Fundamentals EE 3

Chapter 7

Operational Amplifiers

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7.1 Properties

– Amplifiers are essential compoments of many electronic devices
– Often this is realised using Operational Amplifiers (OPAmps)
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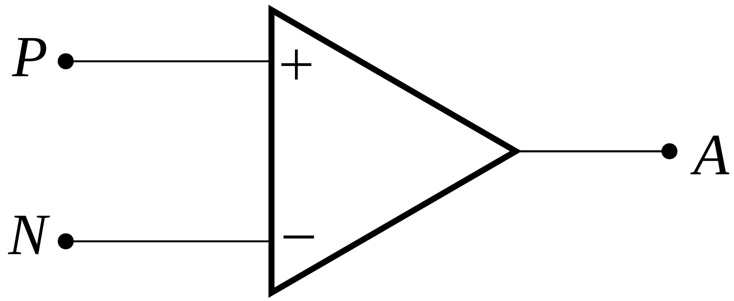
– OPAmps can be produced at low cost
– They are used in a wide range of applications
– The name comes from the application in analog computation



Symbol of an OPAmps (without power supply pins):

7.1 Properties

OPAmps simplify any analog circuit design very much!

These components are universally applicable

OPAmps often are used with feedback loops – not in open loop circuits.

Propterties of ideal OPAmps:

- Infinetely large voltage difference amplification
- Infinetely high input impedance
- Infinetely low output impedance

State-of-the-art OPAmps are in some aspects close to ideal circuits.

But this depends very much on the frequency range!

7.1 Properties

OPAmps are essentially difference amplifiers.

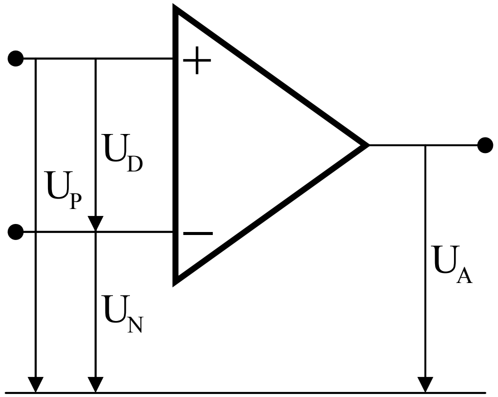
Rising voltage at the non-inverting pin P leads to rising voltage output at A.

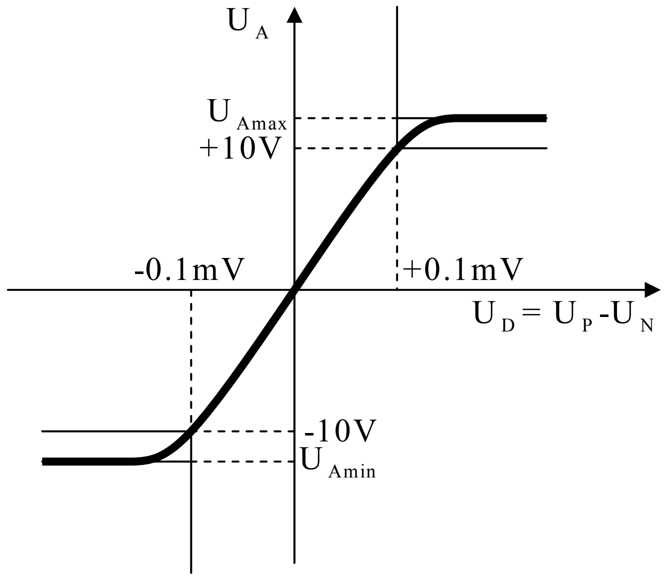
Real OPAmps need more than 3 pins for:

- Positive and negative power supply.
- Pins for modifying open loop frequency response (for incressed stability e.g.)
- For offset compensation

7.1 Properties

The linearity of the difference amplification is limited for any real OPAmp.
Reason: Limited power supply voltage

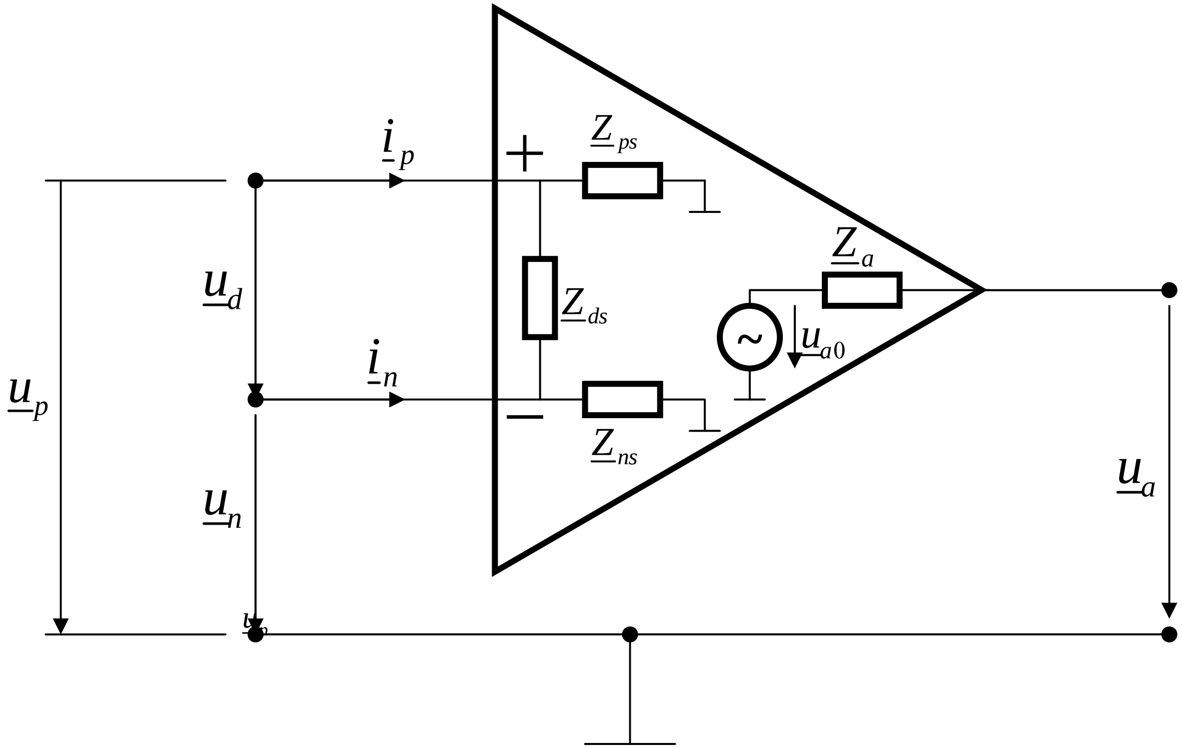




Output voltage over difference voltage $U_D = U_P - U_N$.

7.1.1. AC properties

Other non-ideal behaviour of OPAmps can be shown by means of equivalent circuits.



AC equivalent circuit of an OPAmp

7.1.2. DC properties

For a real OPAmp the output will only be zero at a difference voltage U_0 called offset voltage:

$$U_0 = U_P - U_N \quad \text{for} \quad U_A = 0 \qquad (7.1\text{-}12)$$

This offset voltage can well be compensated. But the drift of the offset cannot be compensated:

$$\Delta U_0(\vartheta, t, U_B) = \frac{\partial U_0}{\partial \vartheta}\Delta\vartheta + \frac{\partial U_0}{\partial t}\Delta t + \frac{\partial U_0}{\partial U_B}\Delta U_B \qquad U_0 = U_N = 0$$

$\frac{\partial U_0}{\partial \vartheta}$ is the temperature coefficient (typical values: 1...100µV per degree)

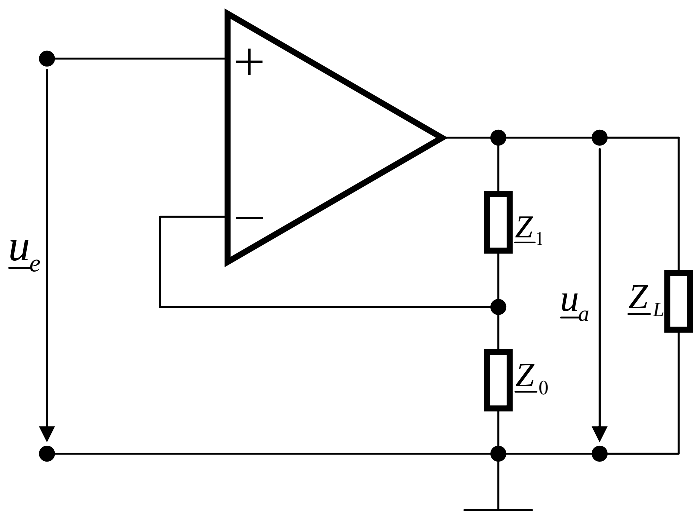
$\frac{\partial U_0}{\partial t}$ is the long-term drift coefficient (order: 10µV ... 1 mV per day)

$\frac{\partial U_0}{\partial U_B}$ takes care of offset dependency on power supply changes (order: 10 µV /V ... 1 mV/V)

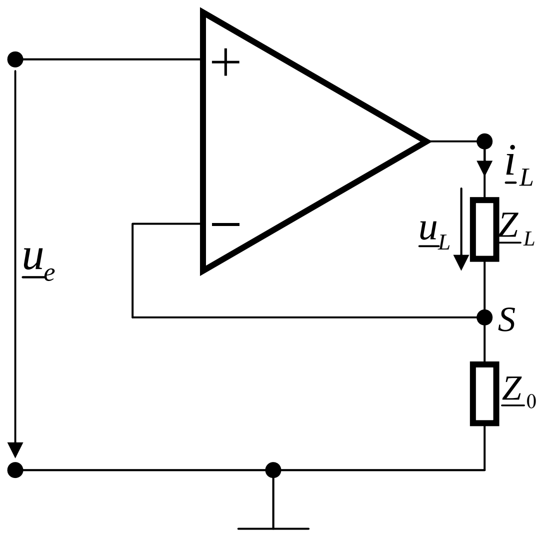
7. 2. Feed back

In general OPAmps are used with negative feed back. The feed back signal can be dependant on output voltage or output current.

These signals can be fed into the input circuitry as a current or as a voltages. Thus 4 cases result.

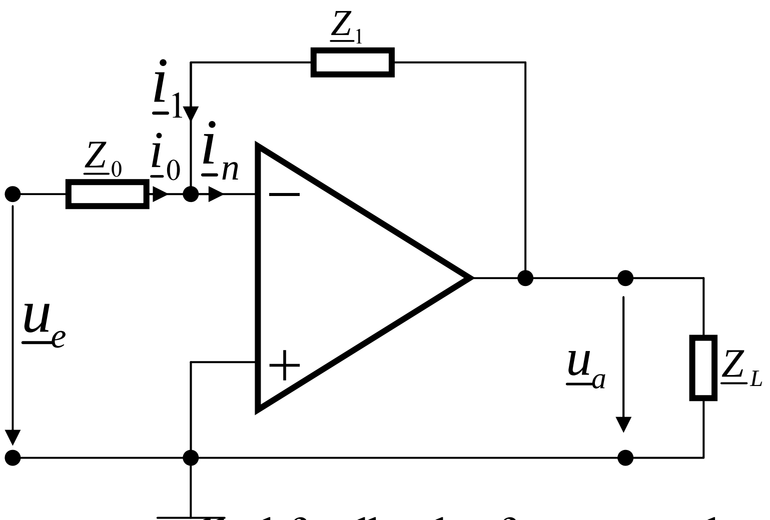


Voltage controlled feed back of output voltage

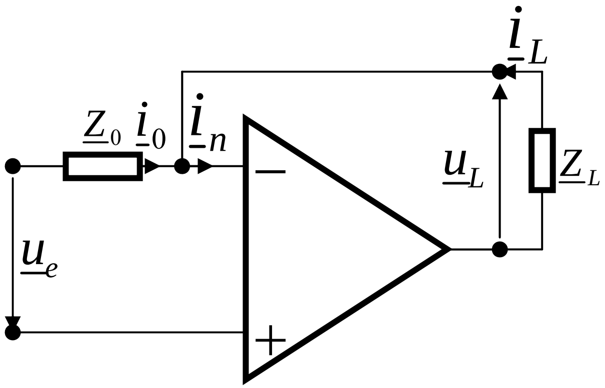


Voltage controlled feedback of output current

7. 2. Feed back



Current controlled feedback of output voltage



Current controlled feedback of output current

7. 3. Inverting amplifier

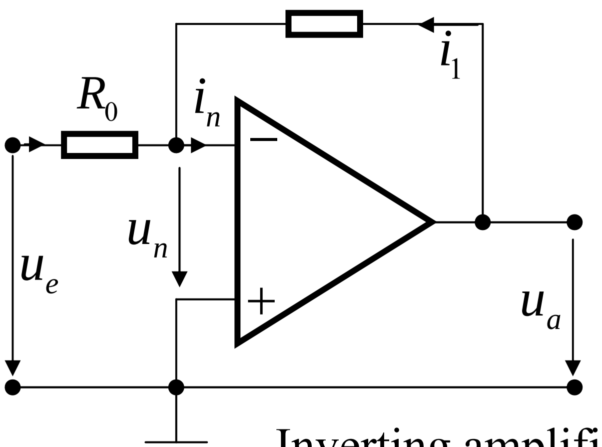
Properties of ideal OPAmps:

Open loop voltage gain: $|\underline{v}| = V \rightarrow \infty$

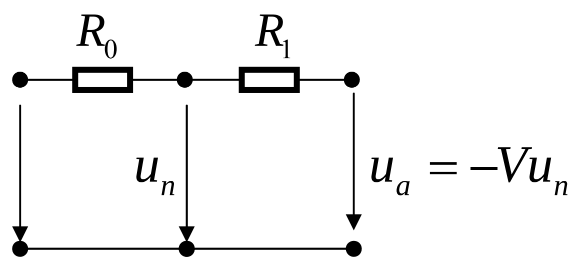
Common mode rejection ratio: $|\underline{G}| \rightarrow \infty, |\underline{v}_{gl}| = V_{gl} = 0$

Output impedance: $Z_a = 0$

Input impedance: $i_P = i_N = 0$



Inverting amplifier



Relation of difference voltage, input and output voltage

7. 3. Inverting amplifier

Detailed calculations show at a voltage jump

$$u_n = u_e \frac{R_1}{R_1 + R_0} \qquad \text{with } u_a = -Vu_n \quad (7.3\text{-}1)$$

after a settling time of few µs when steady-state is reached the value:

$$u_n = u_e \frac{R_1}{R_1 + R_0(1+V)} \qquad (7.3\text{-}2)$$

Due to V >> 1 it holds:

$$u_n = u_e \frac{R_1}{R_1 + VR_0} \qquad (7.3\text{-}3)$$

7. 3. Inverting amplifier

For the steady-state output voltage holds:

$$u_n = u_e \frac{R_1}{R_1 + VR_0}$$

$$u_a = -Vu_n = -\frac{VR_1}{R_1 + R_0 V} u_e = -\frac{R_1}{R_1 / V + R_0} u_e \qquad (7.3\text{-}4)$$

For $V \gg \frac{R_1}{R_0}$ one obtains then:

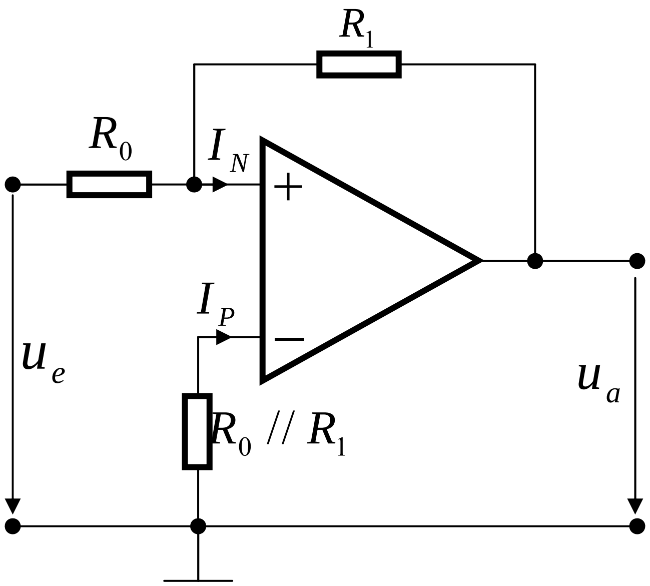
$$u_a = -\frac{R_1}{R_0} u_e \qquad (7.3\text{-}5)$$

$$\frac{u_a}{u_e} = -\frac{R_1}{R_0} \qquad (7.3\text{-}6)$$

7. 3.1. Compensation of bias and offsets

In many cases the input currents can be neglected. For video OPAmps this is not the case. Then these currents can be compensated to a high degree as follows.

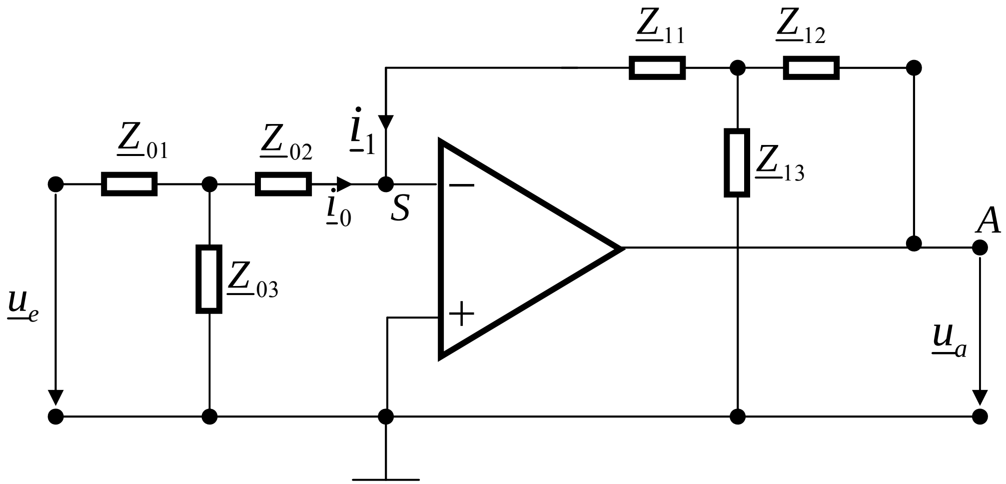
$$I_P \approx I_N$$



Compensation of input current

7.3.2. Inverting amplifier using four-poles

Comprehensive signal processing can be achieved using 2 passive T-circuits.



In the following an ideal OPAmp is assumed. Here the node S is on ground potential.

Moreover it holds: $\underline{i}_0 + \underline{i}_1 = 0$

7.3.2. Inverting amplifier using four-poles

For the currents hold:

$$\underline{i}_0 = \frac{\underline{u}_e}{\underline{Z}_{01} + \underline{Z}_{02} + \frac{\underline{Z}_{01}\underline{Z}_{02}}{\underline{Z}_{03}}}$$

$$\underline{i}_1 = \frac{\underline{u}_a}{\underline{Z}_{11} + \underline{Z}_{12} + \frac{\underline{Z}_{11}\underline{Z}_{12}}{\underline{Z}_{13}}} \qquad (7.3\text{-}26)$$

This gives:

$$\frac{\underline{u}_e}{\underline{Z}_{01} + \underline{Z}_{02} + \frac{\underline{Z}_{01}\underline{Z}_{02}}{\underline{Z}_{03}}} = -\frac{\underline{u}_a}{\underline{Z}_{11} + \underline{Z}_{12} + \frac{\underline{Z}_{11}\underline{Z}_{12}}{\underline{Z}_{13}}} \qquad (7.3\text{-}27)$$

$$A(p) = \frac{\underline{u}_a}{\underline{u}_e} = -\frac{\underline{Z}_{11} + \underline{Z}_{12} + \frac{\underline{Z}_{11}\underline{Z}_{12}}{\underline{Z}_{13}}}{\underline{Z}_{01} + \underline{Z}_{02} + \frac{\underline{Z}_{01}\underline{Z}_{02}}{\underline{Z}_{03}}} \qquad (7.3\text{-}28)$$

7.4. Non-inverting amplifier

By proper selection of the 6 components and their values (using standard design methods) a wide range of system functions A(p) can be realised!

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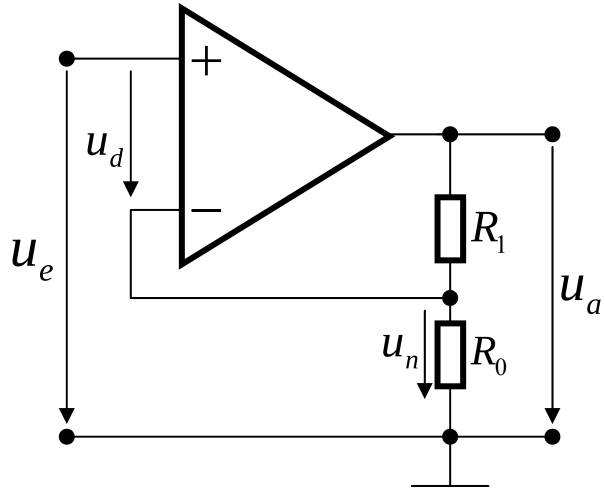
7.4. Non-inverting amplifier

For the non-inverting amplifier holds:

$$u_p = u_e$$

$$u_n = u_e = \frac{R_0}{R_1 + R_0} u_a \qquad (7.4\text{-}1)$$

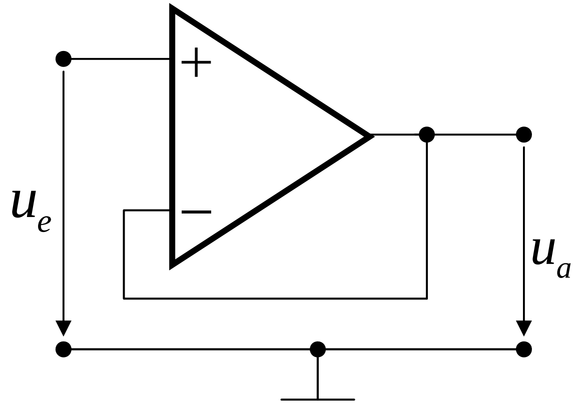


Non-inverting amplifier

Thus it follows:

$$u_a = u_e \frac{R_1 + R_0}{R_0} \qquad (7.4\text{-}2)$$

$$\frac{u_a}{u_e} = 1 + \frac{R_1}{R_0} \qquad (7.4\text{-}3)$$



Voltage follower circuit

7.4. Non-inverting amplifier

Properties of the non-inerting amplifier:
- No inversion of input signal
- Minimum amplification is 1
- Infinetely high input impedance

The following calculation shows the influence of a finite difference amplification:

$$u_n = \frac{R_0}{R_1 + R_0} u_a \qquad (7.4\text{-}4)$$

$$u_d = \frac{u_a}{V} = u_e - u_n \qquad (7.4\text{-}5)$$

$$\frac{u_e}{u_a} = \frac{1}{V} + \frac{u_n}{u_a} = \frac{1}{V} + \frac{R_0}{R_1 + R_0} \qquad (7.4\text{-}6)$$

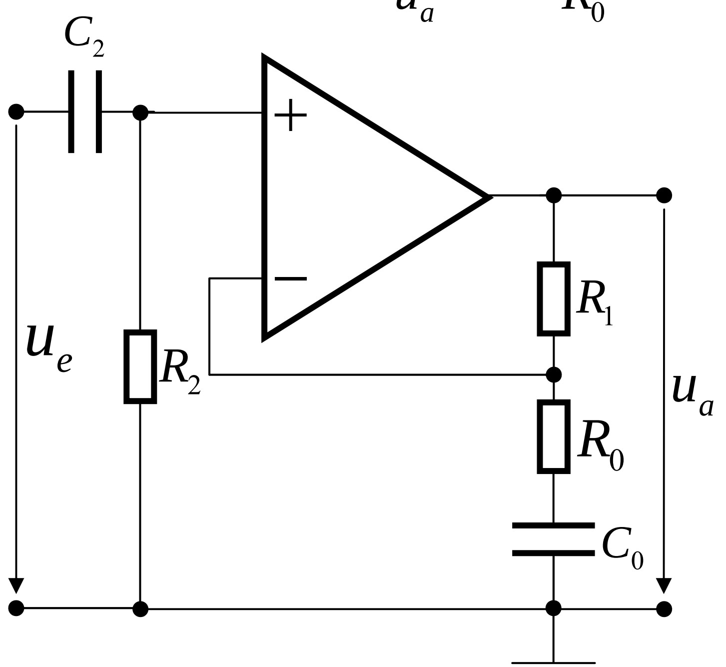
For $V \to \infty$ the result is equal to Gl. (7.4-3).

7.5. AC amplifier

7.5. AC amplifier

For the AC amplifier holds for high frequencies (capacitors work as short-circuits):

$$\frac{u_e}{u_a} = 1 + \frac{R_1}{R_0} \qquad (7.5\text{-}1)$$



AC amplifier circuit

7.5. AC amplifier

For the system function holds:

$$u_p(p) = u_e(p)\frac{R_2}{R_2 + 1/pC_2} = u_e(p)\frac{pT_2}{1+pT_2} \quad \text{mit } T_2 = R_2C_2$$

$$u_n(p) = u_a(p)\frac{R_0 + 1/pC_0}{R_1 + R_0 + 1/pC_0} = u_a(p)\frac{1+pT_0}{1+pT_1} \qquad T_1 = (R_1 + R_0)C_0$$

$$T_0 = R_0C_0$$

$$u_p(p) = u_n(p)$$

$$A(p) = \frac{u_a(p)}{u_e(p)} = \frac{(1+pT_1)\,pT_2}{(1+pT_0)(1+pT_2)} \qquad (7.5\text{-}3)$$

For $p \to \infty$ Results again:

$$\frac{u_a(p)}{u_e(p)} = \frac{pT_1pT_2}{pT_0pT_2} = \frac{T_1}{T_0} = 1 + \frac{R_1}{R_0}$$

7.6. Analog computation circuits

7.6.1. Inverting adder

As the node S has ground potential several resistors R_{0v} can be connected to it without influence of the other currents. So currents adds perfectly.

The circuit can add both currents and input voltages.

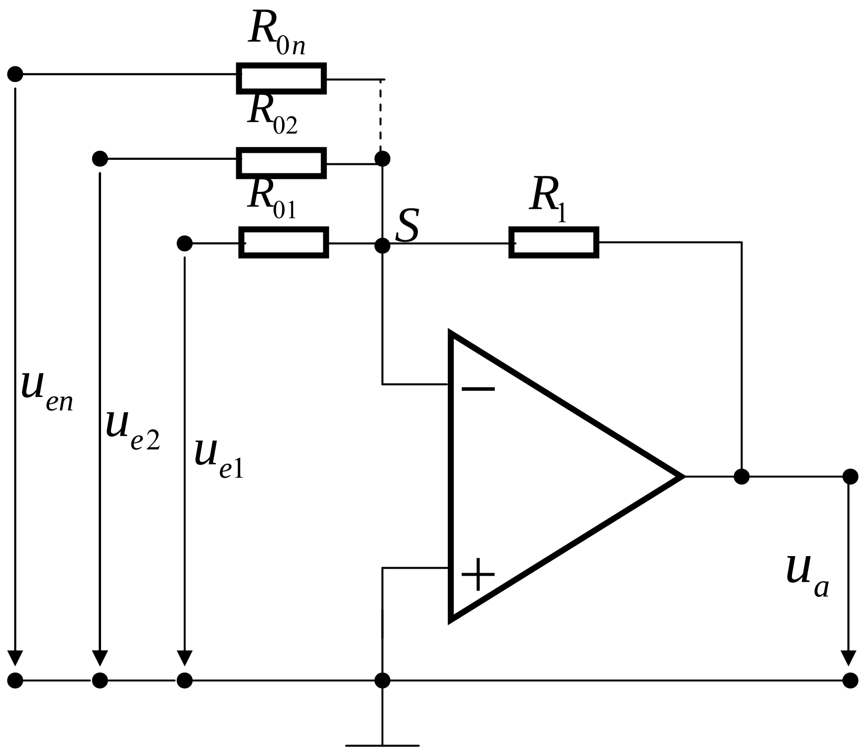
Due to Kirchhoffs rule for node S it can be ontained:

$$\frac{u_{e1}}{R_{01}} + \frac{u_{e2}}{R_{02}} + \ldots + \frac{u_{ev}}{R_{0v}} + \ldots + \frac{u_{en}}{R_{0n}} + \frac{u_a}{R_1} = 0$$

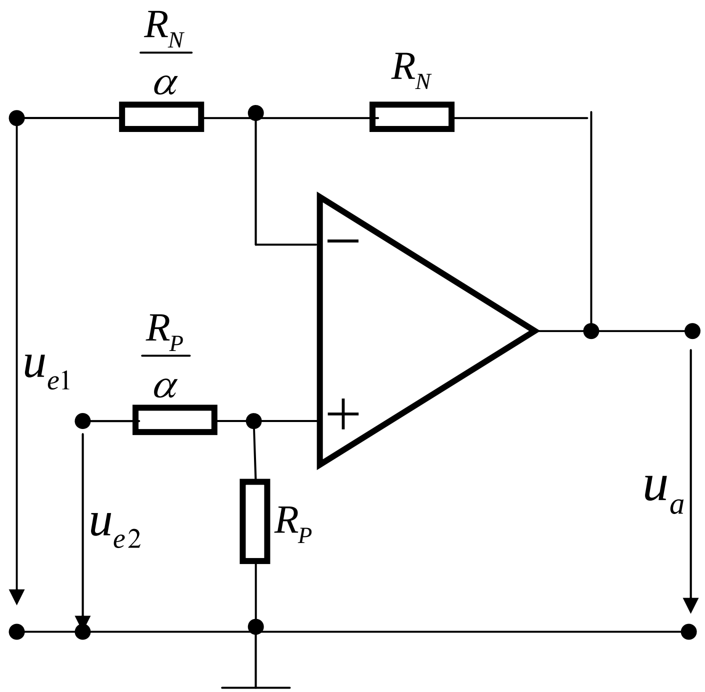
7.6.1. Inverting adder

This gives:

$$-u_a = \frac{R_1}{R_{01}}u_{e1} + \frac{R_1}{R_{02}}u_{e2} + \ldots + \frac{R_1}{R_{0\nu}}u_{e\nu} + \ldots + \frac{R_1}{R_{0n}}u_{en} \qquad (7.6\text{-}1)$$



Inverting adder circuit



Substraction circuit

7.6.2. Subtrahierer

Für an ideal OPAmp in the substraction circuit holds:

$$u_p = \frac{R_p}{R_p + \frac{R_p}{\alpha}} u_{e2} = \frac{1}{1 + \frac{1}{\alpha}} u_{e2} = \frac{\alpha}{1+\alpha} u_{e2} \qquad u_n = \frac{R_N u_{e1} + \frac{R_N}{\alpha} u_a}{R_N + \frac{R_N}{\alpha}} = \frac{u_{e1} + \frac{1}{\alpha} u_a}{1 + \frac{1}{\alpha}} = \frac{\alpha u_{e1} + u_a}{1+\alpha}$$

With $u_p = u_n$ follows:

$$u_a = \alpha (u_{e2} - u_{e1}) \qquad (7.6\text{-}3)$$

The circuit computes the diffence of the 2 voltages and multiplies it by the constant factor α.

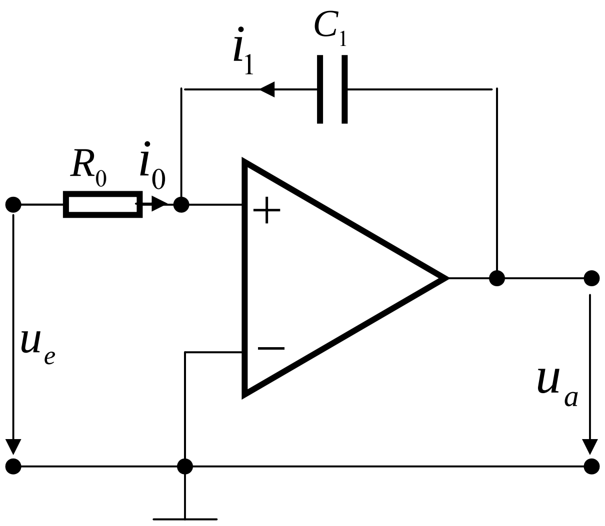
7.6.3. Integrator

For the integrator circuit the following relations hold:

$$i_0 + i_1 = 0$$

$$i_0 = \frac{u_e}{R_0} \qquad i_1 = C_1 \frac{du_a}{dt}$$

$$\frac{u_e}{R_0} + C_1 \frac{du_a}{dt} = 0 \Rightarrow \frac{du_a}{dt} = -\frac{u_e}{R_0 C_1} \qquad (7.6\text{-}19)$$



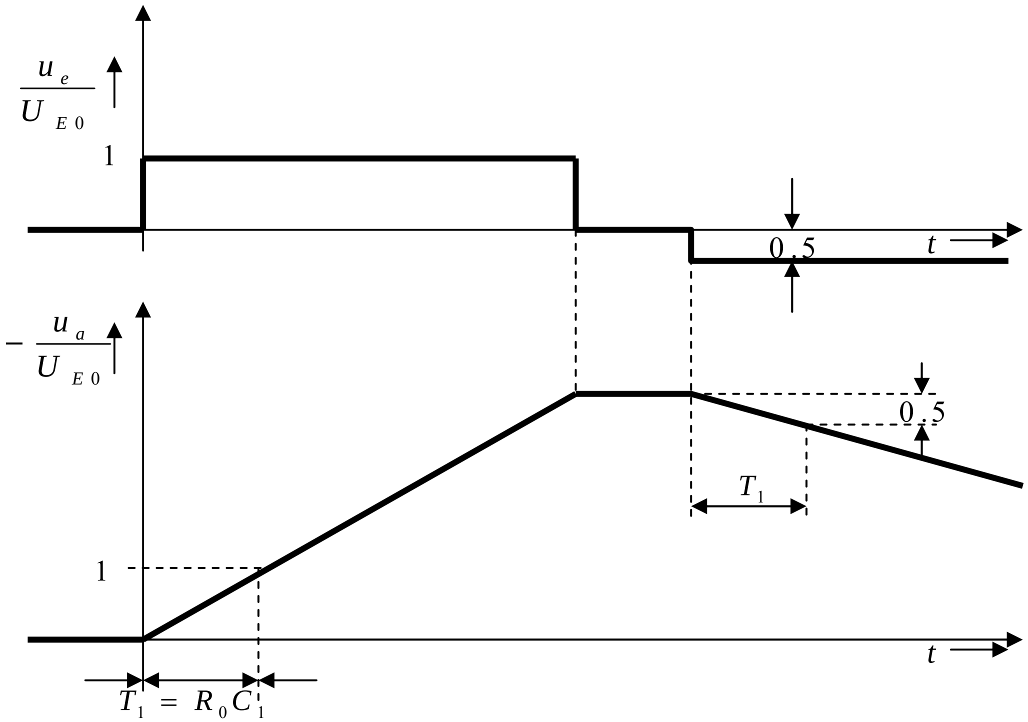
Umkehrintegrator

Thus for the output voltage results:

$$u_a = -\frac{1}{R_0 C_1}\int_0^t u_e dt + U_{a0} \qquad (7.6\text{-}20)$$

U_{a0} is here the output voltage at the start of the integration *(t = 0)* and corresponds to the charge on the capacitor at that time.

7.6.3. Integrator



Example of input and output voltages for an integrator

7.6.4. Differentiator

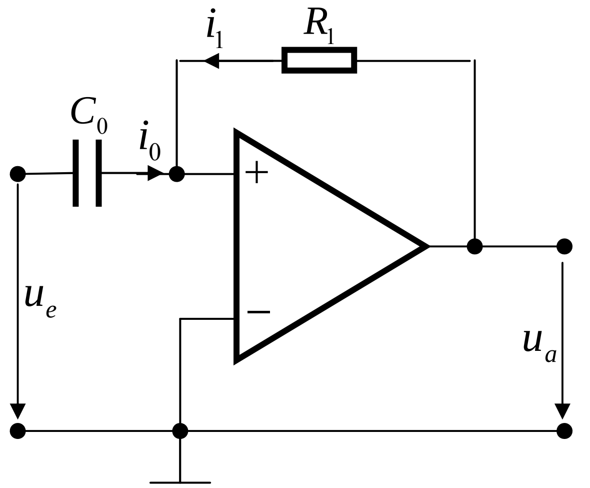
For the ideal differentiator circuit holds:

$$i_0 + i_1 = 0$$

$$i_0 = C_0 \frac{du_e}{dt} \qquad i_1 = \frac{u_a}{R_1}$$

$$C_0 \frac{du_e}{dt} + \frac{u_a}{R_1} = 0$$

$$u_a = -R_1 C_0 \frac{du_e}{dt}$$



The system function of the ideal differentiator circuit has the form:

$$A(p) = -\frac{u_a(p)}{u_e(p)} = pT_D \qquad \text{mit} \qquad T_D = R_1 C_0$$

7.6.4. Differentiator

For several reasons this circuit normally is not used (non real input impedance, magnification of noise).

Using an additional resistor R_0 and a second capacitor a better usable circuit is obtained. For its system function holds:

$$-\frac{u_a(p)}{u_e(p)} = \frac{Z_1(p)}{Z_0(p)}$$

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7.6.4. Differentiator

With $R_1C_1=T_1$ and $R_0C_0=T_0$ results:

$$Z_1(p)=\frac{R_1/pC_1}{R_1+1/pC_1}=\frac{R_1}{1+pT_1}$$

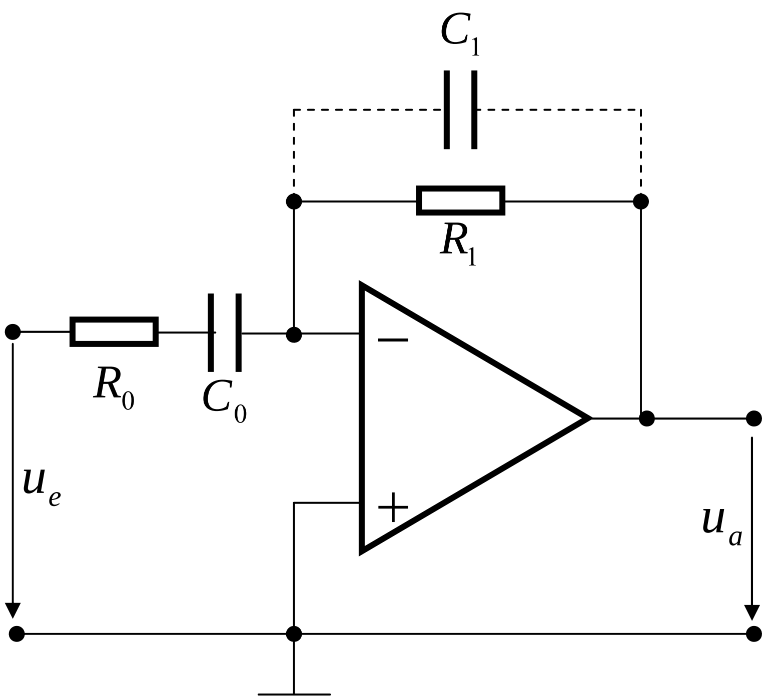
$$Z_0(p)=R_0+1/pC_0=R_0\frac{1+pT_0}{pT_0}$$

$$-\frac{u_a(p)}{u_e(p)}=\frac{Z_1(p)}{Z_0(p)}=\frac{R_1}{R_0}\cdot\frac{pT_0}{(1+pT_0)(1+pT_1)}$$

For $pT_0<<1$ and $pT_1<<1$ holds:

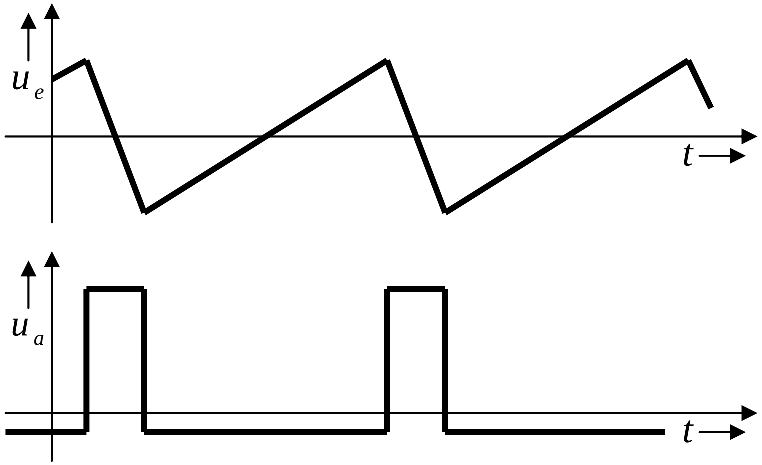
$$-\frac{u_a(p)}{u_e(p)}=\frac{R_1}{R_0}.pT_0$$

For $p\rightarrow\infty$ holds: $-\frac{u_a(p)}{u_e(p)}=\frac{R_1}{R_0}.\frac{1}{pT_1}$



Improved differentiator circuit

7.6.4. Differentiator



Example of input and output voltages for an ideal differentiator