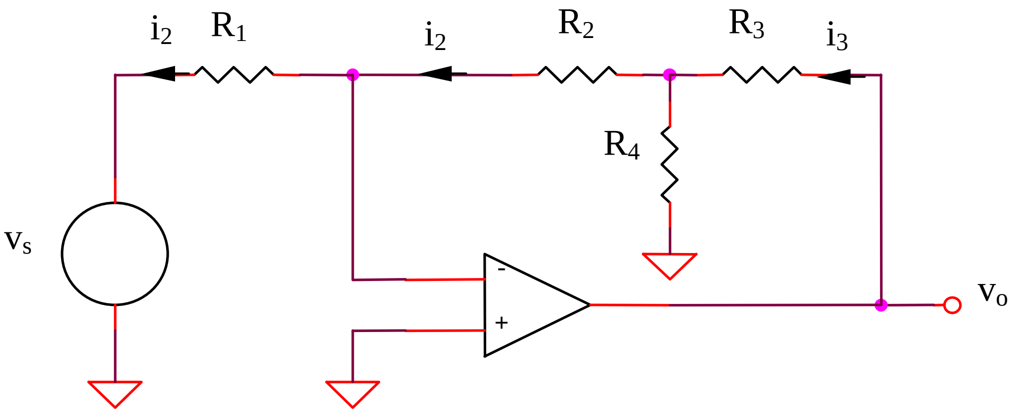
$$v_o = -\frac{1}{RC}\int v_s(t)dt + v_o(0)$$

Differentiating circuit

$$i_1 = C\frac{dv_s}{dt}$$

$$v_o = -Ri_1 = -RC\frac{dv_s}{dt}$$

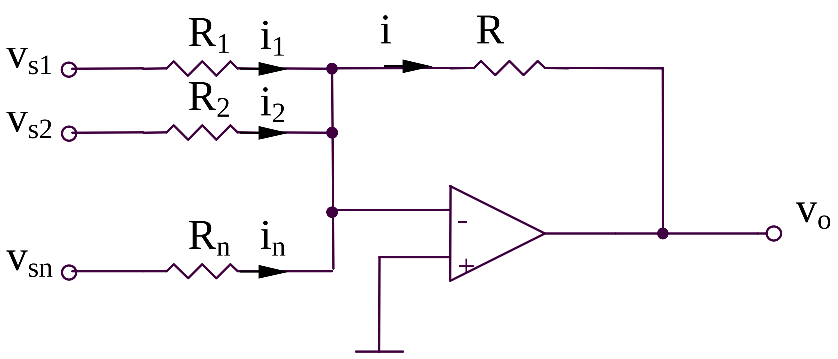
5.2.6. High gain amplifier



$$A = \frac{v_o}{v_s} = \frac{v_o}{i_3}\frac{i_3}{i_2}\frac{i_2}{v_s}$$

$$A = -\frac{R_2R_3 + R_2R_4 + R_3R_4}{R_1R_4}$$

5.2.7. Inverting voltage adder



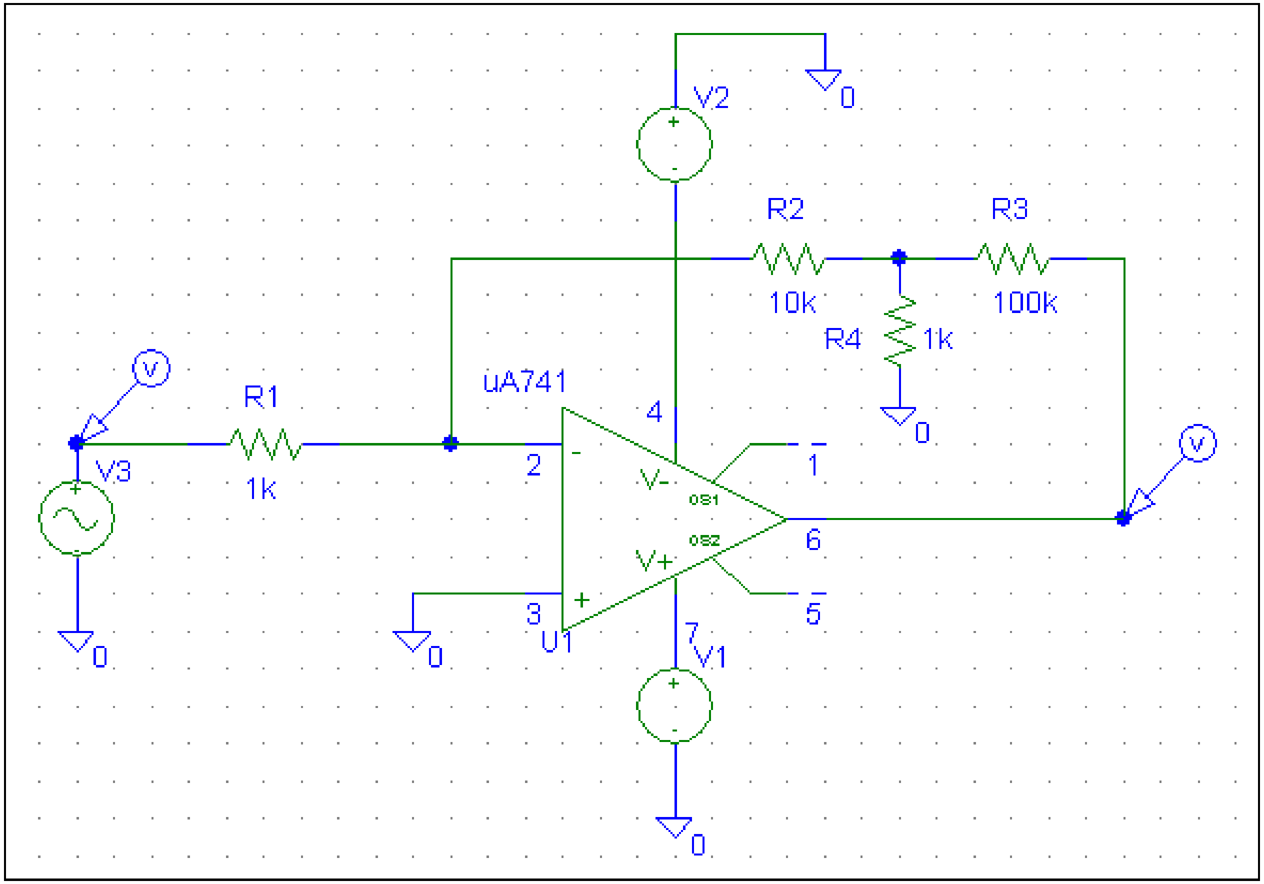
$$i = \sum_{i=1}^{n} i_i = \sum_{i=1}^{n} \frac{v_{si}}{R_i}$$

$$v_o = -Ri = -R\sum_{i=1}^{n} \frac{v_{si}}{R_i}$$

SIMULATIONS for high gain amplifier

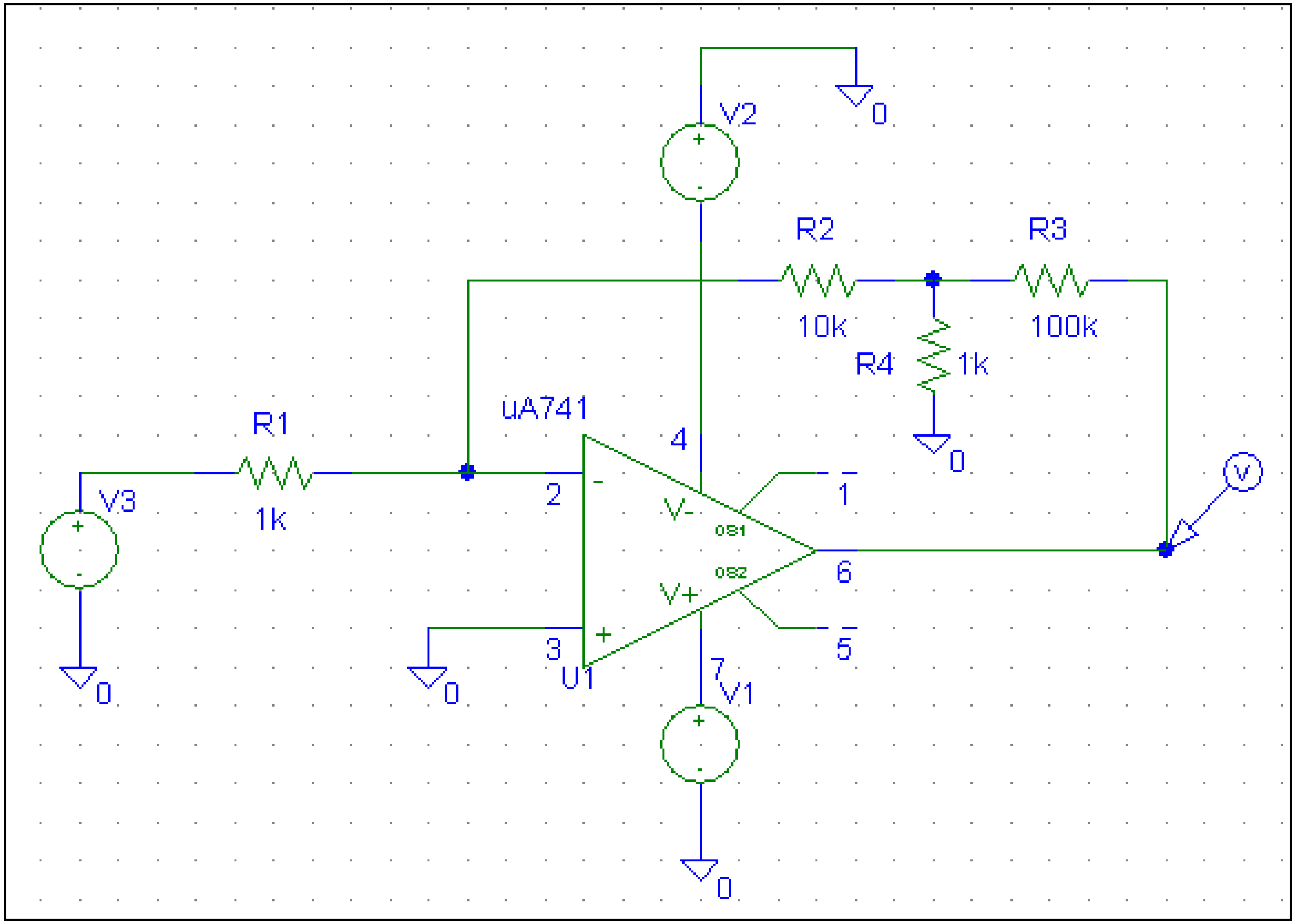
SIMULATIONS for high gain amplifier

SIM 5.3: V_3 (t), V_O (t)



SIMULATIONS for high gain amplifier

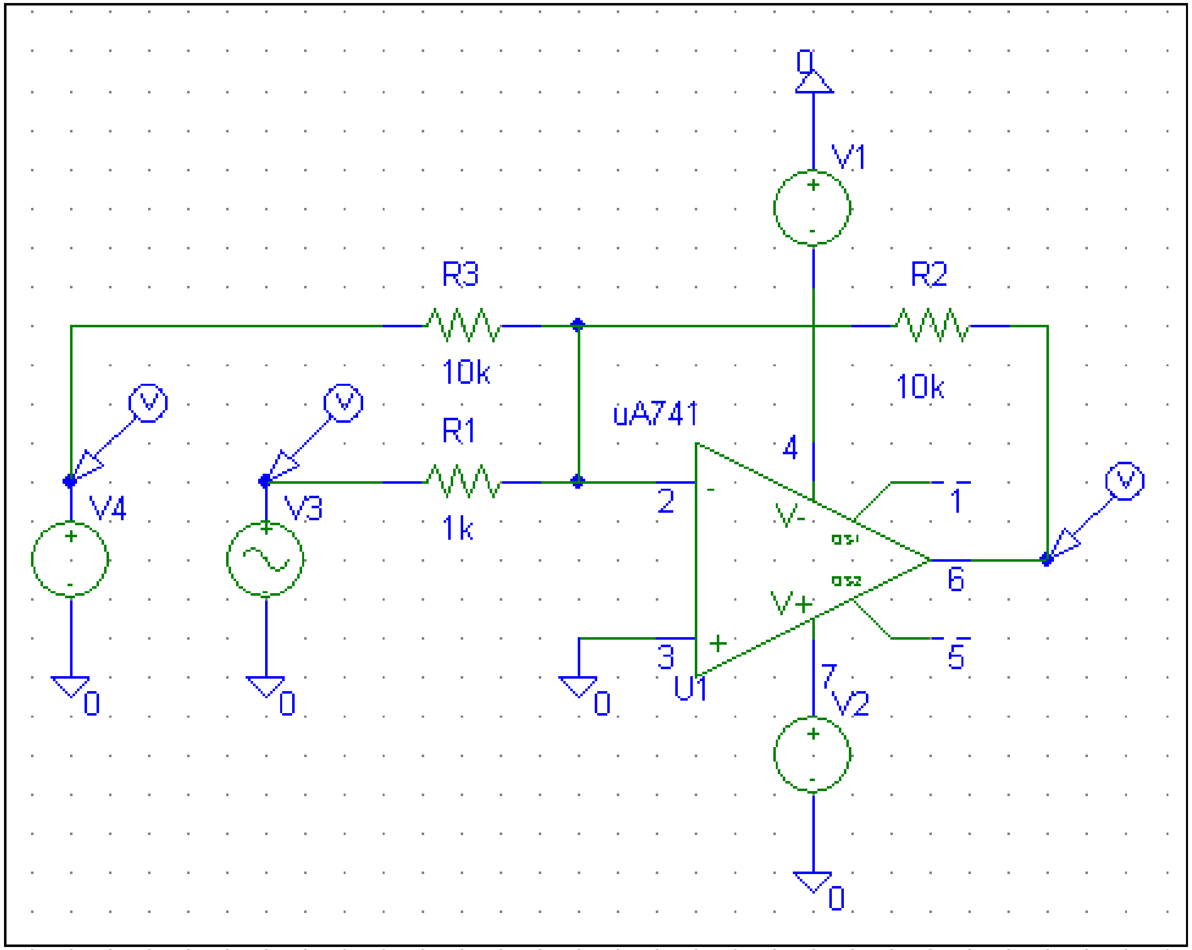
SIM 5.4: V_O (V_3)



SIMULATIONS for inverting voltage adder

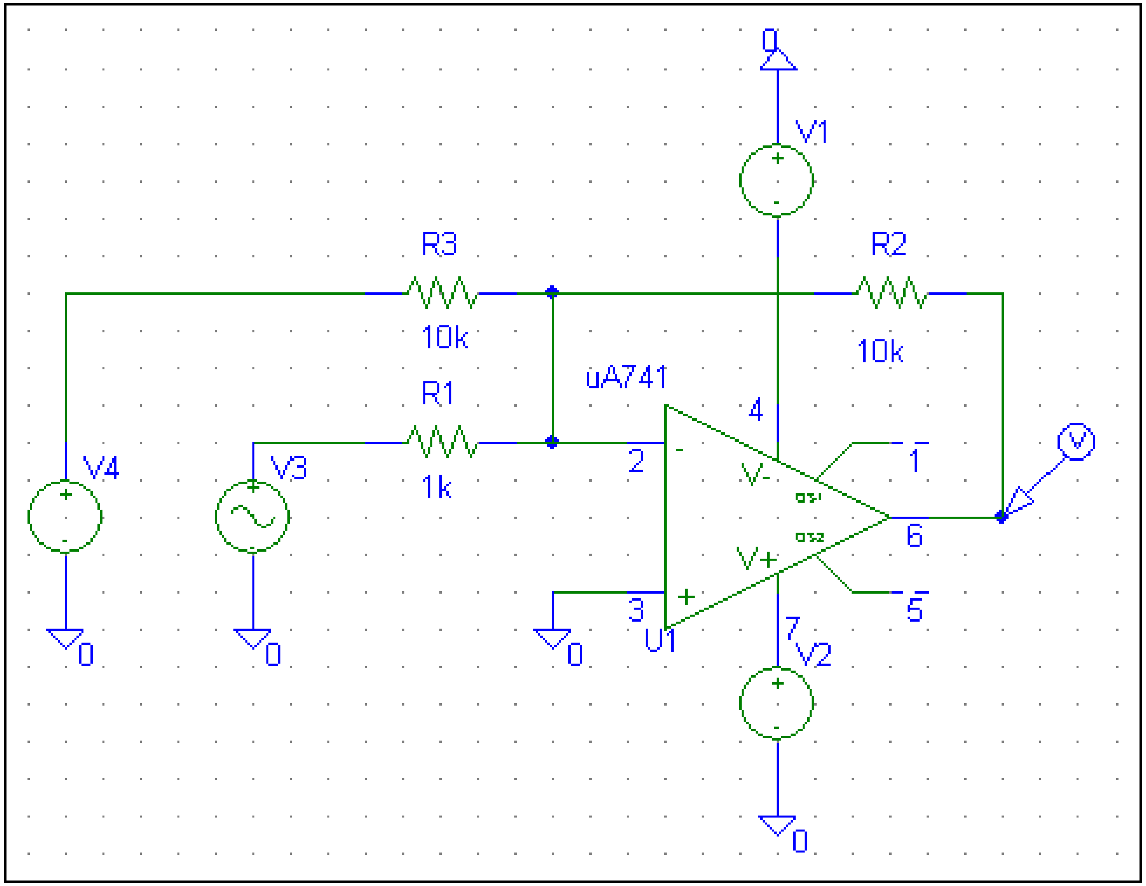
SIMULATIONS for inverting voltage adder

SIM 5.5: V_3 (t), V_4 (t), V_O (t)

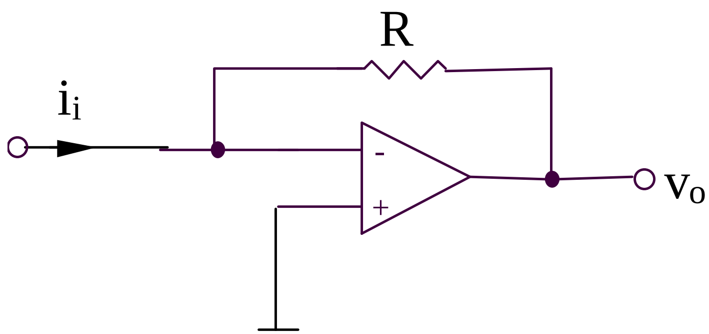


SIMULATIONS for inverting voltage adder

SIM 5.6: V_O (t), V_4 - parameter

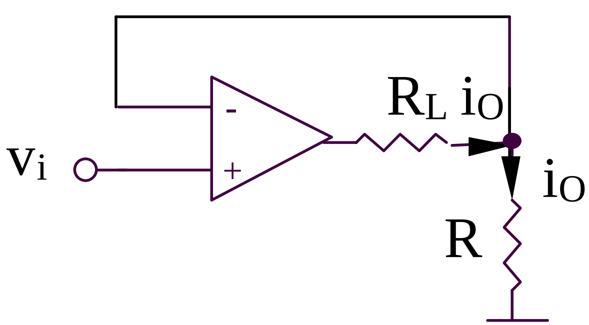


5.2.8. Current-voltage converter



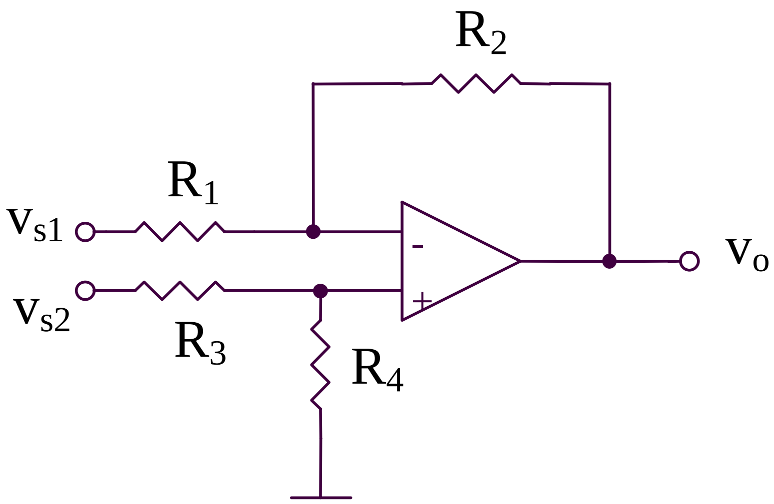
$$v_O = -Ri_i$$

5.2.9. Voltage-current converter



$$i_O = v_i / R$$

5.2.10. Difference circuit (1)



$$v_o = v_{s1}\left(-\frac{R_2}{R_1}\right) + v_{s2}\frac{R_4}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right)$$

For obtain:

$$v_o = A(v_{s2} - v_{s1})$$

is necessary to impose the condition:

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

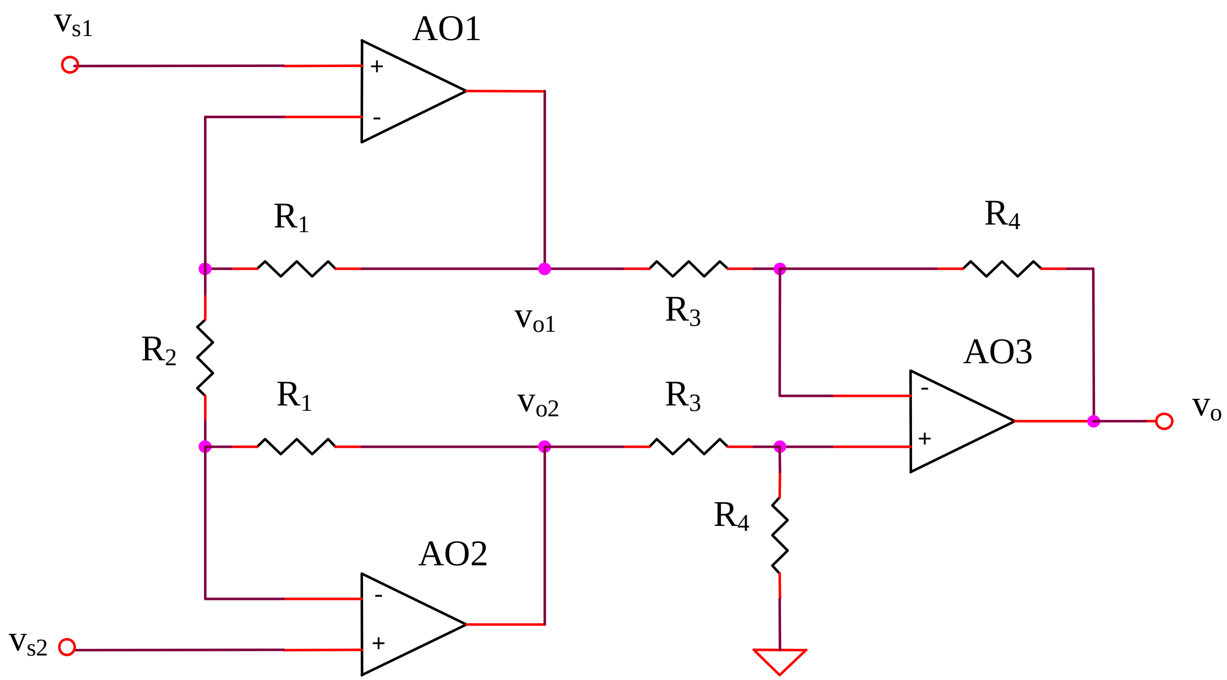
equivalent with:

$$R_1 R_4 = R_2 R_3$$

resulting:

$$v_o = \frac{R_2}{R_1}(v_{s2} - v_{s1})$$

5.2.11. Difference circuit (2)

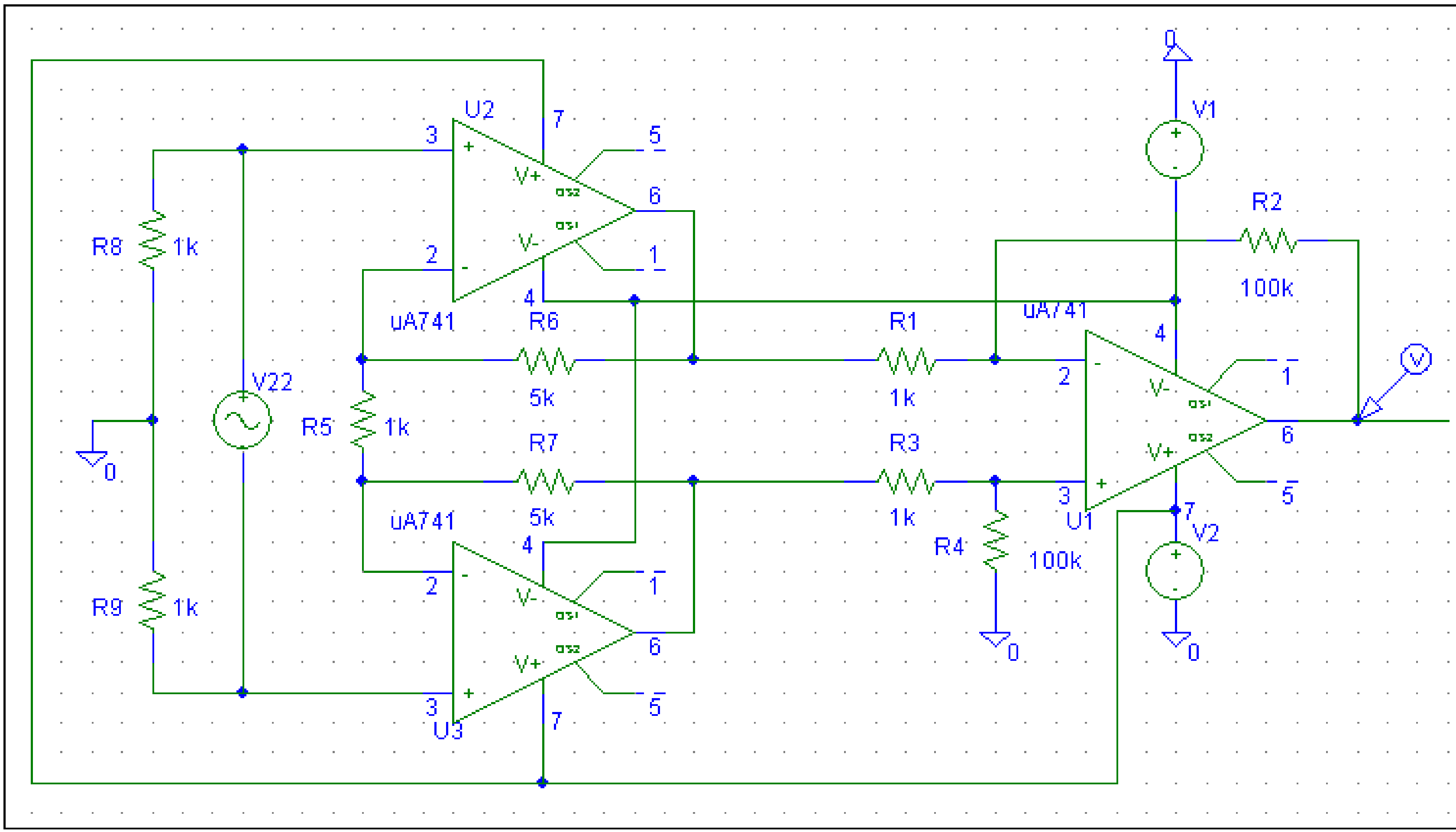


$$\left.\begin{aligned} v_{o1} &= v_{s1}\left(1+\frac{R_1}{R_2}\right)-v_{s2}\frac{R_1}{R_2} \\ v_{o1} &= v_{s2}\left(1+\frac{R_1}{R_2}\right)-v_{s1}\frac{R_1}{R_2} \\ v_o &= \frac{R_4}{R_3}\left(v_{o2}-v_{o1}\right) \end{aligned}\right\} \Rightarrow A = \frac{v_o}{v_{s2}-v_{s1}} = \left(1+2\frac{R_1}{R_2}\right)\frac{R_4}{R_3}$$

<u>SIMULATIONS for difference circuit (2)</u>

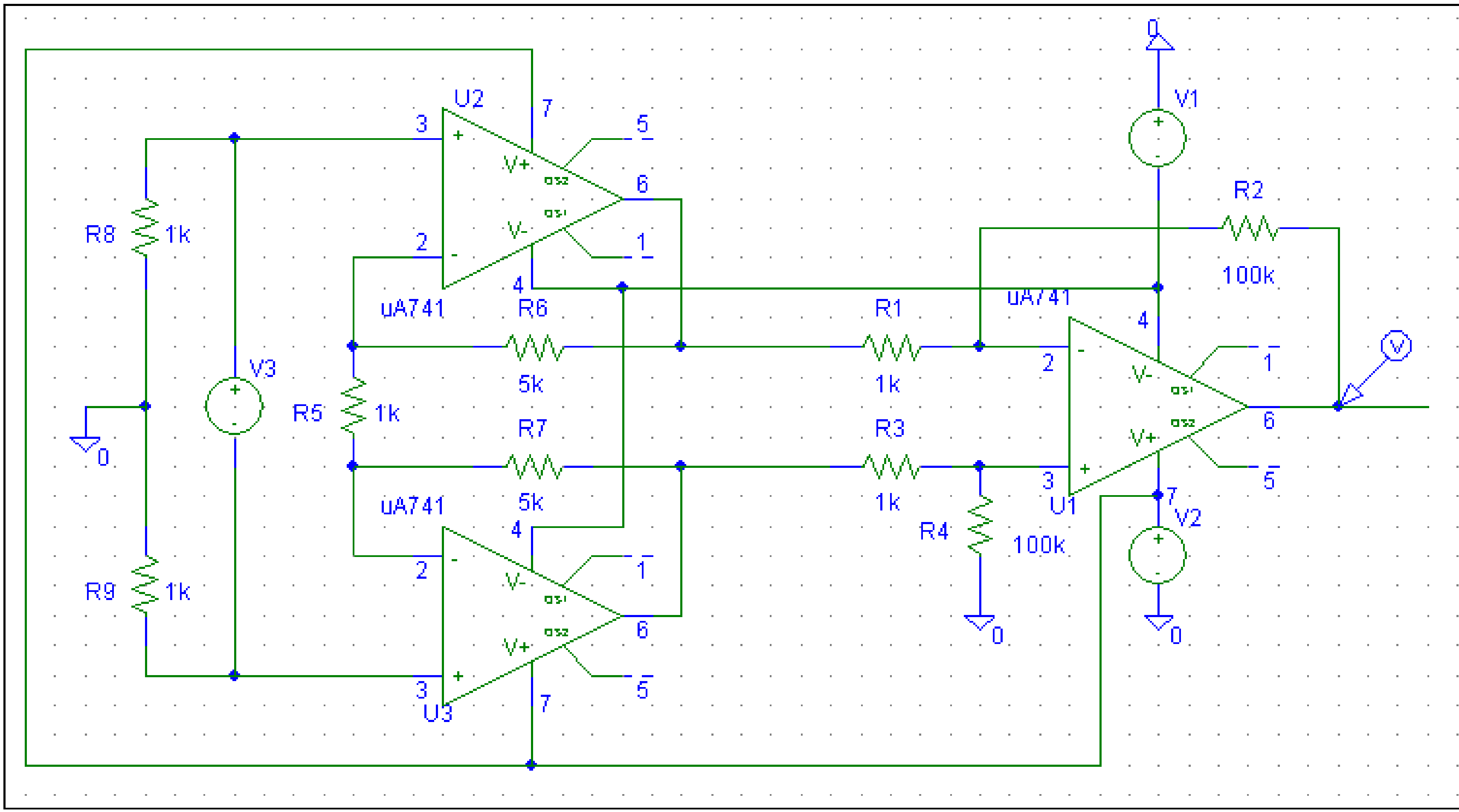
SIMULATIONS for difference circuit (2)

SIM 5.7: V_O (t)

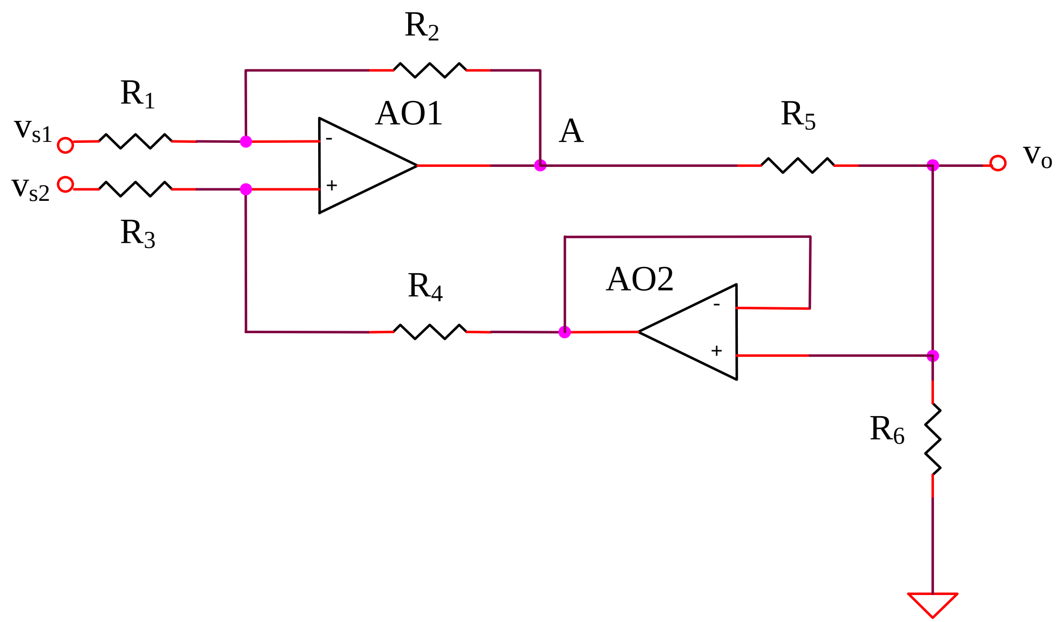


SIMULATIONS for difference circuit (2)

SIM 5.8: V_O (V_3)



5.2.12. Differential circuit (3)

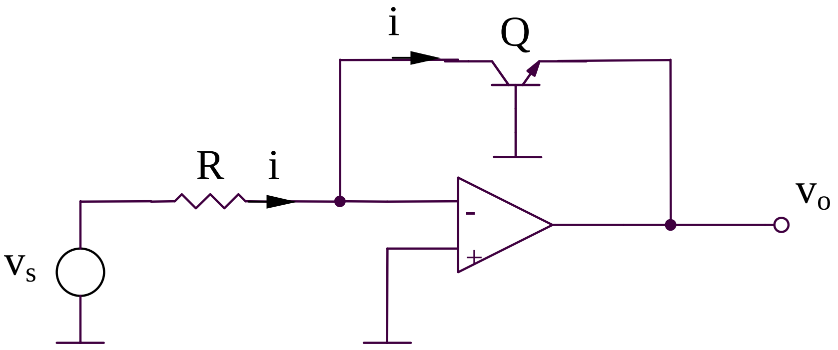


$$\left.\begin{aligned} v_A &= v_{s1}\left(-\frac{R_2}{R_1}\right) + \frac{v_{s2}R_4 + v_oR_3}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right) \\ v_o &= v_A\frac{R_6}{R_5+R_6} \end{aligned}\right\} \Rightarrow v_o\left[\left(1+\frac{R_5}{R_6}\right) - \frac{1+\frac{R_2}{R_1}}{1+\frac{R_4}{R_3}}\right] = v_{s2}\frac{1+\frac{R_2}{R_1}}{1+\frac{R_3}{R_4}} - v_{s1}\frac{R_2}{R_1}$$

$$\left.\begin{aligned} & v_o\left[\left(1+\frac{R_5}{R_6}\right) - \frac{1+\frac{R_2}{R_1}}{1+\frac{R_4}{R_3}}\right] = v_{s2}\frac{1+\frac{R_2}{R_1}}{1+\frac{R_3}{R_4}} - v_{s1}\frac{R_2}{R_1} \\ & v_o = A\left(v_{s2}-v_{s1}\right) \end{aligned}\right\} \Rightarrow$$

$$\Rightarrow R_1R_4 = R_2R_3 \Rightarrow A = \frac{v_o}{v_{s2}-v_{s1}} = \frac{R_6R_2}{R_5R_1}$$

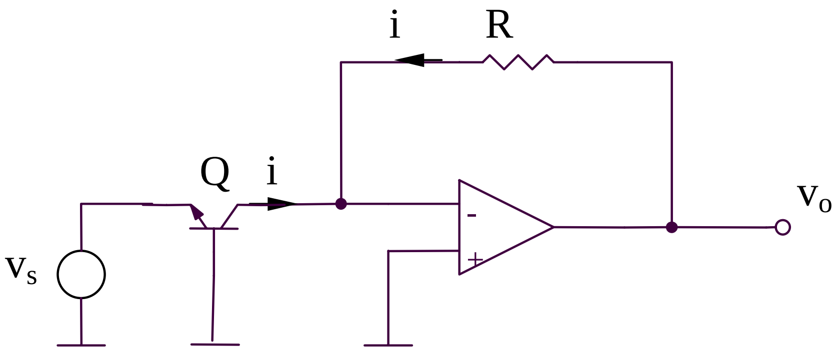
5.2.13. Logarithmic and anti-logarithmic converters



Logarithmic converter

$$v_o = -v_{BE} = -V_{th} \ln\left(\frac{i}{I_S}\right)$$

$$v_o = -V_{th} \ln\left(\frac{v_s}{RI_S}\right)$$



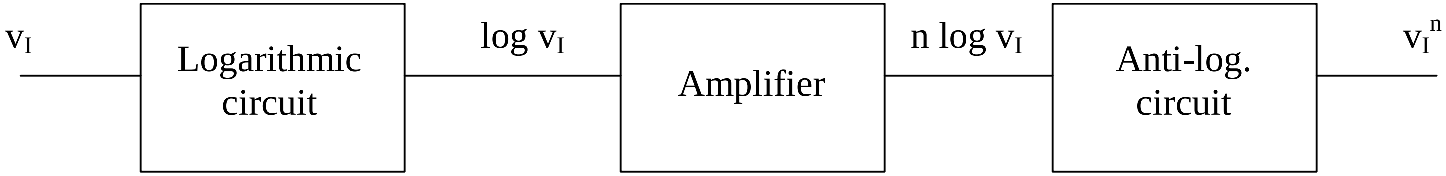
Anti-logarithmic converter

$$v_o = iR$$

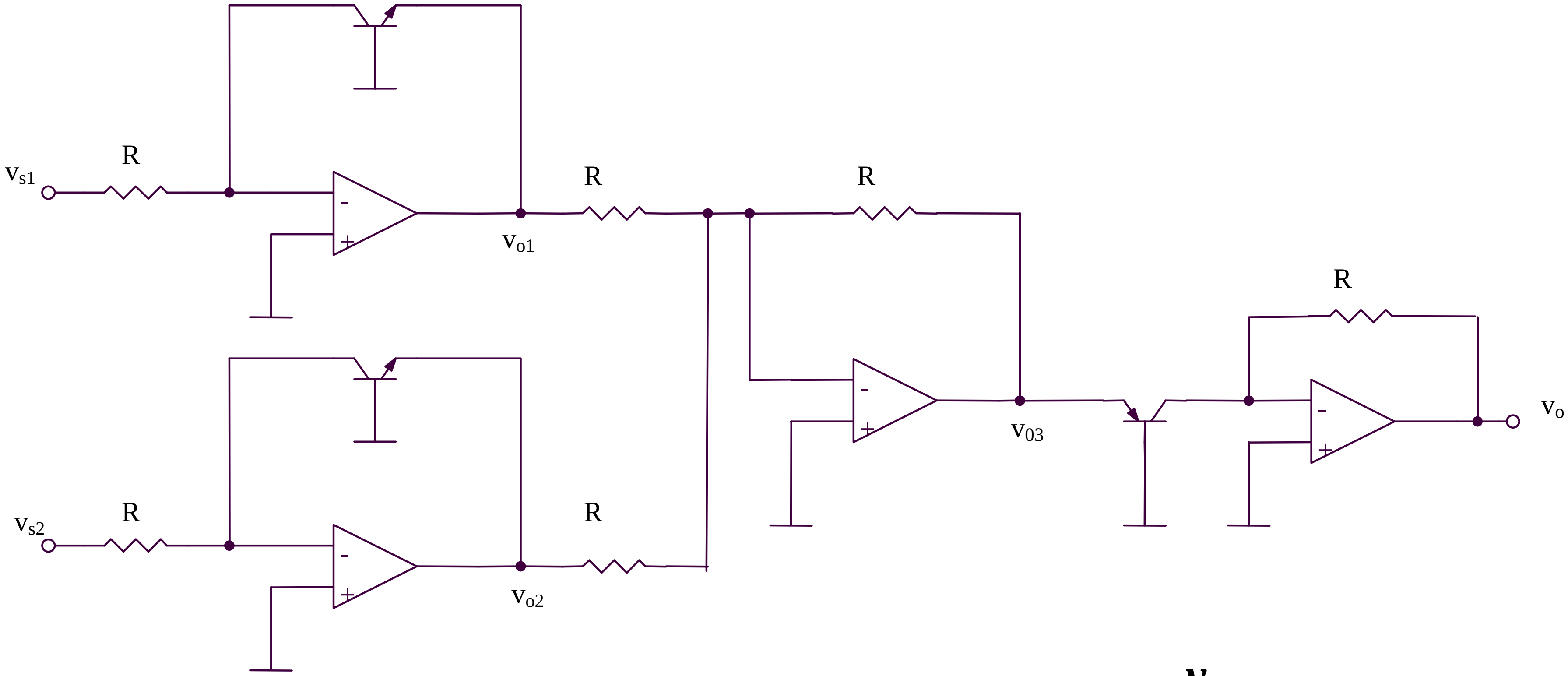
$$i = I_S e^{\frac{v_{BE}}{V_{th}}} = I_S e^{-\frac{v_s}{V_{th}}}$$

5.2.14. Circuit for the function $Y = X^n$

$$X^n = e^{n \ln x}$$



5.2.15. Multiplier circuit

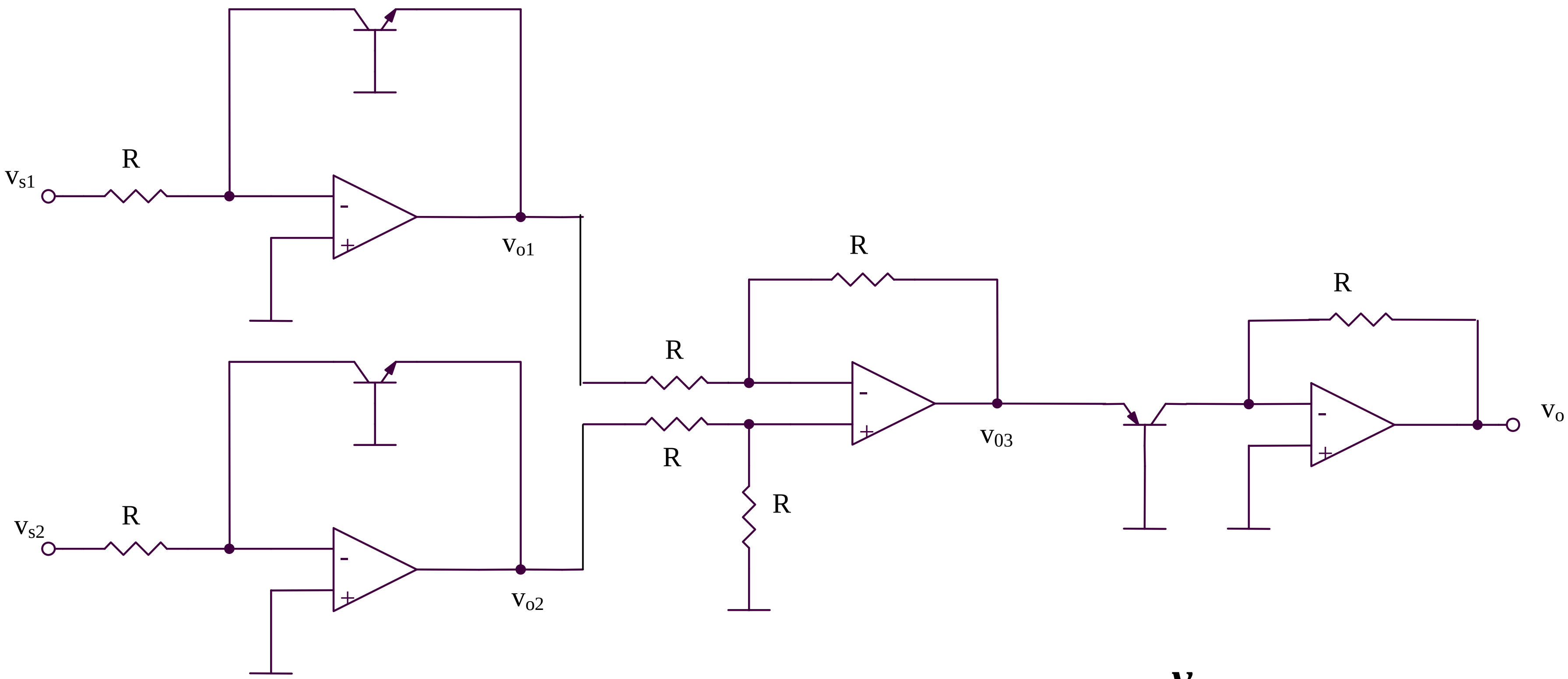


$$v_{o1} = -V_{th} \ln \frac{v_{s1}}{RI_S} \qquad v_{o2} = -V_{th} \ln \frac{v_{s2}}{RI_S}$$

$$v_{o3} = \left(-\frac{R}{R}\right)v_{o1} + \left(-\frac{R}{R}\right)v_{o2} = -(v_{o1} + v_{o2}) = V_{th} \ln \frac{v_{s1}v_{s2}}{R^2 I_S^2}$$

$$v_o = -RI_S e^{\frac{v_{o3}}{V_{th}}} = -\frac{v_{s1}v_{s2}}{RI_S}$$

5.2.16. Divider circuit



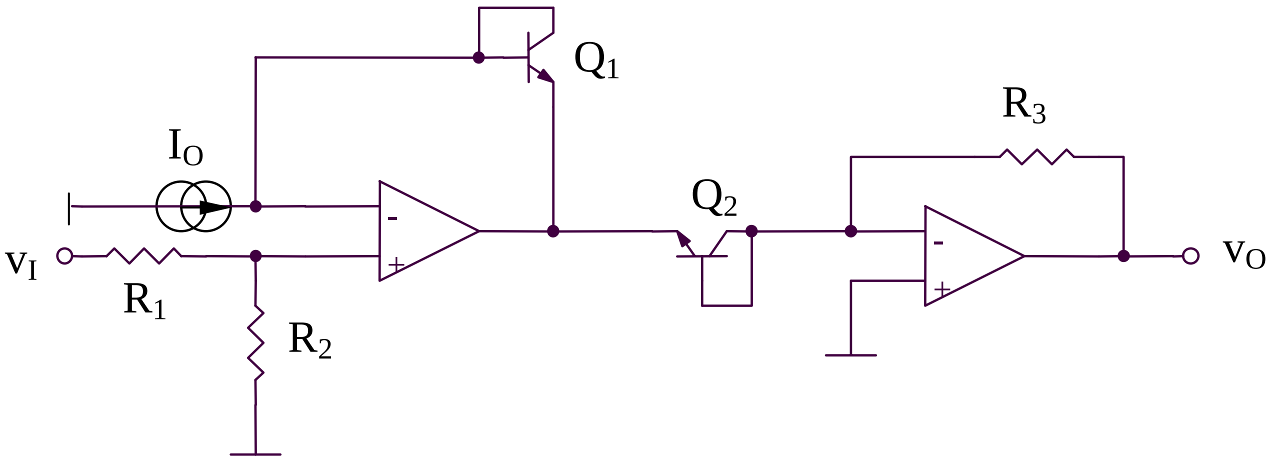
$$v_{o1} = -V_{th} \ln \frac{v_{s1}}{RI_S}$$

$$v_{o2} = -V_{th} \ln \frac{v_{s2}}{RI_S}$$

$$v_{o3} = v_{o2} - v_{o1} = V_{th}\, ln \frac{v_{s1}}{v_{s2}}$$

$$v_o = -RI_S e^{vo3/Vth} = -RI_S \frac{v_{s1}}{v_{s2}}$$

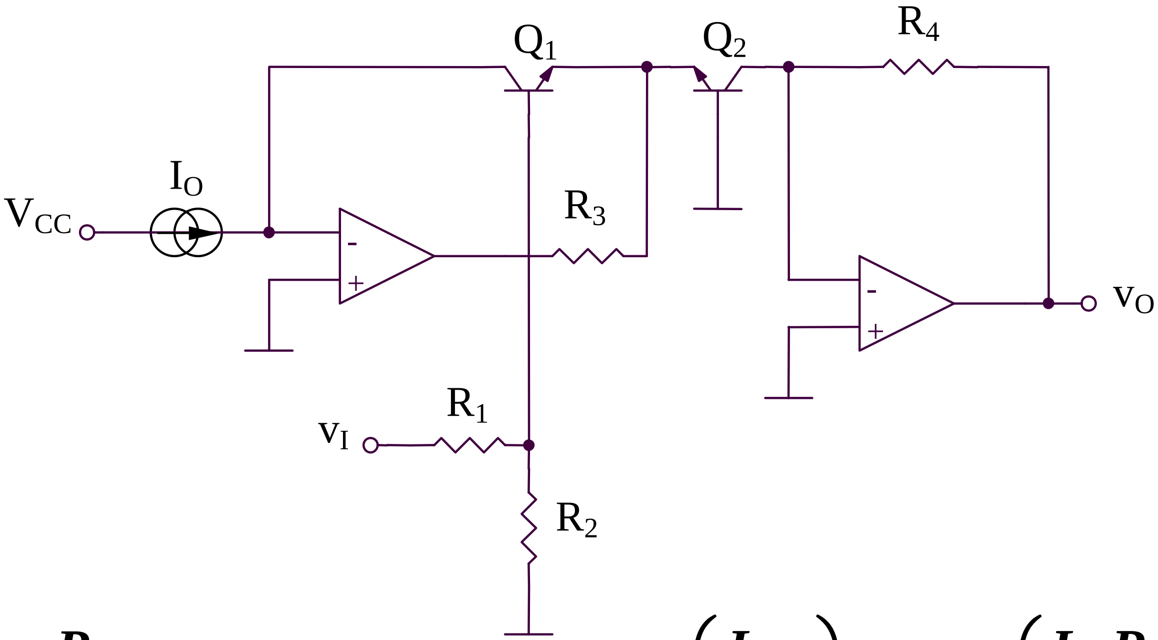
5.2.17. Exponential circuit (1)



$$v_I \frac{R_2}{R_1 + R_2} = v_{BE1} - v_{BE2} = V_{th} \ln\left(\frac{I_{C1}}{I_{C2}}\right) = V_{th} \ln\left(\frac{I_O R_3}{v_O}\right) \Rightarrow$$

$$\Rightarrow v_O = I_O R_3 e^{-\frac{v_I}{V_{th}} \frac{R_2}{R_1 + R_2}}$$

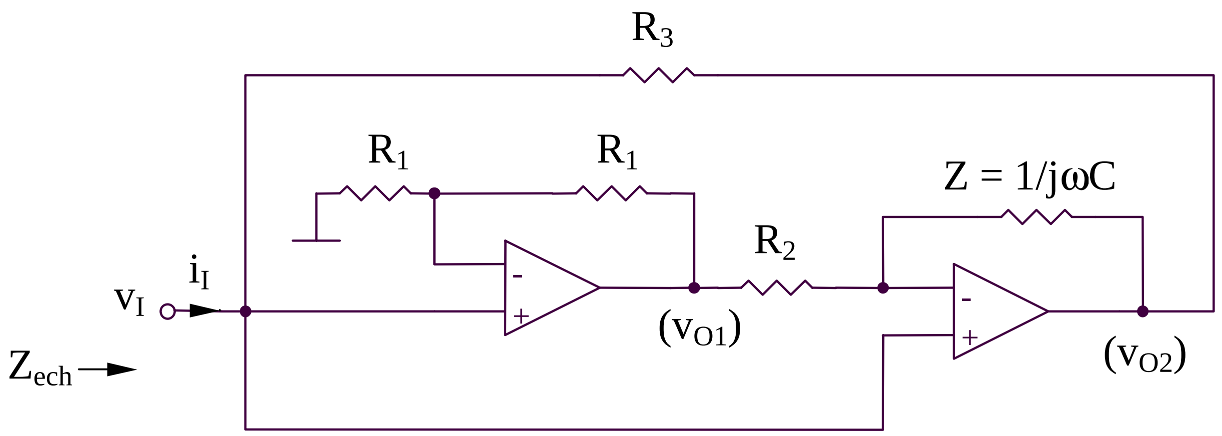
5.2.18. Exponential circuit (2)



$$v_I \frac{R_2}{R_1 + R_2} = v_{BE1} - v_{BE2} = V_{th} \ln\left(\frac{I_{C1}}{I_{C2}}\right) = V_{th} \ln\left(\frac{I_O R_4}{v_O}\right) \Rightarrow$$

$$\Rightarrow v_O = I_O R_4 e^{-\frac{v_I}{V_{th}} \frac{R_2}{R_1 + R_2}}$$

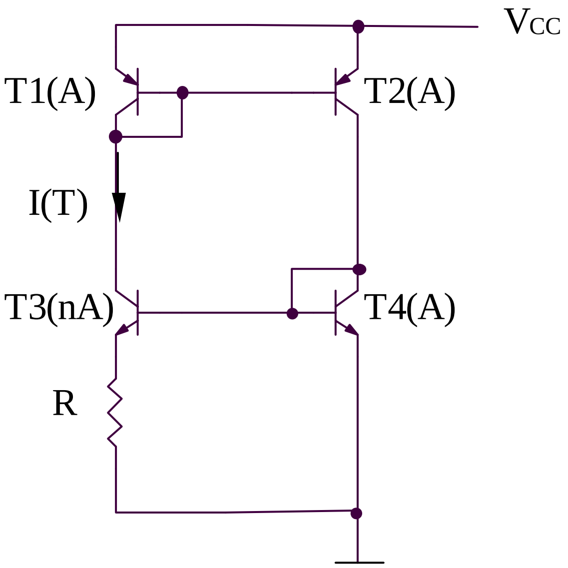
5.2.19. Inductance simulator



$$\left.\begin{aligned} v_{O2} &= v_I\left(1+\frac{Z}{R_2}\right)+v_{O1}\left(-\frac{Z}{R_2}\right) \\ v_{O1} &= 2v_I \end{aligned}\right\} \Rightarrow \left.\begin{aligned} v_{O2} &= v_I\left(1-\frac{Z}{R_2}\right) \\ i_I &= \frac{v_I - v_{O2}}{R_3} \end{aligned}\right\} \Rightarrow i_I = v_I\,\frac{Z}{R_2R_3} \Rightarrow$$

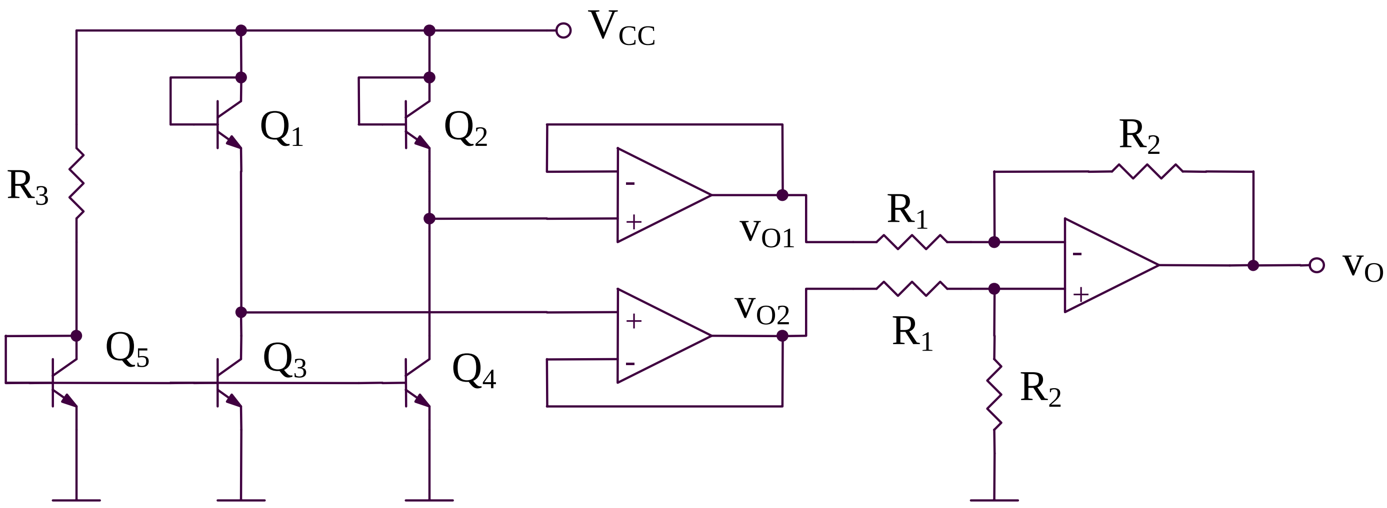
$$\Rightarrow Z_{ech} = \frac{v_I}{i_I} = \frac{R_2R_3}{Z} = j\omega\left(R_2R_3C\right) = j\omega L_{ech} \qquad L_{ech} = R_2R_3C$$

5.2.20. Temperature sensors



$$I(T) = \frac{V_{BE4} - V_{BE3}}{R} = \frac{V_{th}}{R} ln\left(\frac{I_{C4}}{I_{C3}}\frac{I_{S3}}{I_{S4}}\right) = \frac{V_{th}}{R} ln\, n$$

5.2.20. Temperature sensors

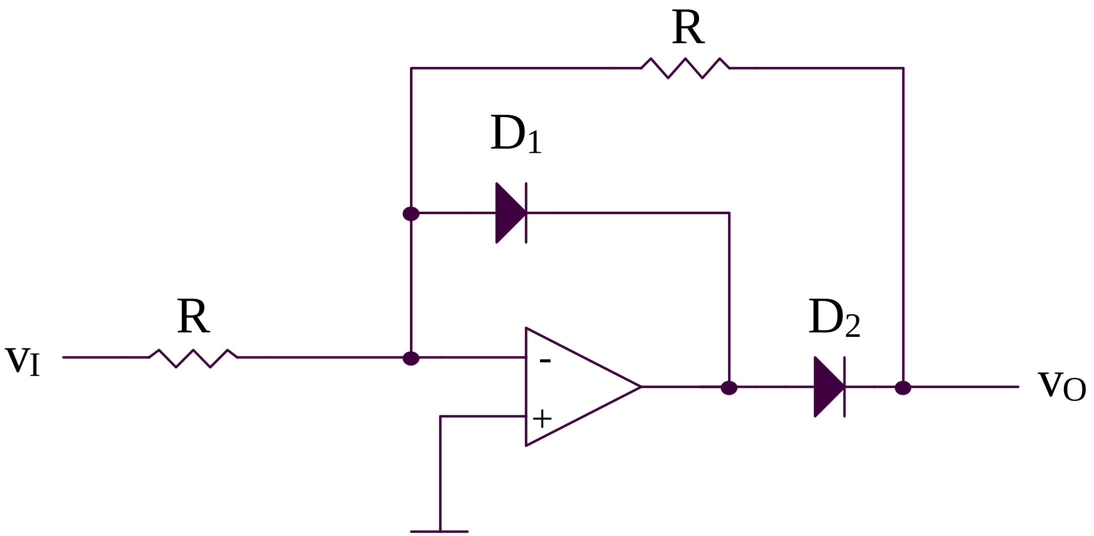


$$v_O = \frac{R_2}{R_1}(v_{O2} - v_{O1}) = \frac{R_2}{R_1}(v_{BE2} - v_{BE1}) = \frac{R_2}{R_1} V_{th} \ln\left(\frac{I_{C2}}{I_{C1}} \frac{I_{S1}}{I_{S2}}\right) \Rightarrow$$

$$\Rightarrow v_O = \frac{R_2}{R_1} V_{th} \ln\left(\frac{I_{C4}}{I_{C3}} \frac{I_{S1}}{I_{S2}}\right) = \frac{R_2}{R_1} V_{th} \ln\left(\frac{I_{S4}}{I_{S3}} \frac{I_{S1}}{I_{S2}}\right) = \frac{R_2}{R_1} V_{th} \ln\left(\frac{A_4}{A_3} \frac{A_1}{A_2}\right) = MT$$

$$M = \frac{R_2}{R_1} \frac{k}{q} \ln\left(\frac{A_4}{A_3} \frac{A_1}{A_2}\right)$$

5.2.21. Half-wave rectifier

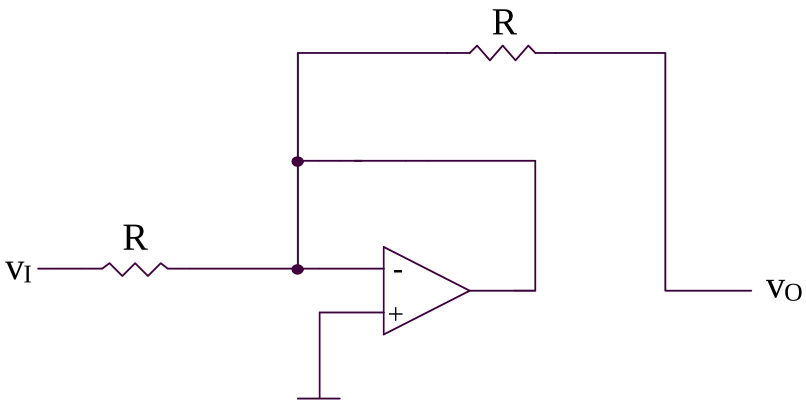


$$v_I > 0 \Rightarrow v_{O1} < 0 \Rightarrow D_1\ open, D_2\ blocked$$

$$v_I < 0 \Rightarrow v_{O1} > 0 \Rightarrow D_2\ open, D_1\ blocked$$

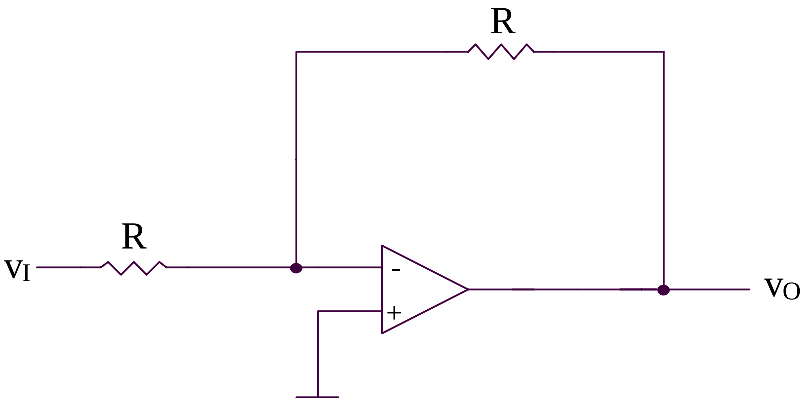
5.2.21. Half-wave rectifier

$v_I > 0$



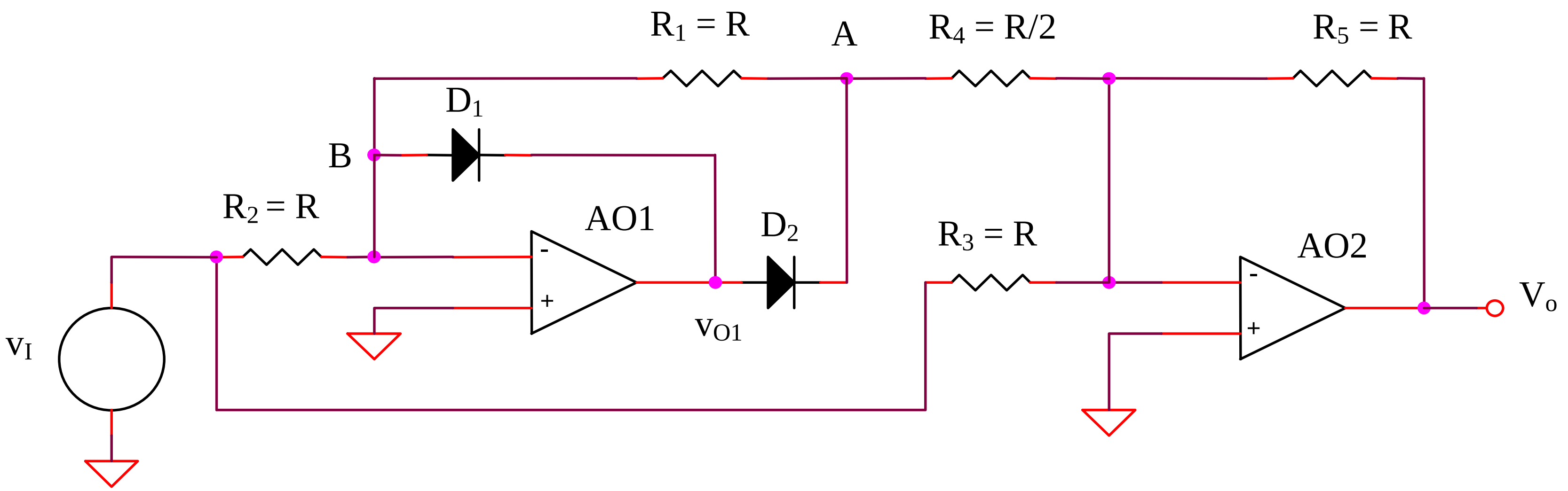
$$v_O = 0$$

$v_I < 0$



$$v_O = -\frac{R}{R} v_I = -v_I$$

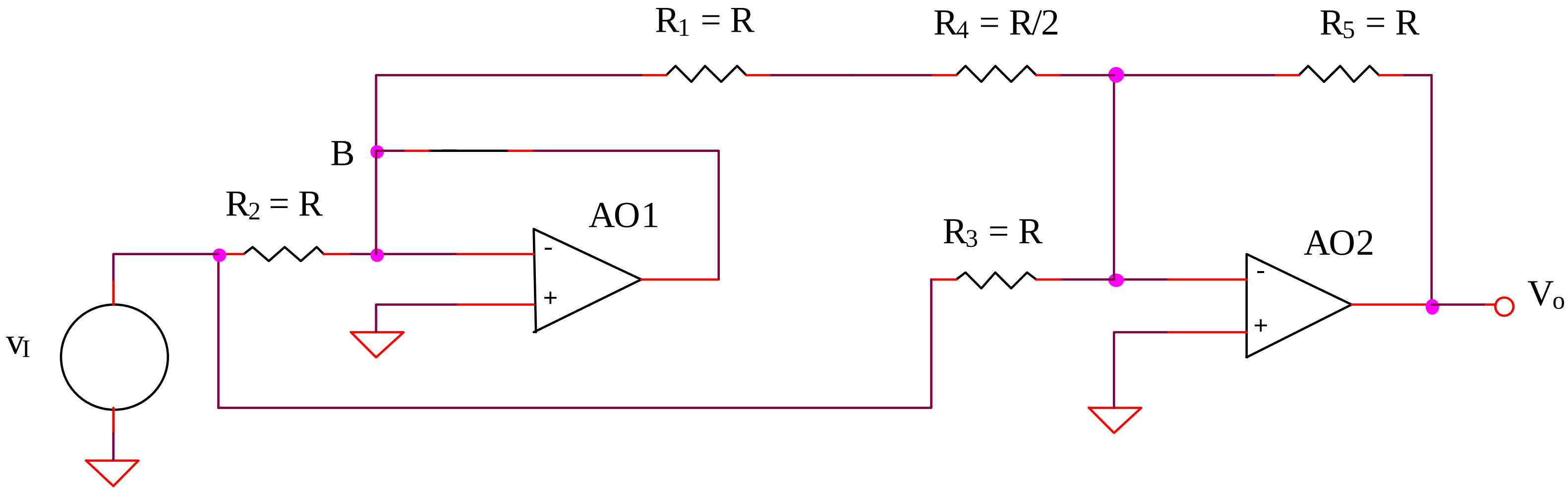
5.2.22. Full-wave rectifier (1)



$$v_I > 0 \Rightarrow v_{O1} < 0 \Rightarrow D_1 \; open, D_2 \; blocked$$

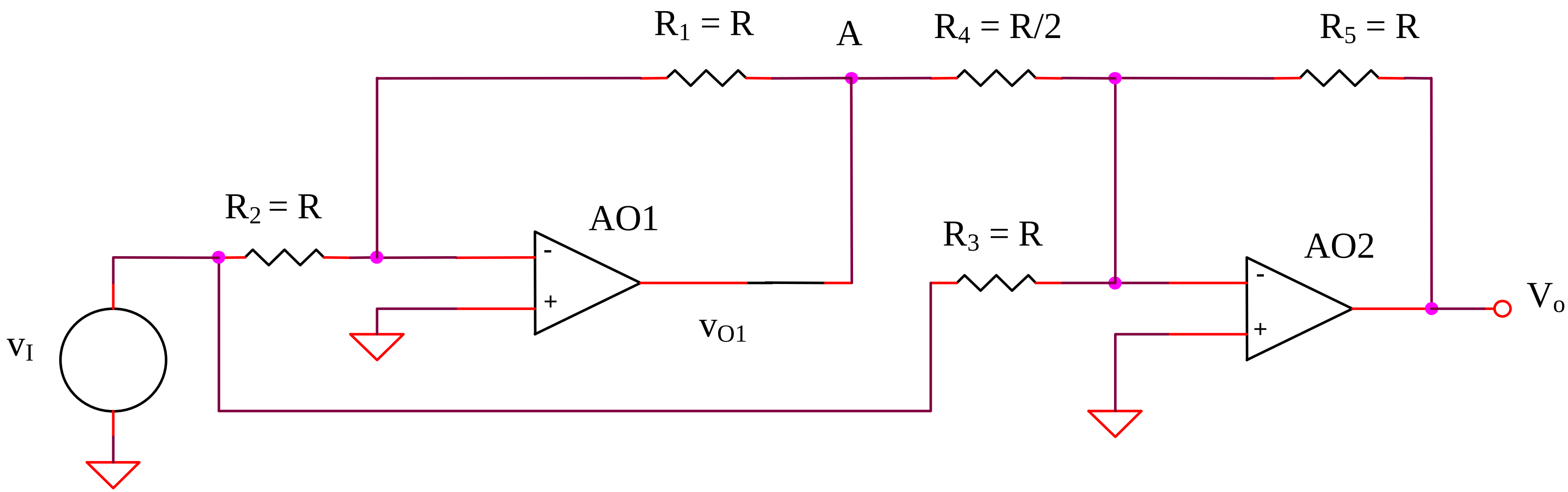
$$v_I < 0 \Rightarrow v_{O1} > 0 \Rightarrow D_2 \; open, D_1 \; blocked$$

5.2.22. Full-wave rectifier (1)



$$v_I > 0 \qquad V_B = 0 \qquad v_O = -\frac{R_5}{R_3} v_I = -v_I$$

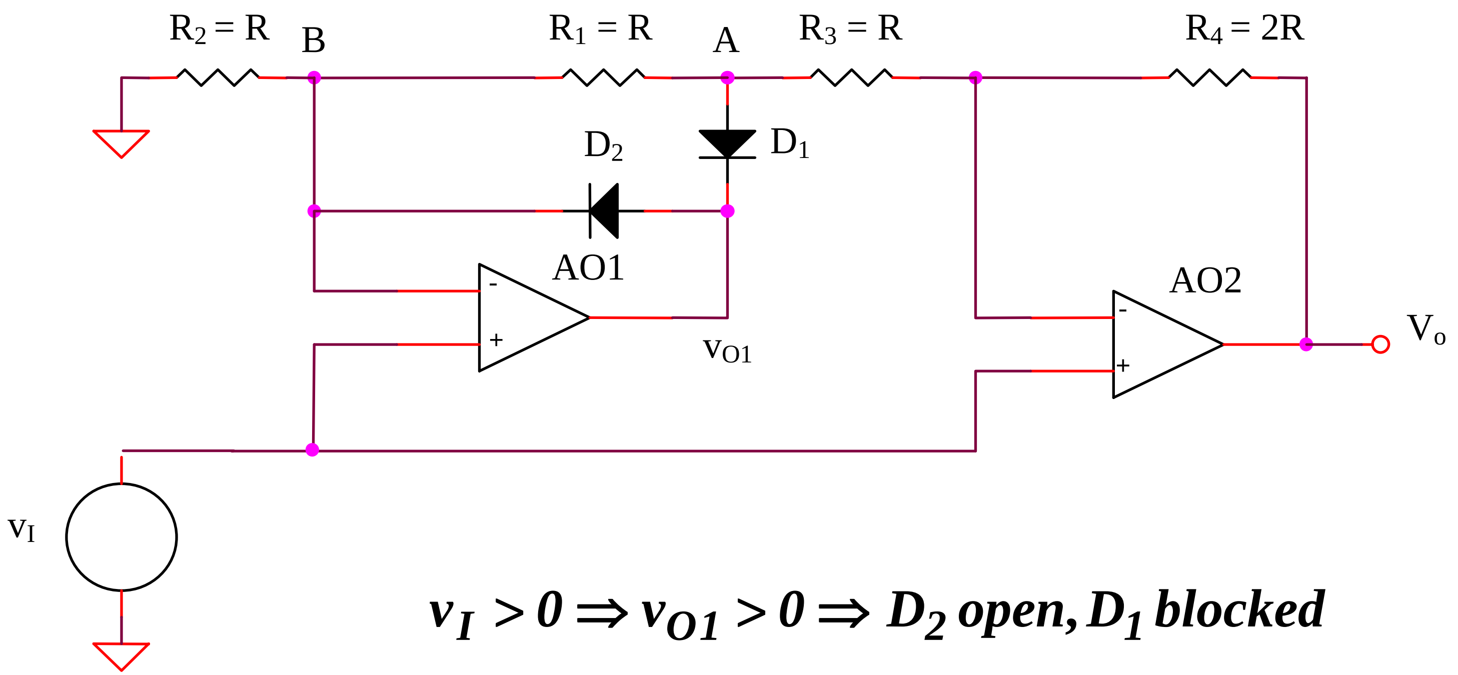
5.2.22. Full-wave rectifier (1)



$v_I < 0$ $\qquad V_A = -\frac{R_1}{R_2} v_I$ $\qquad v_O = -\frac{R_5}{R_4} V_A - \frac{R_5}{R_3} v_I = v_I$

Conclusion: $v_O = -\left| v_I \right|$

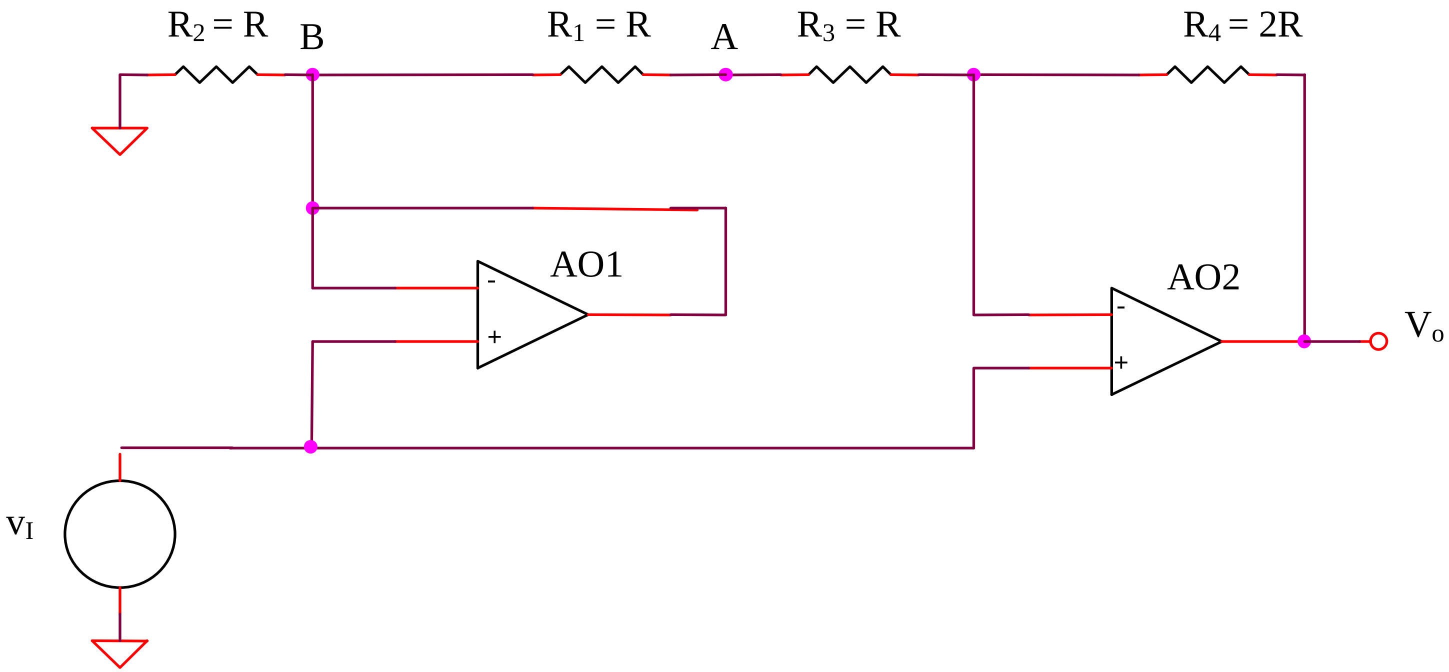
5.2.23. Full-wave rectifier (2)



$$v_I > 0 \Rightarrow v_{O1} > 0 \Rightarrow D_2 \text{ open}, D_1 \text{ blocked}$$

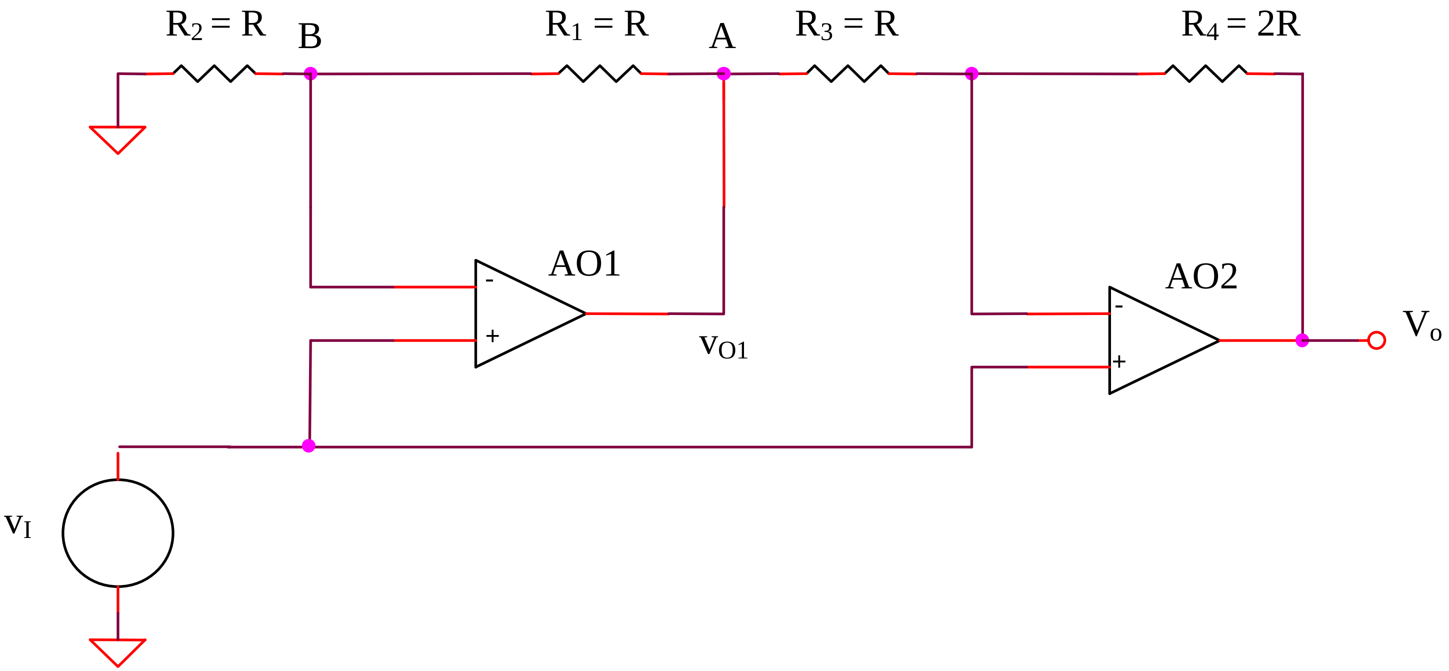
$$v_I < 0 \Rightarrow v_{O1} < 0 \Rightarrow D_1 \text{ open}, D_2 \text{ blocked}$$

5.2.23. Full-wave rectifier (2)



$v_I > 0$ $\quad$ $V_B = v_I$ $\quad$ $v_O = \left(1 + \frac{R_4}{R_1 + R_3}\right)v_I - \frac{R_4}{R_1 + R_3}V_B = v_I$

5.2.23. Full-wave rectifier (2)



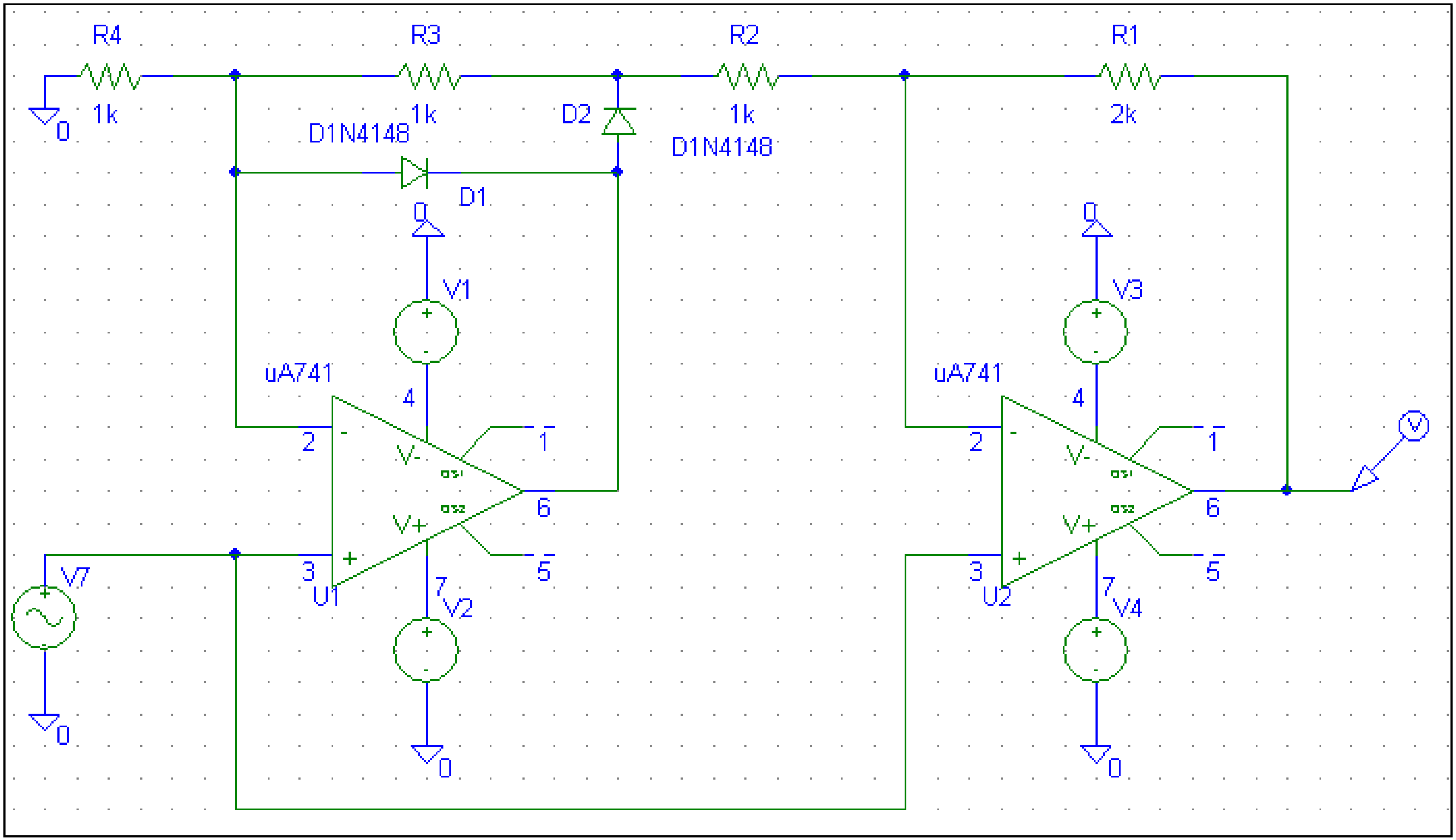
$v_I < 0$ $\qquad V_A = \left(1 + \frac{R_1}{R_2}\right) v_I = 2v_I \qquad v_O = \left(1 + \frac{R_4}{R_3}\right) v_I - \frac{R_4}{R_3} V_A = -v_I$

Conclusion: $v_O = |v_I|$

SIMULATIONS for full-wave rectifier (2)

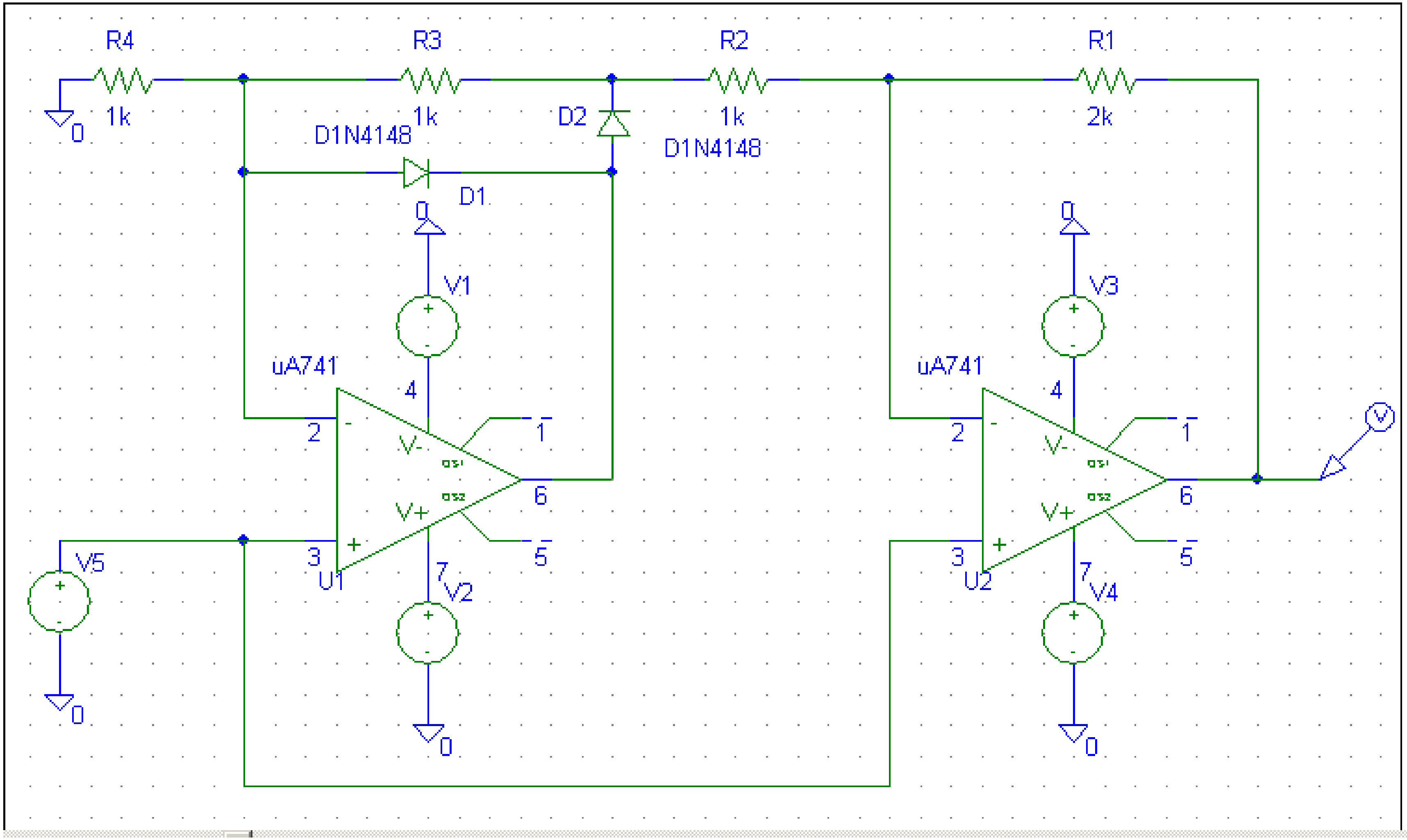
SIMULATIONS for full-wave rectifier (2)

SIM 5.9: V_O (t)

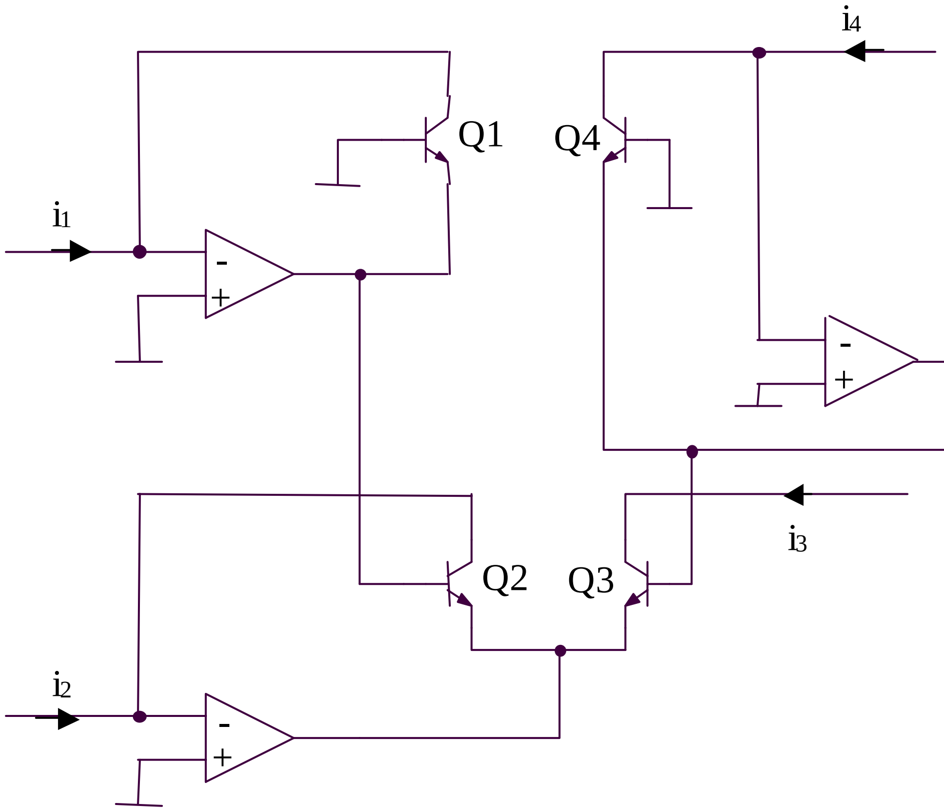


SIMULATIONS for full-wave rectifier (2)

SIM 5.10: V_O (V_5)



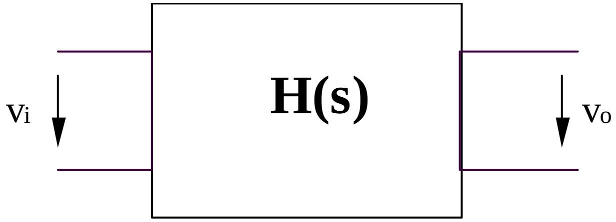
5.2.24. Multifunctional circuit



$$V_{BE1} + V_{BE2} = V_{BE3} + V_{BE4}$$

$$V_{th} \ln\frac{i_1}{I_S} + V_{th} \ln\frac{i_2}{I_S} = V_{th} \ln\frac{i_3}{I_S} + V_{th} \ln\frac{i_4}{I_S} \Rightarrow i_1 i_2 = i_3 i_4$$

5.2.25. Filters



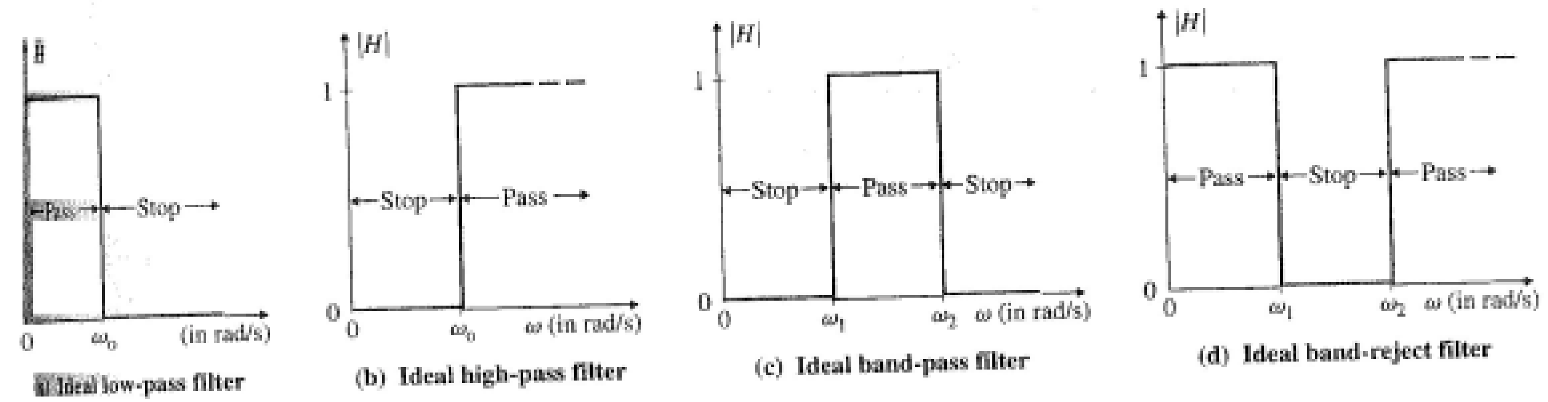
Classification

- **Low-pass filters**
- **High-pass filters**
- **Band-pass filters**
- **Band-reject filters**

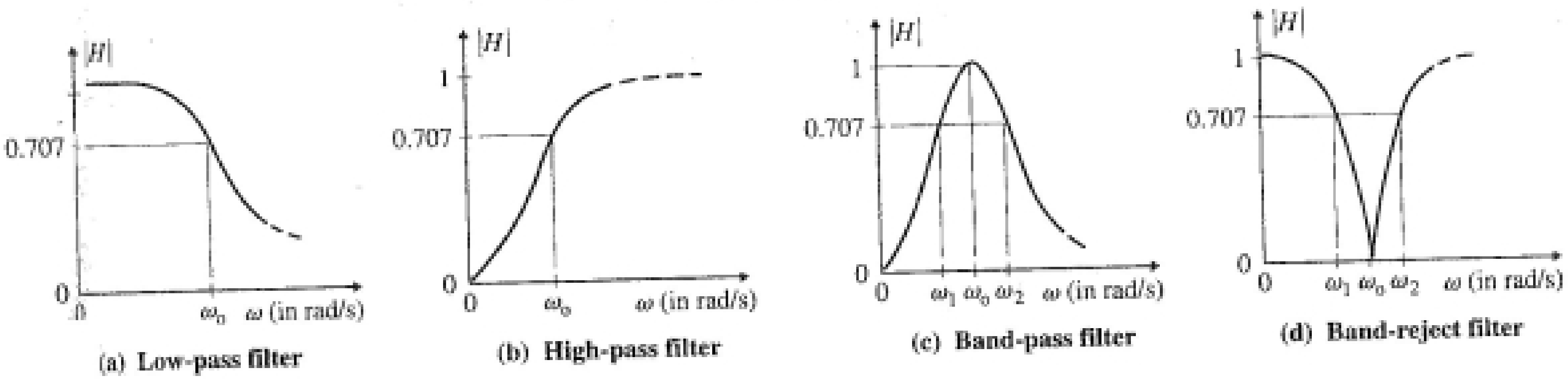
$$H(s)=\frac{a_m s^m+\ldots+a_2 s^2+a_1 s+a_0}{s^n+\ldots+b_2 s^2+b_1 s+b_0}, n \geq m$$

5.2.25. Filters

Ideal filter characteristics



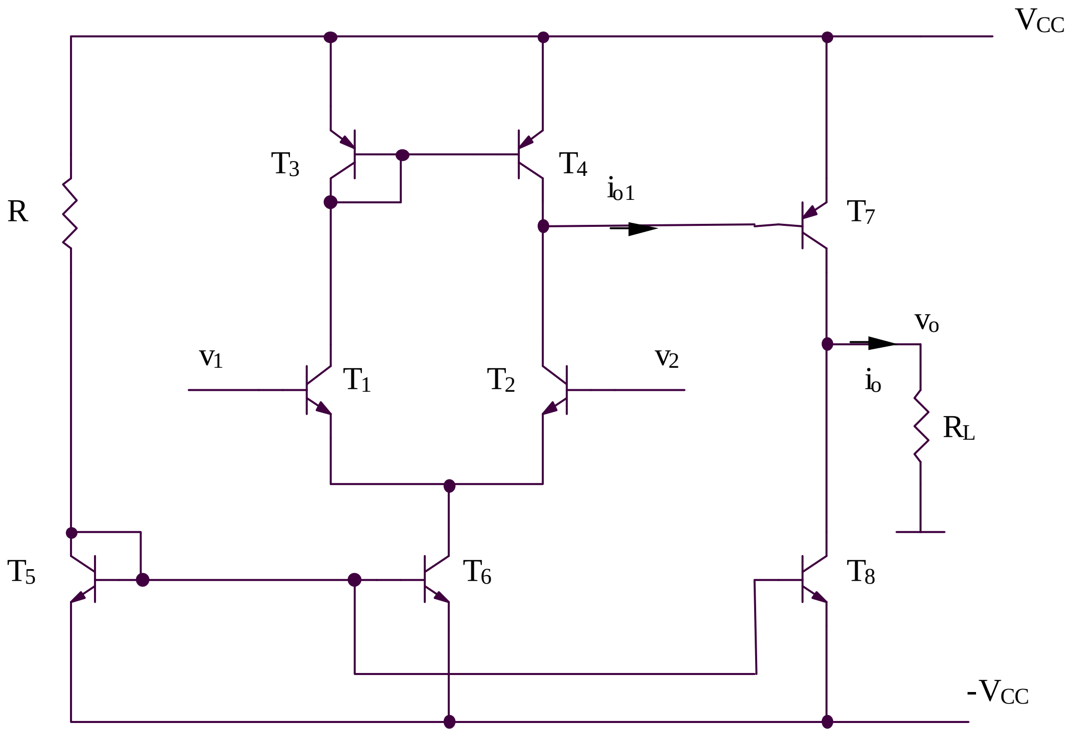
Realistic filter characteristics



5.3. Study of bipolar operational amplifier structures

5.3.1. Study of an operational amplifier with two stages

5.3.1. Study of an operational amplifier with two stages



Static regime

$$I_{C5,6,7,8} = \frac{2V_{CC} - V_{BE}}{R}$$

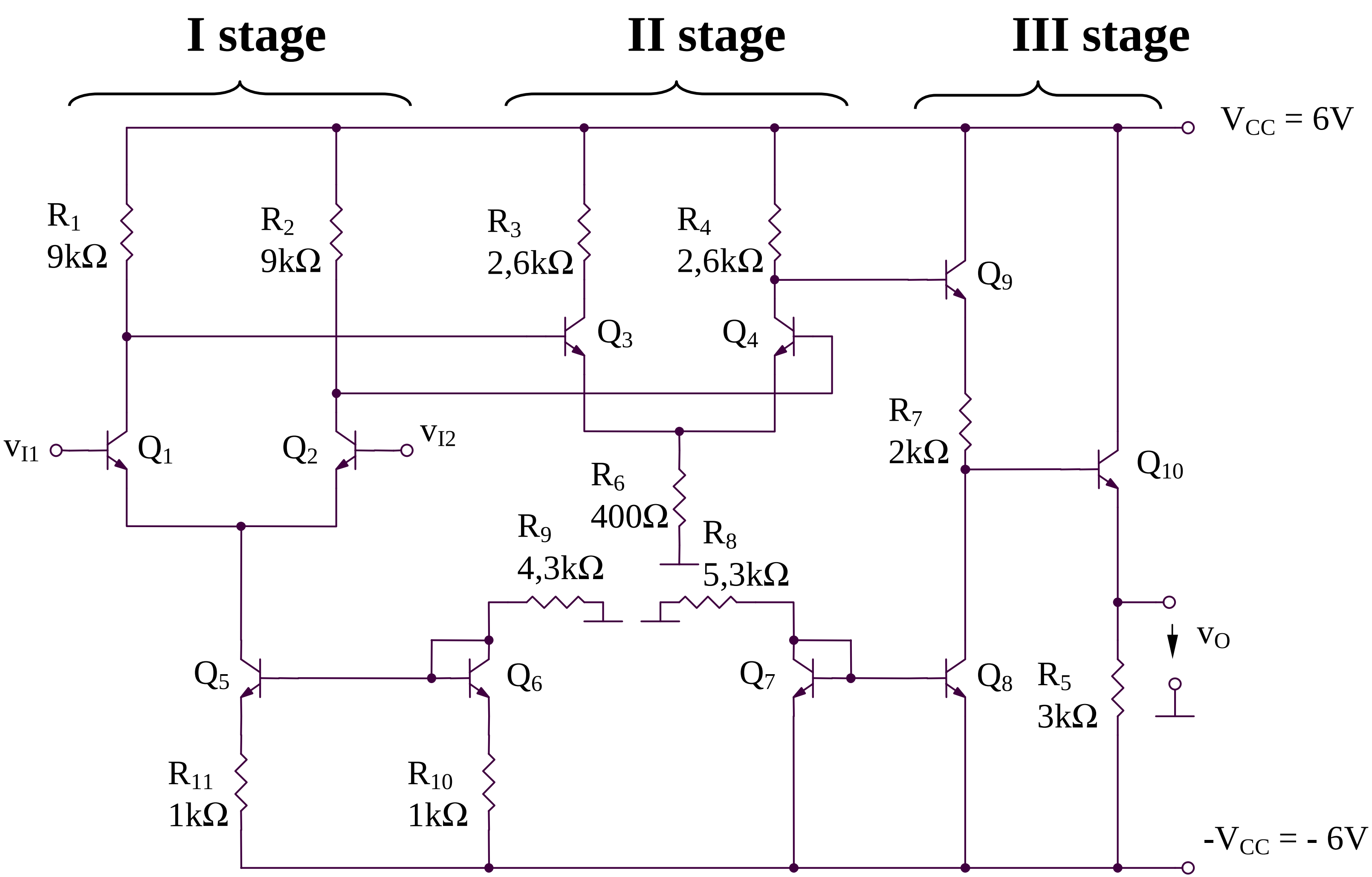
$$I_{C1,2,3,4} = \frac{I_{C5}}{2}$$

Dynamic regime

$$\left.\begin{aligned} i_{o1} &= g_{m1}(v_1 - v_2) \\ A_{dd} &= \frac{v_o}{v_1 - v_2} = \frac{i_o R_L}{v_1 - v_2} = \frac{\beta_7 i_{o1} R_L}{v_1 - v_2} \end{aligned}\right\} \Rightarrow A_{dd} = g_{m1}\beta_7 R_L$$

5.3.2. Study of an operational amplifier with three stages

5.3.2. Study of an operational amplifier with three stages



Static regime

$$I_{C6} = \frac{V_{CC} - V_{BE6}}{R_9 + R_{10}} = 1mA$$

$$I_{C5} = I_{C6}\frac{R_{10}}{R_{11}} = 1mA$$

$$I_{C1} = I_{C2} = \frac{I_{C5}}{2} = 0{,}5mA$$

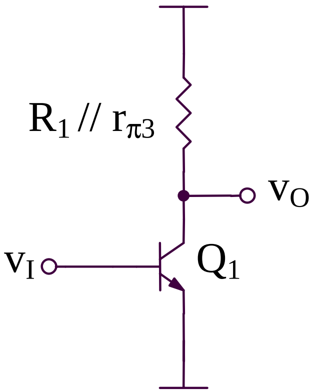
$$I_{C3} = I_{C4} = \frac{V_{CC} - R_2 I_{C2} - V_{BE3}}{2R_6} = 2mA$$

$$I_{C7} = I_{C8} = I_{C9} = \frac{V_{CC} - V_{BE7}}{R_8} = 1mA$$

$$I_{C10} = \frac{2V_{CC} - I_{C4}R_4 - I_{C9}R_7 - V_{BE9} - V_{BE10}}{R_5} \cong 1mA$$

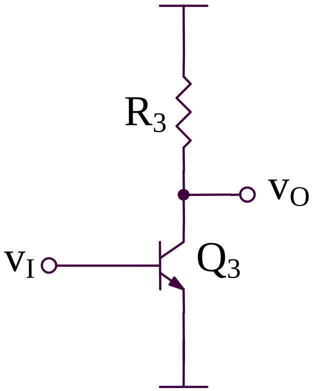
Dynamic regime

Gain of first stage



$$A_{dd\,I} = -g_{m1}\left(R_1 // r_{\pi 3} // r_{o1}\right)$$

Gain of second stage



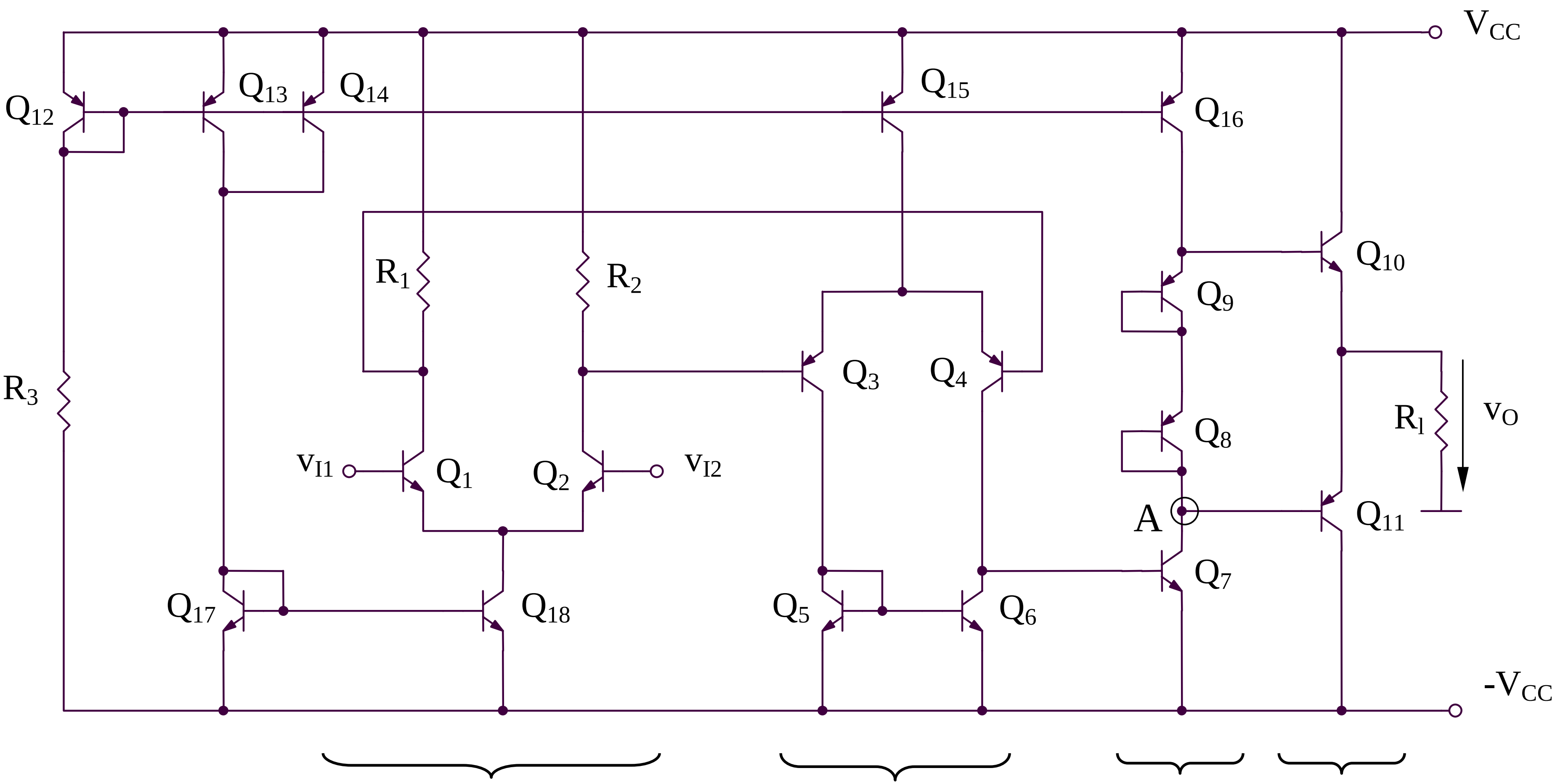
$$A_{dd\,II} \cong -g_{m3}\left(R_3 // r_{o3}\right)\frac{1}{2}$$

Gain of third stage

$$A_{dd\,III} \cong 1$$

5.3.3. Study of an operational amplifier with four stages

5.3.3. Study of an operational amplifier with four stages



I stage **II stage** **III stage** **IV stage**

Static regime

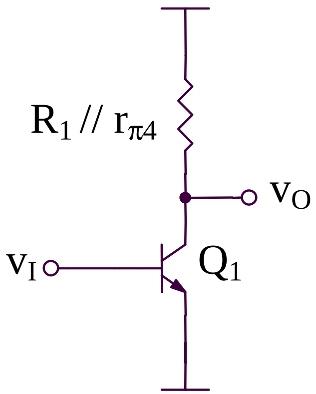
$$I_{C12} = \frac{2V_{CC} - V_{BE}}{R_3} = I_{C13} = I_{C14} = I_{C15} = I_{C16} = I_{C9} = I_{C8} = I_{C7} = I$$

$$I_{C17} = I_{C18} = 2I \qquad I_{C3} = I_{C4} = I_{C5} = I_{C6} = I/2 \qquad I_{C1} = I_{C2} = I$$

$$/V_{BE8}/ + /V_{BE9}/ = V_{BE10} + V_{BE11} \Rightarrow 2V_{th}\ln\frac{I}{I_S} = 2V_{th}\ln\frac{I_{C10}}{I_S} \Rightarrow I_{C10} = I_{C11} = I$$

Dynamic regime

Gain of first stage

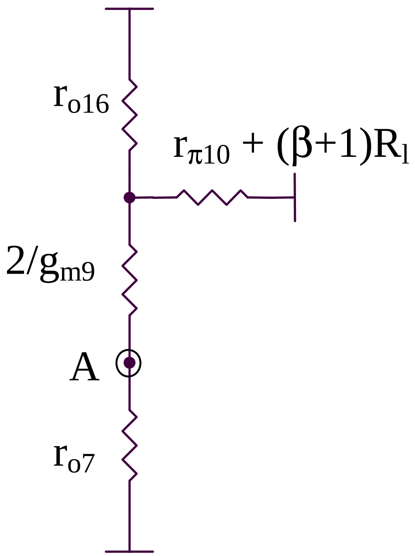


$$A_{dd\,I} = -g_{m1}\left(R_1 // r_{\pi4} // r_{o1}\right)$$

Gain of second stage

$$A_{dd\ II} = g_{m3}\left(r_{o6} \,//\, r_{o4} \,//\, r_{\pi 7}\right)$$

Gain of third stage



$$A_{dd\ III} = -g_{m7}\left(r_{o7} \,//\, r_{o16} \,//\, \beta R_l\right)$$

Gain of fourth stage

$$A_{IV} = \frac{\beta R_l}{r_{\pi 10} + \beta R_l} \cong 1$$

Differential mode input resistance

$$R_{id} = 2r_{\pi 1}$$

Maximal common-mode input range

$$V_{IC}^{\min} = V_{BE1} + V_{CE18sat}$$

$$V_{IC}^{\max} = V_{CC} - R_1 I_{C1} - V_{CE1sat} + V_{BE1}$$

Maximal output voltage range

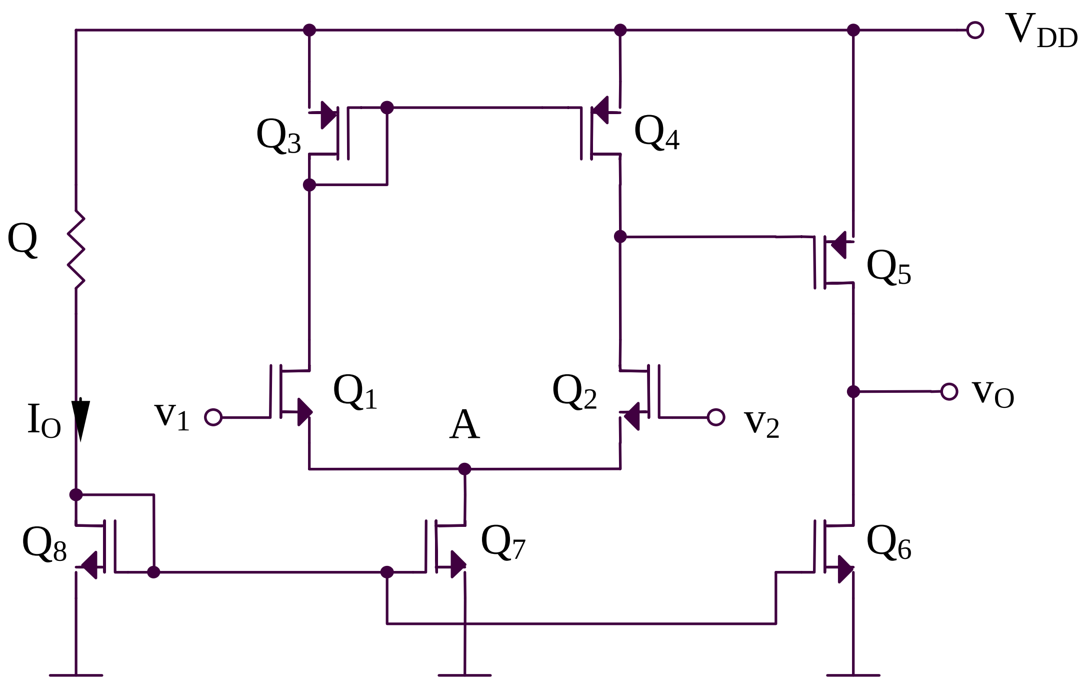
$$V_O^{\max} = \min\left(V_{CC} - /V_{CE16sat}/ - V_{BE10};\ I_{C16}\beta R_l\right)$$

$$V_O^{\min} = -V_{CC} + V_{CE7sat} + /V_{BE11}/$$

5.4. Study of CMOS operational amplifier structures

5.4.1. Study of an operational amplifier with two stages (1)

5.4.1. Study of an operational amplifier with two stages (1)



Static regime

$$\left.\begin{array}{l} RI_O + V_{GS8} = V_{DD} \\ I_O = \dfrac{K}{2}\left(V_{GS8} - V_T\right)^2 \end{array}\right\} \Rightarrow V_{DD} = V_{GS8} + \frac{RK}{2}\left(V_{GS8} - V_T\right)^2 \Rightarrow V_{GS8}\ \left(V_{GS8} > V_T\right)$$

$$\Rightarrow I_O = \frac{K}{2}\left(V_{GS8} - V_T\right)^2$$

$$I_{D5} = I_{D6} = I_{D7} = I_{D8} = I_0$$

$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = I_{D7} / 2 = I_O / 2$$

Dynamic regime

Gain of the circuit

$$A_{dd} = g_{m1}\left(r_{ds2} // r_{ds4}\right) g_{m5}\left(r_{ds5} // r_{ds6}\right)$$

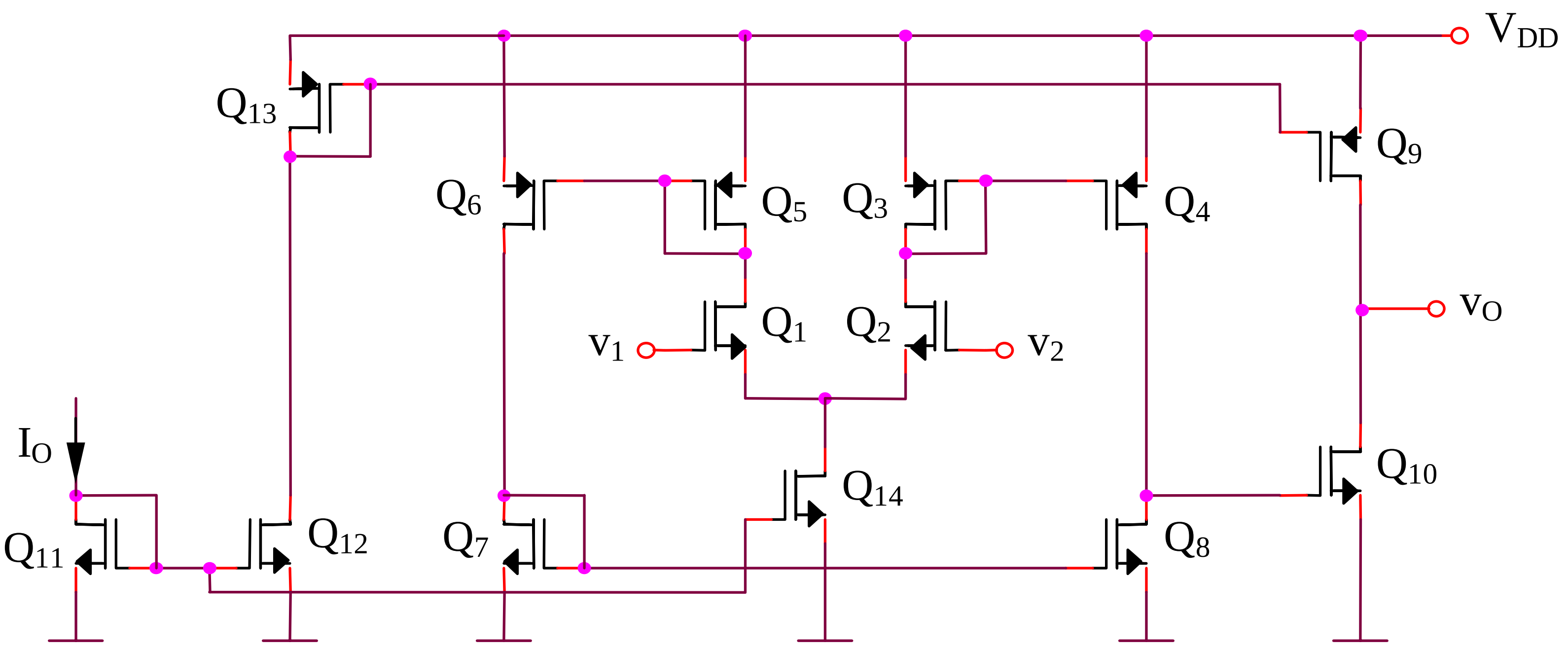
Maximum range of the common-mode input voltage

$$V_{IC}^{\max} = V_{DD} - V_{SG5} - V_{DS2sat} + V_{GS2} = V_{DD} - V_{SG5} + V_T = V_{DD} - \sqrt{\frac{2I_O}{K}}$$

$$V_{IC}^{\min} = V_{DS7sat} + V_{GS1} = V_{GS7} + V_{GS1} - V_T = V_T + \left(\sqrt{2} + 1\right)\sqrt{\frac{I_O}{K}}$$

5.4.2. Study of an operational amplifier with two stages (2)

5.4.2. Study of an operational amplifier with two stages (2)



Static regime

$$I_{D1} = \ldots = I_{D8} = \frac{I_O}{2}$$

$$I_{D9} = \ldots = I_{D14} = I_O$$

Dynamic regime

Gain of the circuit

$$A_{dd} = g_{m1}\left(r_{ds4} // r_{ds8}\right)g_{m10}\left(r_{ds10} // r_{ds9}\right) = \frac{1}{4} g_{m1} g_{m10} r_{ds4} r_{ds10}$$

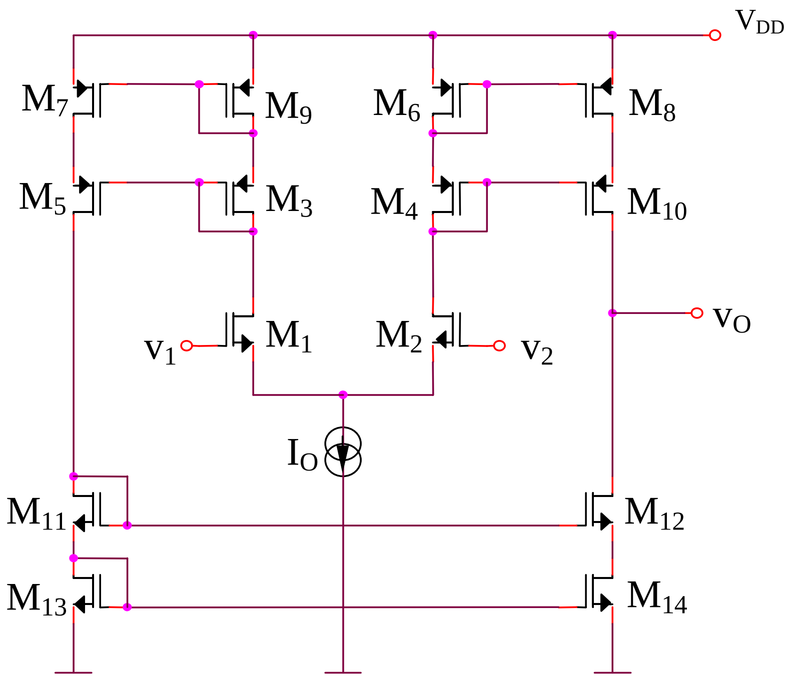
Maximum range of the common-mode input voltage

$$V_{IC}^{\max} = V_{DD} - V_{SG3} - V_{DS2sat} + V_{GS2} = V_{DD} - \sqrt{\frac{I_O}{K}}$$

$$V_{IC}^{\min} = V_{GS2} + V_{DS14sat} = \left(\sqrt{2} + 1\right)\sqrt{\frac{I_O}{K}} + V_T$$

5.4.3. Study of a cascode operational amplifier with one stage (1)

5.4.3. Study of a cascode operational amplifier with one stage (1)



Static regime

$$I_{D1} = I_{D2} = \ldots = I_{D14} = I_O / 2$$

Dynamic regime

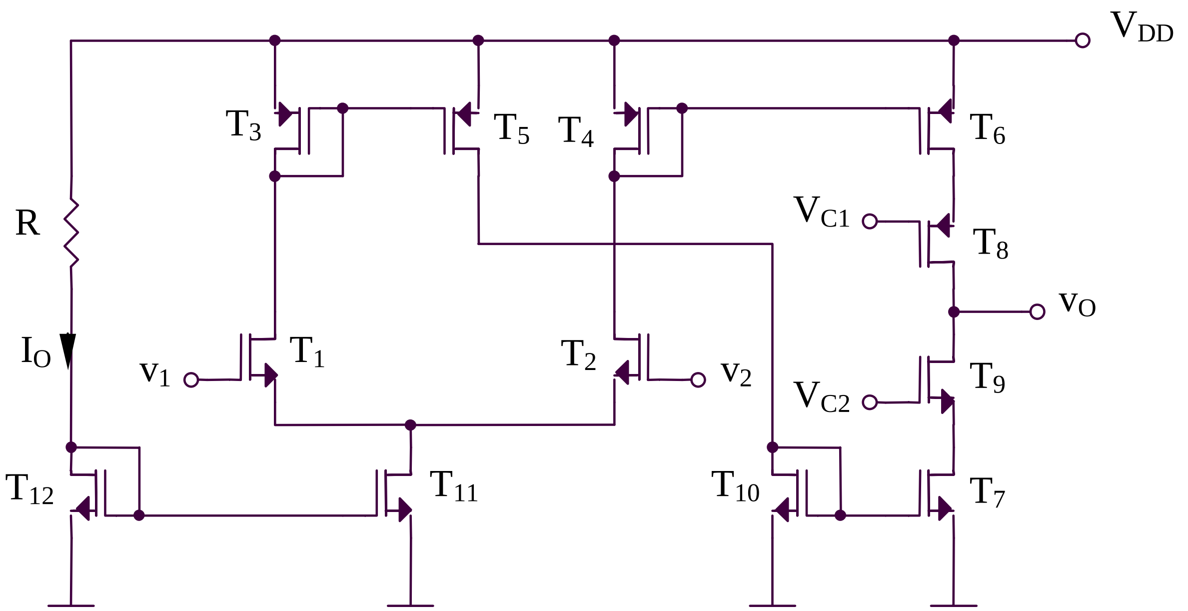
$$R_O = g_{m10} r_{ds10}^2 \,//\, g_{m12} r_{ds12}^2 = \frac{1}{2} g_{m10} r_{ds10}^2$$

$$v_O = g_{m1}(v_2 - v_1) R_O = \frac{1}{2} g_{m1} g_{m10} r_{ds10}^2 (v_2 - v_1)$$

$$a = \frac{1}{2} g_{m1} g_{m10} r_{ds10}^2$$

5.4.4. Study of a cascode operational amplifier with one stage (2)

5.4.4. Study of a cascode operational amplifier with one stage (2)



Static regime

$$I_{D1} = I_{D2} = \ldots = I_{D10} = I_{D11}/2 = I_{D12}/2 = I_O/2$$

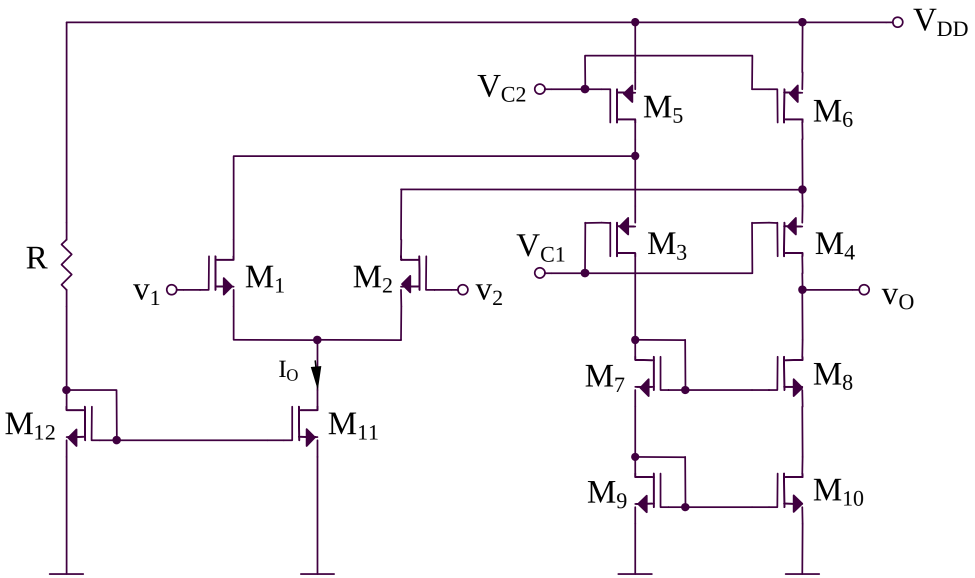
Dynamic regime

$$a = g_{m1} R_O$$

$$R_O = g_{m9} r_{ds9} r_{ds7} \,//\, g_{m8} r_{ds8} r_{ds6} = \frac{1}{2} g_{m9} r_{ds9}^2$$

5.4.5. Folded cascod operational amplifier (1)

5.4.5. Folded cascod operational amplifier (1)



Static regime

$$I_{D1} = I_{D2} = I_O / 2$$

$$I_{D11} = I_{D12} = I_O$$

$$I_{D5} = I_{D6} = \frac{K}{2}(V_{DD} - V_{C2} - V_T)^2$$

$$I_{D3} = I_{D4} = I_{D7} = \ldots$$

$$\ldots = I_{D10} = I_{D6} - I_{D2}$$

Dynamic regime

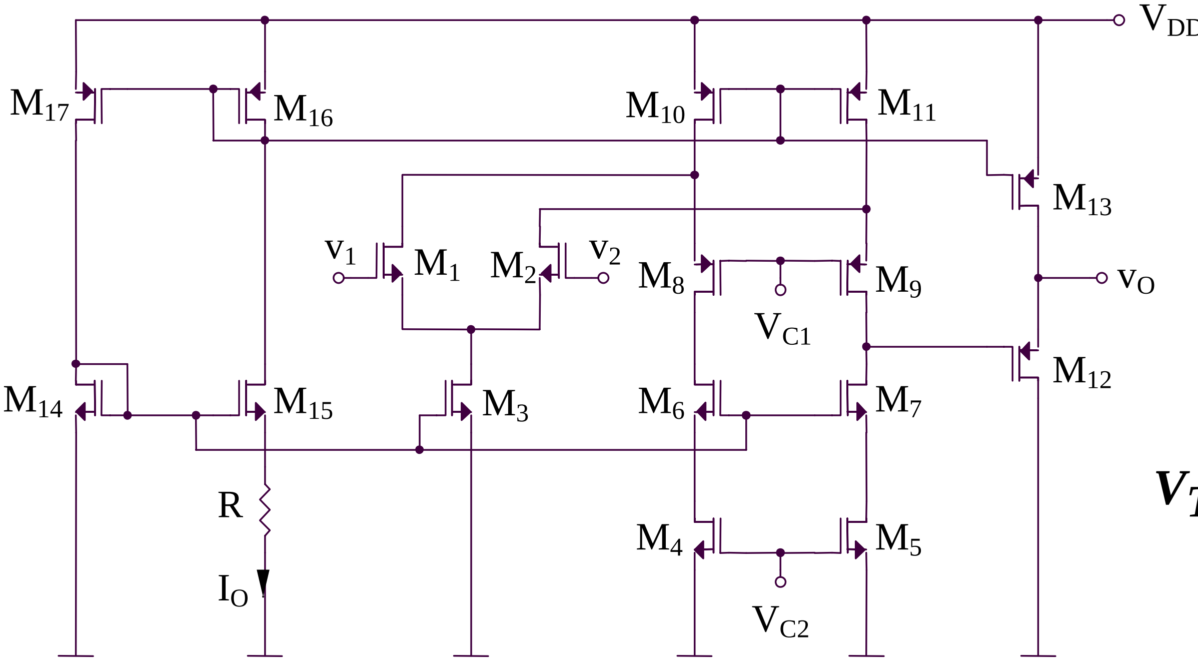
$$i_{D4} - i_{D8} = i_{D4} - i_{D3} = (I_{D6} - i_{D2}) - (I_{D5} - i_{D1}) = i_{D1} - i_{D2}$$

$$a = g_{m1} R_O$$

$$R_O = r_{ds8} g_{m8} r_{ds10} // [r_{ds4} g_{m4} (r_{ds6} // r_{ds2})]$$

5.4.6. Folded cascod operational amplifier (2)

5.4.6. Folded cascod operational amplifier (2)



Static regime

$$V_{C2} \rightarrow I_{D4} = I_{D5} = I_O / 2$$

$$K_{15} = 4K_{14} = 4K$$

$$V_{GS14} = V_{GS15} + I_O R$$

$$V_T + \sqrt{\frac{2I_O}{K}} = V_T + \sqrt{\frac{2I_O}{4K}} + I_O R$$

$$I_O = \frac{1}{2KR^2}$$

$$I_{D1} = I_{D2} = I_{D4} = \ldots = I_{D9} = \frac{I_O}{2}$$

$$I_{D3} = I_O = I_{D10} = \ldots = I_{D17}$$

Dynamic regime

$$i_{D9} - i_{D7} = i_{D9} - i_{D8} = (I_{D11} - i_{D2}) - (I_{D10} - i_{D1}) = i_{D1} - i_{D2}$$

$$a_1 = g_{m1} R_O$$

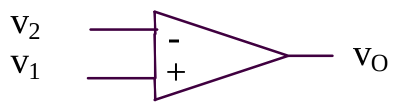
$$a_1 = g_{m1}\{r_{ds7} g_{m7} r_{ds5} // [r_{ds9} g_{m9}(r_{ds11} // r_{ds2})]\}$$

$$a_2 \cong 1$$

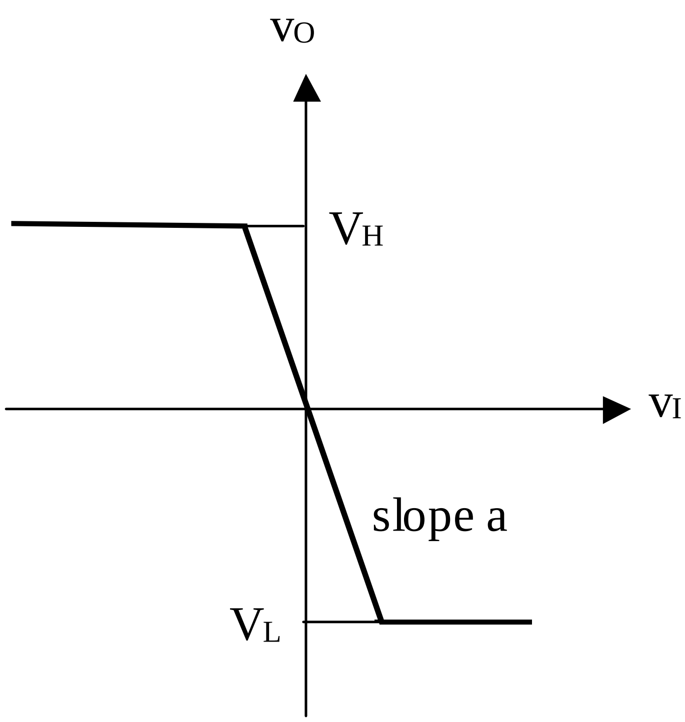
5.5. Comparators

5.5.1. Simple comparator

5.5.1. Simple comparator

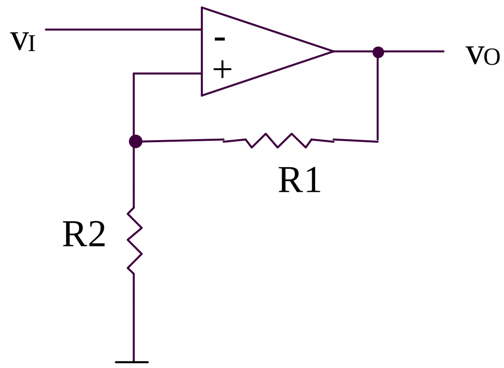


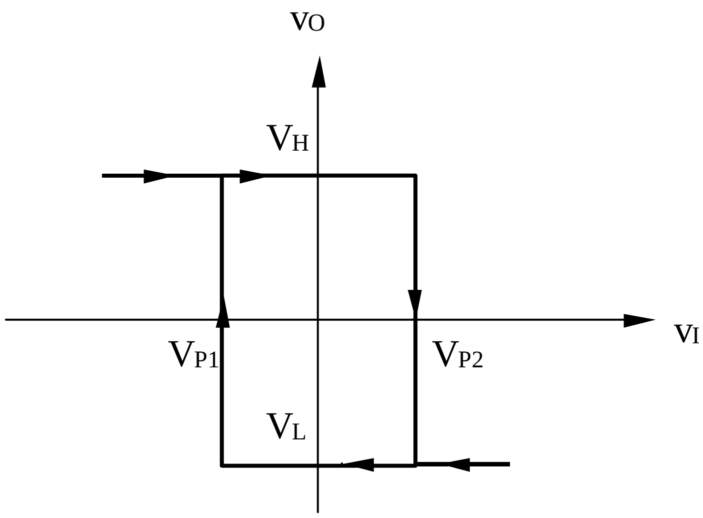
$$v_1 > v_2 \Rightarrow v_O = V_H$$
$$v_1 < v_2 \Rightarrow v_O = V_L$$



5.5.2. Comparator with histerezis

5.5.2. Comparator with histerezis





$$V_{P1} = V_H \frac{R_2}{R_1 + R_2}$$

$$V_{P2} = V_L \frac{R_2}{R_1 + R_2}$$