Operational Amplifiers

I. The Ideal Operational Amplifier (OpAmp)

1. Introduction

The operational amplifier is an integrated circuit with a balanced input. These are the most widely used analog integrated circuits because of their universality, simplicity and performance.

The operational amplifier (OpAmp) now benefits from such performance that the actual component is very close to its idealized characteristics. This is the reason why we will only study the perfect operational amplifier for which the "defects" of the component are ignored.

Symbol of the OpAmp:

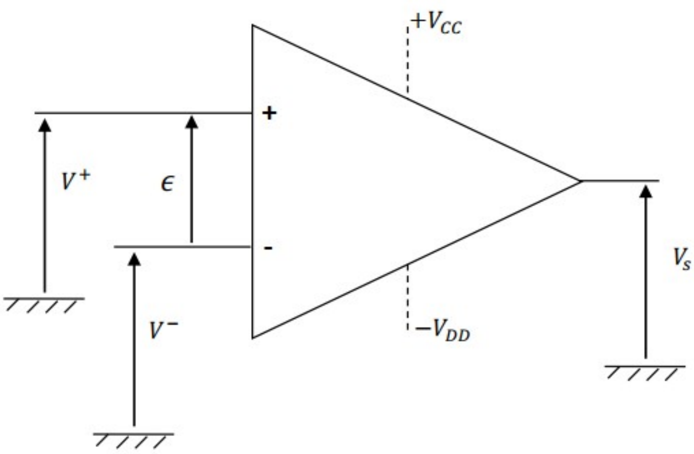


Figure 1: OpAmp

- Dual power supply $+V_{CC}/-V_{DD}$ (from 3 to 50 V). Generally, the power is symmetrical ($V_{CC}=V_{DD}$)
- 2 inputs:
  - ✔ one non inverting input marked +, and
  - ✔ one inverting input marked –,
- Differential input voltage: $\varepsilon=V^+-V^-$

- The output delivering the voltage V_S
- Amplification coefficient: A_d such that $V_S = A_d . \varepsilon$.

2. Characteristics of the perfect OpAmp

a. Transfer characteristic: $v_s = f(v_e)$

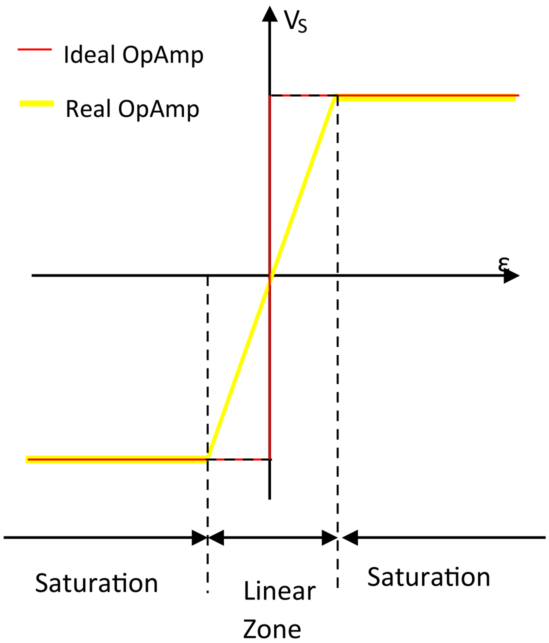


Figure 2: Transfer Characteristics

There are 2 zones:

- <u>Linear domain</u>: $v_s = A_d . \varepsilon$. The differential amplification, A_d is very large (>105) so tending towards $+\infty$. In this case, the OpAmp is said to be "ideal".
- <u>Saturation zones</u>: $v_s = cst = \pm V_{sat}$ according to the sign of ε. (The saturation voltages are very close to the supply voltage)

b. Impedance and input currents

The impedances of both inputs are very high (∞): the input currents are therefore zero: $i^+ = i^- = 0$

c. Output impedance

The output impedance of the OpAmp is zero: the voltage v_s is independent of the output current i_s.

II. Implementation of the operational amplifier

1. Stability study

a. Concept of feedback

Looping the output on an input is called feedback.

It is indeed difficult to control the output voltage because the A_d amplification is very important and a very low value of the input voltage is sufficient to kill the OpAmp. To remedy this, we take a fraction of the output voltage and subtract it from the input voltage in order to obtain a difference close to 0. In this way, we will be able to work in the linear domain.

b. Functional representation and stability study

Graphical elements (addition, subtraction and multiplication by a constant) can be used to achieve functional representation of schematics (Figure 3). We then obtain the functional diagram, also called "block diagram".

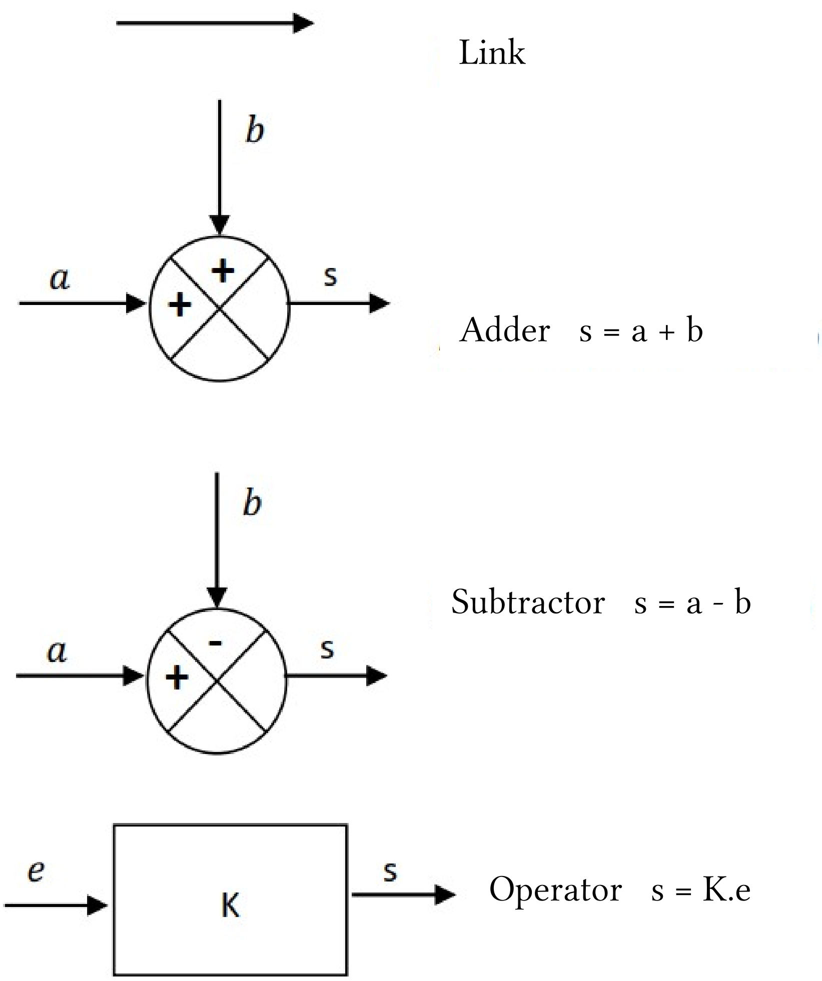
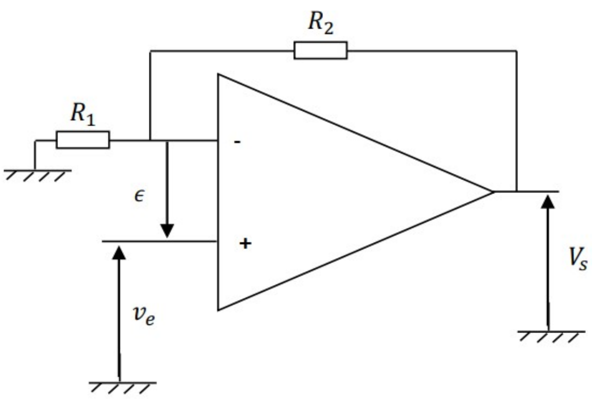
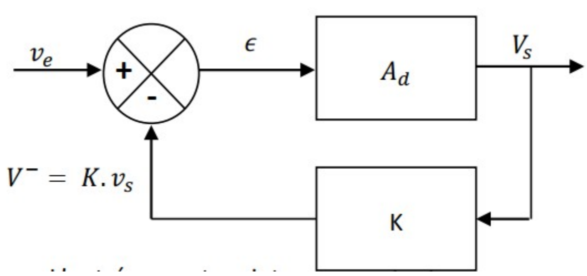


Figure 3: Graphical symbols used for a functional representation

$$v_e = Cst$$



Functional diagram



The input v_e is maintained constant

- If $v_s \nearrow$, $V^- \nearrow$, $\varepsilon \searrow$ then $V_S \searrow$

  => there is compensation

- If $v_s \searrow$, $V^- \searrow$, $\varepsilon \nearrow$ then $V_S \nearrow$

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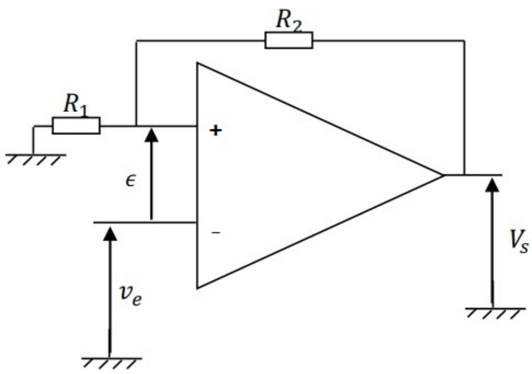
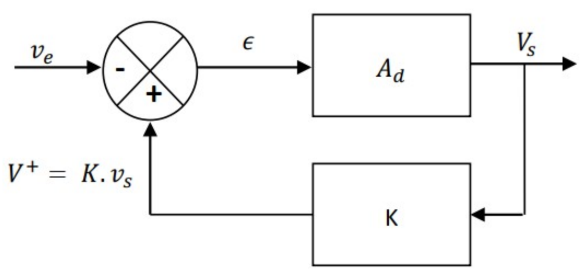


Functional diagram



The input v_e is maintained constant

- If $v_s \nearrow$, $V^+ \nearrow$, $\varepsilon \nearrow$ then $V_S \nearrow$

  => there is no compensation

- If $v_s \searrow$, $V^- \searrow$, $\varepsilon \searrow$ then $V_S \searrow$

  => there is no compensation

2. Conclusion: Mode of study of OpAmp circuits

To know how the OpAmp works, just observe the circuit and take into account the feed-back:

- If the feedback is on the inverting input (negative feedback), the OpAmp works linearly, so $\varepsilon = 0$.

- If the feedback is on the non-inverting input (positive feedback) or if there is no feedback, the OpAmp saturates and $v_s = \pm V_{sat}$ according to the sign ε.

III. Linear applications of perfect operational amplifiers

1. Follower circuit

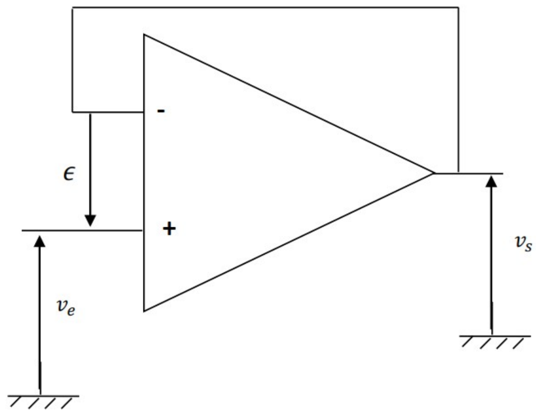
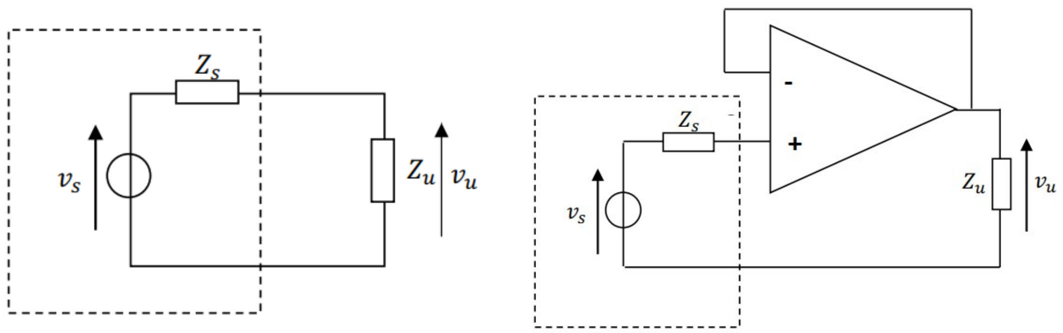


Figure 4: Follower circuit

The circuit has negative feedback. The OpAmp therefore operates in linear mode and we have ε = 0, i.e.: $v^+ = v^-$.

Now, here we have: $\begin{cases} v^+ = v_e \\ v^- = v_s \end{cases}$ => $\boxed{v_s = v_e}$

<u>Interest of such an arrangement</u> : Consider the 2 editings below:



In the editing on the left (assembly without OpAmp), the formula of the voltage divider bridge gives us:

$$v_u = \frac{Z_u}{Z_u + Z_s} . v_s$$

We therefore get only a fraction of the output voltage of the upstream stage.

On the other hand, in the editing on the right, where a follower circuit has been inserted between the output of the upstream stage and the load impedance Z_u, we obtain:

$$v_u = v_s$$

2. Amplifier editing

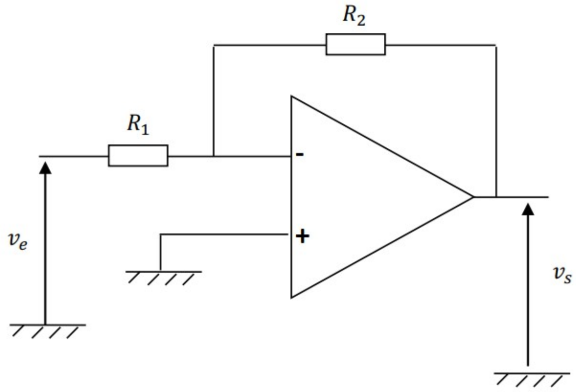


Figure 5: Amplifier editing

The editing has negative feedback. The OpAmp therefore operates in linear mode and we have ε = 0, i.e. : $v^+ = v^-$.

Here we have: $\begin{cases} v^+ = 0 \\ v^- = \dfrac{\dfrac{v_e}{R_1} + \dfrac{v_s}{R_2}}{\dfrac{1}{R_1} + \dfrac{1}{R_2}} \end{cases}$ (Millman's theorem). We thus obtain: $\boxed{v_s = -\dfrac{R_2}{R_1} . v_e}$

3. Difference amplifier (subtractor editing)

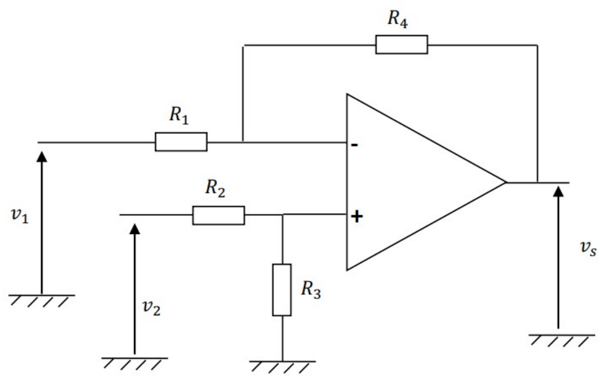


Figure 6: subtractor editing

It is shown that: $v_s = \dfrac{R_1 + R_4}{R_2 + R_3} . \dfrac{R_3}{R_1} . V_2 - \dfrac{R_4}{R_1} . v_1$

Note: If $R_1 = R_2$ and $R_3 = R_4$, we obtain: $\boxed{v_s = \dfrac{R_4}{R_1} . (v_2 - v_1)}$

4. Summator editing

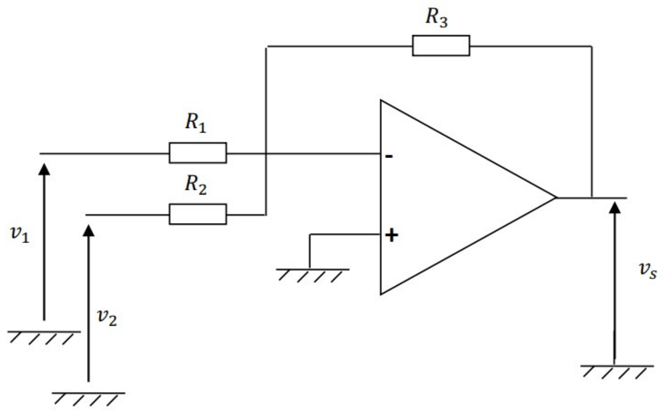
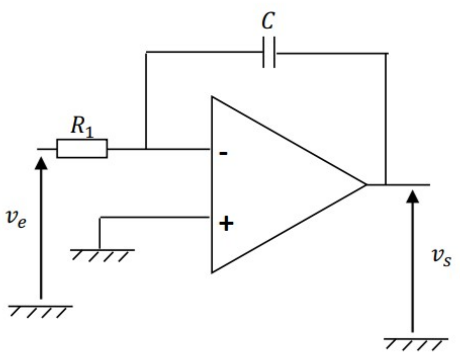


Figure 7: Adder editing

It is shown that: $\boxed{v_s = -R_3\left(\frac{v_1}{R_1} + \frac{v_2}{R_2}\right)}$

5. Integrator and derivator editings



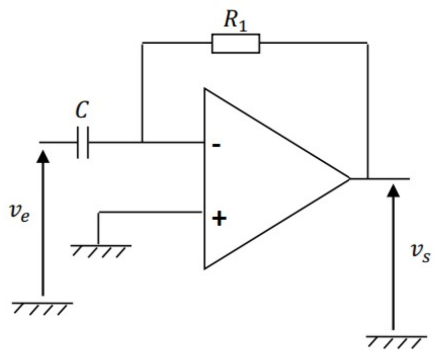


Figure 8: Integrator *Derivator*

These circuits have negative feedback. The OpAmps therefore operate in linear mode and we have:

ε = 0, i.e. : $v^+ = v^-$.

Moreover, they are ideal, we have: $i^+ = i^- = 0$.

The current i in C is expressed as follows:

$i = C.\frac{dv_c}{dt}$ and we have $v_c = -v_s$

=> $\boxed{v_s(t) = -\frac{1}{r.C}.\int v_e(t)\,dt}$

The current i in C is expressed as follows:

$i = C.\frac{dv_c}{dt} = -\frac{v_s}{R}$ and we have $v_c = v_e$

=> $\boxed{v_s(t) = -r.C.\frac{dv_e}{dt}}$

IV. Nonlinear applications of perfect operational amplifiers

1. Voltage comparator

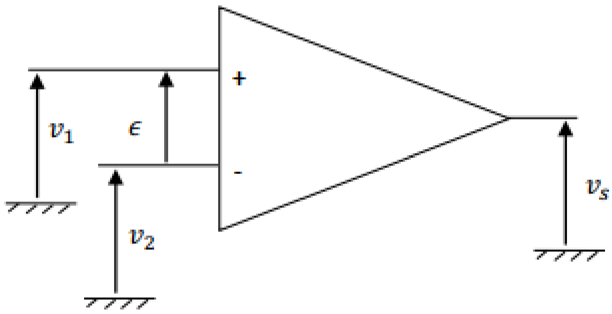


Figure 9: Voltage comparator

Here, there is no feedback. The OpAmp therefore operates in saturated mode. We therefore have: $v_s = \pm V_{sat}$, according to the sign of ε.

Which then gives us: $\begin{cases} v_s = +V_{sat} \ \ if \ \ v_1 > v_2 \\ v_s = -V_{sat} \ \ if \ \ v_1 < v_2 \end{cases}$ it is a **comparison function**.

2. Two-threshold comparator: Schmitt trigger

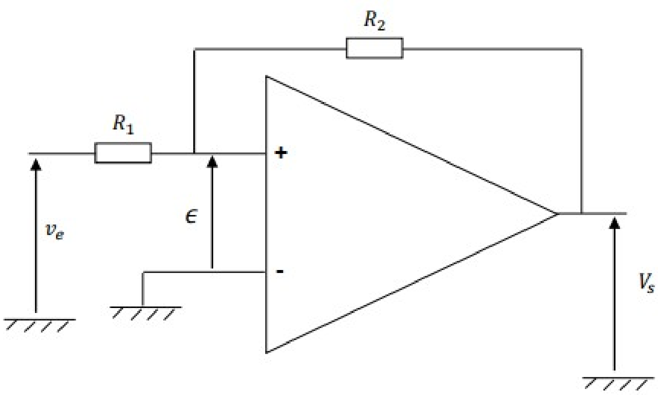


Figure 10: Two-threshold comparator: Schmitt trigger

The OpAmp here works in saturated mode because there is positive feedback. The application of Millman's theorem at the node of the non-inverting input gives:

$$\varepsilon = \frac{\frac{v_e}{R_1} + \frac{v_s}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{R_1 . v_s + R_2 . v_e}{R_1 + R_2}$$

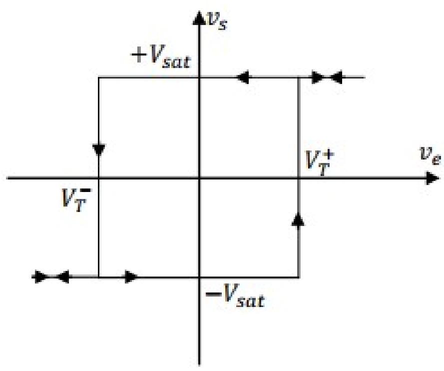
and we have $\varepsilon = v^+ - v^-$, therefore:

$$\varepsilon = v^+ - v^- = \frac{R_1 . v_s + R_2 . v_e}{R_1 + R_2}$$

There will be a switch of the output (i.e. v_s will change from $+V_{sat}$ to $-V_{sat}$ and vice versa) when $\varepsilon=0$, i.e. say for $v_e=-\frac{R_1}{R_2}.v_s$. Since $v_s=\pm V_{sat}$, we will have two symmetric switching thresholds, namely:

$$\begin{cases} V_T^+=+\frac{R_1}{R_2}.V_{sat} \\ V_T^-=-\frac{R_1}{R_2}.V_{sat} \end{cases}$$

We will therefore have: $\boxed{\begin{cases} v_s=+V_{sat} \text{ if } v_e>V_T^- \\ v_s=-V_{sat} \text{ if } v_e<V_T^+ \end{cases}}$ which makes it possible to trace the following characteristic $v_s=f(v_e)$



V. Other editings: Exercises

1. Threshold-free diode

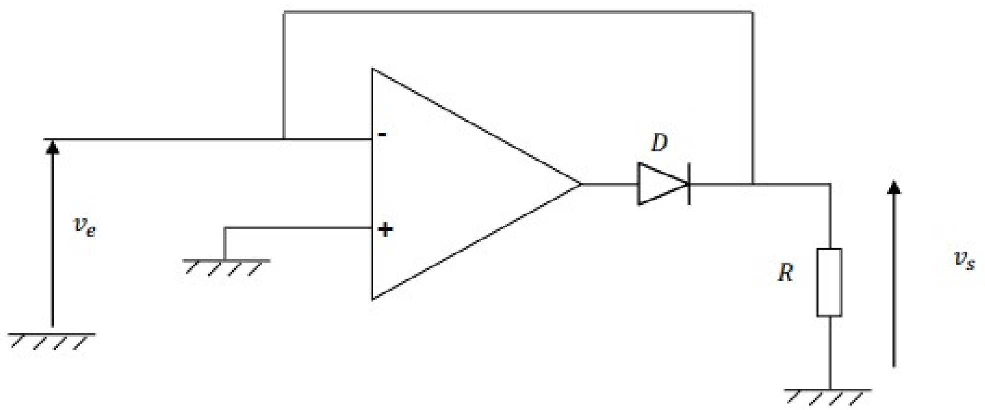


Figure 11: Threshold-free diode

plot $v_s(t)$ if $v_e(t)=v_E.\sin(\omega t)$)

2. Negative resistance simulator

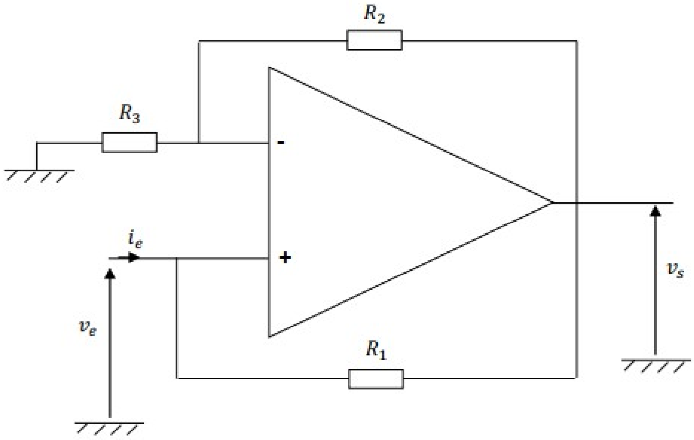


Figure 12: Negative resistance simulator

Express v_e based on i_e