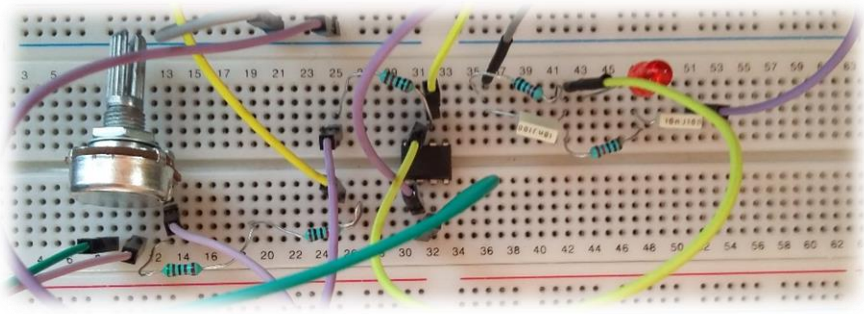


FUNDAMENTAL ELECTRONIC CIRCUITS

Assist. prof. Laura-Nicoleta IVANCIU, Ph.D.

C7 – Feedback circuits

Contents

➢ To begin with

- What is feedback? How do we recognize it in a circuit? What components can be placed on the feedback loop?
- What are the types of feedback?
- Is positive feedback always good for the circuit? Is negative feedback always bad for the circuit?

➢ What is feedback?

= technique in which the output of the system is used to influence the behavior and properties of the system

- the effect produced by a certain cause influences the following action of that cause

➢ How do we recognize feedback in a system/circuit?

- (a fraction of) the output is fed back at the input of the system
- backwards connection from output to input

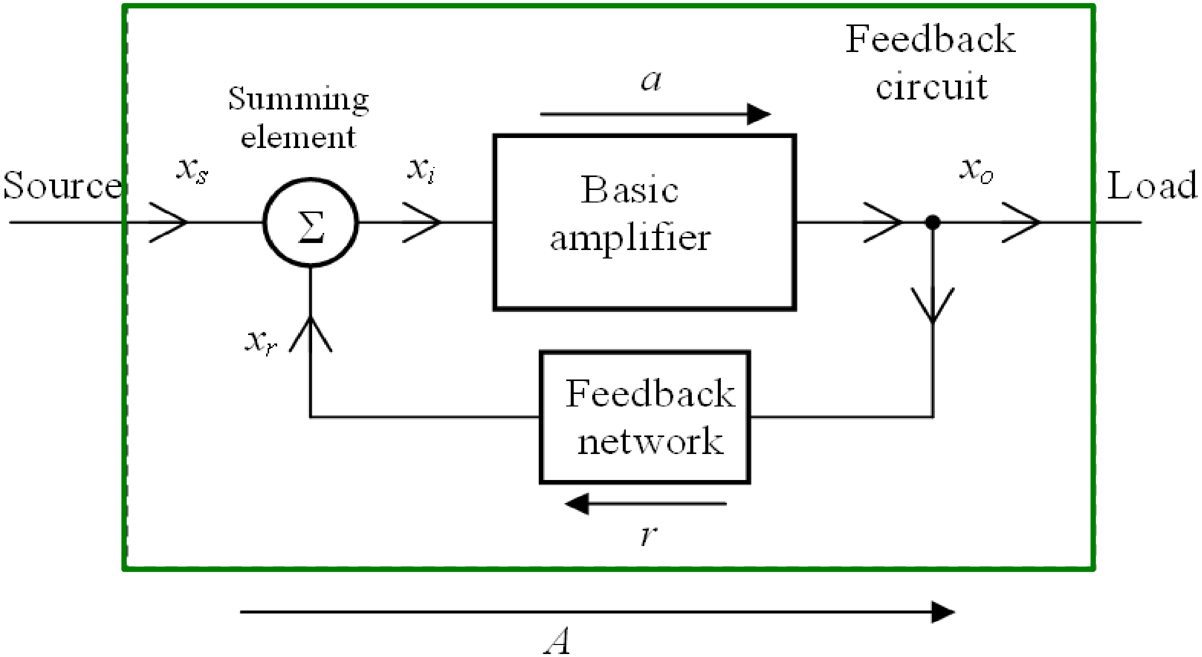
➢ Types of feedback

- ***negative feedback*** (degenerative) **NF**
  - the signal fed back from the output ***reduces*** the effect of the input signal; stabilizing effect
- ***positive feedback*** (regenerative) **PF**
  - the signal fed back from the output ***intensifies*** the effect of the input signal; leads to instability

➢ Feedback loop made of

- a wire – total feedback
- resistor(s) – i.e. comparators, amplifiers
- capacitor(s) – i.e. integrators
- complex structures (resistors, capacitors, transistors, etc)

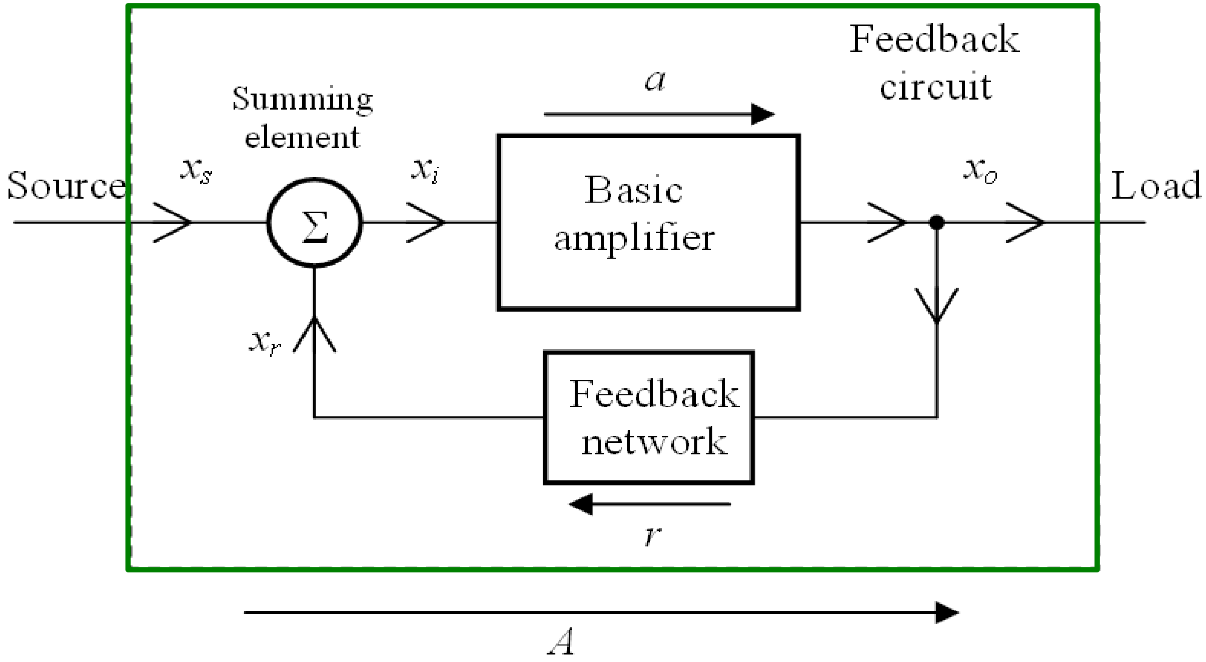
➢ General structure of a feedback circuit



x_s – source signal, obtained from an external signal source
x_o – output signal, fed to the load and to the feedback network
x_r – feedback signal, provided by the feedback network
x_i – input signal of the basic amplifier, provided by the summing element

All signals can be either voltages or currents!

General structure of a feedback circuit

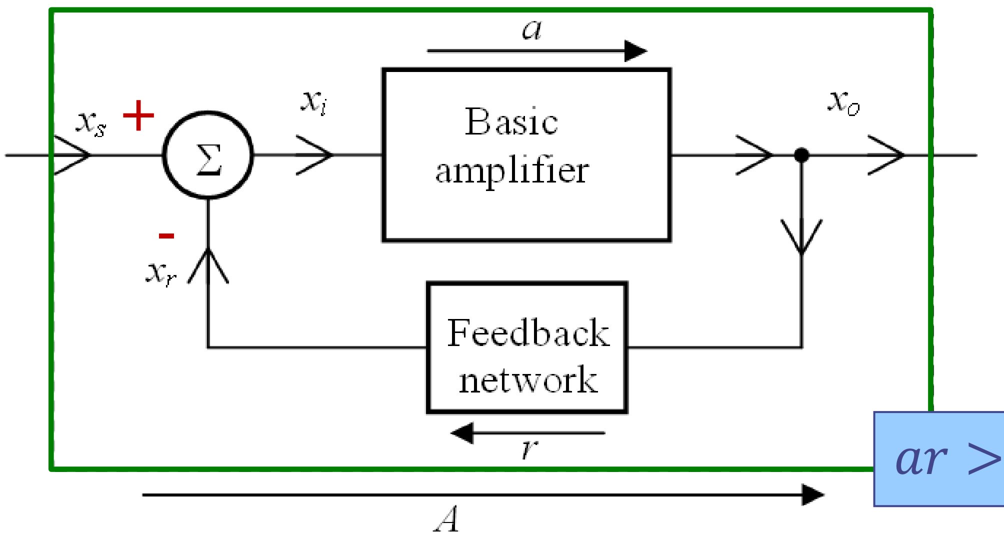


- transmittance of the basic amplifier: $a = \frac{x_o}{x_i}$ gain of the basic amplifier; open loop gain
- transmittance of the feedback network: $r = \frac{x_r}{x_o}$ feedback factor; transmittance of reverse path
- transmittance of the feedback circuit: $A = \frac{x_o}{x_s}$ gain of the feedback amplifier

➢ Feedback types

Negative feedback

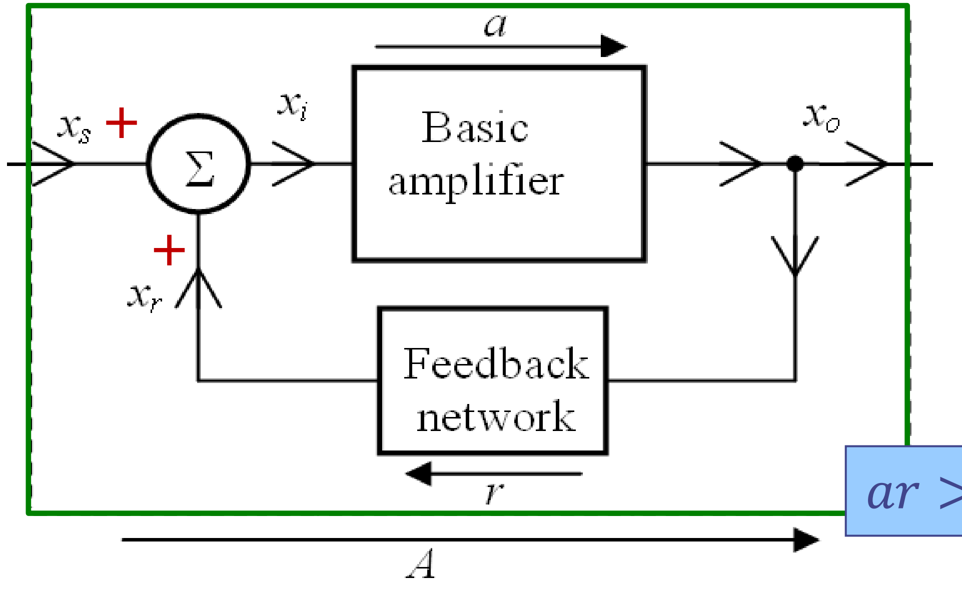
$$x_i = x_s - x_r$$



$$ar > 0$$

Positive feedback

$$x_i = x_s + x_r$$



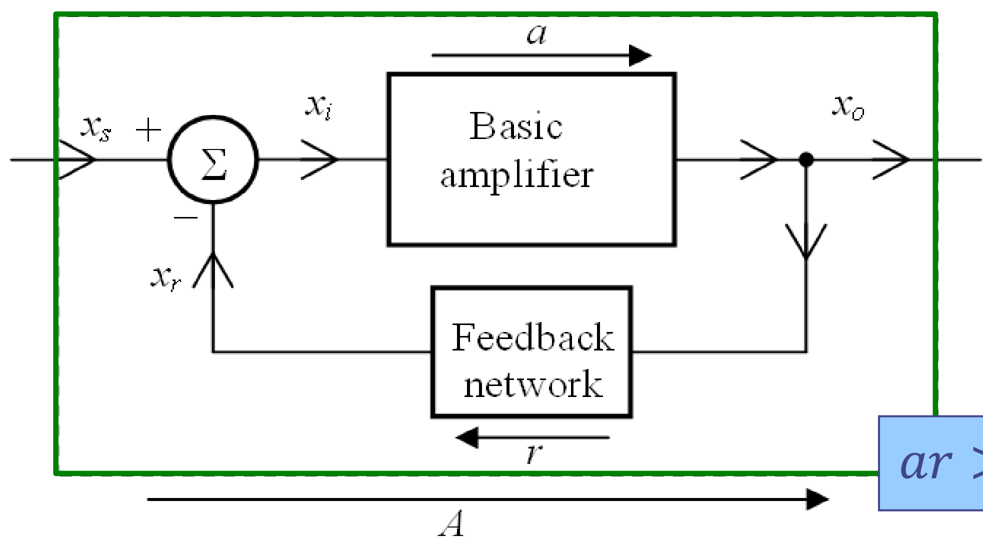
$$ar > 0$$

Ideal feedback premises

- each block is unilateral (one way signal transmission)
- the feedback network block does not load the output of the basic amplifier
  (*a* = constant, w/ or w/out the feedback network)
- assume the source resistance and the load resistance are included in the basic amplifier

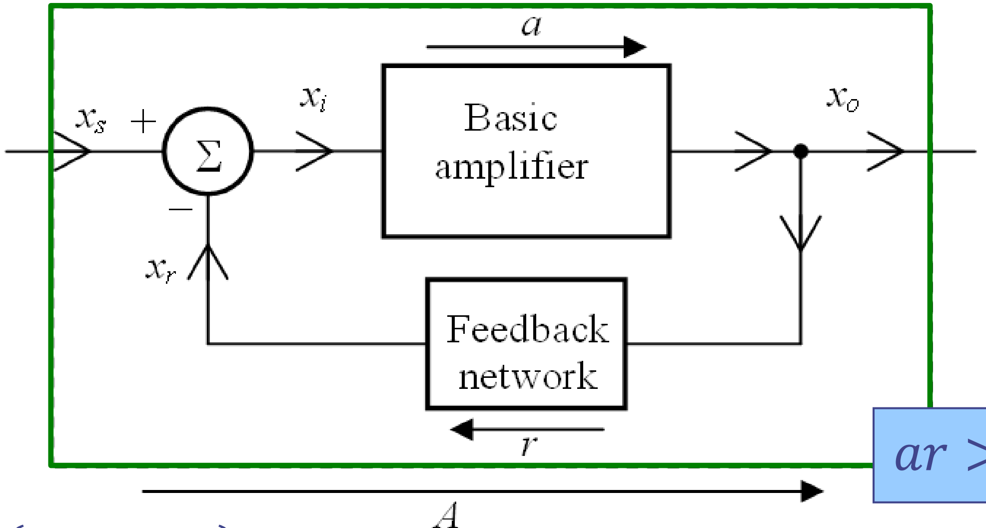
Negative feedback

$$x_i = x_s - x_r$$



$$ar > 0$$

How can *A* be computed, using *a* and *r*?



$ar > 0$

➢ Negative feedback

$$A = \frac{x_o}{x_s}$$

$$x_o = a \cdot x_i$$

$$x_i = x_s - x_r$$

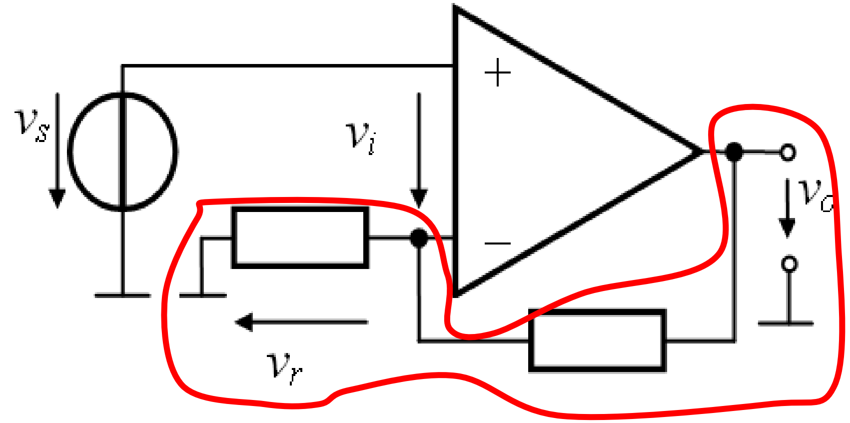
$$x_r = r \cdot x_o = r \cdot A \cdot x_s$$

$$x_i = x_s - x_r = x_s - r \cdot A \cdot x_s = x_s(1 - r \cdot A)$$

$$x_o = a \cdot x_s(1 - r \cdot A)$$

$$A = \frac{x_o}{x_s} = \frac{a \cdot x_s(1 - r \cdot A)}{x_s} = a(1 - r \cdot A)$$

$$A = \frac{a}{1 + ar}$$

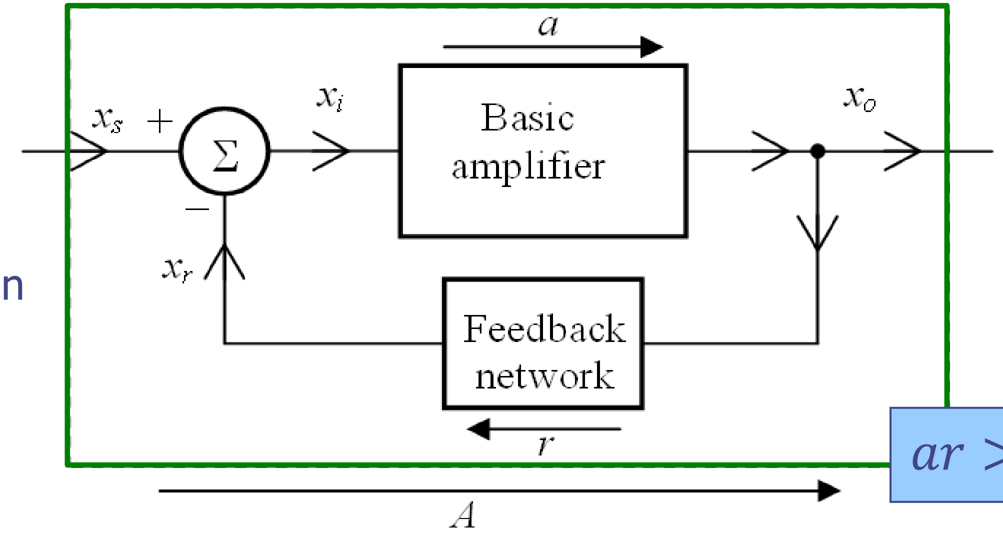


feedback network

$$v_i = v_s - v_r$$

Ideal feedback circuits

➢ Negative feedback



$$A = \frac{a}{1 + ar}$$ fundamental equation of the NF

$ar > 0$

$|A| < |a|$

ar – loop gain $\quad ar > 0$

$1 + ar$ – amount of feedback $\quad 1 + ar > 0$

If $ar \gg 1$ (e.g. for OpAmp $a \to \infty$) $\quad A \approx \frac{1}{r}$

The gain of the feedback amplifier is (almost) entirely determined by the feedback network: accurate, predictable and stable

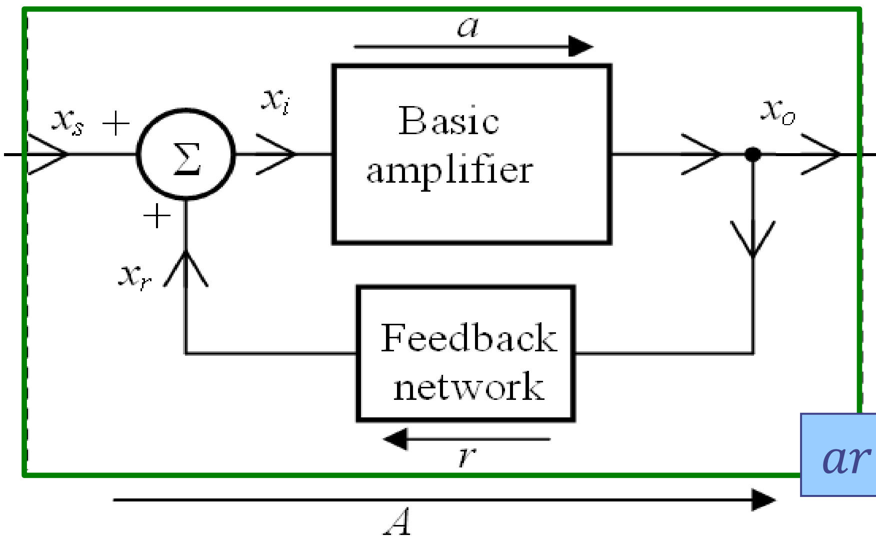
BUT the gain decreases.

Negative feedback - example

	$a = 1000, r = 0.009$	$a = 10000, r = 0.009$
$ar = ?$	$ar = 1000 \cdot 0.009 = 9$	$ar = 10000 \cdot 0.009 = 90$
$1 + ar = ?$	$1 + ar = 1 + 9 = 10$	$1 + ar = 1 + 90 = 91$
$A = ?$	$A = \frac{a}{1+ar} = \frac{1000}{10} = 100$ $A \approx \frac{1}{r} = \frac{1}{0.009} = 111.1$	$A = \frac{a}{1+ar} = \frac{10000}{91} \approx 109.89$ $A \approx \frac{1}{r} = \frac{1}{0.009} = 111.1$

Higher ar results in a more accurate $A \approx \frac{1}{r}$ approximation.

➢ Positive feedback



$ar > 0$

$$A = \frac{x_o}{x_s}$$

$$x_o = a \cdot x_i$$

$$x_i = x_s + x_r$$

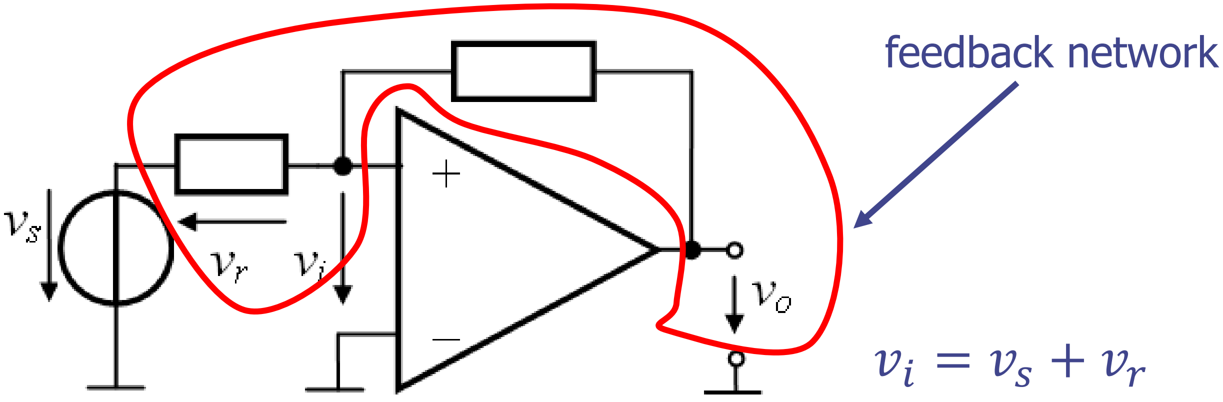
$$x_r = r \cdot x_o = r \cdot A \cdot x_s$$

$$x_i = x_s + x_r = x_s + r \cdot A \cdot x_s = x_s(1 + r \cdot A)$$

$$x_o = a \cdot x_s(1 + r \cdot A)$$

$$A = \frac{x_o}{x_s} = \frac{a \cdot x_s(1 + r \cdot A)}{x_s} = a(1 + r \cdot A)$$

$$A = \frac{a}{1 - ar}$$



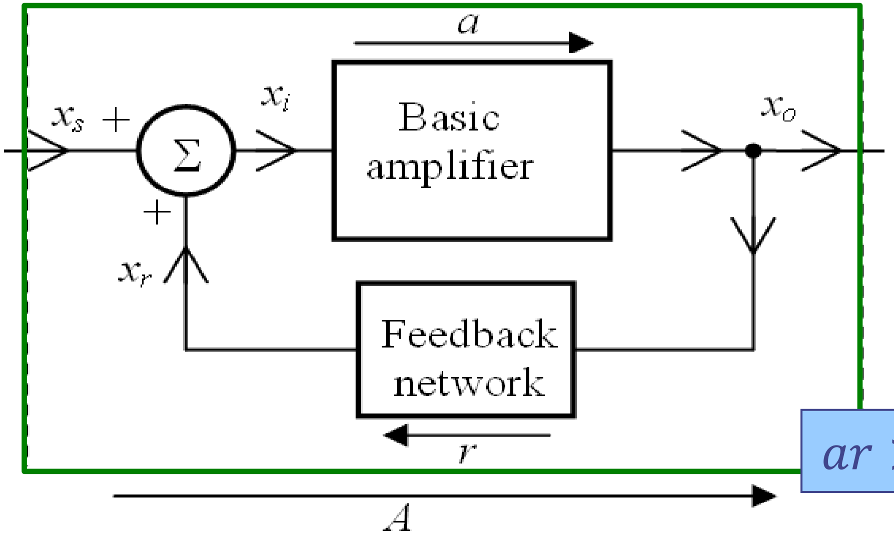
$v_i = v_s + v_r$

Ideal feedback circuits

➢ Positive feedback

$$A = \frac{a}{1 - ar}$$

fundamental equation of the PF



$ar > 0$

$|A| > |a|$ - gain increases, but other parameters get worse

$ar > 0$ – loop gain

$1 - ar$ – amount of feedback

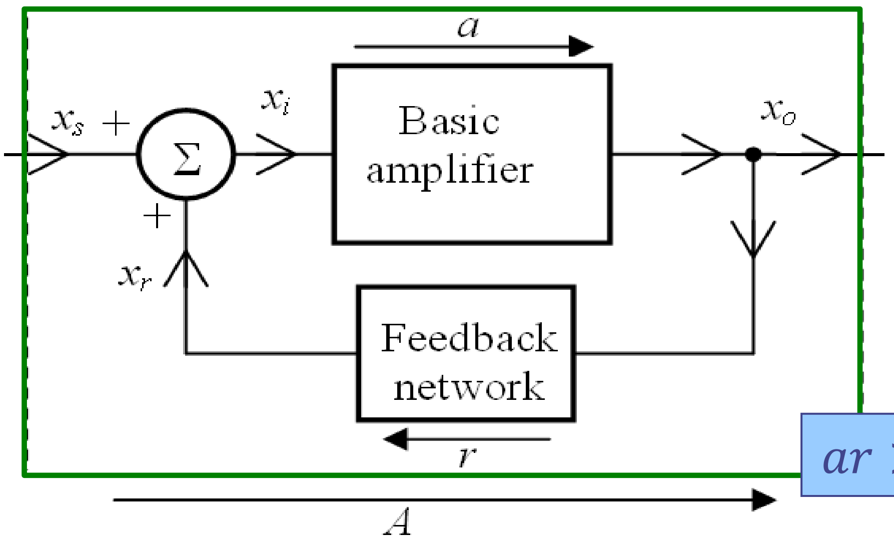
$0 < 1 - ar < 1$ – keeps the amplifier in the linear domain

What if $ar = 1$? Or $ar > 1$?

Ideal feedback circuits

Positive feedback

$$A = \frac{a}{1 - ar}$$ fundamental equation of the PF



$ar > 0$

Special cases of PF:

- $(1 - ar) = 0; \quad ar = 1; \quad A \to \infty$

$x_o = Ax_s$ $\quad x_o$ - finite only if $x_s = 0$

- used in signal generators (sinusoidal oscillators – see C10)

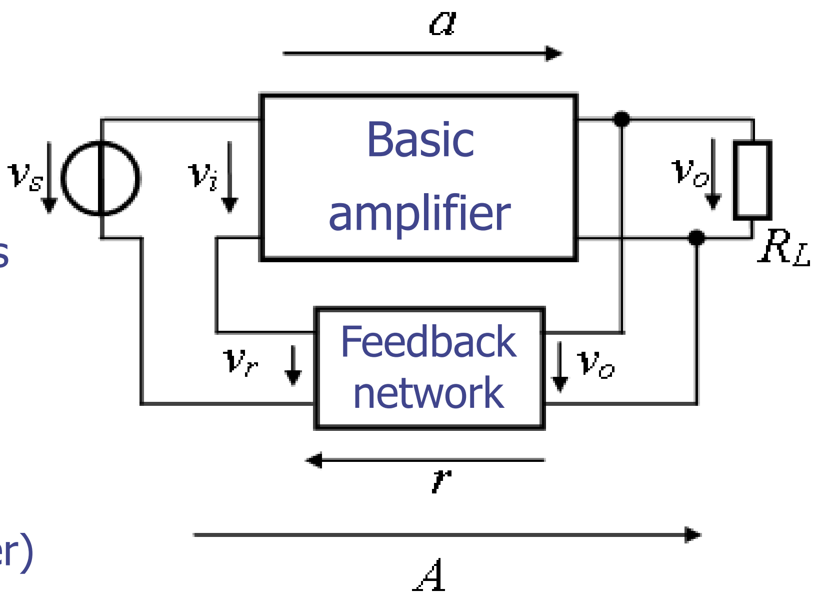
- $ar > 1$

- used in multivibrator circuits, bistable circuits (see C11, C12)

➢ Feedback topologies

- based on the types of input and output signals (voltage/current)

- voltage – voltage (series - parallel)
- voltage - current (series - series)
- current - voltage (parallel - parallel)
- current – current (parallel - series)



Input: based on the method of summing up the signals
- voltage: series connection (in a loop)
- current: parallel connection (in a node)

Output: based on how the signals are measured
- voltage: in parallel (measurement with the voltmeter)
- current: in series (measurement with the ammeter)

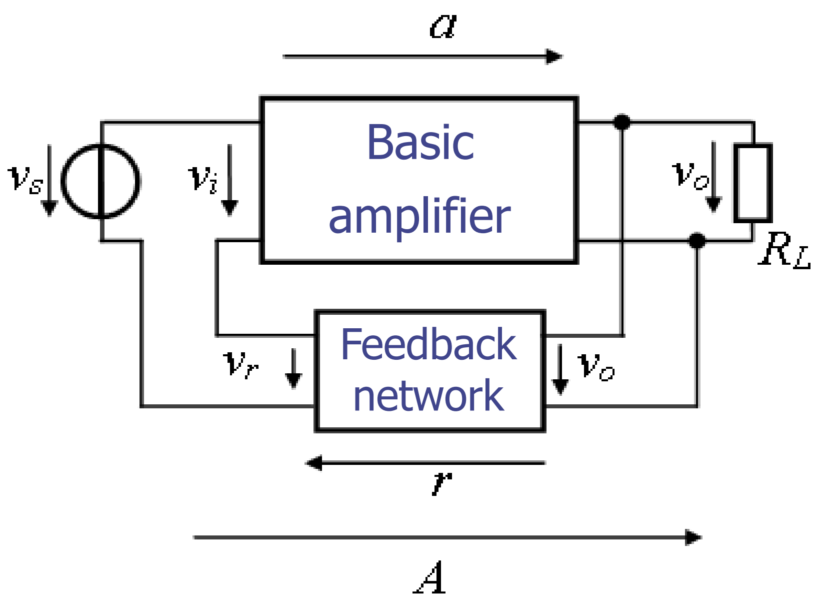
Analysis of the feedback amplifier

Ideal feedback:

- no restrictions on the basic amplifier
- all other components are assumed ideal:
  - ✓ the feedback network – a controlled source
  - ✓ the source resistance and the load resistance are included in the basic amplifier

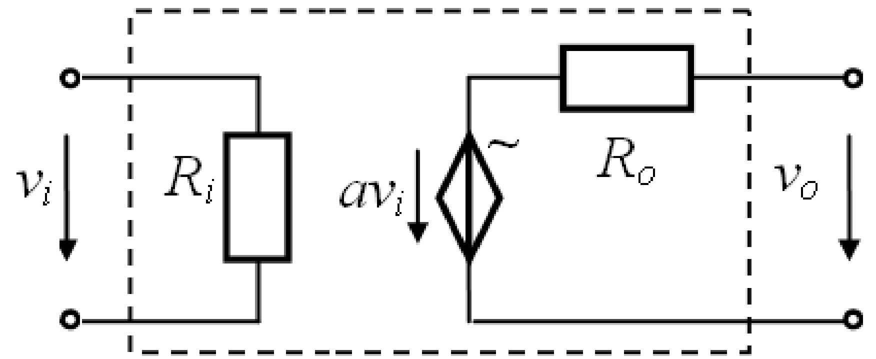
Real feedback:

- the feedback network loads the input and output of the basic amplifier

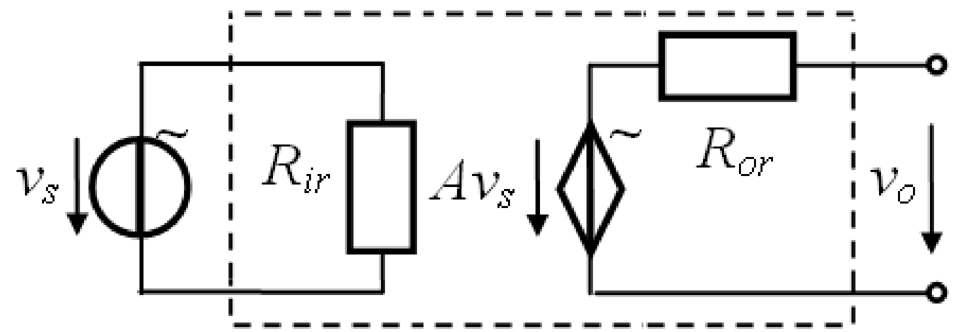


➢ Voltage-voltage topology, ideal feedback

Equivalent model of the basic amplifier



Equivalent model of the feedback amplifier



$$A = \frac{a}{1 + ar}$$

Gain of the feedback amplifier

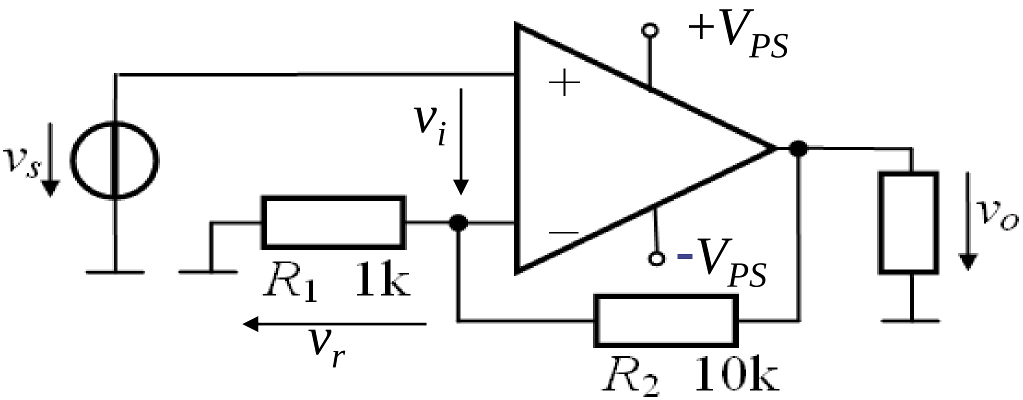
$$R_{ir} = R_i(1 + ar)$$

Input resistance of the feedback amplifier

$$R_{or} = \frac{R_o}{1 + ar}$$

Output resistance of the feedback amplifier

➢ Voltage-voltage topology, ideal feedback - example



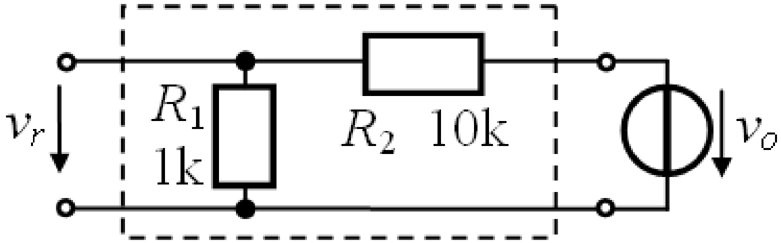
Assume OpAmp LM741

Typical values:

$$a = 2 * 10^5; R_i = 2\text{M}\Omega; R_o = 50\ \Omega$$

Compute the gain, input and output resistances for the feedback amplifier.

Feedback network:



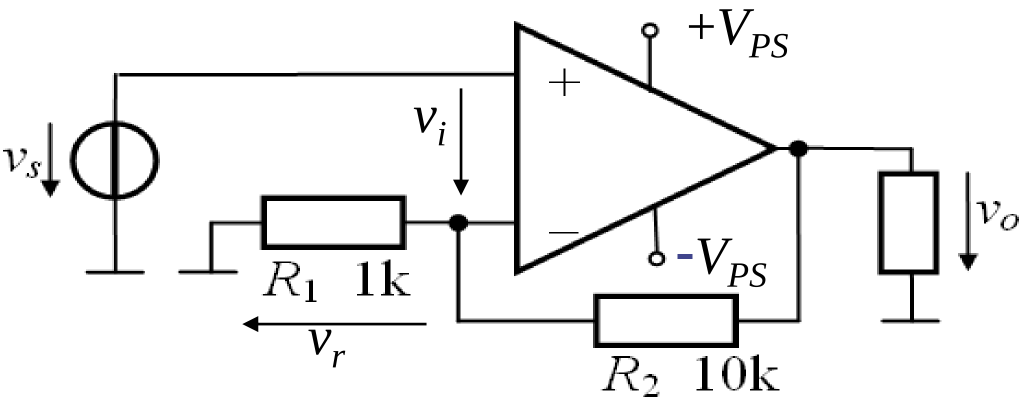
$$r = \frac{v_r}{v_o} = \frac{R_1}{R_1 + R_2} = \frac{1}{1 + 10} \approx 0.091$$

$$1 + ar = 1 + 200000 \cdot 0.091 = 18201$$

$$A = \frac{a}{1 + ar} = \frac{200000}{18201} = 10.988$$

$$A \approx \frac{1}{r} = 1 + \frac{R_2}{R_1} = 1 + \frac{10}{1} = 11$$

➢ Voltage-voltage topology, ideal feedback - example



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Typical values:

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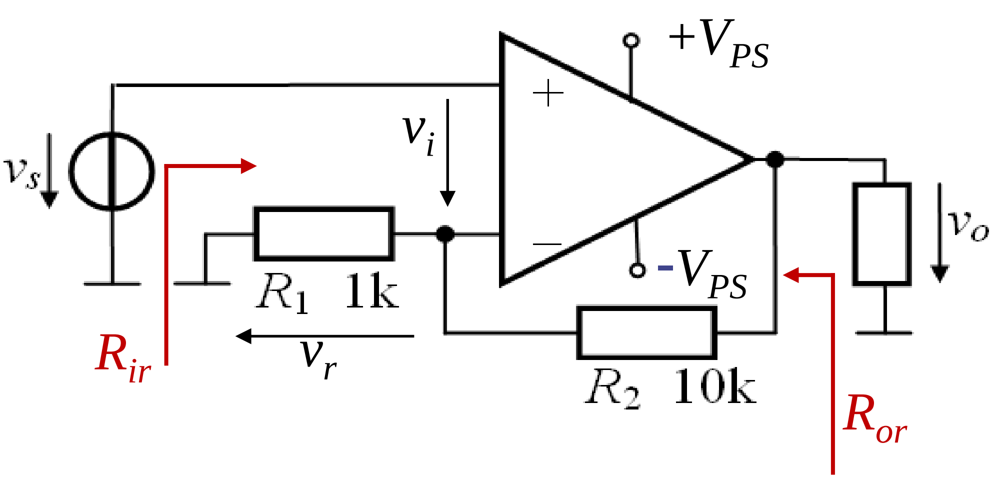
Compute the gain, input and output resistances for the feedback amplifier.



$$R_{ir} = R_i(1 + ar) = 36.4\ \mathrm{G}\Omega$$

$$R_{ir} \to \infty$$

$$R_{or} = \frac{R_o}{1 + ar} = 2.7\ \mathrm{m}\Omega$$

$$R_{or} \to 0$$

Effects of NF on the parameters of an amplifier

By adding NF, the properties of the feedback amplifier are changed with respect to the properties of the basic amplifier:

- gain – reduced
- gain sensitivity – reduced
- nonlinear distortion – reduced
- active region - wider
- bandwidth – wider
- effect of the noise - can be reduced
- input and output impedances – improved

Effects of NF on the parameters of an amplifier

Reduction of the gain

$$A = \frac{a}{1+ar} \qquad ar > 0 \qquad |A| < |a|$$

If $ar \gg 1$ (e.g. for OpAmp $a \to \infty$) $A \approx \dfrac{1}{r}$

The gain can be increased by adding a pre-amplifier stage.

Improvement of the input and output resistances

Voltage **input**: $R_{ir} = R_i(1+ar)$

Current **input**: $R_{ir} = \dfrac{R_i}{1+ar}$

Improvement = { increase for voltage; decrease for current }

Voltage **output**: $R_{or} = \dfrac{R_o}{1+ar}$

Current **output**: $R_{or} = R_o(1+ar)$

Improvement = { decrease for voltage; increase for current }

Effects of NF on the parameters of an amplifier

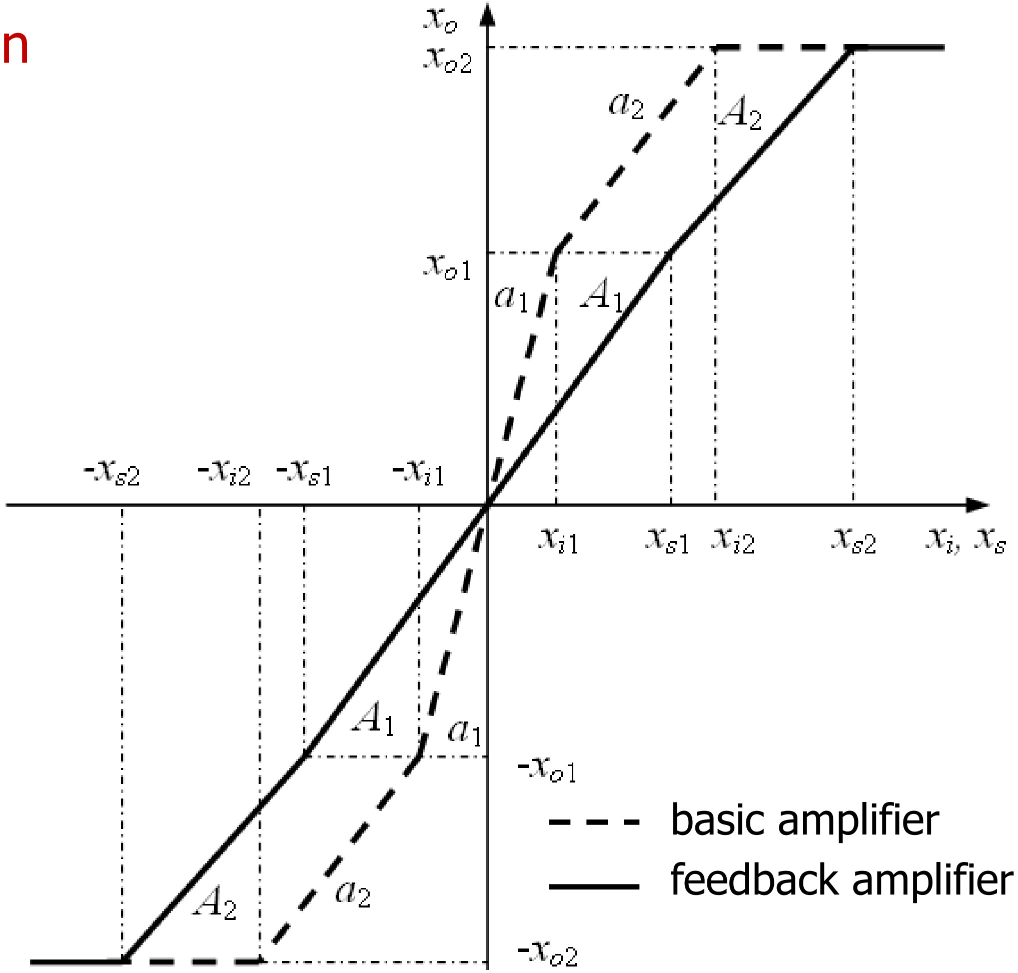
Reduction of the nonlinear distortion

- linear gain for small-signal, around the operating point
- if the input signal increases, the gain becomes nonlinear

$$a_1 \xrightarrow{\text{NF}} A_1 = \frac{a_1}{1 + a_1 r}$$

$$a_2 \xrightarrow{\text{NF}} A_2 = \frac{a_2}{1 + a_2 r}$$

By adding NF, the difference between A_1 and A_2 is smaller than the difference between a_1 and a_2.



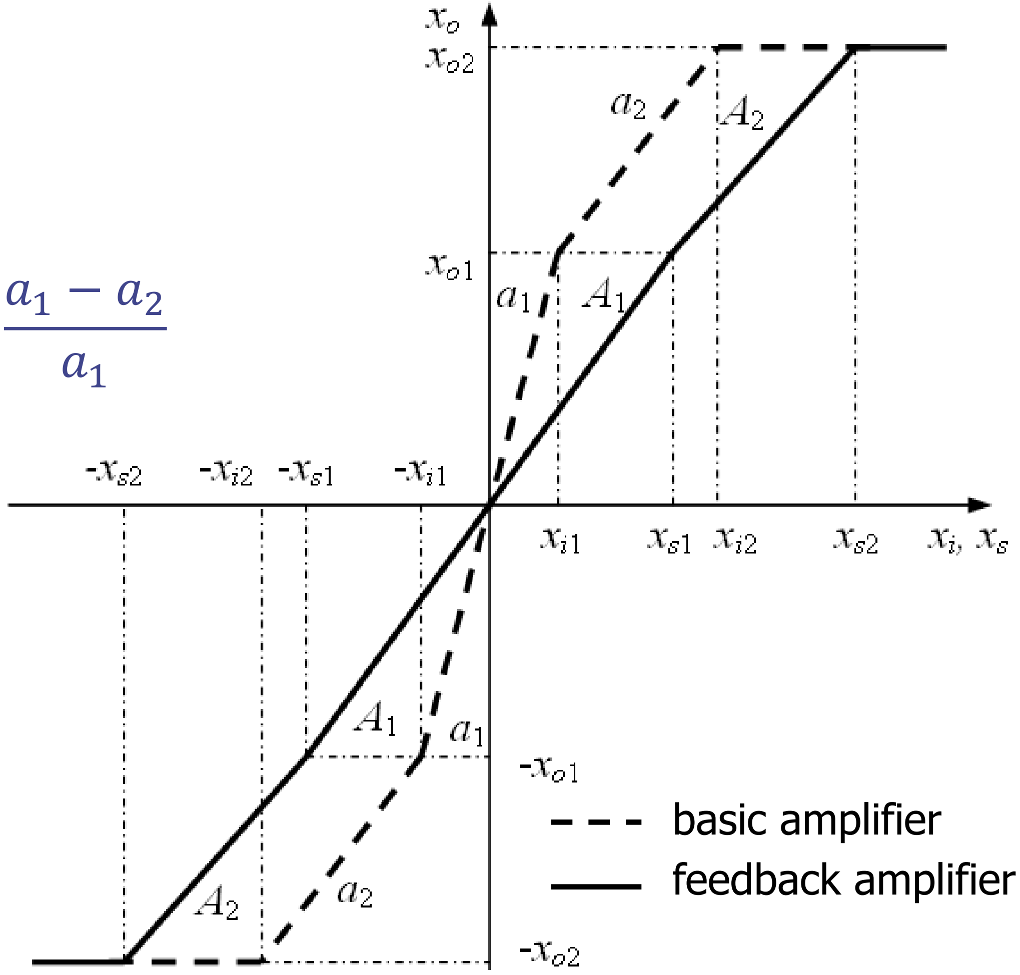
Effects of NF on the parameters of an amplifier

Active region - wider

basic amplifier $[-x_{i2}; x_{i2}]$

NF amplifier $[-x_{s2}; x_{s2}]$

Variation of the gain: $\dfrac{A_1 - A_2}{A_1} = \dfrac{1}{1 + a_2 r}\dfrac{a_1 - a_2}{a_1}$



Example

$a_1 = 100 \quad a_2 = 50 \quad r = 0.09$

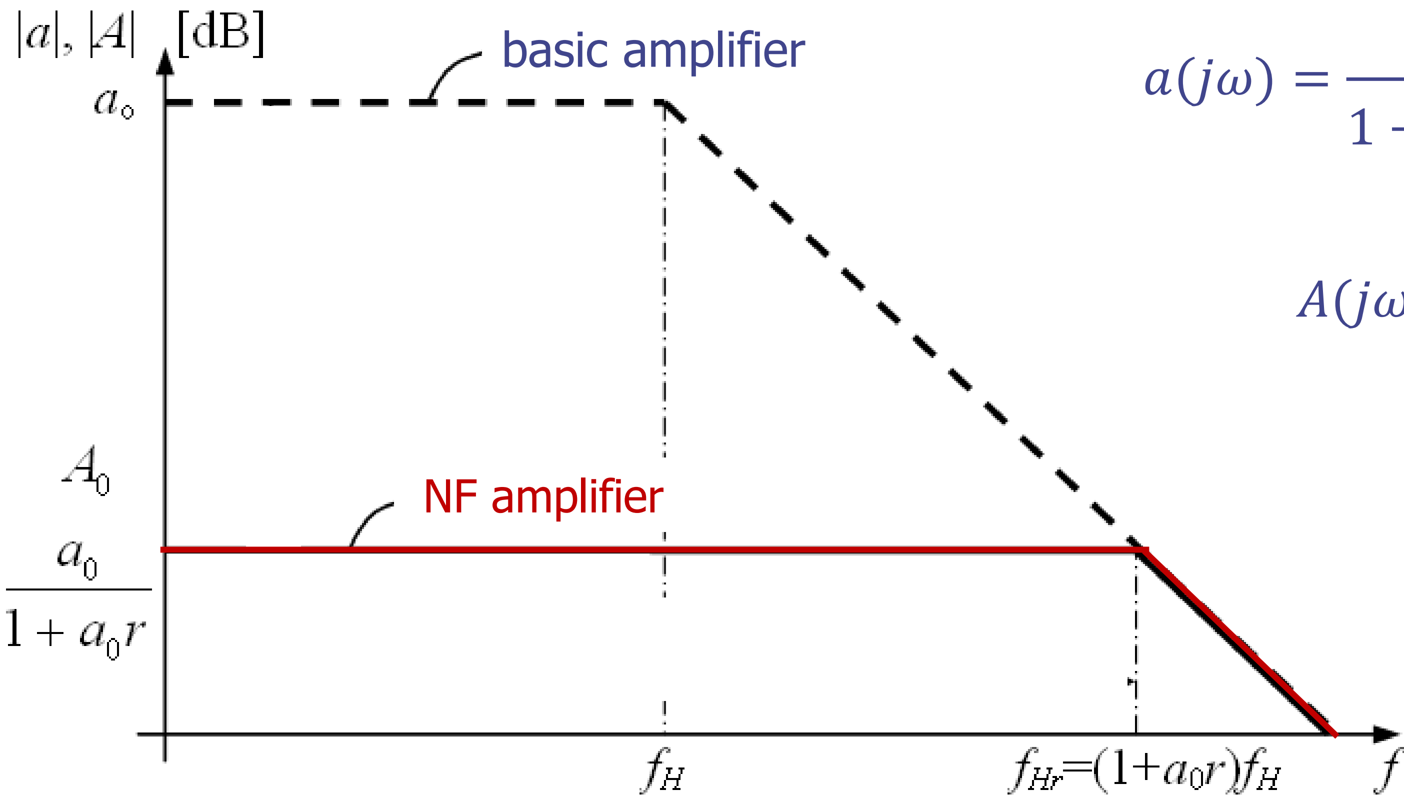
$$A_1 = \frac{100}{1 + 100 \cdot 0.09} = 10$$

$$A_2 = \frac{50}{1 + 50 \cdot 0.09} = 9.1$$

$$\frac{a_2 - a_1}{a_1} = 50\% \qquad \frac{A_2 - A_1}{A_1} = 9\%$$

➢ Effects of NF on the parameters of an amplifier

Bandwidth - wider



Low-pass-type amplifier

$$a(j\omega) = \frac{a_0}{1 + j\frac{\omega}{\omega_H}} = \frac{a_0}{1 + j\frac{f}{f_H}}$$

$$A(j\omega) = \frac{a(j\omega)}{1 + a(j\omega)r}$$

$$A_0 = \frac{a_0}{1 + a_0 r}$$

$$f_{Hr} = f_H(1 + a_0 r)$$

➢ Effects of NF on the parameters of an amplifier

Bandwidth - wider

	basic amplifier	NF amplifier
gain	a_0	$A_0 = \dfrac{a_0}{1 + a_0 r}$
bandwidth	$B = f_H$	$B_r = f_{Hr}$

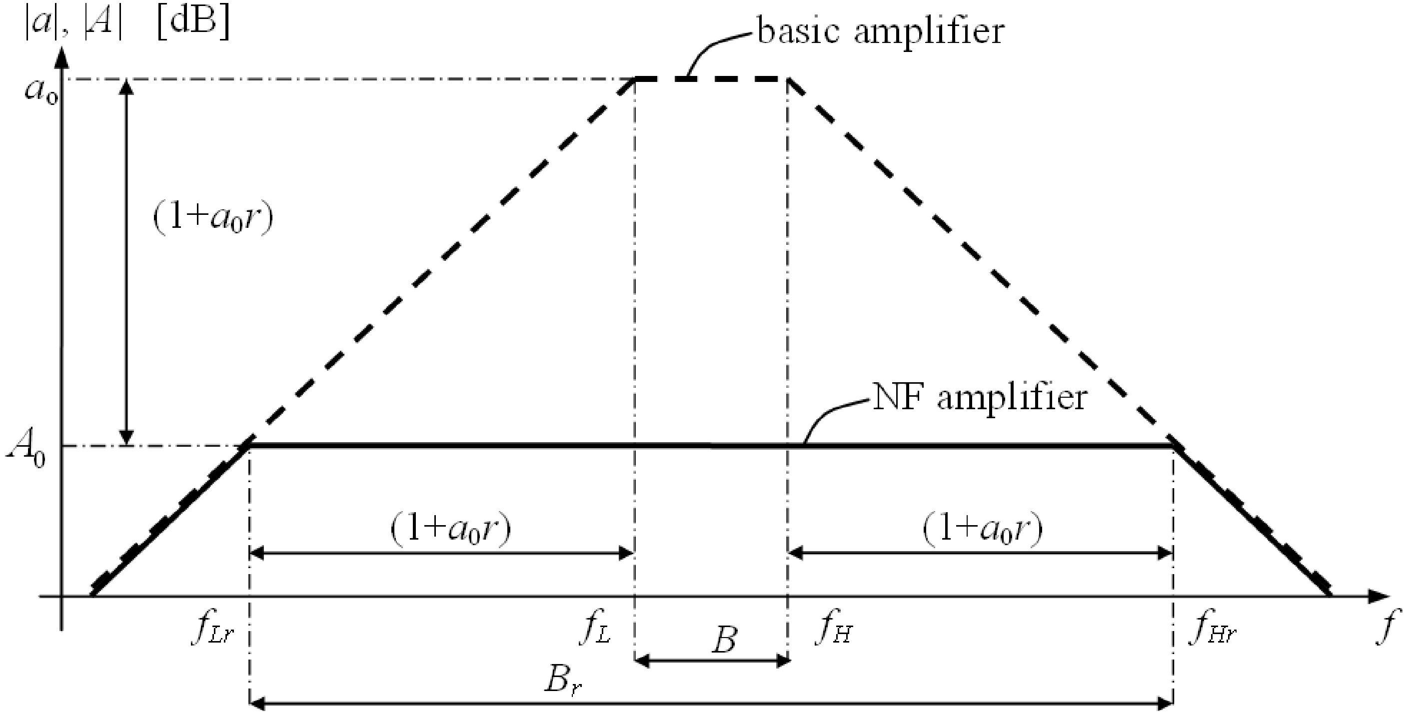
But $f_{Hr} = f_H(1 + a_0 r)$ so $B_r = (1 + a_0 r)B$

Consequence: $A_0 B_r = a_0 B$ constant **GBW** (gain-bandwidth product)

By adding NF, the gain **decreases** the same number of times the bandwidth **increases**.

➢ Effects of NF on the parameters of an amplifier

Bandwidth - wider

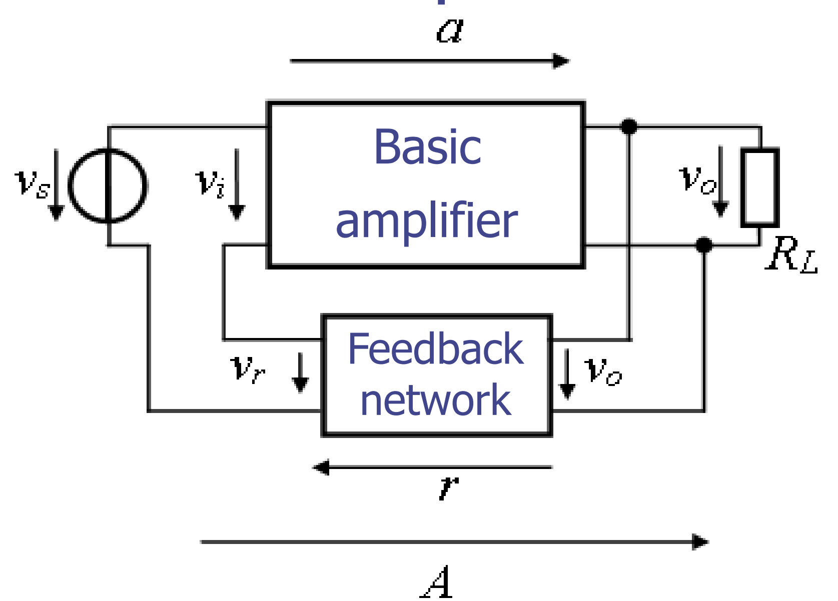


For high-pass-type amplifiers, the effect of adding NF is similar.

➢ Effects of NF on the parameters of an amplifier

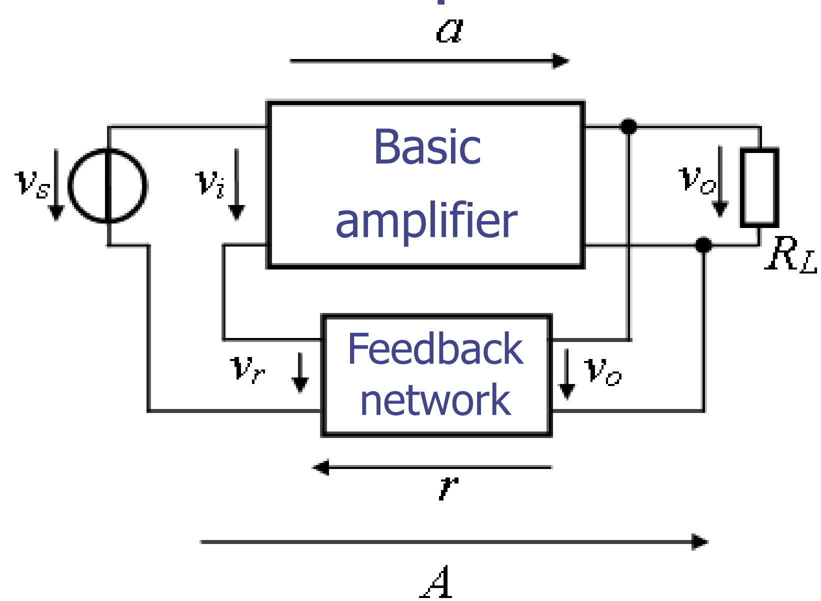
Example

$a = 1000$
$r = 0.099$



a) What is the relation between v_s, v_r and v_i?
b) What are the expression and value of the feedback gain, A?
c) What is the feedback topology?
d) If $v_s(t)$=50sinωt[mV] what are the expressions for $v_o(t)$, $v_r(t)$ and $v_i(t)$? Plot them.
e) If the input and output resistances of the basic amplifier are $R_i = 20$ KΩ, $R_o = 5$ KΩ, compute the input and output resistances of the feedback amplifier.
f) What is the bandwidth of the feedback amplifier if the basic amplifier is low-pass-type with 16 KHz bandwidth?

➢ Effects of NF on the parameters of an amplifier



Summary

- gain – reduced
- gain sensitivity – reduced
- nonlinear distortion – reduced
- active region - wider
- bandwidth – wider
- input and output impedances – improved

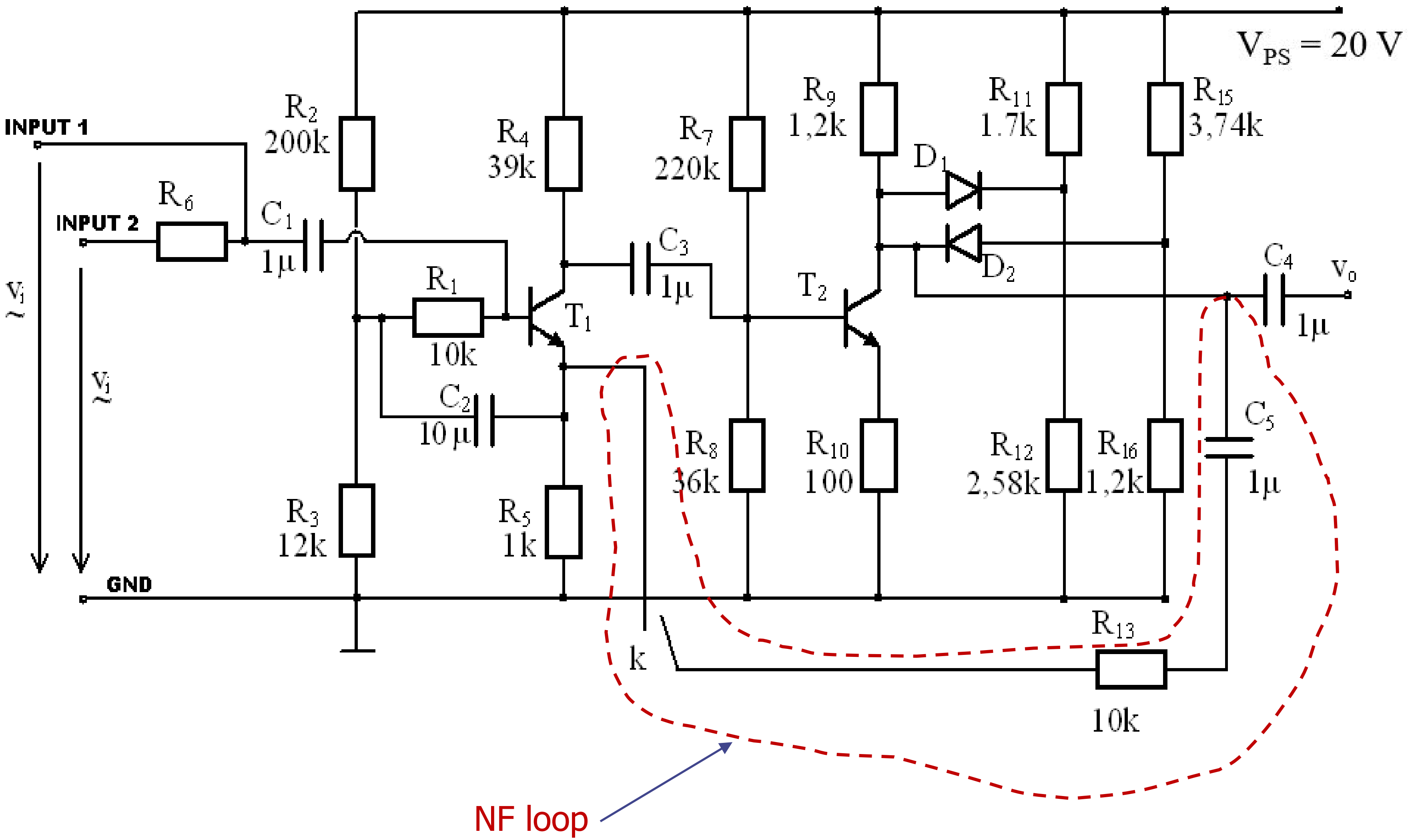
	basic amplifier	NF amplifier
gain	a_0	$A_0 = \frac{a_0}{1 + a_0 r}$
bandwidth	$B = f_H$	$B_r = (1 + a_0 r)B$

$$R_{ir} = R_i(1 + ar)$$

$$R_{or} = \frac{R_o}{1 + ar}$$

Adding Negative Feedback yields positive effects!

➢ An NF circuit w/out OpAmp



Summary

- Intro
- General structure
- Ideal feedback circuits
- Feedback topologies
- Analysis of the feedback amplifier
- Effects of NF on the parameters of an amplifier

Next week: DC voltage regulators