Announcements:

- Provide your feedback on Practical Lectures:
  - Please tap here to proceed…
- Reading material:
  - Microelectronics: Circuit Analysis and Design, Chapter 12:
    - Sec. 12.1 – Introduction to Feedback
    - Sec. 12.2 – Basic Feedback Concepts
    - Sec. 12.3 – Ideal Feedback Topologies
- Practice exercises:
  - Microelectronics: Circuit Analysis and Design, Chapter 12:
    - Ex. 12.1-12.7
- Assignment 2:
  - Release on LM (Week 7): 8PM Wednesday, 30 October
  - Due: 11:59PM Friday, 8 November (Week 8)
- Next lecture:
  - Week 8: No lectures – Reading week (office hours remain the same);
  - Week 9: New lecture: Stability of Amplifier Circuits with Feedback.
- Slides corrections:
  - Highlighted with blue font

Introduction to Feedback

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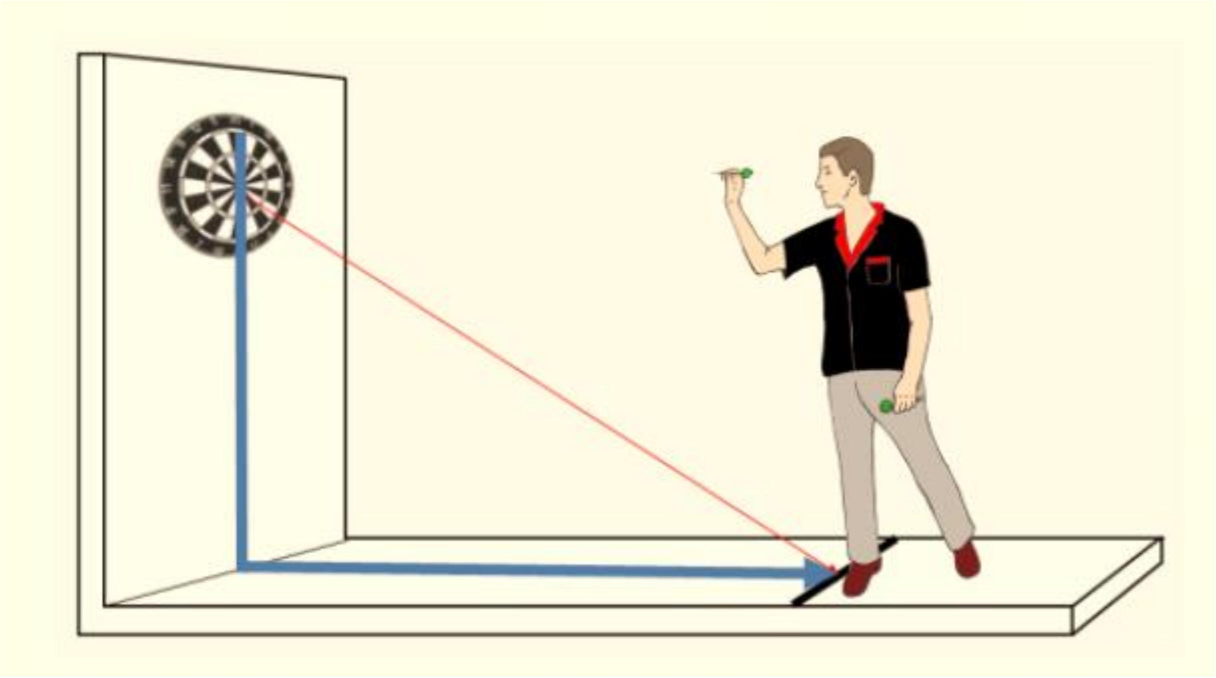
Outline

- Part 1: Introduction to Feedback:
  - Introduce the structure, terminology, and notations in the feedback control concept;
- Part 2: Basic Feedback Concepts
  - Analyze and obtain the transfer function of the ideal feedback system, and determine characteristics (advantages) of the feedback system;
- Part 3: Ideal Feedback Topologies:
  - Analyze a few ideal feedback amplifier circuit configurations and determine circuit characteristics including input and output resistances.

Part 1: Introduction to Feedback

What is feedback?

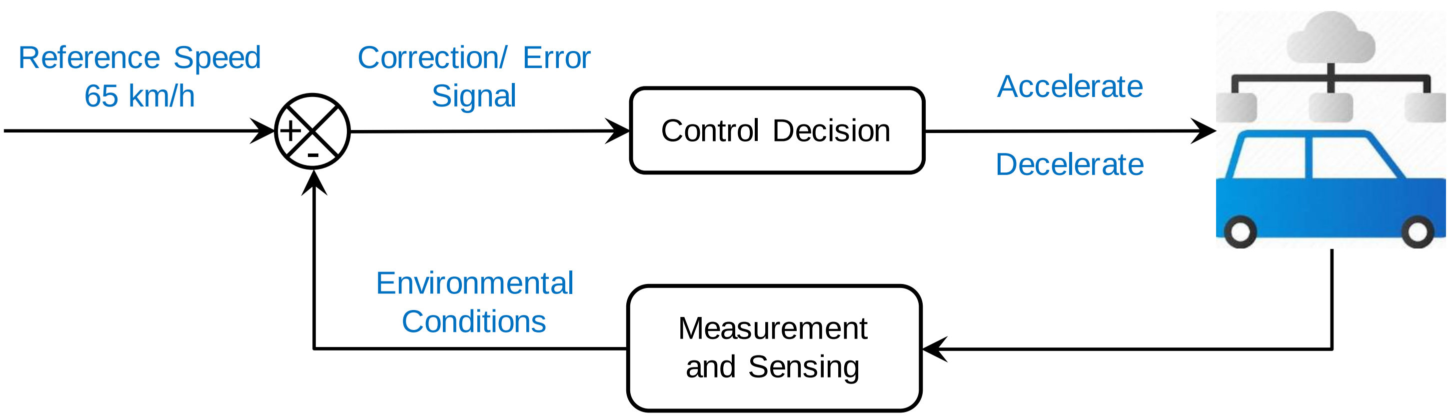
Example 1: Darts aim and throw



- If you fail at the first time, you will re-adjust the force and the direction to correct it
- This mechanism of **correction** based on the **output** is called **feedback**

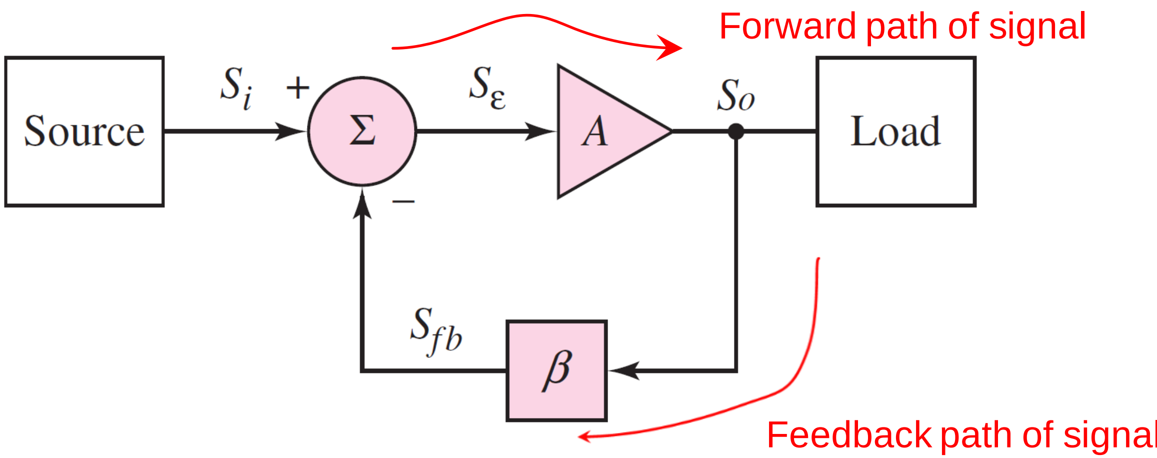
Example 2: Autopilot car driving

Any other examples?



Feedback Structure

In a feedback system, a signal that is **proportional to the output** is fed back to the input and **combined with the input signal** to produce a desired system response:



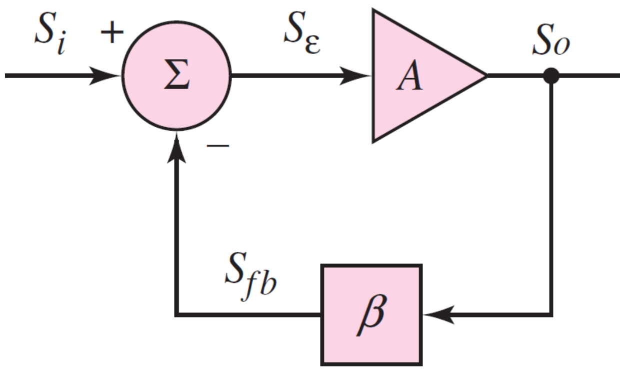
- S represents a signal of some description, it can be **either a voltage or a current**.
- The forward path **amplifies** the signal with a basic amplifier with an open-loop gain A
- The feedback path **samples** the output signal and produces a feedback signal S_{fb}, where β is feedback transfer function
- The feedback signal is **subtracted** from input source signal, producing error signal S_ϵ
- Notice the error signal is the input for the basic amplifier.

This is the structure of the ideal feedback system, which we will study in this lecture.

Ideal Closed-Loop Signal Gain

By saying ideal, we mean:

- The input signal transmits through the amplifier only and none through the feedback loop;
- The output signal transmits through the feedback loop only and none through the amplifier;
- No loading effects.



Let us analyze the system output wrt to input

1.From the figure, the output signal is:

$$S_o = A\,S_\varepsilon$$

2. At the summing node, we have:

$$S_\varepsilon = S_i - S_{fb}$$

3. The feedback signal is:

$$S_{fb} = \beta\,S_o$$

4.Therefore, the output is found as:

$$S_o = A\left(S_i - S_{fb}\right) = A\,S_i - \beta\,A\,S_o$$

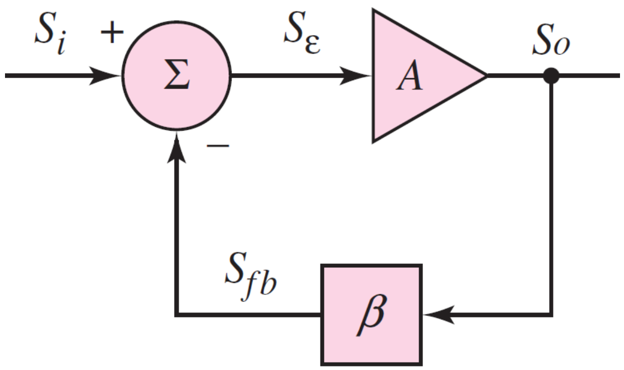
5.After rearrangement, the ideal **closed-loop gain** is found as:

$$A_f = \frac{S_o}{S_i} = \frac{A}{(1+\beta A)} = \frac{A}{(1+T)}$$

where $T = \beta A$ is the loop gain.

Terminology and Notions

$$A_f = \frac{S_o}{S_i} = \frac{A}{(1+\beta A)} = \frac{A}{(1+T)}$$



A_f is the closed-loop gain

A is the open-loop gain

β is the feedback transfer function

$T = \beta A$ is called loop gain

$1 + \beta A$ is called feedback factor

Notice since $S_o = A\, S_\varepsilon$ and $S_{fb} = \beta\, S_o$. Therefore, we have:

$$T = \beta A = S_{fb}/S_\varepsilon$$

In general, the magnitude and phase of the loop gain are also functions of frequency (of the input signal) and they become important for determining the stability of the feedback circuits (will see later).

Normally, the error signal is small, so the expected **loop gain** is large. If the **loop gain** is very large ($\beta A \gg 1$), then:

$$A_f = \frac{S_o}{S_i} = \frac{A}{(1+\beta A)} \approx \frac{A}{\beta A} = \frac{1}{\beta}$$

and <u>the **closed loop gain** is dependent on the **feedback transfer function** only</u>.

<u>**This is a very important result, indicating that**</u>

- the overall system gain is **no longer dependent** on the gain of the amplifier (A)
- Just make sure that the open loop gain of the amplifier is **large**, so that $\beta A \gg 1$ and the closed-loop gain will be instead set by the **feedback fraction**
- In electronic systems, this often just involves **choosing some resistors** that can be tightly controlled quite easily – and adjusted if desired

Also notice that the closed-loop gain is **reduced** by the feedback factor $(1+\beta A)$ (because this is negative feedback). This quantity is given its special name because it occurs so frequently in feedback theory – <u>it is this same factor by which almost every property of the amplifier circuit is changed e.g. input and output impedances as well as bandwidth</u>

Exercise

Calculate the required feedback transfer function β for the open-loop gain 10^5 to obtain the closed-loop gain 50.

Solution

1. According to the feedback equation, we have

$$A_f = \frac{A}{(1+\beta A)} \quad \text{or} \quad 50 = \frac{10^5}{\left(1+\beta(10^5)\right)}$$

2. Therefore, $\beta = 0.01999$

Note that $A_f \cong \frac{1}{\beta} = 50.025$

It verifies that if the open-loop gain is large enough, the closed-loop gain is set by the feedback transfer function only.

Part 2: Basic Feedback Concepts

Gain Sensitivity of the feedback system

The sensitivity can be quantified by taking the derivative of A_f with respect to A, while assuming β being a constant:

$$A_f = \frac{S_o}{S_i} = \frac{A}{(1+\beta A)}$$

$$\frac{dA_f}{dA} = \frac{1}{(1+\beta A)} - \frac{A}{(1+\beta A)^2}\beta = \frac{1}{(1+\beta A)^2} \quad \text{or} \quad dA_f = \frac{dA}{(1+\beta A)^2}$$

Dividing both sides by the closed-loop gain A_f yields:

$$\frac{dA_f}{A_f} = \frac{\frac{dA}{(1+\beta A)^2}}{\frac{A}{(1+\beta A)}} = \frac{1}{(1+\beta A)} \cdot \frac{dA}{A}$$

The change in the open-loop gain A of an amplifier (e.g., due to the temperature variation), leads to $(1+\beta A)$ times smaller change in the closed-loop gain A_f.

Exercise

Consider a general feedback system with parameters $A = 5 \cdot 10^5$ and $A_f = 50$. Calculate the closed-loop gain when open-loop gain is decreased by 15%. What is the corresponding percentage change?

Solution

1. According to the feedback gain equation, we have:

$$A_f(A) = \frac{A}{(1 + \beta A)}$$

2. Therefore, the feedback transfer function is:

$$\beta = \frac{1}{A_f} - \frac{1}{A} = 0.019998$$

3. For 15% decrease of the open-loop gain, closed-loop gain is:

$$A_f(0.85 \cdot A) = \frac{0.85 \cdot A}{(1 + 0.85 \cdot \beta A)} \approx 49.999$$

4. In relative values:

$$\frac{dA_f}{A_f} = \frac{49.999 - 50}{50} = -0.002\%$$

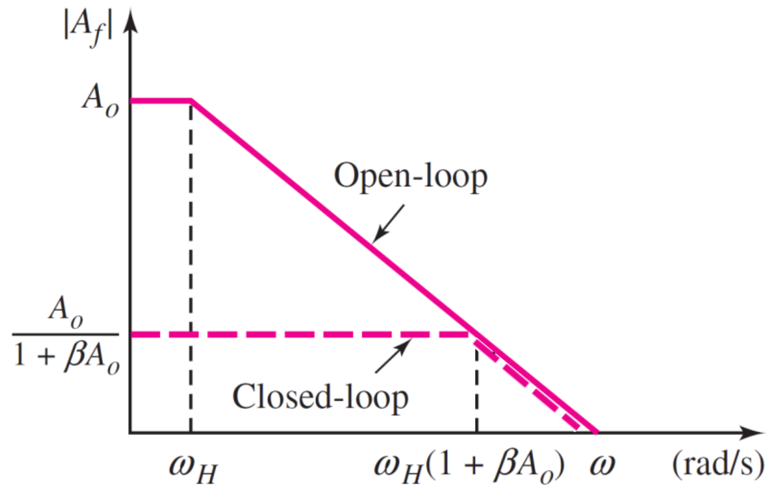
Bandwidth Extension of the feedback system

Assuming the frequency response of a basic amplifier (without feedback) is characterized by a single pole, we can write:

$$A(s) = \frac{A_o}{1 + \frac{s}{\omega_H}}$$

A_o: low-frequency or midband gain

ω_H: upper 3 dB or corner frequency



For the closed-loop gain:

$$A_f(s) = \frac{A(s)}{(1+\beta A(s))} = \frac{\frac{A_o}{1+\frac{s}{\omega_H}}}{\left(1+\beta\frac{A_o}{1+\frac{s}{\omega_H}}\right)} =$$

$$= \frac{A_o}{(1+\beta A_o)} \cdot \frac{1}{1+\frac{s}{\omega_H(1+\beta A_o)}}$$

$\frac{A_o}{(1+\beta A_o)}$: Low frequency closed-loop gain (A_{fo})

$\omega_H(1+\beta A_o)$: Upper 3 dB frequency (ω_{fH})

We can observe that the gain-bandwidth product will give:

$$A_{fo}\omega_{fH} = \frac{A_o}{(1+\beta A_o)} \cdot \omega_H(1+\beta A_o) =$$

$$= A_o\omega_H$$ – **constant value**

- The low-frequency closed loop gain is **reduced** by a factor of $(1+\beta A_o)$;
- The bandwidth is **extended** by a factor of $(1+\beta A_o)$;
- Therefore, the gain-bandwidth product is essentially a constant.

Exercise

Consider a feedback amplifier with an open-loop low-frequency gain of $A_0 = 10^4$, an open-loop bandwidth of $\omega_H = 2\pi \times 100\ rad/s$, and a closed-loop low-frequency gain $A_f(0) = 50$. Determine the bandwidth of a feedback amplifier ω_{fH}

Solution:

1. Low frequency closed-loop gain is expressed: $A_f(0) = \dfrac{A_0}{1 + \beta A_0}$

2. The feedback factor is then found: $1 + \beta A_0 = \dfrac{A_0}{A_f(0)} = \dfrac{10^4}{50} = 200$

3. The closed-loop bandwidth is feedback factor times more than the open-loop:

$$\omega_{fH} = \omega_H(1 + \beta A_0) = 2\pi \times 100 \frac{rad}{s} \times 200 = 2\pi \times 20{,}000 \frac{rad}{s}$$

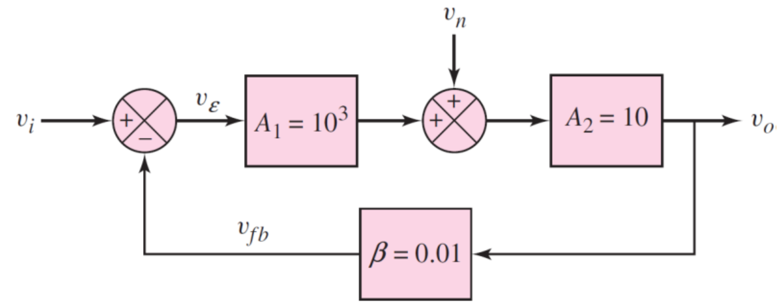
Noise Sensitivity

Noise signal generated within an amplifier can be reduced significantly with the feedback.

First, let us make few definitions:

- The input signal-to-noise ratio: $SNR_i = \frac{S_i}{N_i} = \frac{v_i}{v_n}$ – input source signal, – input noise signal
- The output signal-to-noise ratio: $SNR_o = \frac{S_o}{N_o} = \frac{A_i\, S_i}{A_n\, N_i}$

Consider two amplifiers, where the noise signal is generated between them:



1. The output voltage is: $v_o = A_1 A_2 v_\varepsilon + A_2 v_n$

2. Where the error signal is: $v_\varepsilon = v_i - v_{fb} = v_i - \beta v_o$

3. Solving 1. for v_o will give: $v_o = \frac{A_1 A_2}{(1 + \beta A_1 A_2)} \cdot v_i + \frac{A_2}{(1 + \beta A_1 A_2)} \cdot v_n \cong \frac{1}{\beta} \cdot v_i + \frac{1}{\beta A_1} \cdot v_n$

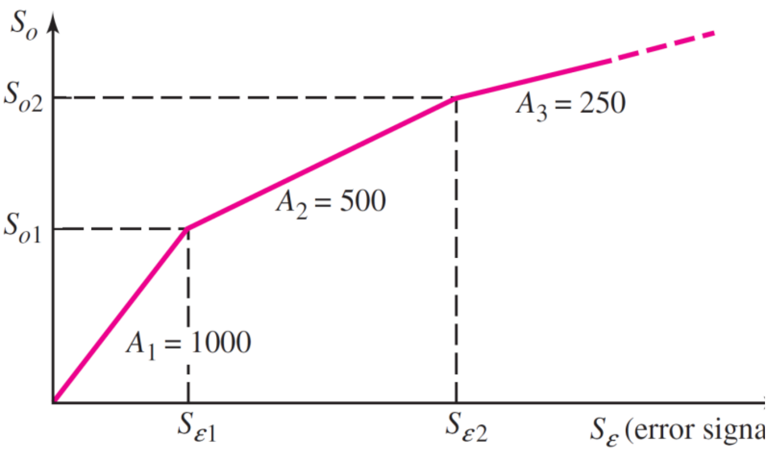
4. Finally, the output SNR: $SNR_o = \frac{S_o}{N_o} = \frac{1/\beta \cdot v_i}{1/\beta A_1 \cdot v_n} = A_1 \frac{S_i}{N_i}$

A large signal-to-noise ratio allows the signal to be detected without any loss of information.

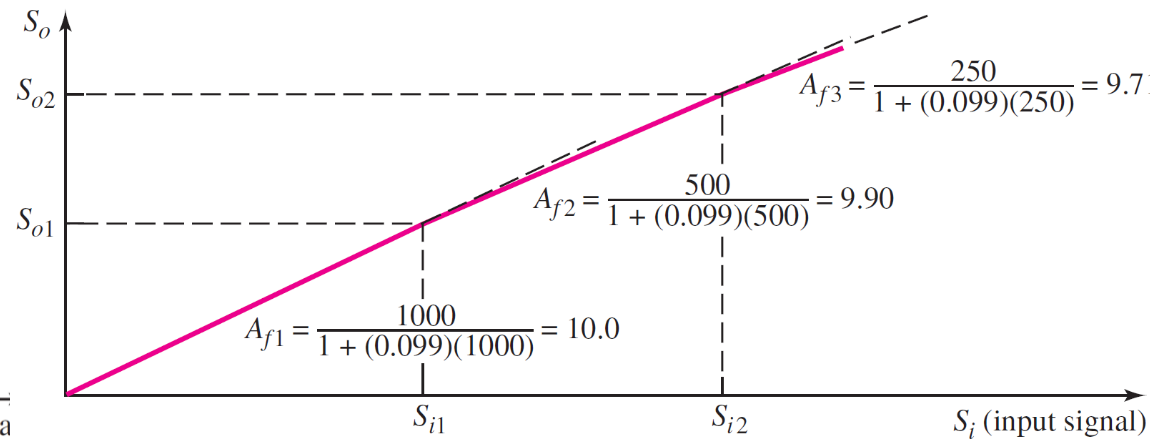
Nonlinear Distortion of the feedback system

Distortion in an output signal is caused by **a change in the basic amplifier gain**, which relates to the nonlinear properties of BJT transistors:

For example, let us assume that the basic amplifier gain is:



For $\beta = 0.099$, the closed-loop gain will look as follows:



- Whereas the open-loop gain changes by a factor of 2, the closed loop gain changes by only 1% and 2%
- A smaller change in gain means **less distortion**

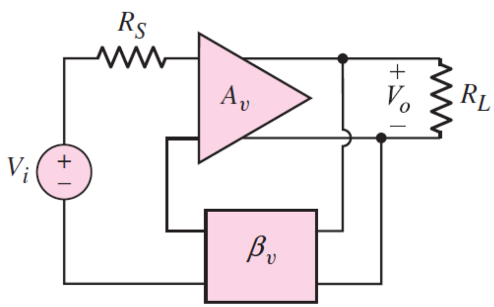
Part 3:
Ideal Feedback Topologies

Basic Feedback Circuit Connection

There are four basic feedback topologies, based on the parameter to be amplified (voltage or current) and the output parameter (voltage or current).

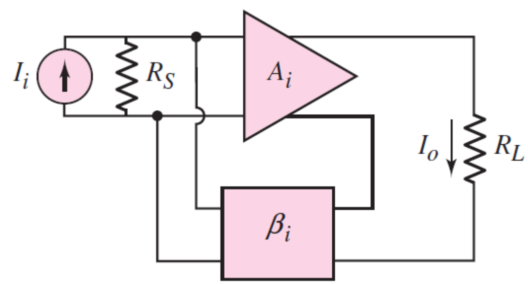
These topologies are distinguished by the types of feedback connections at the input and output of circuits, respectively:

Voltage amplifier:



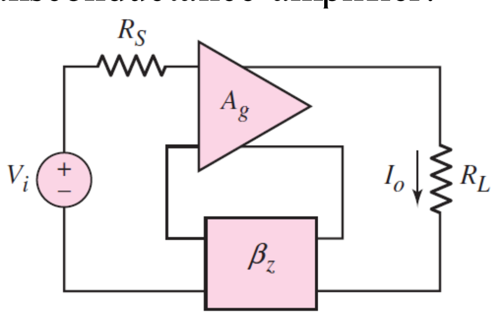
(a) Series–shunt

Current amplifier:



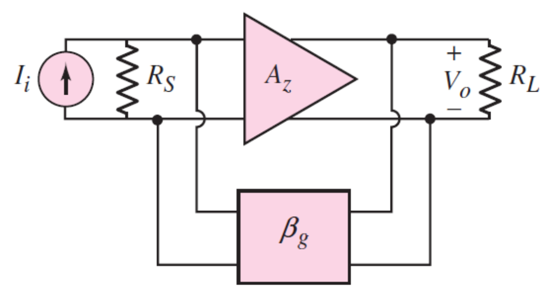
(b) Shunt–series

Transconductance amplifier:



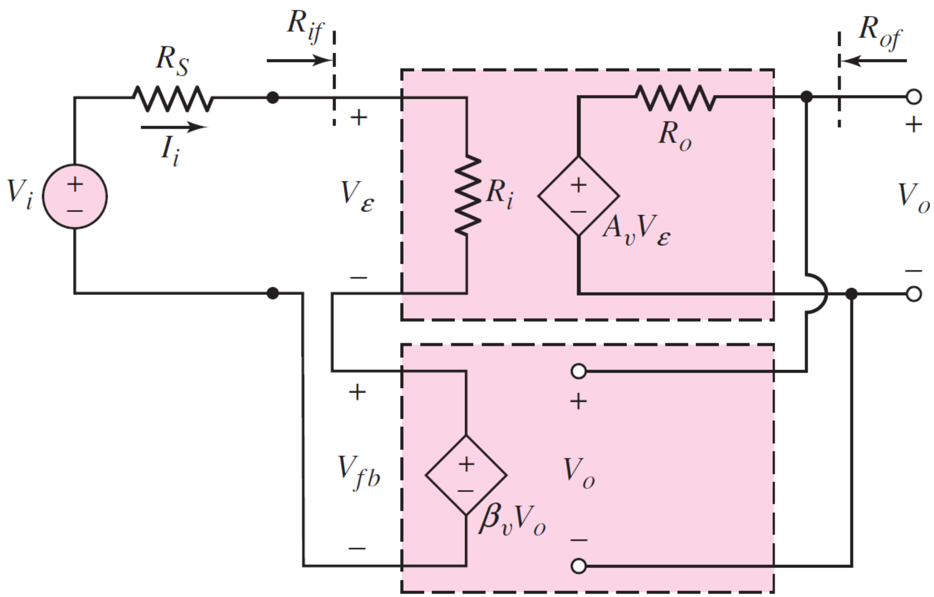
(c) Series–series

Transresistance amplifier:



(d) Shunt–shunt

Series-Shunt Configuration (voltage amplifier):



- The circuit consists of a basic voltage amplifier with an input resistance R_i and open-loop voltage gain A_v;
- The feedback circuit samples the output voltage and produces a feedback voltage V_{fb}, which is in series with the input voltage V_i;
- The error signal voltage $V_\varepsilon = V_i - V_{fb}$ is amplified in the basic voltage amplifier (negative feedback loop).

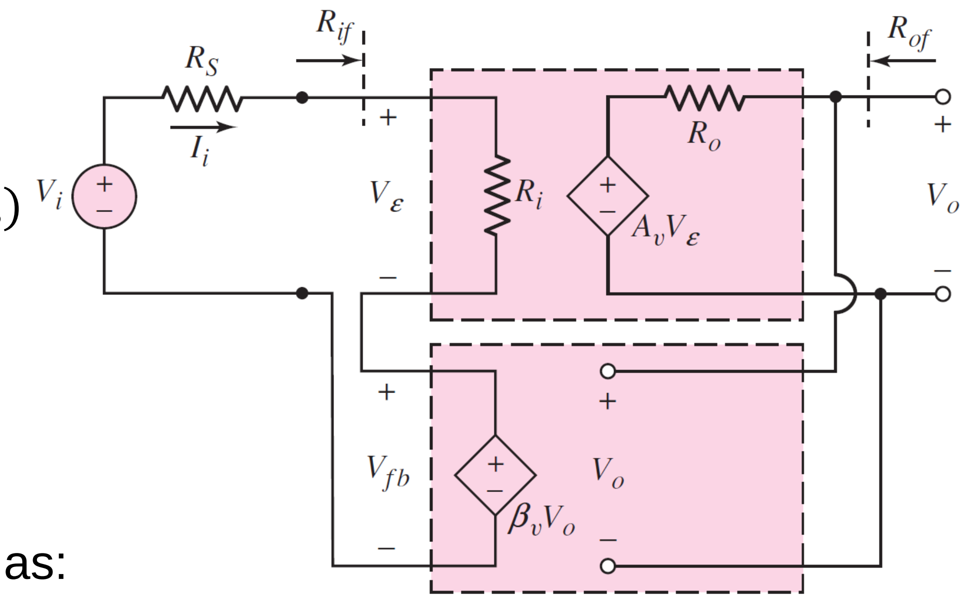
Let us analyze the circuit using electric laws (i.e., KVL):

1. If the output voltage is: $V_o = A_v V_\varepsilon$

2. The feedback voltage is: $V_{fb} = \beta_v V_o$

3. The voltage transfer function is then: $A_{vf} = \dfrac{V_o}{V_i} = \dfrac{A_v V_\varepsilon}{V_\varepsilon + V_{fb}} = \dfrac{A_v}{1 + \beta_v A_v}$

Series-Shunt Configuration (voltage amplifier):



Input resistance (R_{if})

1. Applying KVL to the input loop:

$$V_i = V_\varepsilon + V_{fb} = V_\varepsilon + \beta_v V_o = V_\varepsilon(1 + \beta_v A_v)$$

2. Finding V_ε will give:

$$V_\varepsilon = \frac{V_i}{(1 + \beta_v A_v)}$$

3. Now the input current can be found as:

$$I_i = \frac{V_\varepsilon}{R_i} = \frac{V_i}{R_i(1 + \beta_v A_v)}$$

4. The effective **input resistance** of the series input connection is:

$$R_{if} = \frac{V_i}{I_i} = R_i(1 + \beta_v A_v)$$

A large input resistance is a desirable property of a voltage amplifier. This eliminates loading effects on the input signal source.

Series-Shunt Configuration (voltage amplifier):

Output resistance (R_{of})

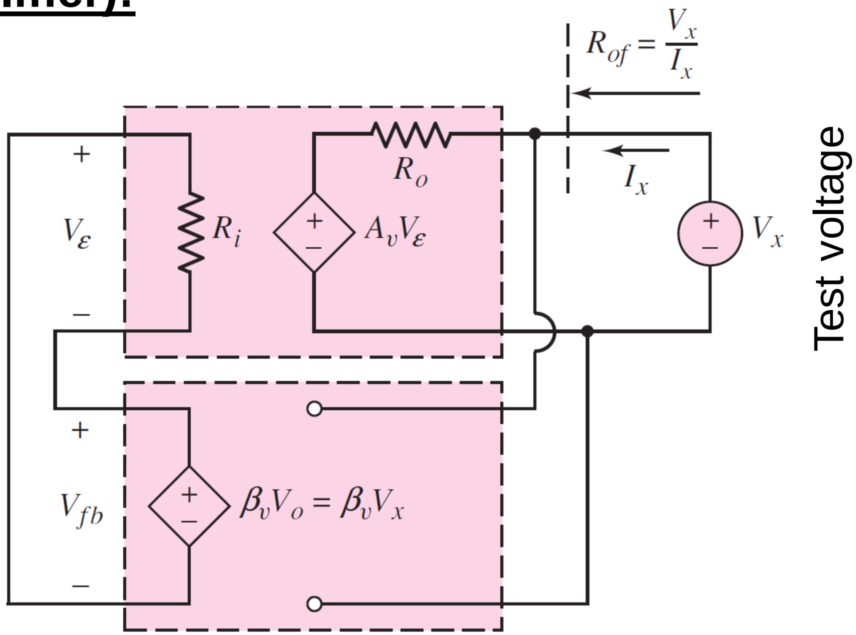
0. Short-circuit input and apply test voltage to the output;

1. Applying KVL to the input loop:

$$V_\varepsilon = -\beta_v V_x$$

2. From the output loop, the output current can be found as:

$$I_x = \frac{V_x - A_v V_\varepsilon}{R_o} = \frac{V_x(1 + \beta_v A_v)}{R_o}$$



3. The effective **output resistance** of the shunt output connection is:

$$R_{of} = \frac{V_x}{I_x} = \frac{R_o}{(1 + \beta_v A_v)}$$

A small output resistance is a desirable property of a voltage amplifier. This eliminates loading effects on the output signal when an output load is connected.

Exercise: Consider a series–shunt feedback amplifier in which the open-loop gain is $A_v = 10^5$ and the closed-loop gain is $A_f = 50$. Assume the input and output resistances of the basic amplifier are $R_i = 10$ kOhm and $R_o = 20$ kOhm, respectively.

Task: Calculate the input resistance of a series input connection and the output resistance of a shunt output connection for an ideal feedback voltage amplifier.

Solution:

1. The voltage transfer function of an ideal voltage amplifier with feedback is:

$$A_{vf} = \frac{V_o}{V_i} = \frac{A_v V_\varepsilon}{V_\varepsilon + \beta_v A_v V_\varepsilon} = \frac{A_v}{1 + \beta_v A_v}$$

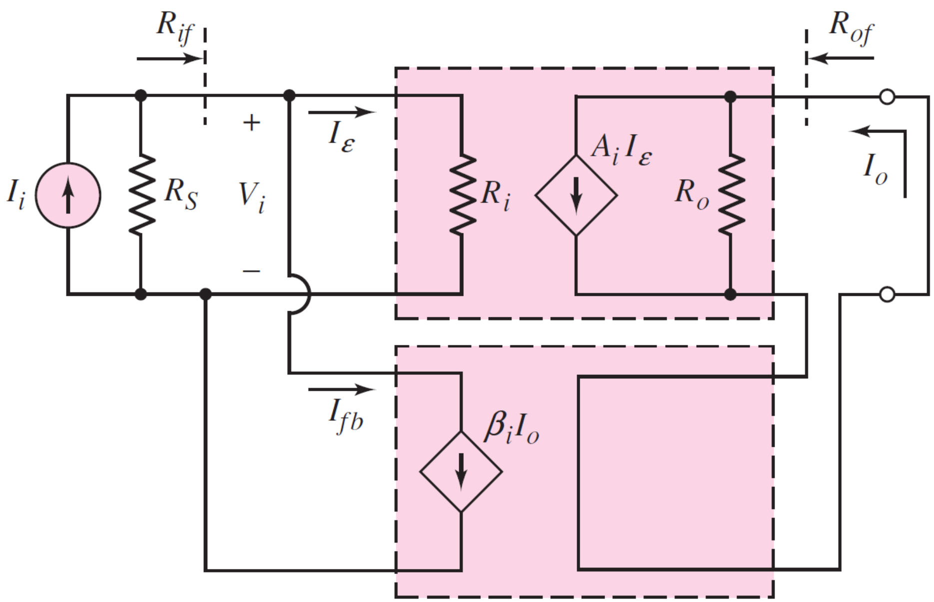
2. Therefore, the feedback factor is: $1 + \beta_v A_v = \dfrac{A_v}{A_{vf}} = 2{,}000$

3. The input resistance is: $R_{if} = R_i(1 + \beta_v A_v) = 20$ MOhm

4. The output resistance is: $R_{of} = \dfrac{R_o}{(1 + \beta_v A_v)} = 10\ \mathrm{Ohm}$

With a series input connection, the input resistance increases drastically, and with a shunt output connection, the output resistance decreases substantially, with negative feedback. These are the desired characteristics of a voltage amplifier.

Shunt-Series Configuration (current amplifier):



- The circuit consists of a basic current amplifier with an input resistance R_i and open-loop current gain A_i;
- The feedback circuit samples the output current and produces a feedback current I_{fb}, which is in shunt with the input current I_i.
- The error signal current $I_\varepsilon = I_i - I_{fb}$ is amplified in the basic current amplifier (negative feedback loop).

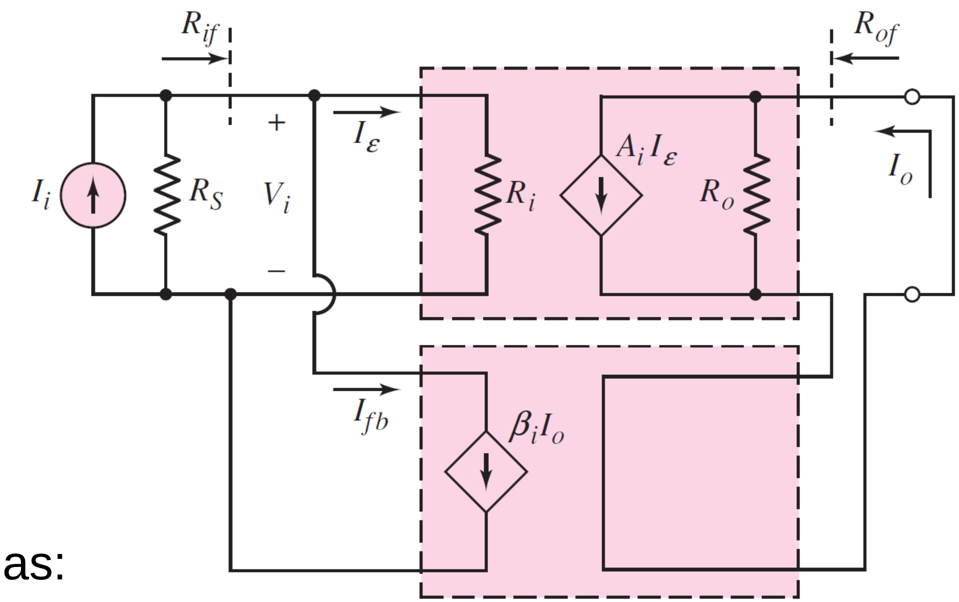
Let us analyze the circuit using electric laws (i.e., KCL):

1. In short circuit output: $I_o = A_i I_\varepsilon$

2. The feedback current is: $I_{fb} = \beta_i I_o$

3. The current transfer function is then: $A_{if} = \dfrac{I_o}{I_i} = \dfrac{A_i I_\varepsilon}{I_\varepsilon + \beta_i A_i I_\varepsilon} = \dfrac{A_i}{1 + \beta_i A_i}$

Shunt-Series Configuration (current amplifier):



Input resistance (R_{if})

1. Applying KCL to the input circuit:

$$I_i = I_\varepsilon + I_{fb} = I_\varepsilon + \beta_i I_o = I_\varepsilon(1 + \beta_i A_i)$$

2. Finding I_ε will give:

$$I_\varepsilon = \frac{I_i}{(1 + \beta_i A_i)}$$

3. Now the input voltage can be found as:

$$V_i = I_\varepsilon R_i = \frac{I_i R_i}{(1 + \beta_i A_i)}$$

4. The effective **input resistance** of the shunt input connection is:

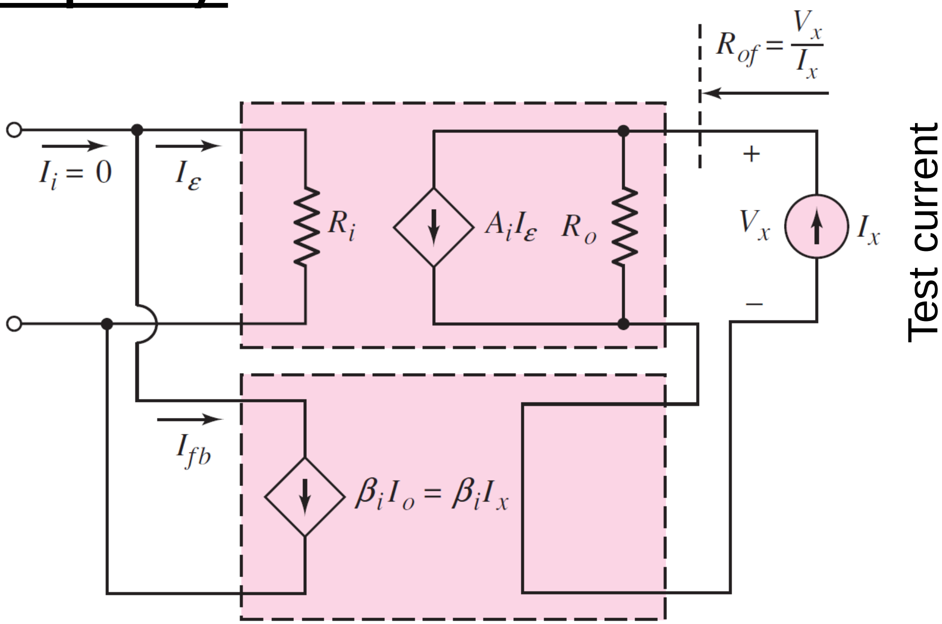
$$R_{if} = \frac{V_i}{I_i} = \frac{R_i}{(1 + \beta_v A_v)}$$

A small input resistance is a desirable property of a current amplifier, to avoid loading effects on the input signal current source.

Shunt-Series Configuration (current amplifier):

Output resistance (R_{of})

0. Open-circuit input and apply test current to the output;



1. Applying KCL to the input circuit:

$$I_\varepsilon = -\beta_i I_x$$

2. From the output loop, the output voltage can be found as:

$$V_x = (I_x - A_i I_\varepsilon)R_o = [I_x - A_i(-\beta_i I_x)]R_o = I_x(1 + \beta_i A_i)R_o$$

3. The effective **output resistance** of the series output connection is:

$$R_{of} = \frac{V_x}{I_x} = (1 + \beta_i A_i)R_o$$

A large output resistance is a desirable property of a current amplifier, to avoid loading effects on the output due to a load connected to the amplifier output.

Exercise: Consider a shunt–series feedback amplifier in which the open-loop gain is $A_i = 10^5$ and the closed-loop gain is $A_f = 50$. Assume the input and output resistances of the basic amplifier are $R_i = 10$ kOhm and $R_o = 20$ kOhm, respectively.

Task: Calculate the input resistance of a shunt input connection and the output resistance of a series output connection for an ideal feedback current amplifier.

Solution:

1. The current transfer function of an ideal feedback current amplifier is:

$$A_{if} = \frac{I_o}{I_i} = \frac{A_i I_\varepsilon}{I_\varepsilon + \beta_i A_i I_\varepsilon} = \frac{A_i}{1 + \beta_i A_i}$$

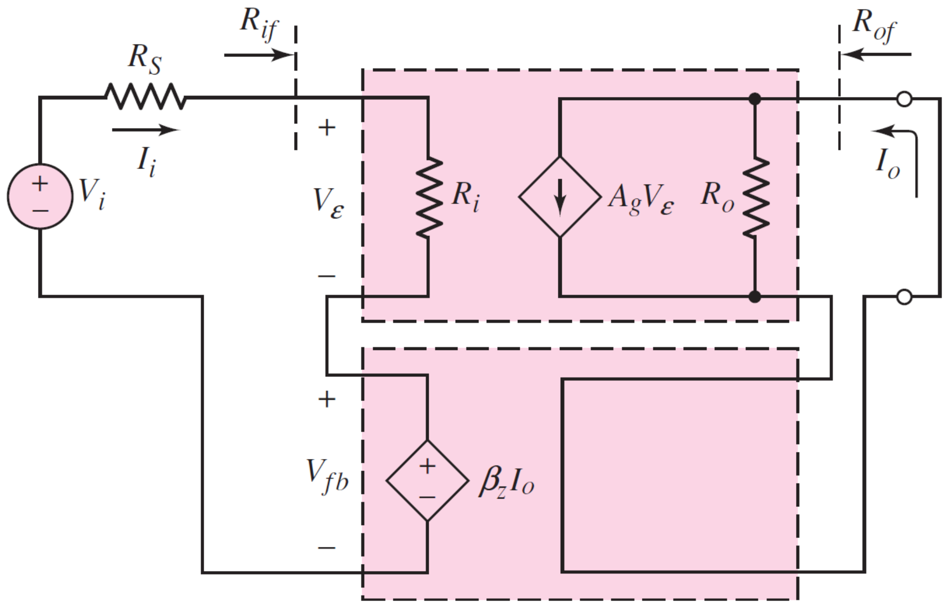
2. Therefore, the feedback factor is: $1 + \beta_i A_i = \dfrac{A_i}{A_{if}} = 2{,}000$

3. The input resistance is: $R_{if} = \dfrac{R_i}{(1 + \beta_v A_v)} = 5$ Ohm

4. The output resistance is: $R_{of} = R_o(1 + \beta_v A_v) = 40\ \mathrm{MOhm}$

With a shunt input connection, the input resistance decreases drastically, and with a series output connection, the output resistance increases substantially, assuming negative feedback. These are the desired characteristics of a current amplifier.

Series-Series Configuration (transconductance amplifier):



- The circuit consists of a basic amplifier that converts the error voltage to an output current with a gain A_g and an input resistance R_i;
- The feedback circuit samples the output current and produces a feedback voltage V_{fb}, which is in series with the input signal voltage V_i;
- The error signal voltage $V_\varepsilon = V_i - V_{fb}$ is amplified in the basic amplifier, creating the negative feedback loop.

Let us analyze the circuit:

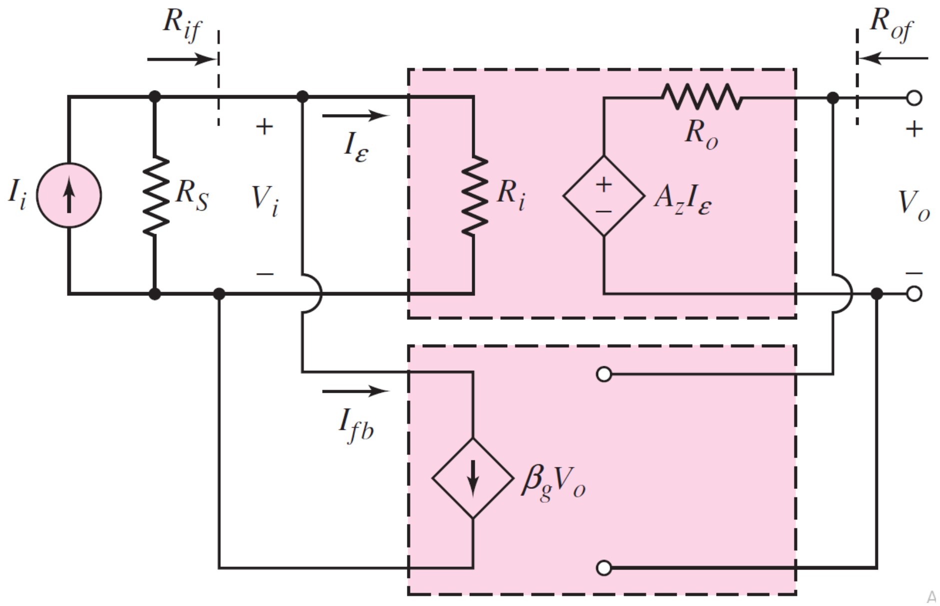
1. In short circuit output: $I_o = A_g V_\varepsilon$

2. The feedback voltage is: $V_{fb} = \beta_z I_o$

3. The current-to-voltage transfer function: $A_{gf} = \frac{I_o}{V_i} = \frac{A_g V_\varepsilon}{V_\varepsilon + \beta_z A_g V_\varepsilon} = \frac{A_g}{1 + \beta_z A_g}$

4. Input and output resistances: **Try deriving them on your own!!!**

Shunt-Shunt Configuration (transresistance amplifier):



- The circuit consists of a basic amplifier that converts the error current to an output voltage with a gain A_z and an input resistance R_i;
- The feedback circuit samples the output voltage and produces a feedback current I_{fb}, which is in shunt with the input signal current I_i;
- The error signal current $I_\varepsilon = I_i - I_{fb}$ is amplified in the basic amplifier, creating the negative feedback loop.

Let us analyze the circuit :

1. In open circuit output: $V_o = A_z I_\varepsilon$
2. The feedback current is: $I_{fb} = \beta_g V_o$
3. The voltage-to-current transfer function: $A_{zf} = \dfrac{V_o}{I_i} = \dfrac{A_z I_\varepsilon}{I_\varepsilon + \beta_g A_z I_\varepsilon} = \dfrac{A_z}{1 + \beta_g A_z}$
4. Input and output resistances: **Try deriving them on your own!!!**

Methods for identifying feedback connections

Input side:

Method 1: If the feedback affects input signal in terms of voltage, it is voltage application (series applied); otherwise, if the feedback affects input signal in terms of current it is current application (shunt applied)

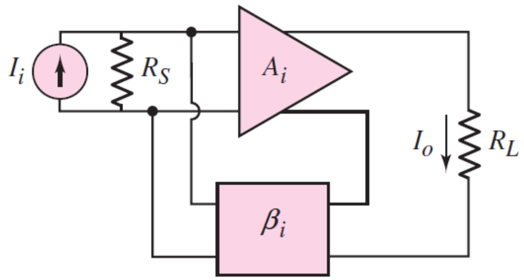
Method 2: if the feedback loop is connected to the same input terminal as the signal source, it is current application (shunt applied); otherwise, it is voltage application (series applied) ***(Recommended)***

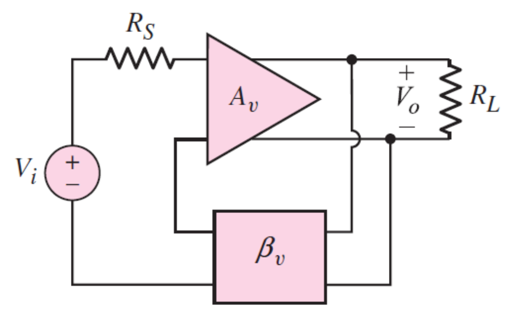
Output side:

Method 1: Short-circuit the output voltage/load, if the feedback signal disappears, it is voltage sensing (shunt derived); otherwise, it is current sensing (series derived) ***(Recommended)***

Method 2: If the feedback is directly connected to the output terminal (positive side), it is voltage sensing (shunt derived); otherwise, it is current sensing (series derived) ***(More convenient but prone to mistake)***

Consider two distinct feedback topologies:





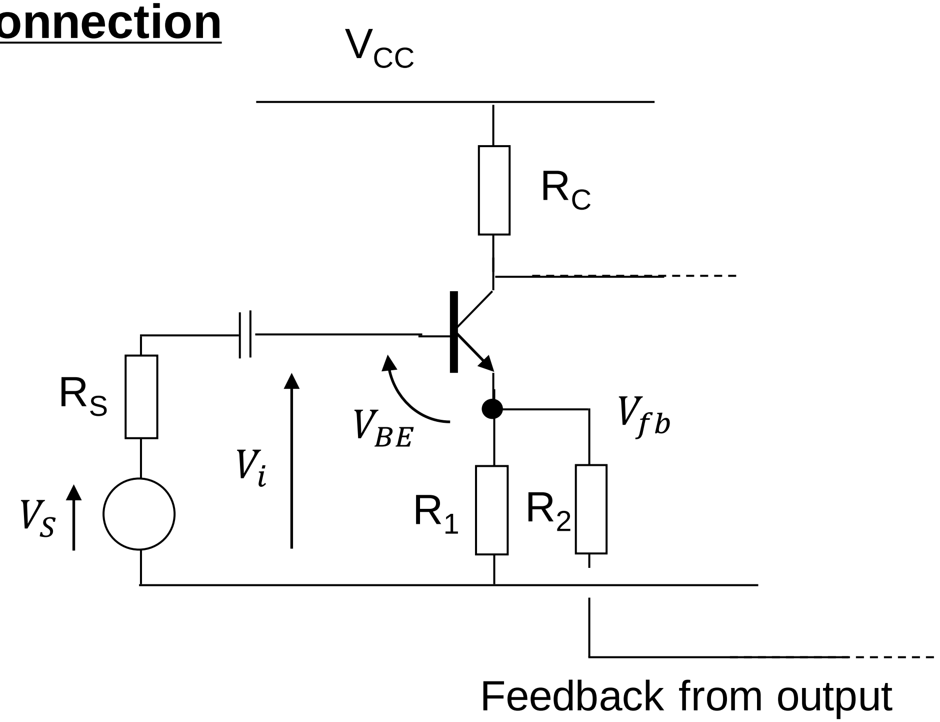
Some Practical Examples – Input Connection

Applying Method 1:

- The input signal is connected to the base of the transistor; the feedback loop is connected to the emitter terminal
- The feedback loop affects the input signal in terms of voltage:

$$V_{BE} = V_i - V_{fb} = V_\varepsilon$$

- It is therefore a ***SERIES APPLIED*** feedback

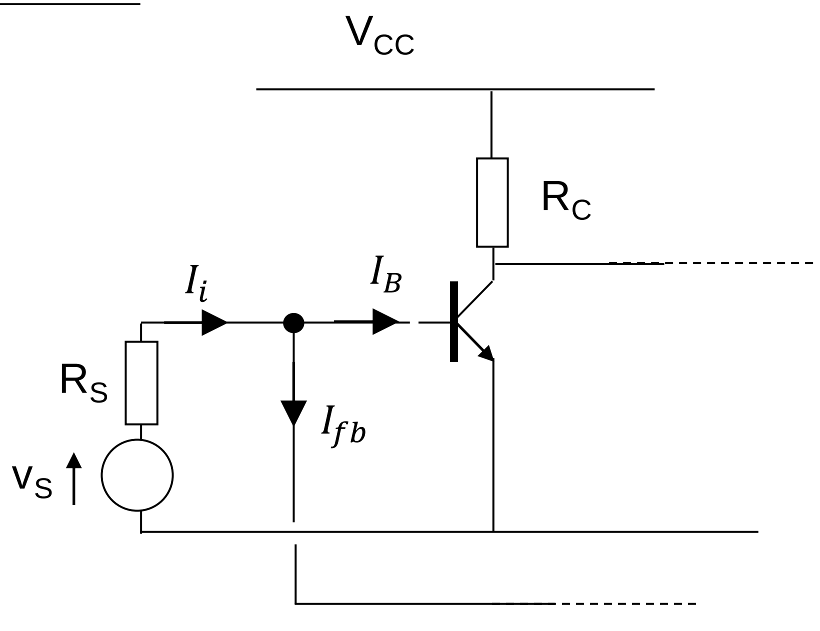


Applying Method 2:

- The feedback is not connected to the same terminal as signal source
- It is therefore voltage application - ***SERIES APPLIED*** feedback

The input impedance will therefore be increased by this series applied feedback connection

Some Practical Examples – Input Connection



Applying Method 1:

- The input signal is connected to the base of the transistor; the feedback loop is also connected to the base terminal
- Therefore, according to KCL the feedback signal affects the input signal in terms of current:

$$I_B = I_i - I_{fb} = I_\varepsilon$$

- It is therefore a ***SHUNT APPLIED*** feedback

The input impedance will therefore be reduced by this shunt applied feedback connection

Applying Method 2:

- The feedback loop is connected to the same terminal as the signal source, in this case, the base of the transistor
- It is therefore current application – ***SHUNT APPLED***

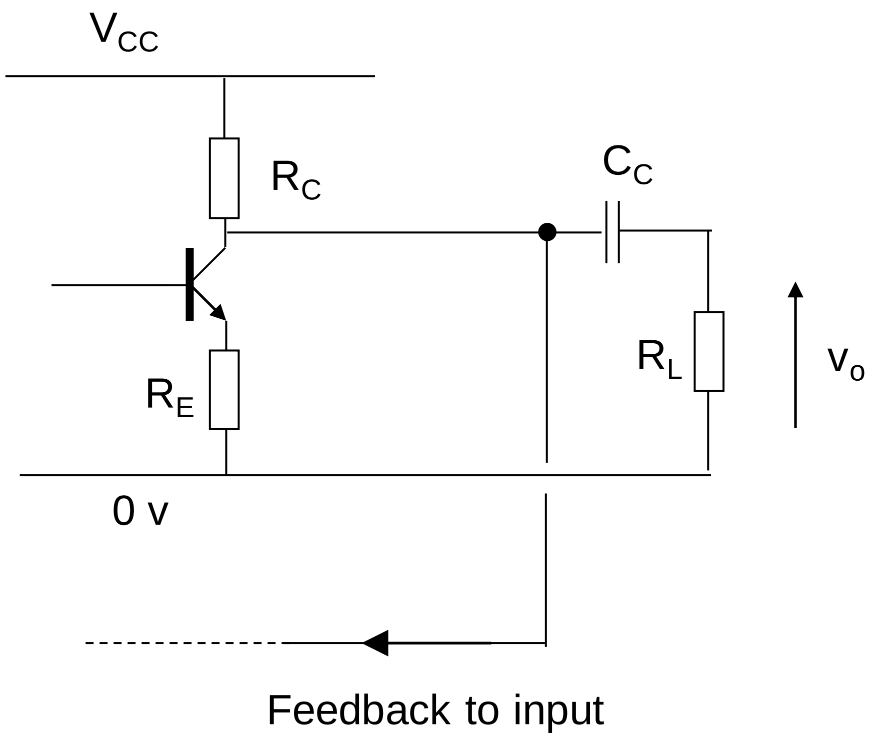
Some Practical Examples – Output Connection

Applying Method 1:

- Short-circuit the output voltage
- The feedback loop is then grounded, and the feedback signal disappears
- It is therefore sensing the output voltage – ***SHUNT DERIVED***

Applying Method 2:

- The feedback signal is being taken from the collector of a common emitter amplifier, same as the output terminal
- There is a direct connection to the output voltage terminal so it is clearly sensing the output voltage
- It is therefore ***SHUNT DERIVED*** feedback

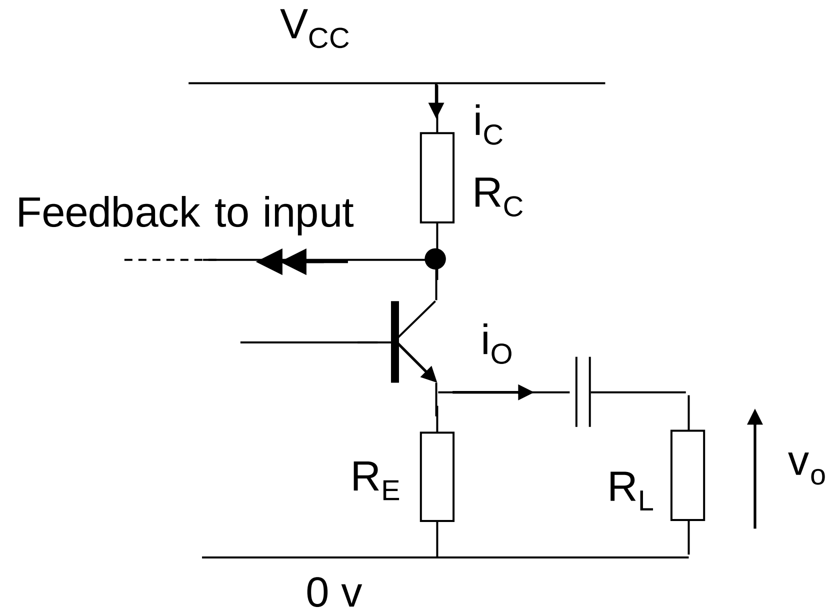


The output impedance will be reduced by the shunt derived feedback

Some Practical Examples – Output Connection

Applying Method 1:

- Short-circuit the output voltage
- The feedback loop still passes signal (its monitoring I_c)
- It is therefore sensing the output current – ***SERIES DERIVED***



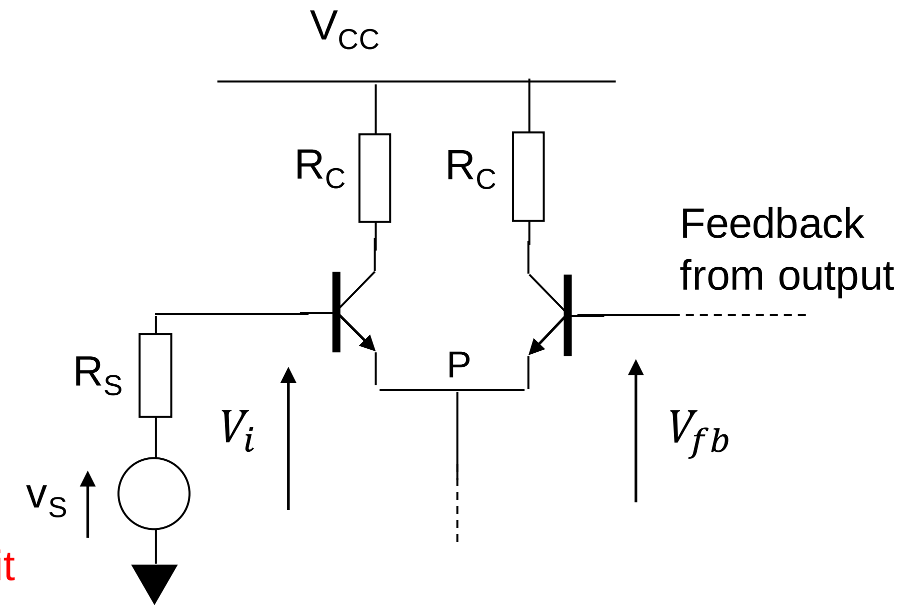
Applying Method 2:

- The output voltage is being taken from across the emitter resistor but the feedback is taken from across a collector resistor
- There is no direct connection to the output voltage
- It is therefore ***SERIES DERIVED*** feedback

The feedback is series derived so the output impedance will be increased

Exercise

Identifying the feedback topology at the input side of this circuit. How this feedback will affect the input impedance?



Solution

Applying Method 1:

- The input signal is connected to the left transistor; the feedback loop is connected to the right transistor
- Therefore, we can write:

$$V_d = V_i - V_{fb} = V_\varepsilon$$

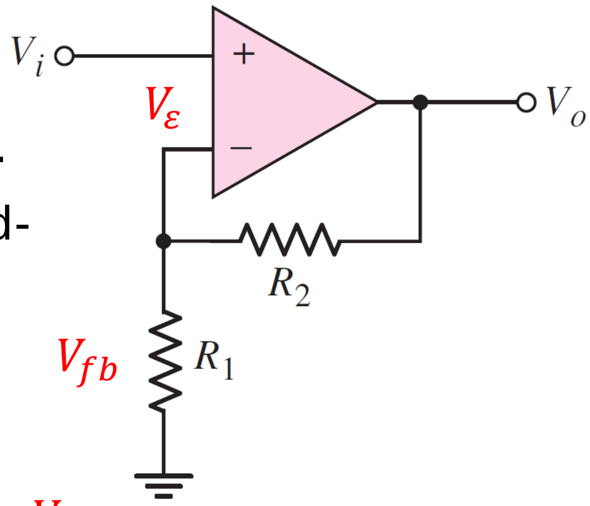
- Since the input voltage is subtracted, it is a ***SERIES APPLIED*** feedback

Applying Method 2:

- There is no direct connection to the source.
- In this case it is clearly a ***SERIES APPLIED*** connection

Finally, the input impedance will be increased by the series applied feedback connection.

Exercise: Consider the op-amp circuit in which the open-loop gain is $A_v = 10^4$ and input resistance $R_i = 50\ \mathrm{kOhm}$. Resistances $R_1 = 10\ \mathrm{kOhm}$ and $R_2 = 90\ \mathrm{kOhm}$.



Task: Identify feedback connection, determine the closed-loop gain and equivalent input resistance.

Solution: 0. Feedback connection: series-shunt

1. Denote the error and feedback signals

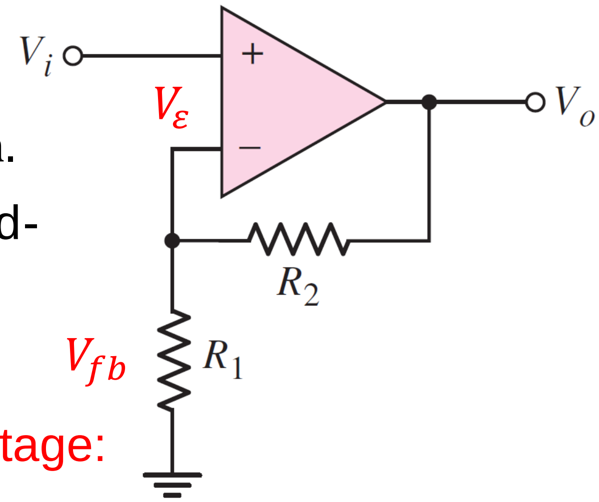
2. The feedback voltage can be found as: $V_{fb} = \dfrac{R_1}{R_1 + R_2} V_O$

3. Noting that $V_\varepsilon = V_i - V_{fb}$, output voltage can be found as:

$$V_o = A_v V_\varepsilon = A_v(V_i - V_{fb}) = A_v\left(V_i - \frac{R_1}{R_1 + R_2} V_o\right)$$

4. After rearrangement, we can find the closed-loop gain as:

$$A_{vf} = \frac{V_o}{V_i} = \frac{A_v}{1 + \dfrac{R_1}{R_1 + R_2} A_v} = 9.99$$



Exercise: Consider the op-amp circuit in which the open-loop gain is $A_v = 10^4$ and input resistance $R_i = 50\ \mathrm{kOhm}$. Resistances $R_1 = 10\ \mathrm{kOhm}$ and $R_2 = 90\ \mathrm{kOhm}$.

Task: Identify feedback connection, determine the closed-loop gain and equivalent input resistance.

Solution:

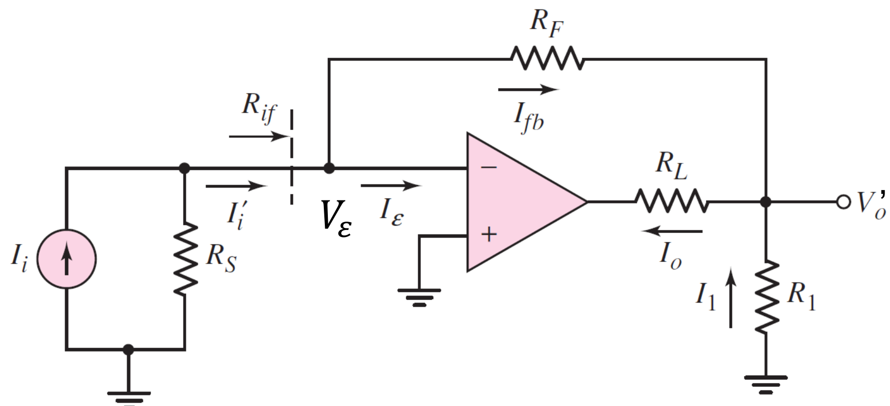
5. To find the input resistance, first let us derive input voltage:

$$V_i = V_\varepsilon + V_{fb} = V_\varepsilon + \frac{R_1}{R_1 + R_2} V_o = V_\varepsilon + \frac{R_1}{R_1 + R_2} A_v V_\varepsilon$$

6. Now the input resistance can be found as:

$$R_{if} = \frac{V_i}{I_i} = \frac{V_\varepsilon \left(1 + \frac{R_1}{R_1 + R_2} A_v\right)}{V_\varepsilon / R_i} = R_i \left(1 + \frac{R_1}{R_1 + R_2} A_v\right) = 50.05\ \mathrm{MOhm}$$

Exercise: Consider the op-amp circuit in which the basic amplifier voltage gain is A_v, input resistance is R_i, and output resistance is R_o. Resistances $R_1, R_F, R_L, and\ R_S$ are also known.



Task: Determine the type of op-amp, its open-loop gain, feedback transfer function (FTF), and closed-loop gain.

Solution:

0. Feedback connection: shunt-series.

Therefore, it is CURRENT op-amp.

1. Its open-loop current gain can be found as: $A_i = \dfrac{I_o}{I_\varepsilon} = \dfrac{V_o/R_o}{V_\varepsilon/R_i} = A_v \dfrac{R_i}{R_o}$

2. To find FTF, remember how it is defined ($\beta_i = I_{fb}/I_o$) and try formulating $I_o(I_{fb})$:

$$I_o = I_{fb} + I_1 = I_{fb} - \frac{V_o'}{R_1} = I_{fb} - \frac{I_\varepsilon R_i - I_{fb}R_F}{R_1} = I_{fb} - \frac{\frac{I_o}{A_i}R_i - I_{fb}R_F}{R_1}$$

3. After rearrangement we can find FTF as: $\beta_i = \dfrac{I_{fb}}{I_o} = \dfrac{1 + R_i/(R_1 A_i)}{1 + R_F/R_1} \approx \dfrac{1}{1 + R_F/R_1}$

4. Finally, knowing A_i and β_i, the closed-loop gain is found: $A_{if} = \dfrac{A_i}{1 + \beta_i A_i} = \cdots$

Advantages of Negative Feedback

1. Negative feedback reduces the sensitivity of the gain on parameters of an amplifier such as transistor current gain etc.
2. Negative feedback allows us to set gain to any value we want (up to the limit of A_{OL}).
3. Negative feedback increases the bandwidth of the amplifier.
4. Negative feedback reduces distortion
5. Negative feedback allows us to adjust the input and output impedances of an amplifier.

BUT these advantages do not come FREE!

Disadvantages of Negative Feedback

1. Negative feedback always reduces the gain of an amplifier.
2. Over certain frequency ranges, it can be that negative feedback changes from negative to positive with catastrophic results. Positive feedback increases the gain of the amplifier and the amplifier could then oscillate – no longer any use as an amplifier

Announcements:

- Provide your feedback on Practical Lectures:
  - Please tap here to proceed…
- Reading material:
  - Microelectronics: Circuit Analysis and Design, Chapter 12:
    - Sec. 12.1 – Introduction to Feedback
    - Sec. 12.2 – Basic Feedback Concepts
    - Sec. 12.3 – Ideal Feedback Topologies
- Practice exercises:
  - Microelectronics: Circuit Analysis and Design, Chapter 12:
    - Ex. 12.1-12.7
- Assignment 2:
  - Release on LM (Week 7): 8PM Wednesday, 30 October
  - Due: 11:59PM Friday, 8 November (Week 8)
- Next lecture:
  - Week 8: No lectures – Reading week (office hours remain the same);
  - Week 9: New lecture: Stability of Amplifier Circuits with Feedback.
- Slides corrections:
  - Highlighted with blue font

See you in the next lecture...

The End