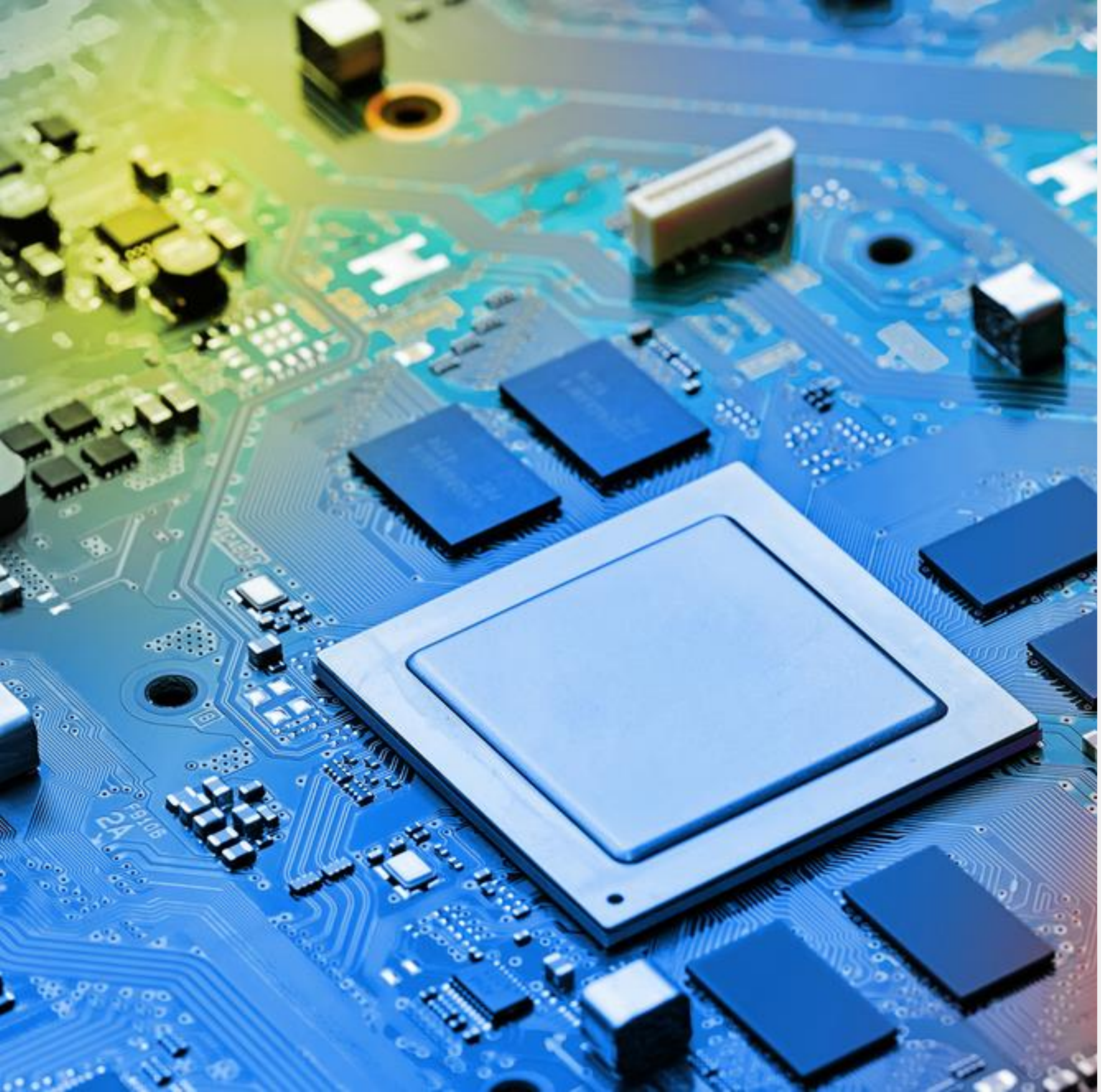


NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

EE3019 – Integrated Electronics

Part 1d – Feedback Circuits

Learning Objectives

By the end of this lesson, you should be able to:

- Explain the general feedback structure and characteristics of a negative feedback amplifier.
- Explain the advantages of a negative feedback amplifier.
- Discuss the four feedback topologies.
- Describe the procedures of feedback amplifier analysis.
- Analyse the loading effect of feedback analysis.
- Execute the examples on negative feedback amplifier.
- Identify the Gain (A_f), Input Impedance $\left(R_{if}\right)$ and Output Impedance (R_{of}) of a feedback amplifier.

Feedback: Outline

01 The General **Feedback Structure**

02 Characteristics of **Negative Feedback Amplifier**

03 The 4 Basic Feedback **Topologies**

04 Procedures of Feedback Amplifier **Analysis**

05 **Loading Effect** of Feedback network

06 **Examples** of Feedback Amplifier Analysis

Reference:

- Sedra and Smith, “Microelectronic Circuits”, 5th Edition, 2014 Chapter 8.

1. The General Feedback Structure

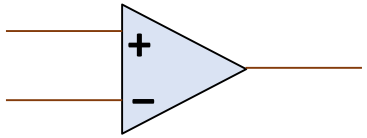
Single-loop Feedback Amplifier

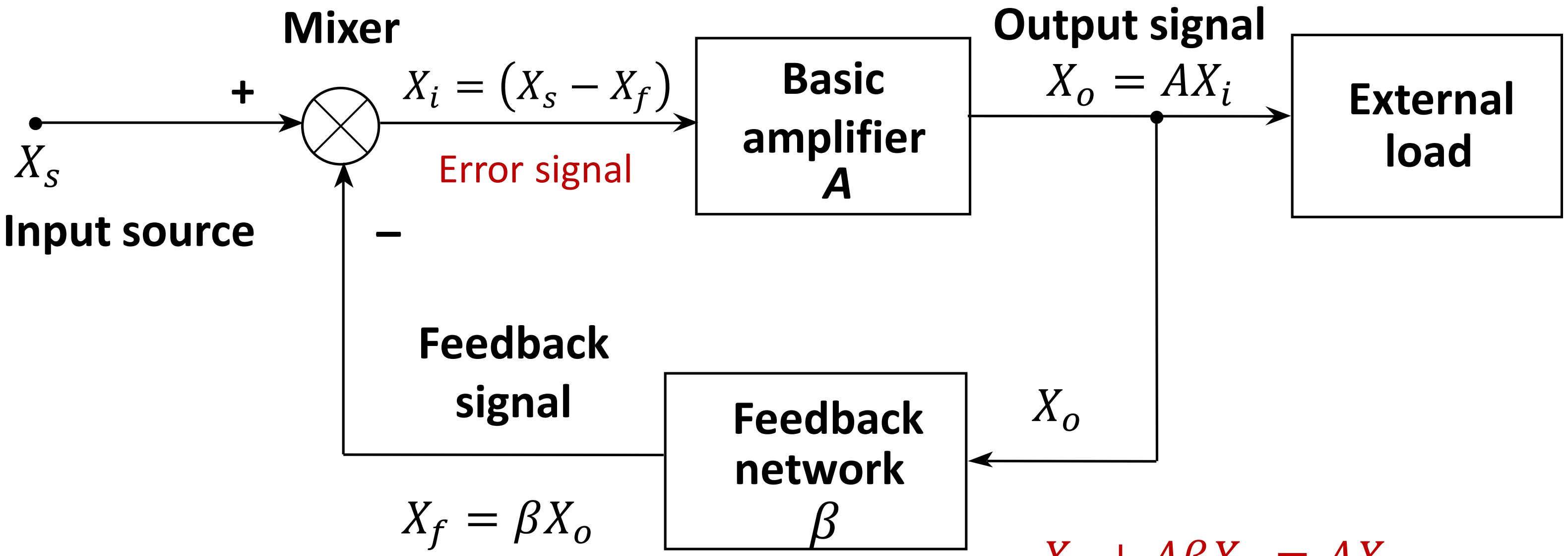
$X_i = X_s - X_f$ - (1)

$X_o = AX_i$ -(2)

$X_f = \beta X_o$ -(3)

$\mathrm{A} = 100 \pm 20$





$X_f = \beta X_o$

$\beta \leq 1$

From (1), (2) and (3):

$X_o = A(X_s - \beta X_o)$

$X_o + A\beta X_o = AX_s$

$X_o(1 + A\beta) = AX_s$

$\frac{X_o}{X_s} = \frac{A}{1 + A\beta} = A_f$

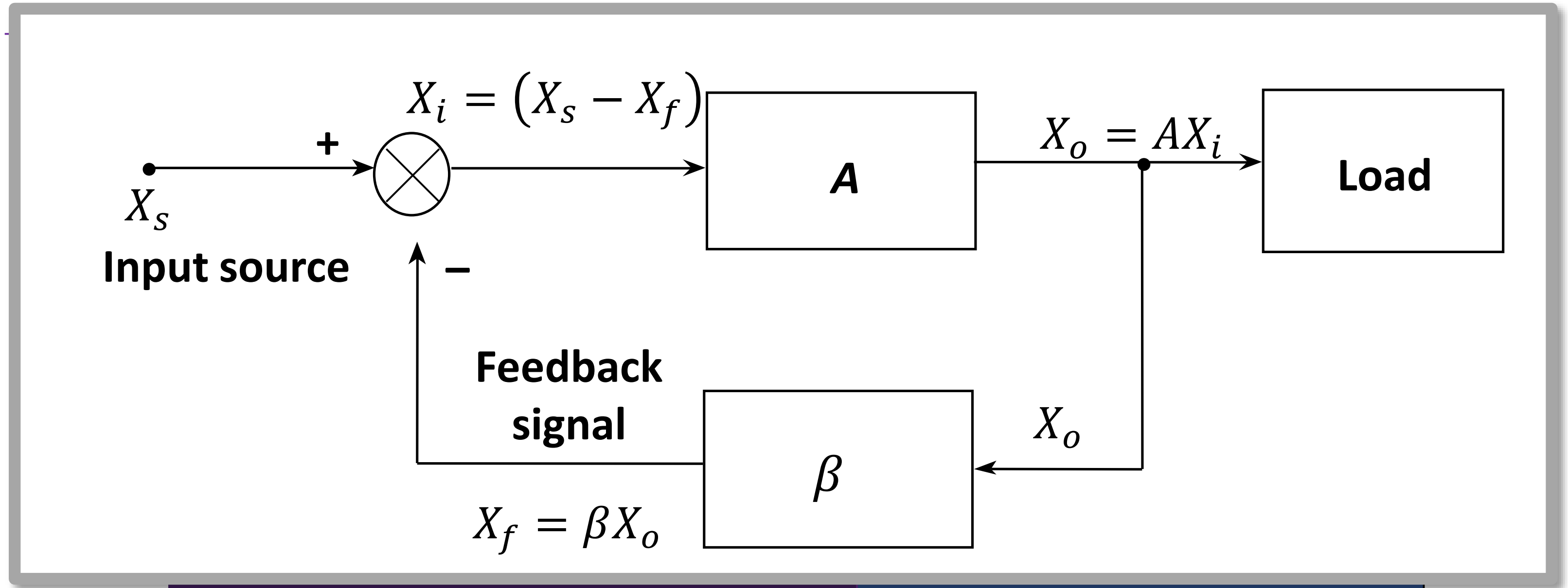
Gain of Negative Feedback Amplifier

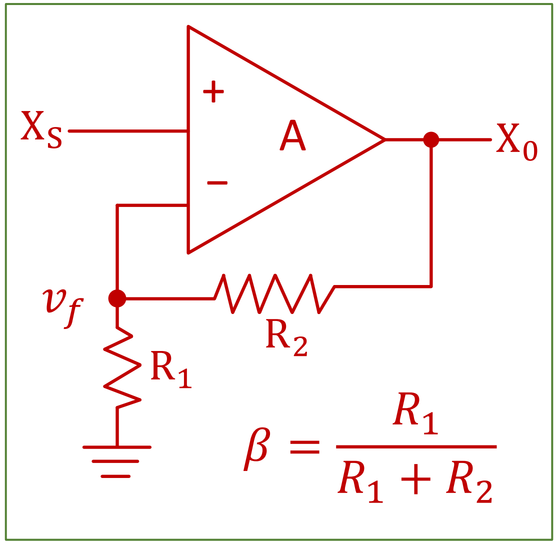
Gain of Feedback amplifier:

$$A_f = \frac{X_o}{X_s} = \frac{A}{1 + A\beta}$$

In many circuits, $A\beta >> 1$ then:

$$A_f \approx \frac{1}{\beta}$$





<u>Notation</u>:

A : Basic Amp. Open-loop Gain (without feedback)

β : Feedback factor

$A\beta$:Loop gain (determine the stability of the feedback Amp)

1+$A\beta$: Amount of feedback

A_f : Closed-loop Gain (with feedback)

2. Characteristics of Negative Feedback Amplifier

Advantages

- **A. Gain De-sensitivity**
- B. Reduced Frequency Distortion
- C. Noise Reduction
- D. Reduced Non-Linear Distortion
- E. I/P and O/P Impedance Change

All these are obtained at the expense of **GAIN REDUCTION**.

A. Gain De-sensitivity

Closed-loop Gain, $A_f = \dfrac{A}{1 + A\beta}$ – (1)

Taking Differential on both sides:

$d\left(\dfrac{u}{v}\right) = \dfrac{vdu - udv}{v^2}$

i.e. $dA_f = \dfrac{(1 + A\beta)dA - A\beta\, dA}{(1 + A\beta)^2}$ $\Rightarrow$ $dA_f = \dfrac{dA}{(1 + A\beta)^2}$ – (2)

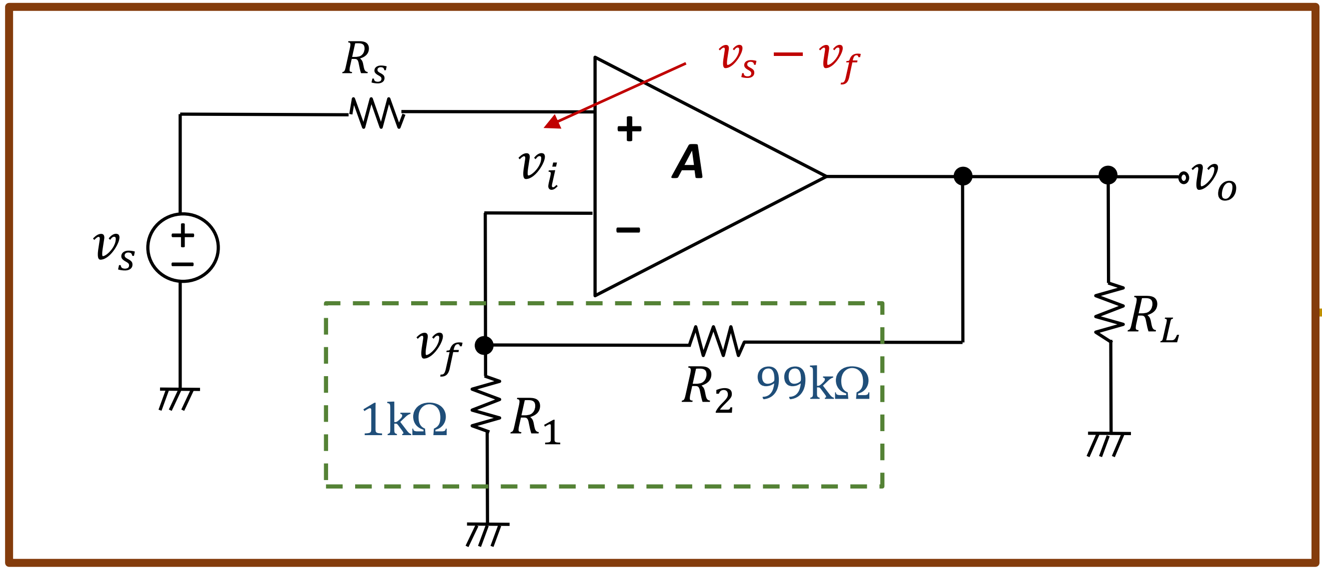
$\dfrac{(2)}{(1)}$: $\dfrac{dA_f}{A_f} = \dfrac{1}{(1 + A\beta)}\dfrac{dA}{A}$ – (3)

Gain sensitivity of A_f is reduced by $1 + A\beta$

The de-sensitivity factor is $(1 + A\beta)$, which is the amount of feedback.

A. Gain De-sensitivity

Example 1



$$v_f = \frac{R_1}{R_1 + R_2} v_o \Rightarrow \beta = \frac{v_f}{v_o} = \frac{R_1}{R_1 + R_2}$$

If A = ∞ (idea)

$$\frac{v_o}{v_s} = 1 + \frac{R_2}{R_1} = 1 + \frac{99}{1} = 100$$

If $A = 10^5$ and $\beta = 0.01$, then closed-loop gain is:

$$A_f = \frac{A}{1 + A\beta} = \frac{10^5}{1 + 10^5 \times 10^{-2}} = \frac{10^5}{1001} = 99.9$$

$$20\log A_f = 20\log\left(\frac{\mathrm{A}}{1 + \mathrm{A}\beta}\right) = \underbrace{20\log \mathrm{A}}_{\mathrm{dB}} - \underbrace{20\log(1 + A\beta)}_{\mathrm{dB}}$$

A. Gain De-sensitivity

Example 1 (Contd.)

Loop gain, $A\beta = 10^3$. Amount of feedback, $1 + A\beta = 1001$

$A = 10^5$, $\beta = 0.01$ and $A_f = 99.9$

Expressed in dB: A_f(dB) = A (dB) − $(1+A\beta)$(dB)

In dB, the difference between open-loop gain, A, and closed-loop gain, A_f, is the amount of feedback $(1 + A\beta)$.

If the op-amp gain of A decreased by 10%, the corresponding decrease in A_f is given by:

Gain de-sensitivity reduces by 1001 times.

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

where (1+Aβ) is also known as the desensitivity factor

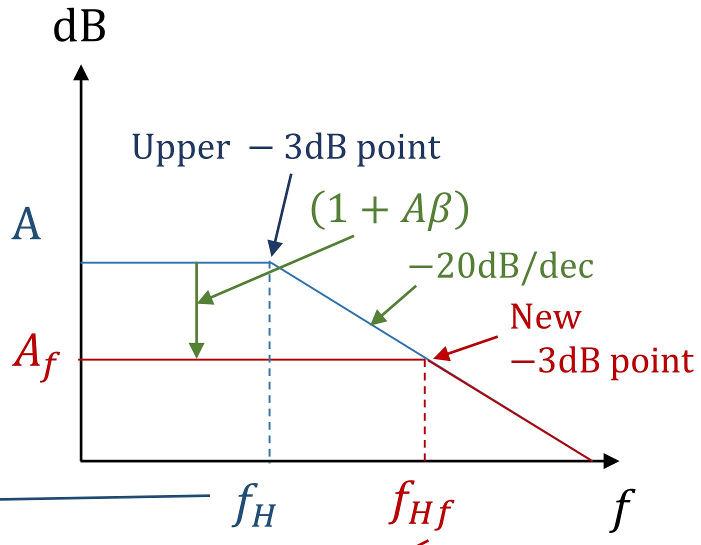
$$= \frac{1}{1001} \times \frac{-10}{100} = -0.01\%$$

(very small)

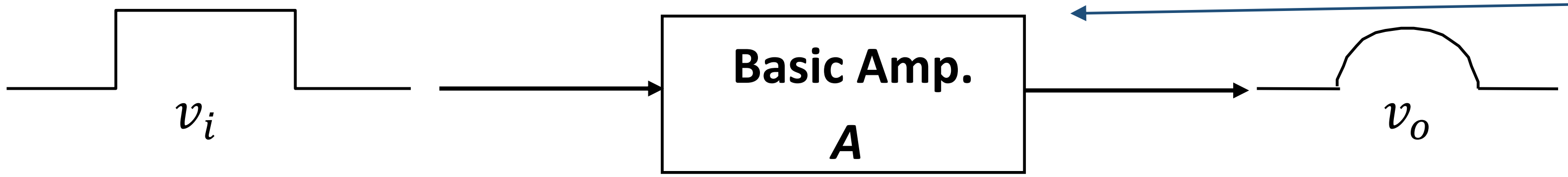
B. Bandwidth Extension

Reduction of frequency distortion

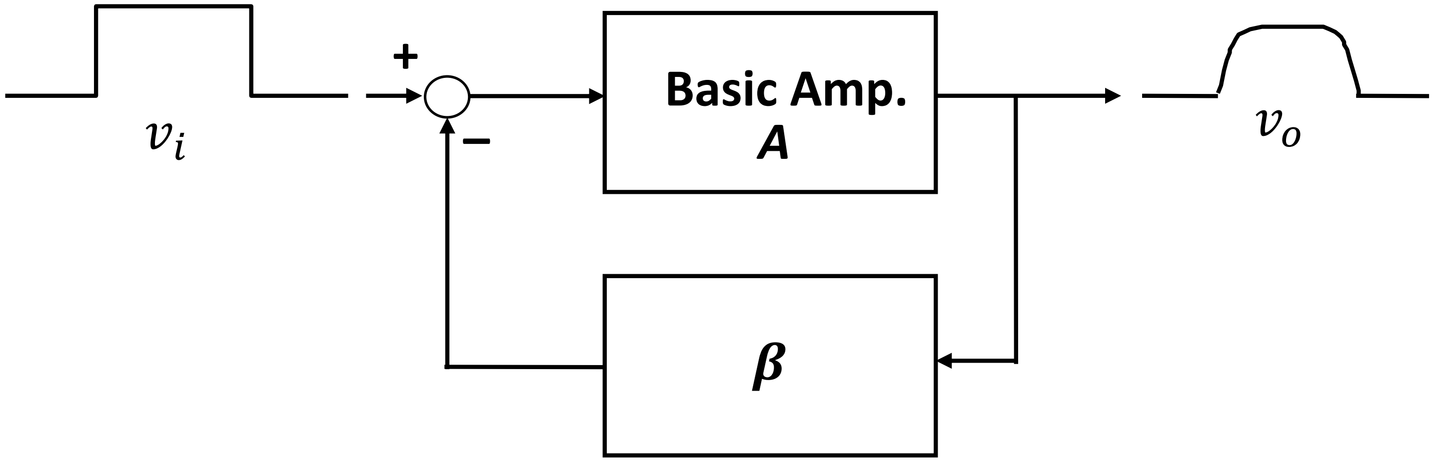
For a basic amplifier, *A:*



a. Without **negative feedback**:



b. With **negative feedback** added :



(a) Extension of Bandwidth : $\omega_H = 2\pi f_H$

Mid-band gain

Low pass function

$$A(s) = A_m F_H(s)$$

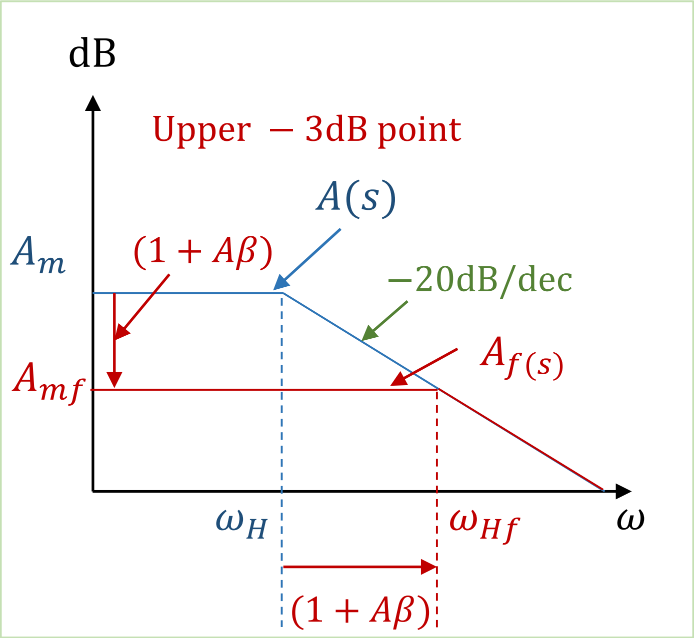
Low pass response

Consider the case where $F_H(s)$ is characterised by a dominant pole.

$$A(s) = \frac{A_m}{1 + \frac{S}{\omega_H}} = \frac{A_m}{1 + \frac{j\omega}{\omega_H}} \qquad F_H = \frac{1}{1 + \frac{S}{\omega_H}}$$

The closed-loop gain is given by:

$$A_f(s) = \frac{A(s)}{1 + A(s)\beta} = \frac{\frac{A_m}{1 + {}^{S}/_{\omega_H}}}{1 + \frac{A_m\beta}{1 + {}^{S}/_{\omega_H}}}$$



(a) Extension of Bandwidth : ω_H (Contd.)

$$\therefore \quad A_f(s) = \frac{\overbrace{\frac{A_m}{1+A_m\beta}}^{A_{mf}}}{1+\frac{s}{\underbrace{\omega_H(1+A_m\beta)}_{\omega_{Hf}}}} = \frac{A_{mf}}{1+\frac{s}{\omega_{Hf}}}$$

Closed-loop Amp
Mid-band gain

where $A_{mf} = \dfrac{A_m}{1+A_m\beta}$

ω_{Hf}

$$\omega_{Hf} = \omega_H(1+A_m\beta)$$

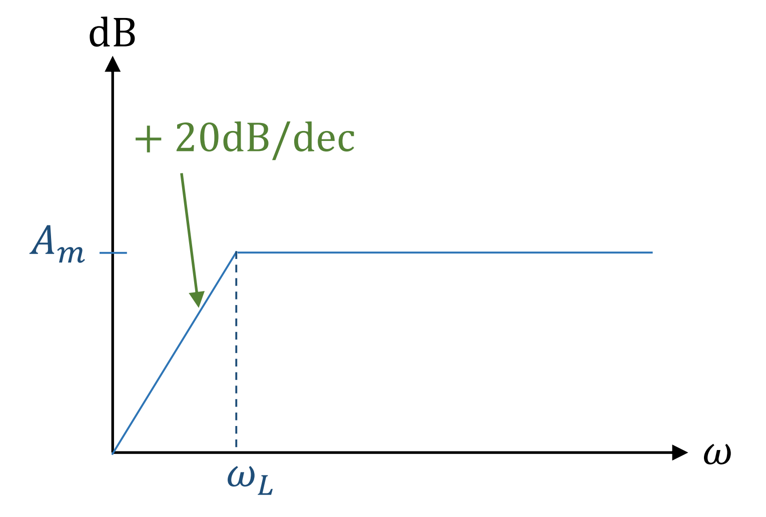
Upper 3-dB frequency is increased by a factor equal to the amount of feedback ($1 + A_m\beta$) when negative feedback is applied.

(b) Extension of Bandwidth : ω_L

$$A(s) = A_m F_L(s)$$ High pass response

Consider $F_L(s)$ being characterised by a dominant pole, ω_L and a zero at 0.

$$A(s) = A_m \frac{s}{s+\omega_L}$$



The closed-loop gain is:

$$A_f(s) = \frac{A(s)}{1+A(s)\beta} = \frac{A_m \frac{s}{s+\omega_L}}{1+\frac{A_m\beta\, s}{s+\omega_L}}$$

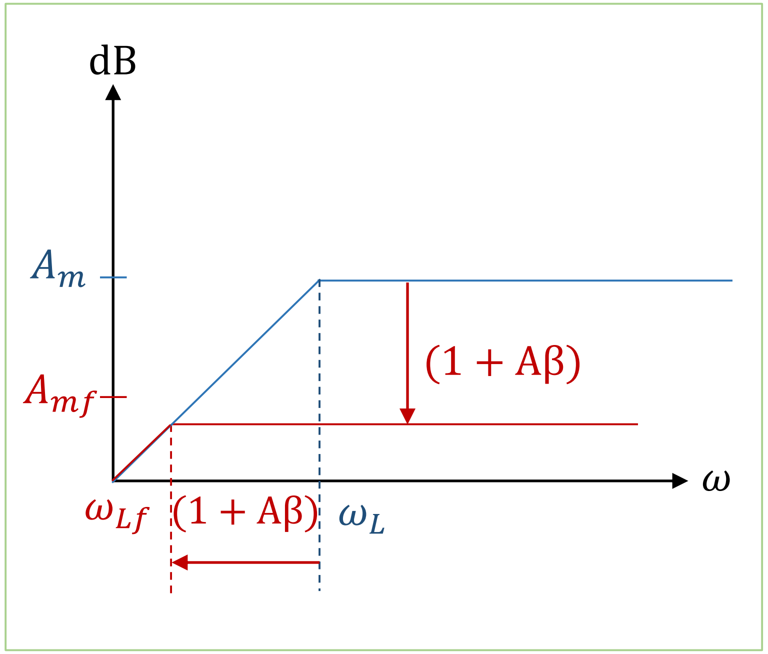
(b) Extension of Bandwidth : ω_L (Contd.)

$$A_f(s) = \frac{\overbrace{\frac{A_m}{1 + A_m\beta}}^{A_{mf}} s}{s + \underbrace{\frac{\omega_L}{1 + A_m\beta}}_{\omega_{Lf}}}$$

$\therefore$ $$A_f(s) = \frac{A_{mf}\, s}{s + \omega_{Lf}}$$

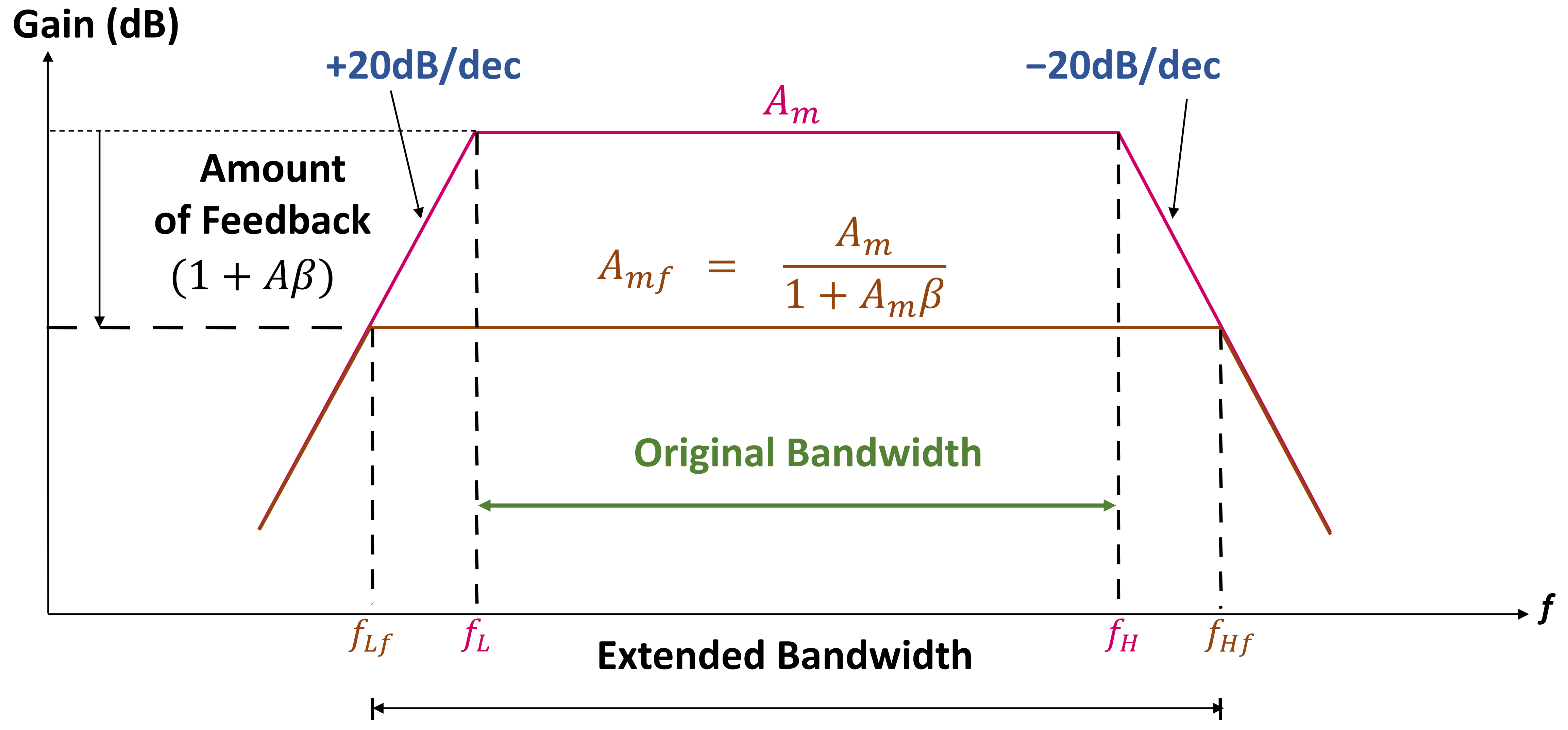
$$A_{mf} = \frac{A_m}{1 + A_m\beta}$$

$$\omega_{Lf} = \frac{\omega_L}{1 + A_m\beta}$$



$\therefore$ Lower 3-dB frequency is decreased by $\frac{1}{1 + A_m\beta}$ when negative feedback is applied.

Graphical Representation



Example 2

Given:

$A = 10^5$

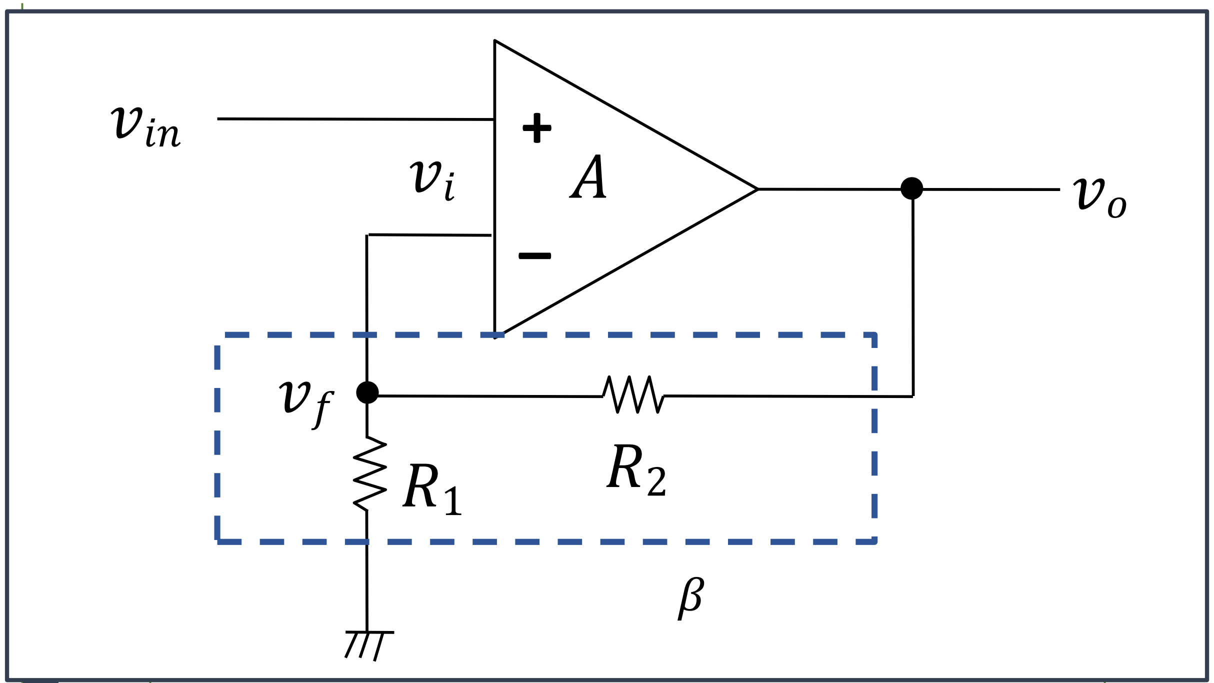
$\beta = \frac{1}{100} = \frac{v_f}{v_0}$

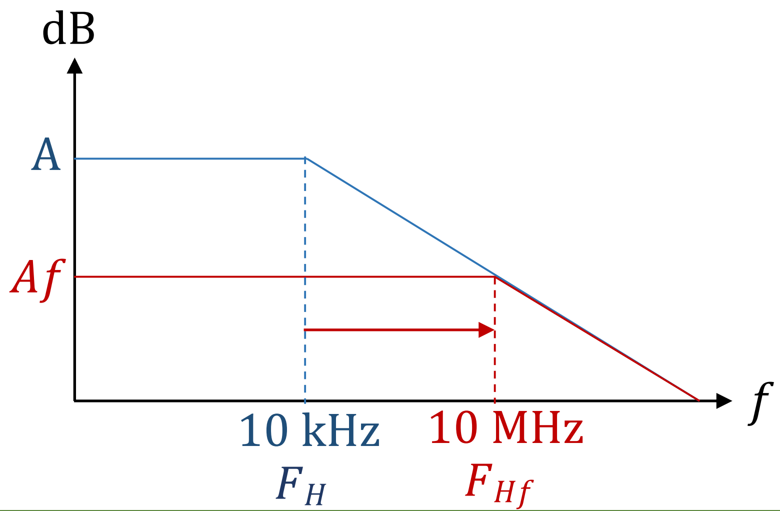
$F_H = 10 \text{ kHz},$

$F_{Hf} = (1 + A\beta)F_H$

$\left(1 + 10^5 \times \frac{1}{100}\right) 10 \text{ kHz}$

= **10.01 MHz**

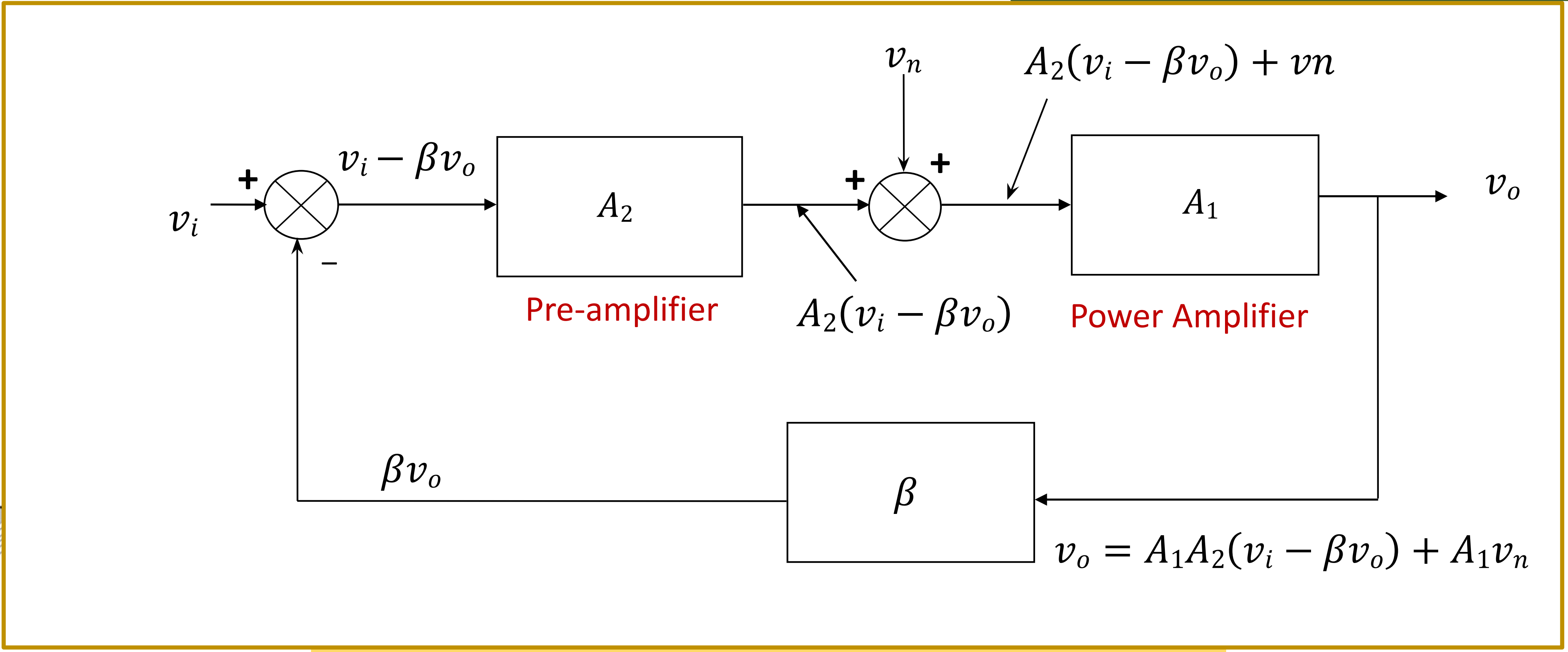




C. Noise Reduction

Noise reduction by negative feedback is possible with the special configuration displayed below.

Here A_1 is a noisy amplifier and A_2 is a noise-free amplifier.



C. Noise Reduction

Output, $v_o = A_1 A_2 (v_i - \beta v_o) + A_1 v_n$

$$v_o = \underbrace{\frac{A_1 A_2}{1 + A_1 A_2 \beta} v_i}_{\text{Signal}} + \underbrace{\frac{A_1}{1 + A_1 A_2 \beta} v_n}_{\text{Noise}}$$

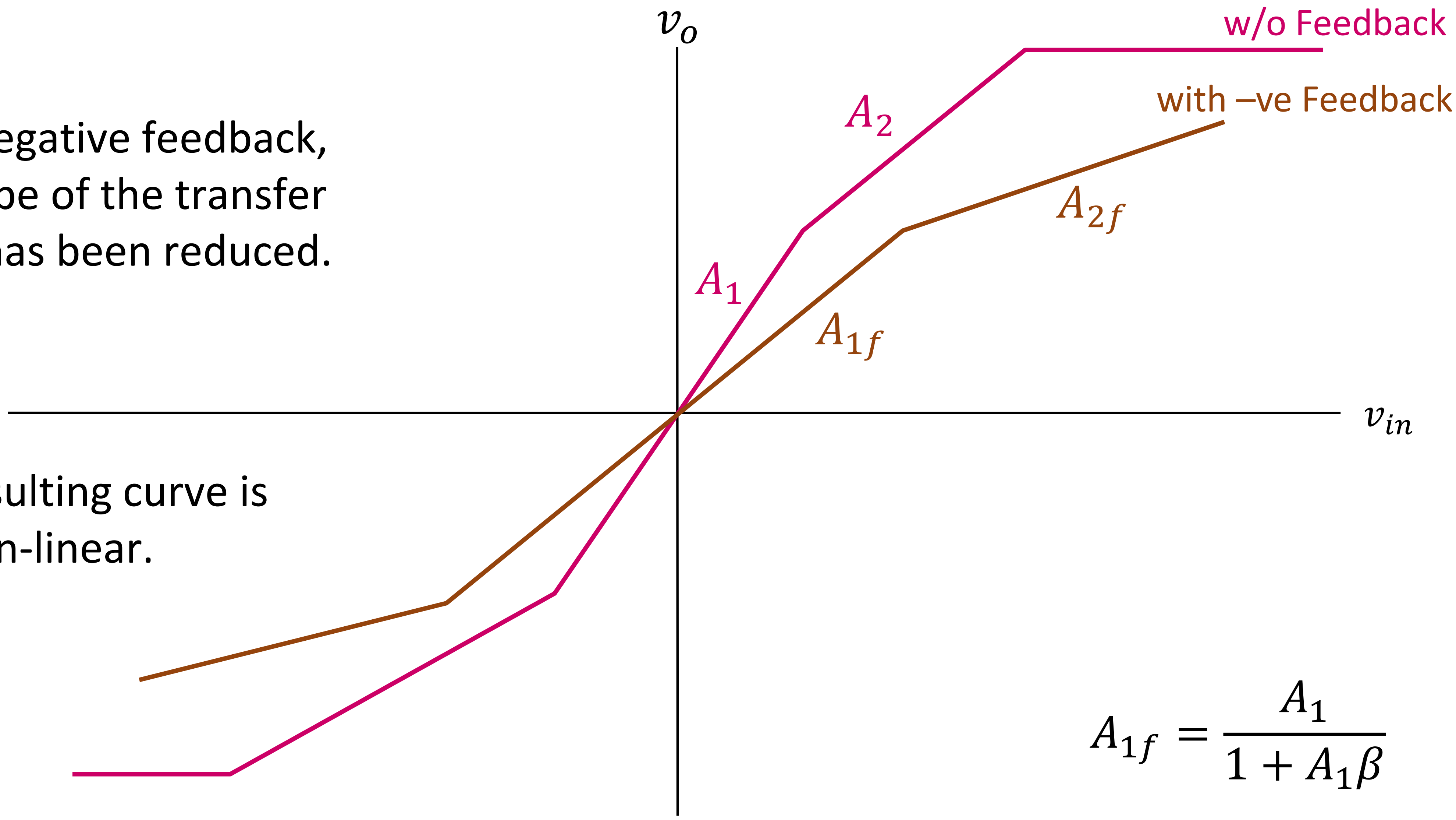
Signal-to-noise Ratio at output: $\therefore \frac{S}{N_f} = \frac{A_1 A_2 v_i}{A_1 v_n} = A_2 \frac{v_i}{v_n}$

Improved by A_2 with negative feedback

D. Non-linear Distortion Reduction

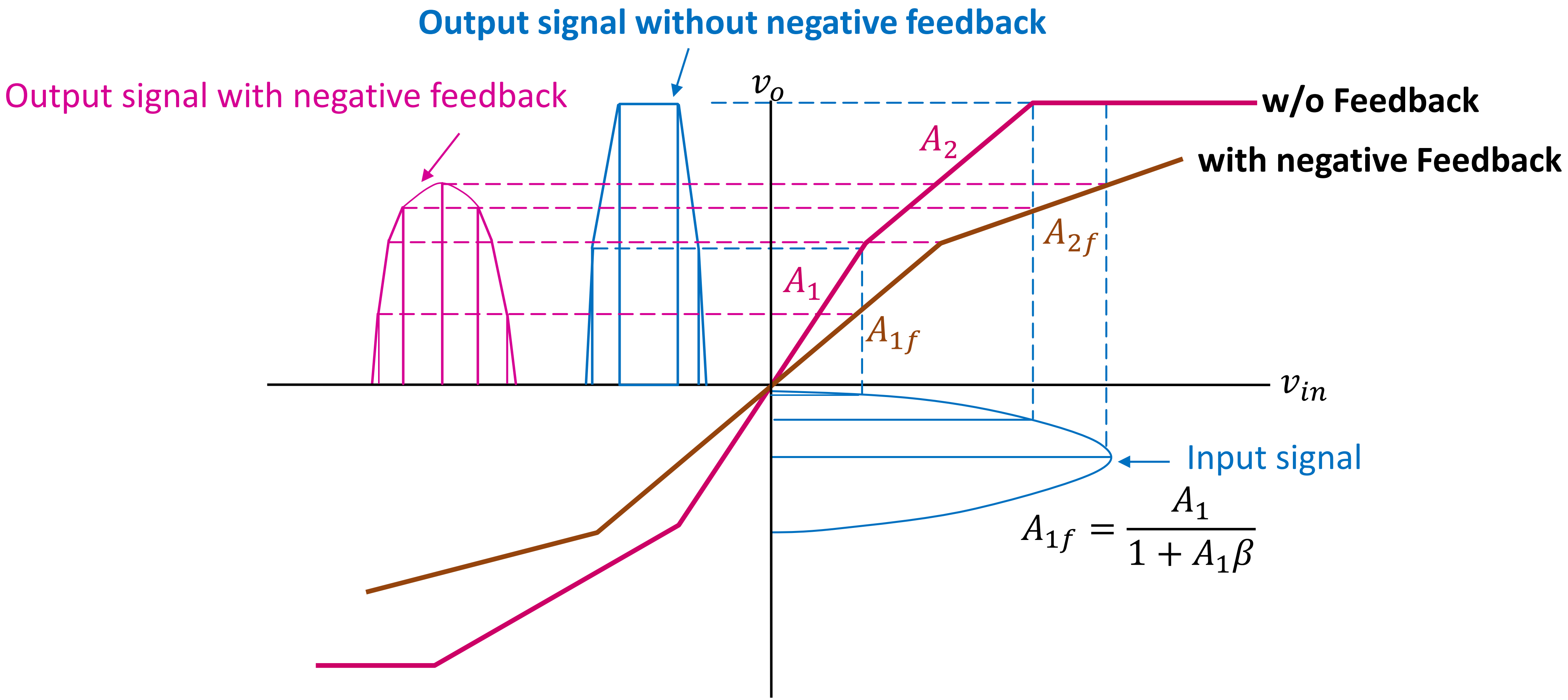
With negative feedback, the slope of the transfer curve has been reduced.

The resulting curve is less non-linear.



$$A_{1f} = \frac{A_1}{1 + A_1\beta}$$

D. Non-linear Distortion Reduction



$$A_{1f} = \frac{A_1}{1 + A_1\beta}$$

With negative feedback, the slope of the transfer curve has been reduced.

The resulting curve is less non-linear.

Basic Feedback Topologies

Mixing	:	Sampling
I/P		O/P

Overview

There are four basic feedback topologies:

A. Voltage Amplifier + Example: Series-Shunt Feedback

Voltage or parallel sampling $\frac{v_o}{v_i}$

B. Current Amplifier + Example: Shunt-Series Feedback

Current or series sampling $\frac{I_o}{I_i}$

C. Trans-conductance Amplifier + Example: Series-Series Feedback

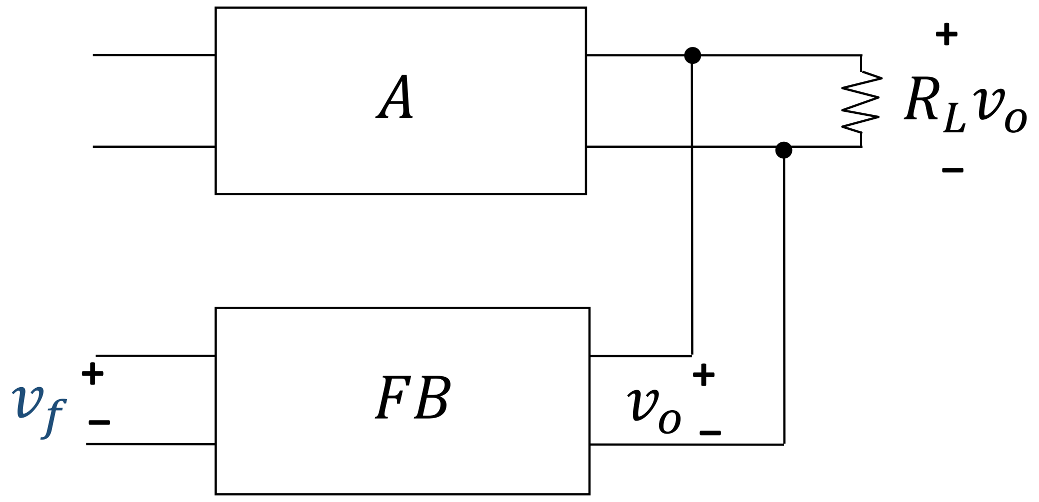
$\frac{I_o}{v_i}$

D. Trans-resistance Amplifier + Example: Shunt-Shunt Feedback

$\frac{v_o}{I_i}$

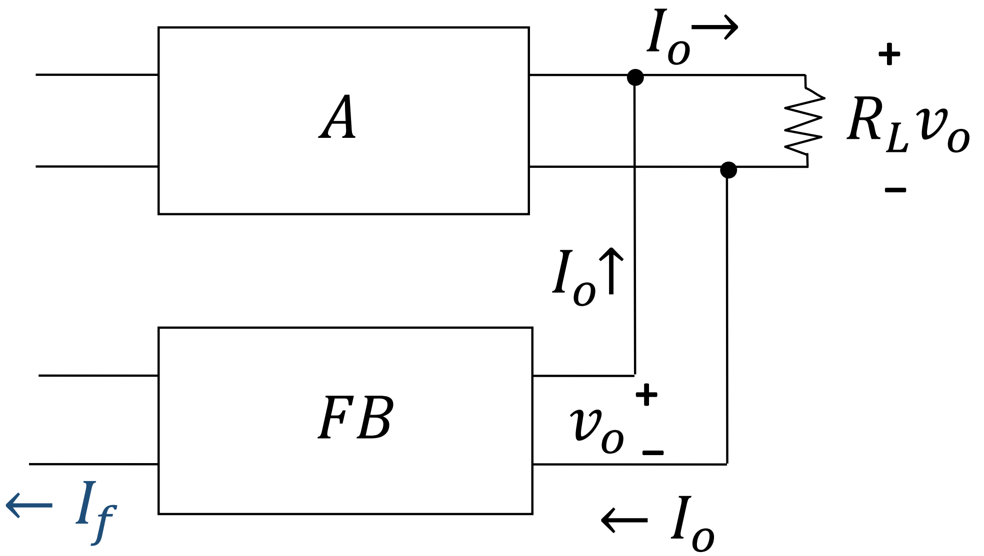
Feedback Topologies – Sampling (at output)

The sampling of the output signal of an amplifier can be in series with the load or in shunt with the load depending on the type of output signal (i.e. voltage or current).



Voltage Sampling (Shunt-Sampling)

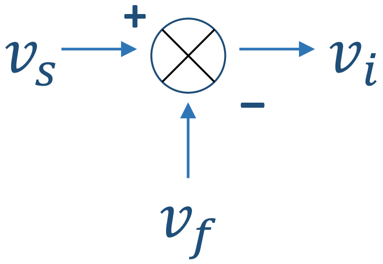
Feedback Topologies – Sampling (Contd.)

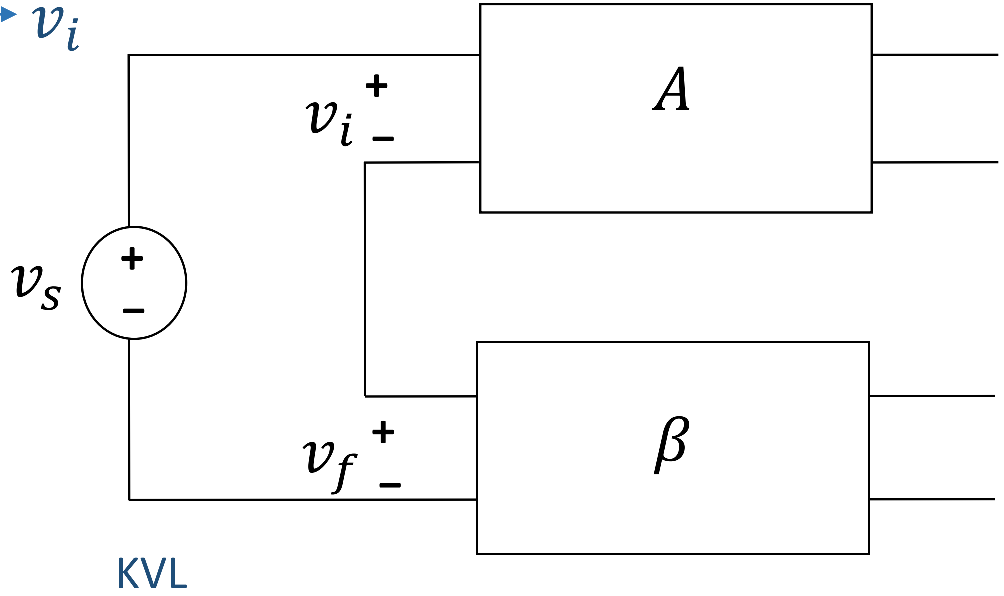


Current Sampling (**Series-Sampling**)

Feedback Topologies – Mixing (at Input)

The mixing of the feedback signal at the input of an amplifier can be in **series** with source or in **shunt** with source depending on the type of input (i.e. voltage or current).



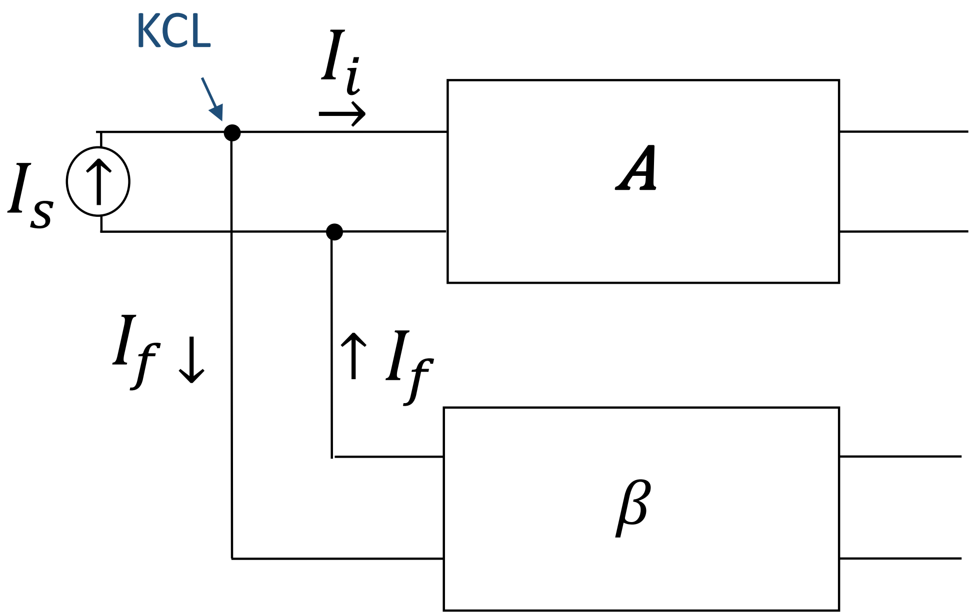


$$v_i = v_s - v_f$$

Voltage mixing (**Series-mixing**)

Feedback Topologies – Mixing (Contd.)

$$I_i = I_s - I_f$$



Current mixing (**Shunt**-mixing)

Feedback Topology

The Feedback Topology depends on:

The **type of amplifier** used for the basic amplifier block.

∵The type of signal (**voltage** or **current**) of the input and output of the feedback network block must be identical to those of the basic amplifier block.

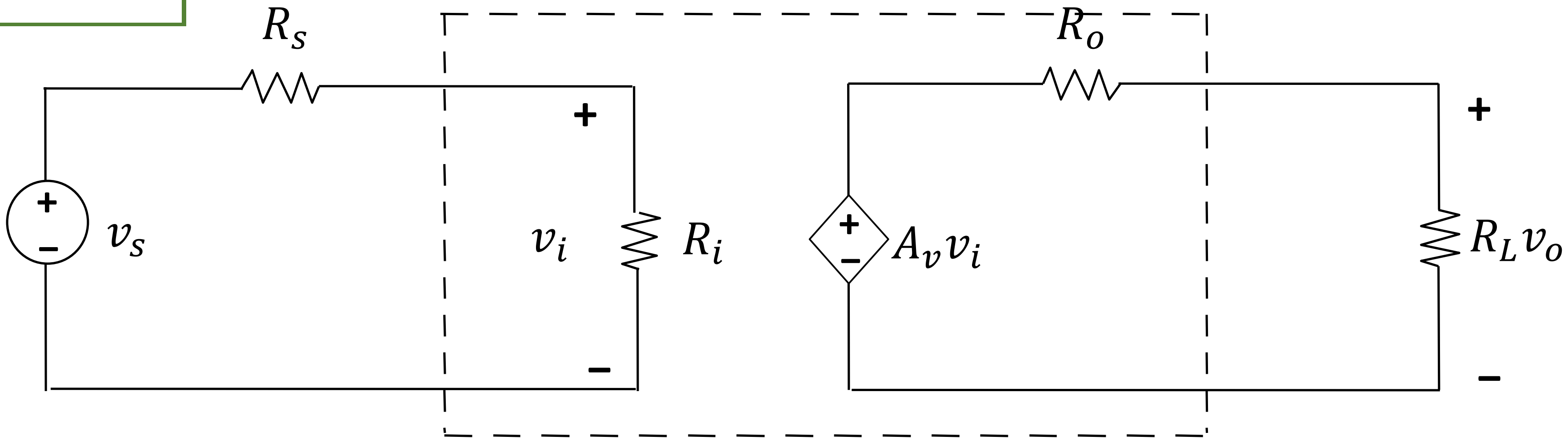
∴There are **FOUR** basic feedback topologies with four different types of amplifier.

A. Voltage Amplifier

∴ Feedback Topology is **voltage** mixing (at input) and **voltage** sampling (at output).

Input Signal : **Voltage**, v_i
Output Signal : **Voltage**, v_o

$$A_v = \frac{v_o}{v_i}$$



Ideal Voltage Amp. $R_i \rightarrow \infty$
$R_o \rightarrow 0$

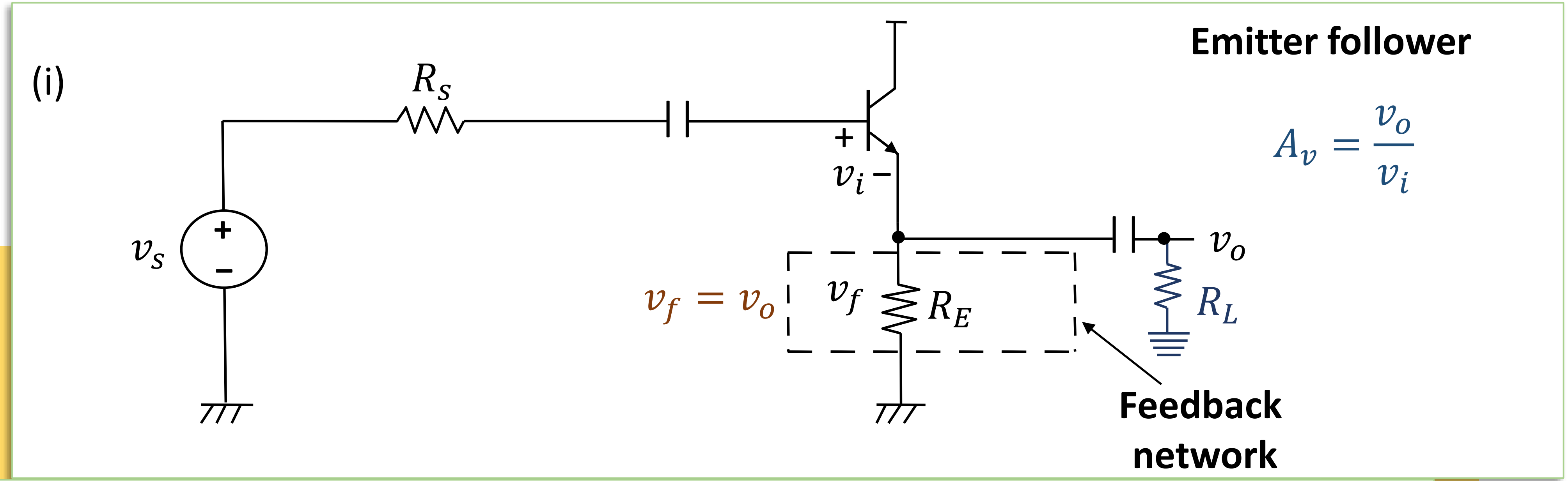
i.e. A <u>voltage amplifier</u> with negative feedback is a <u>**Series – Shunt**</u> feedback amplifier.

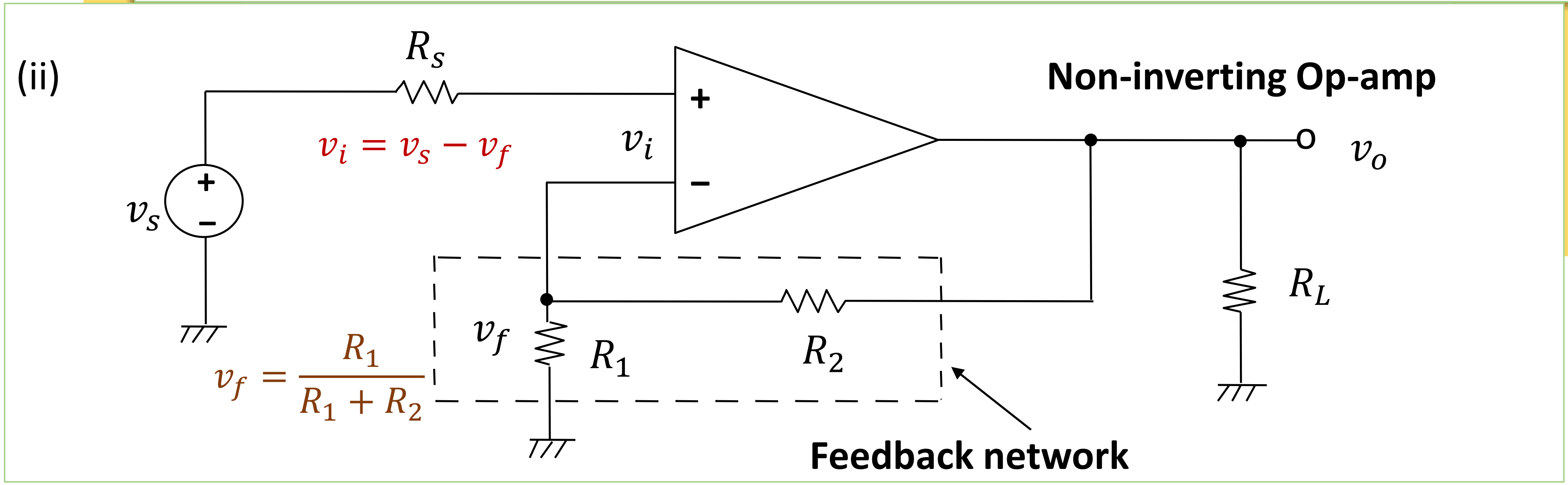
↑ Mixing ↑ Sampling

Series-Shunt Feedback Amplifier

Example 3

(Voltage Mixing - Voltage Sampling)





Series-Shunt Feedback Amplifier

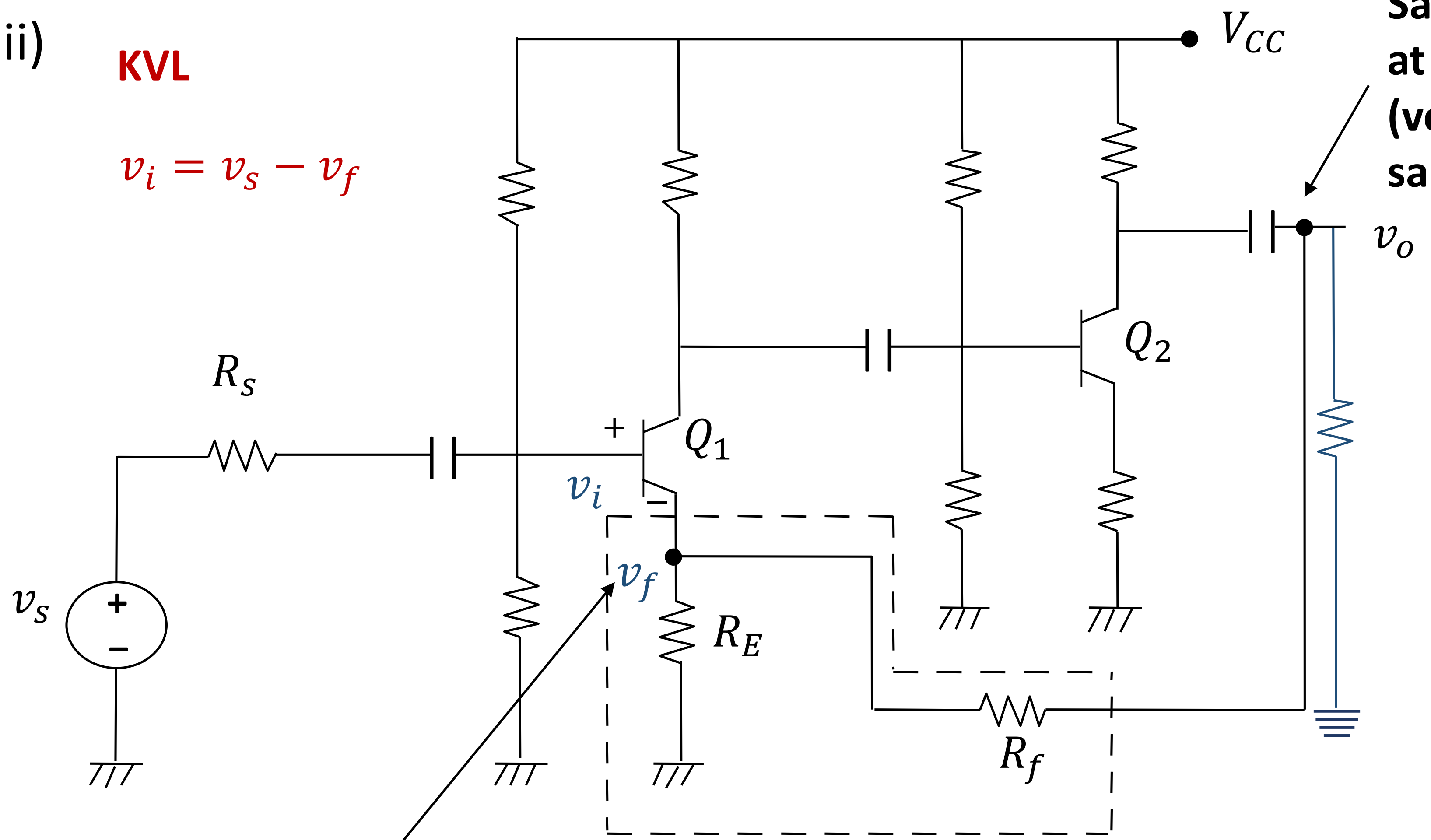
Example 3 (Contd.)

(Voltage Mixing - Voltage Sampling)

(iii)

KVL

$v_i = v_s - v_f$



Sample is taken at output node (voltage sampling)

$A_v = \frac{v_o}{v_s}$

Feedback signal is connected in series with external excitation source (voltage mixing)

$v_f = \frac{R_E}{R_E + R_F} v_o$

Feedback from collector (voltage sampling) at output to emitter at input

B. Current Amplifier

∴ Feedback topology for current amplifer is **current** mixing (at input) and **current** sampling (at output).

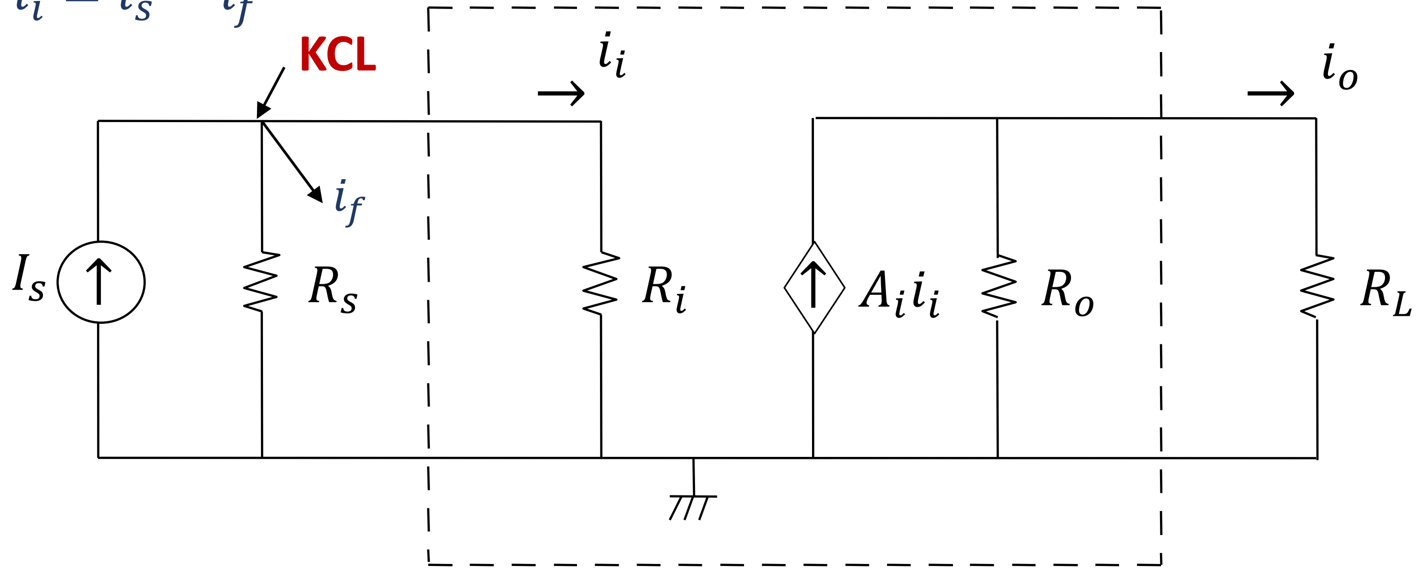
i.e. A <u>current amplifier</u> with negative feedback is a **<u>Shunt - Series</u>** feedback amplifier.

Input Signal : **Current**, i_i

Output Signal : **Current**, i_o

$$A_i = \frac{i_o}{i_i}$$

$$i_i = i_s - i_f$$



Ideal Current Amp.

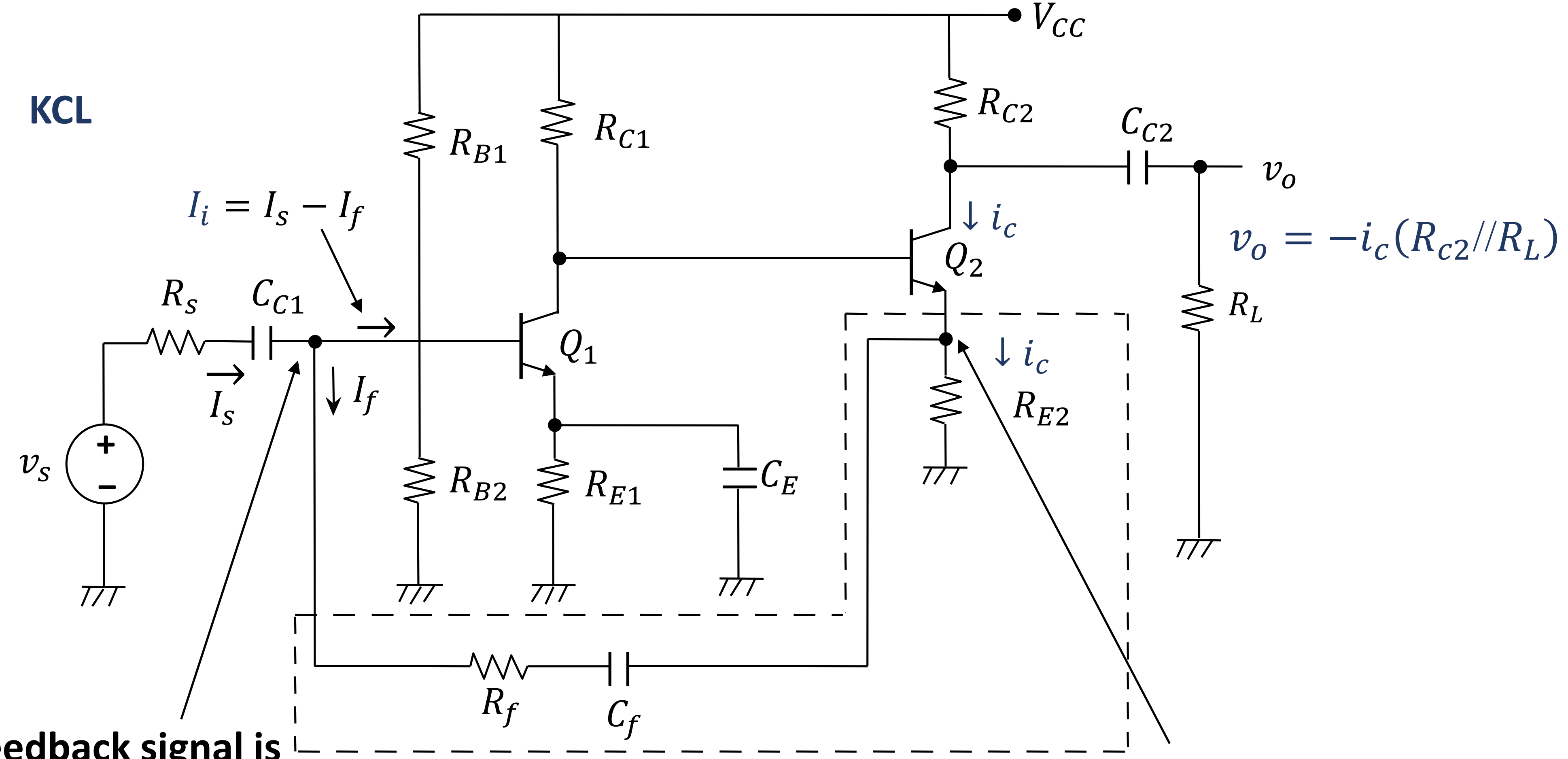
$R_i \rightarrow 0$

$R_o \rightarrow \infty$

Shunt-Series Feedback Amplifier

Example 4:

(Current mixing - Current sampling)



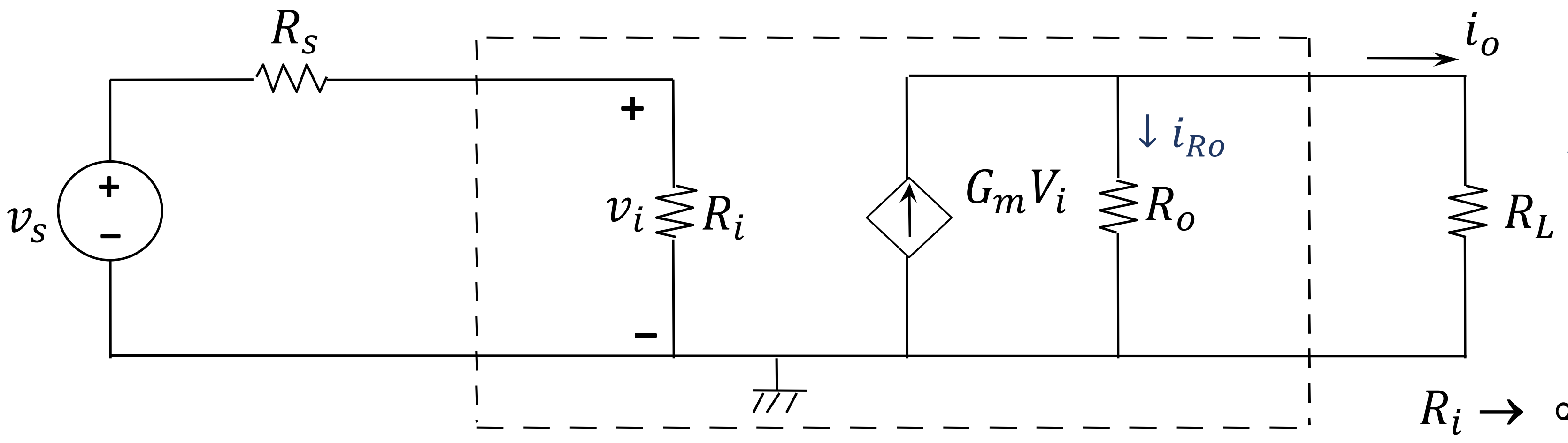
Feedback signal is connected in parallel with external source (Current mixing)

Feedback Network

Sample is taken from the output loop, not the output node (Current sampling)

C. Trans-conductance Amplifier

Input Signal : **Voltage**, v_i
Output Signal : **Current**, i_o



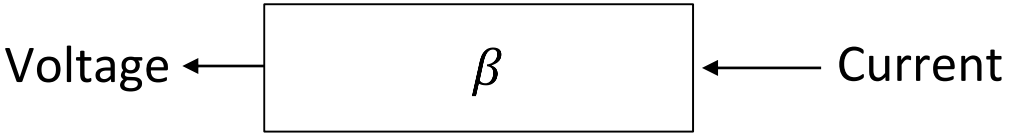
$$A = \frac{i_o}{v_s}$$

Ideal Case

$R_i \to \infty$ max v_i

$R_o \to \infty$ max i_o

∴ Feedback network I/O signal:

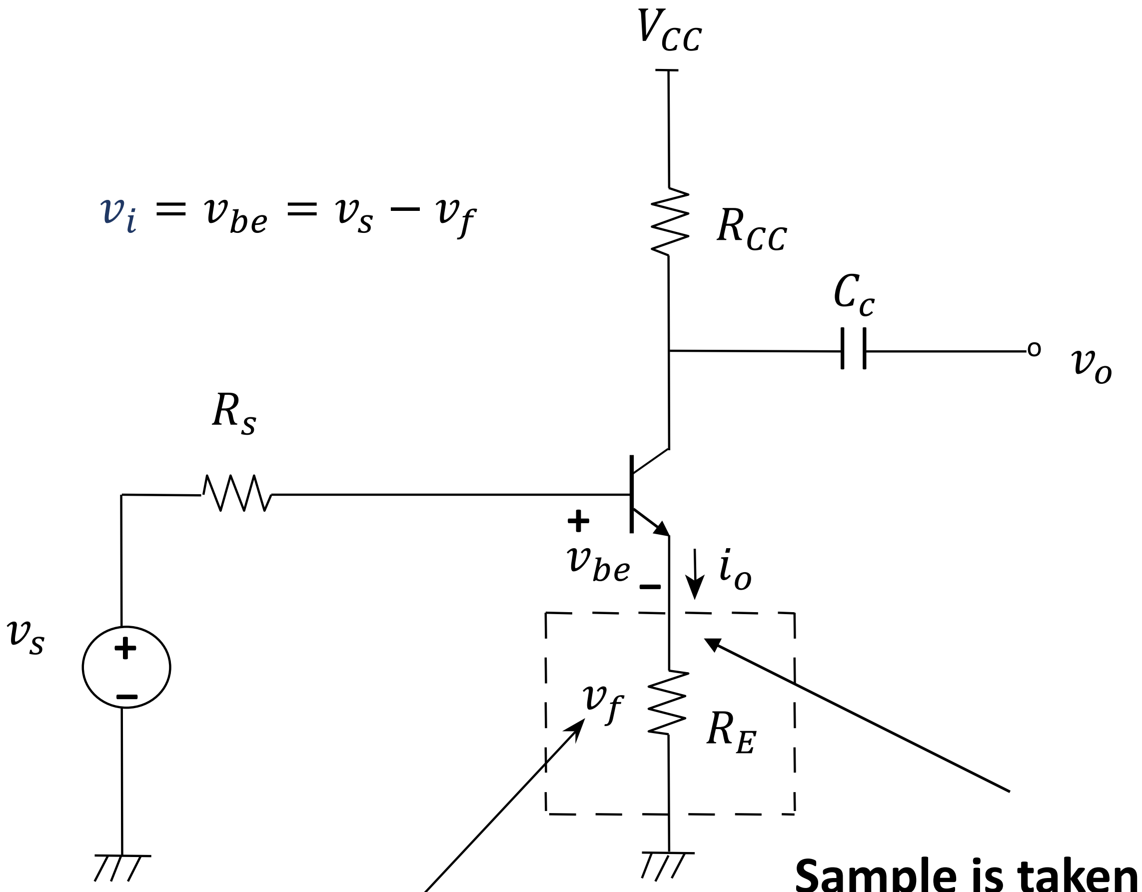


Feedback topology is **current** sampling (at o/p) and **voltage** mixing (at i/p) i.e.
Trans-conductance Amp. with negative feedback is a **Series-Series** Feedback Amplifier.

Series-Series Feedback Amplifier

Example 5:
(Voltage Mixing – Current Sampling)

(i)



$\boxed{\dfrac{i_o}{v_s}}$

v_f is connected in series with v_s (Voltage mixing)

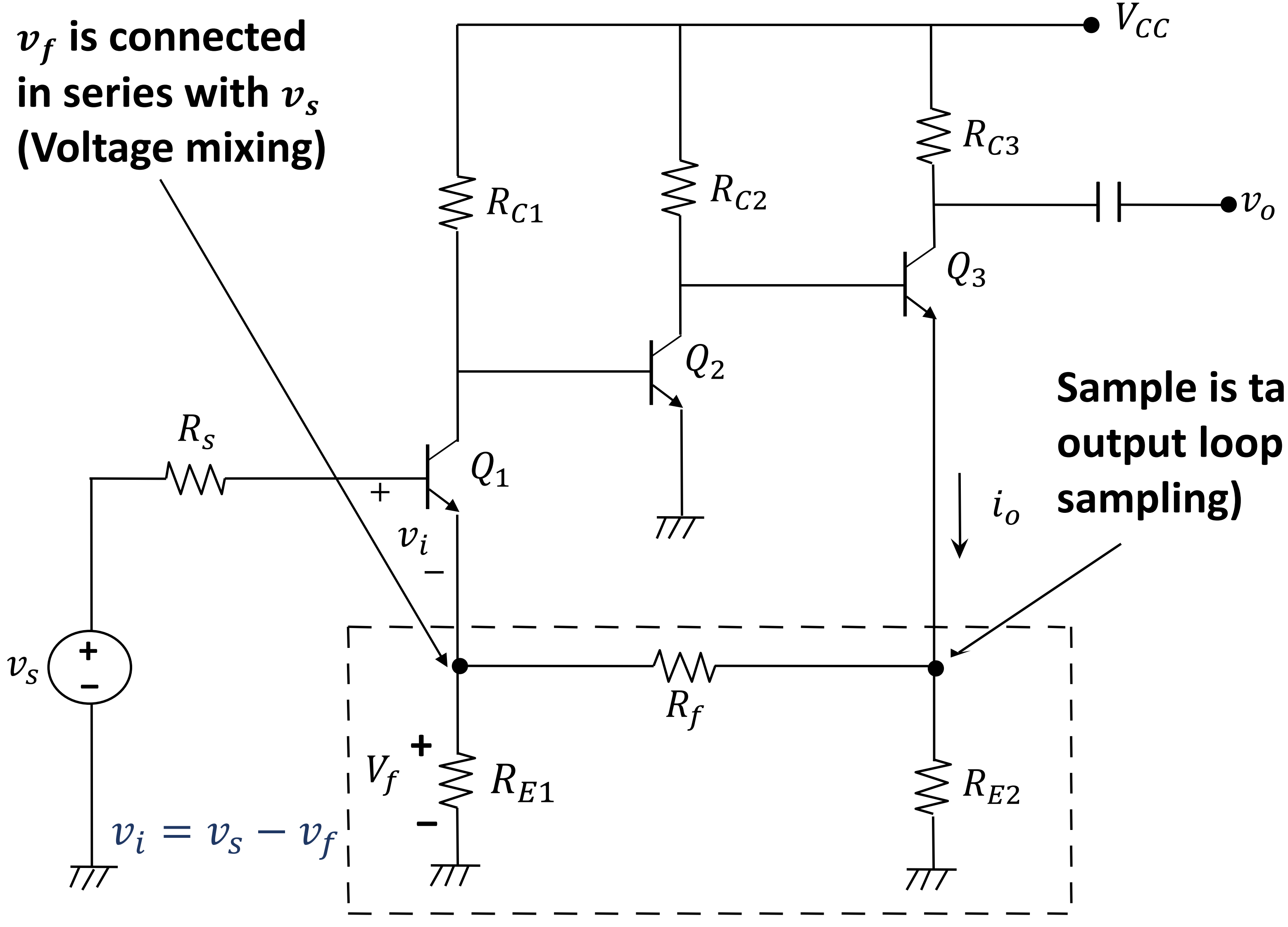
Sample is taken from output loop (Current sampling)

Series-Series Feedback Amplifier

Example 5:
(Contd.)

(Voltage Mixing - Current Sampling)

(ii)



$$A = \frac{i_o}{v_i}$$

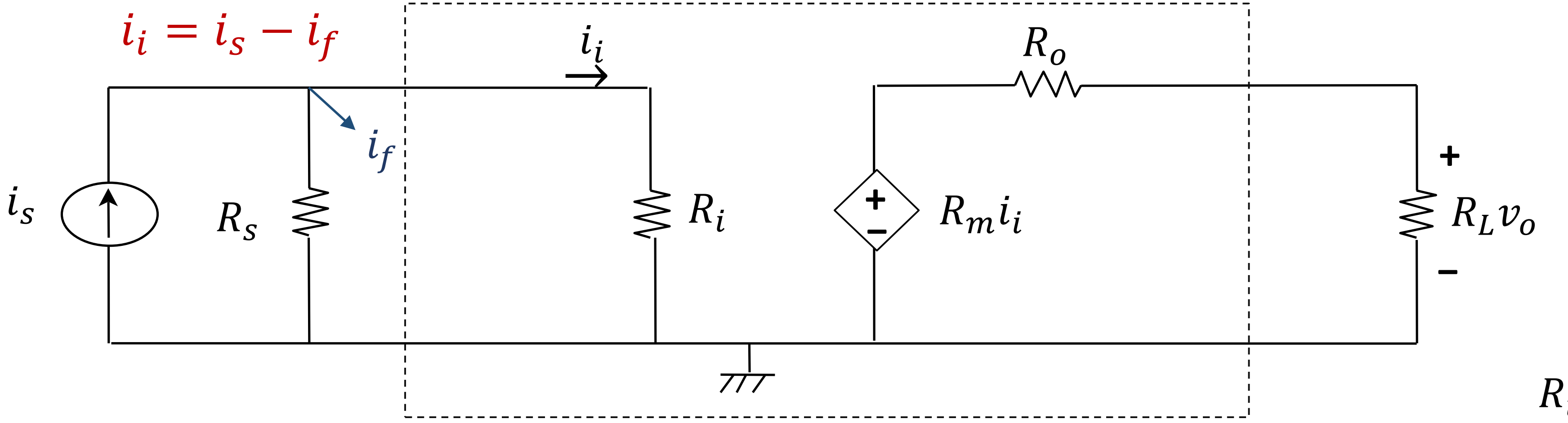
D. Trans-resistance Amplifier

Input Signal : Current, i_i

Output Signal : Voltage, v_o

KCL

$$i_i = i_s - i_f$$



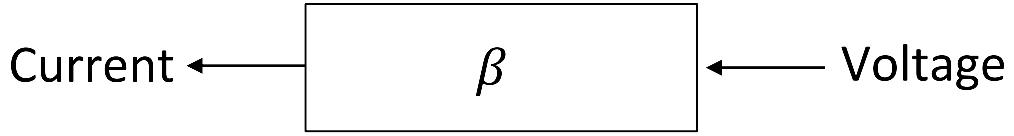
$$\frac{v_o}{i_i}$$

Ideal Case

$R_i \rightarrow 0$

$R_o \rightarrow 0$

Feedback network I/O signal:

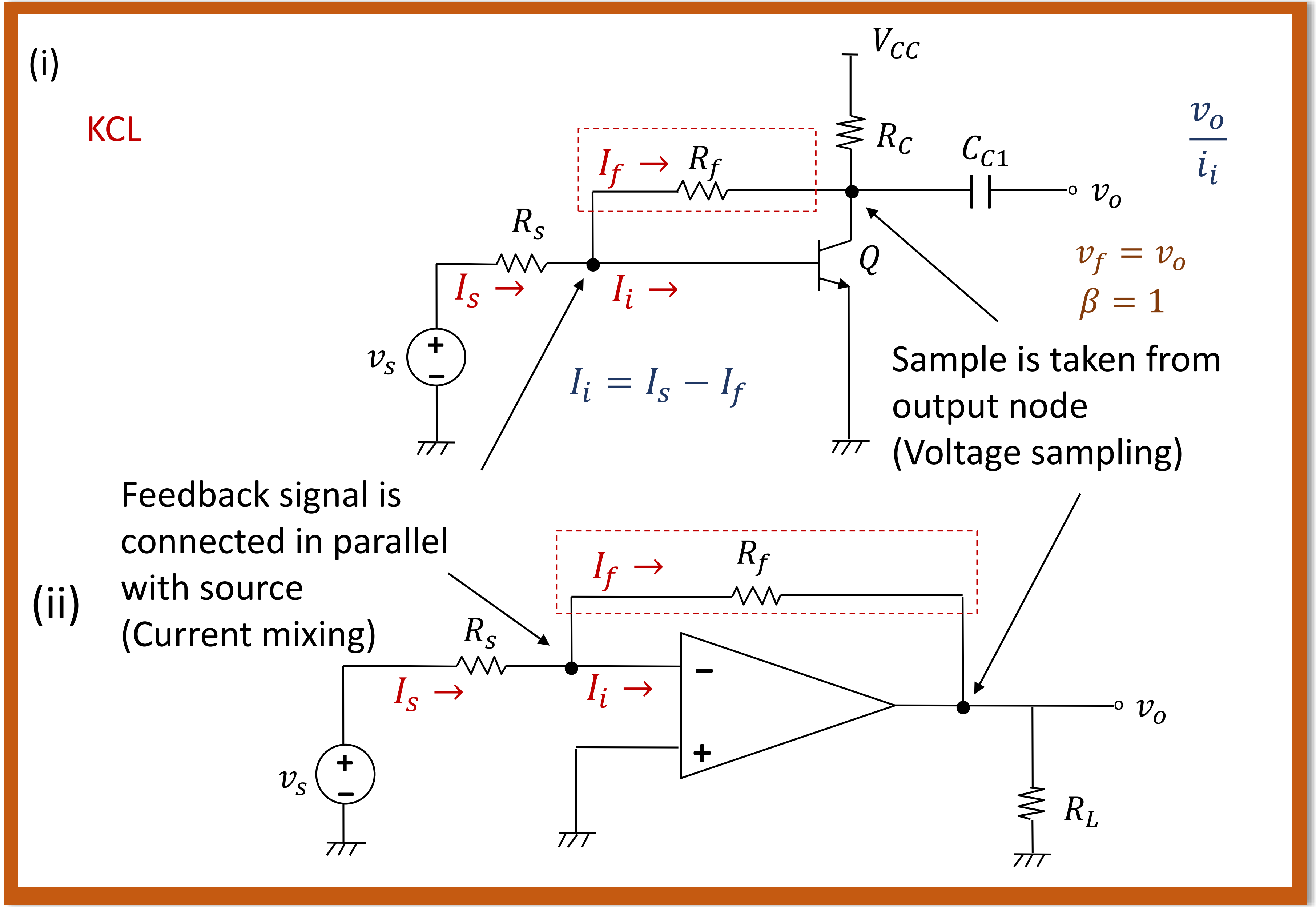


Feedback topology is **voltage** sampling and **current** mixing, i.e., Trans-resistance Amp. with Negative Feedback is **Shunt-Shunt** Feedback Amplifier.

Shunt-Shunt Feedback Amplifier

Example 6:

Shunt-Shunt Feedback Amplifier (current mixing – voltage sampling)



Input and Output Resistance of an Amplifier

Effect of feedback on Input and Output Resistance of an Amplifier

Change of R_{in} and R_{out} depends on:

(i) Mixing method

(ii) Sampling method

To maximise the o/p drive

Series $R \uparrow$

Multiply

For **Series-Mixing** or **Series-Sampling**

$$R_f = R(1 + A\beta)$$

i.e. with feedback, the I/O resistance is increased by a factor equal to the amount of feedback

For **Shunt-Mixing** or **Shunt-sampling**

Parallel $R \downarrow$

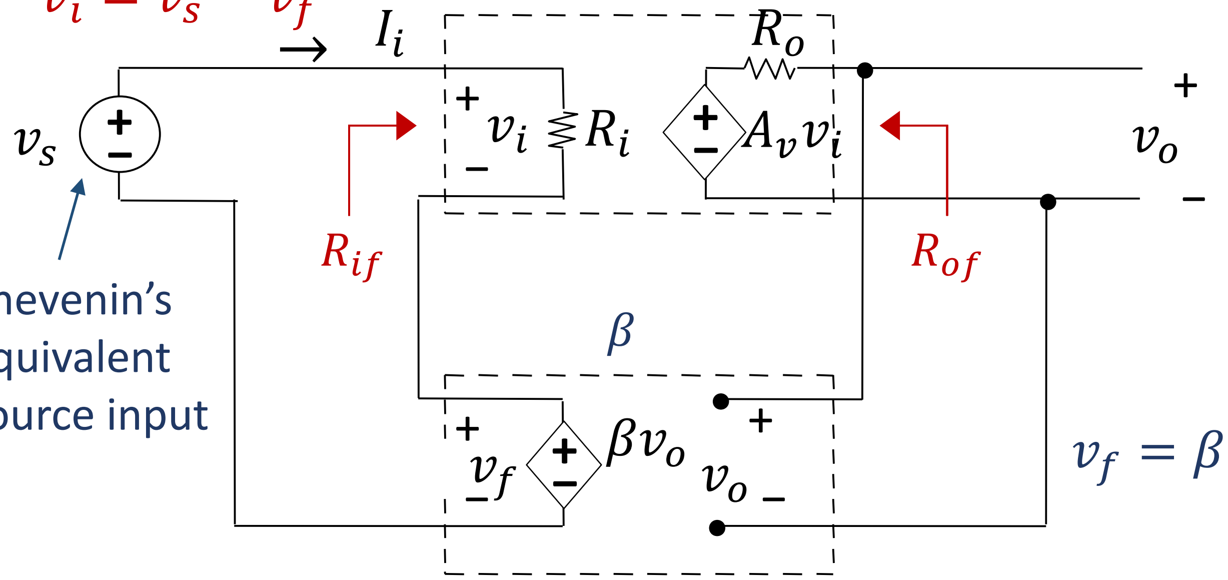
Divide

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

i.e. I/O resistance decreases by a factor equal to the amount of feedback

R_{if} and R_{of} of the Series-Shunt Feedback Amplifier

$v_i = v_s - v_f$



$A_f = \dfrac{v_o}{v_s}$

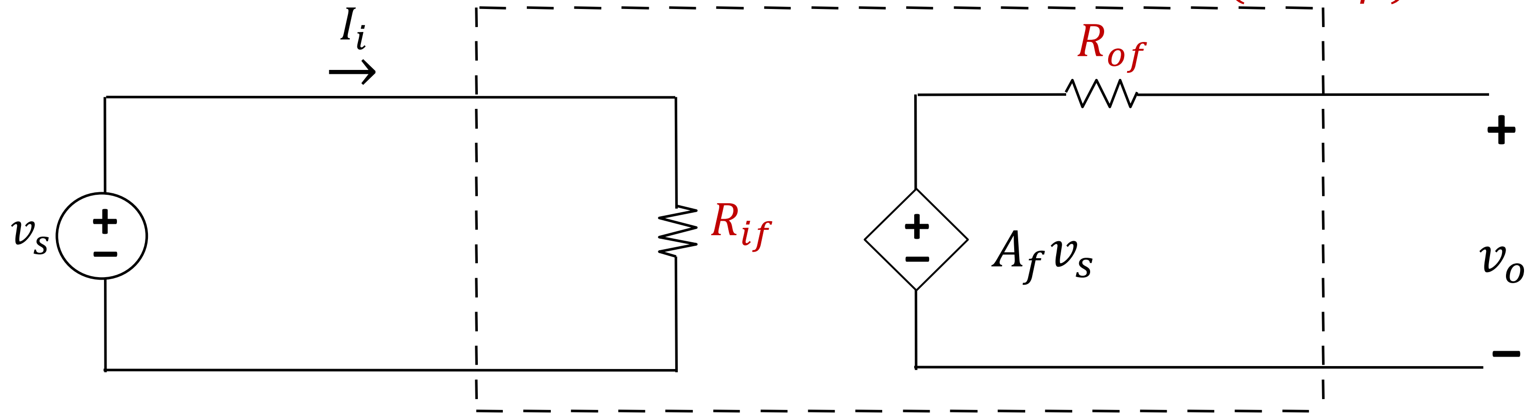
$v_f = \beta v_o$

Ideal Series-Shunt Feedback Amplifier

$R_{if} = R_i(1 + A\beta)$: Series

$R_{of} = \dfrac{R_o}{(1 + A\beta)}$: (Shunt)

$A_f = \dfrac{A}{1 + A\beta}$



Equivalent Circuit

Input Resistance, R_{if}

$$v_s = v_i + v_f$$

But

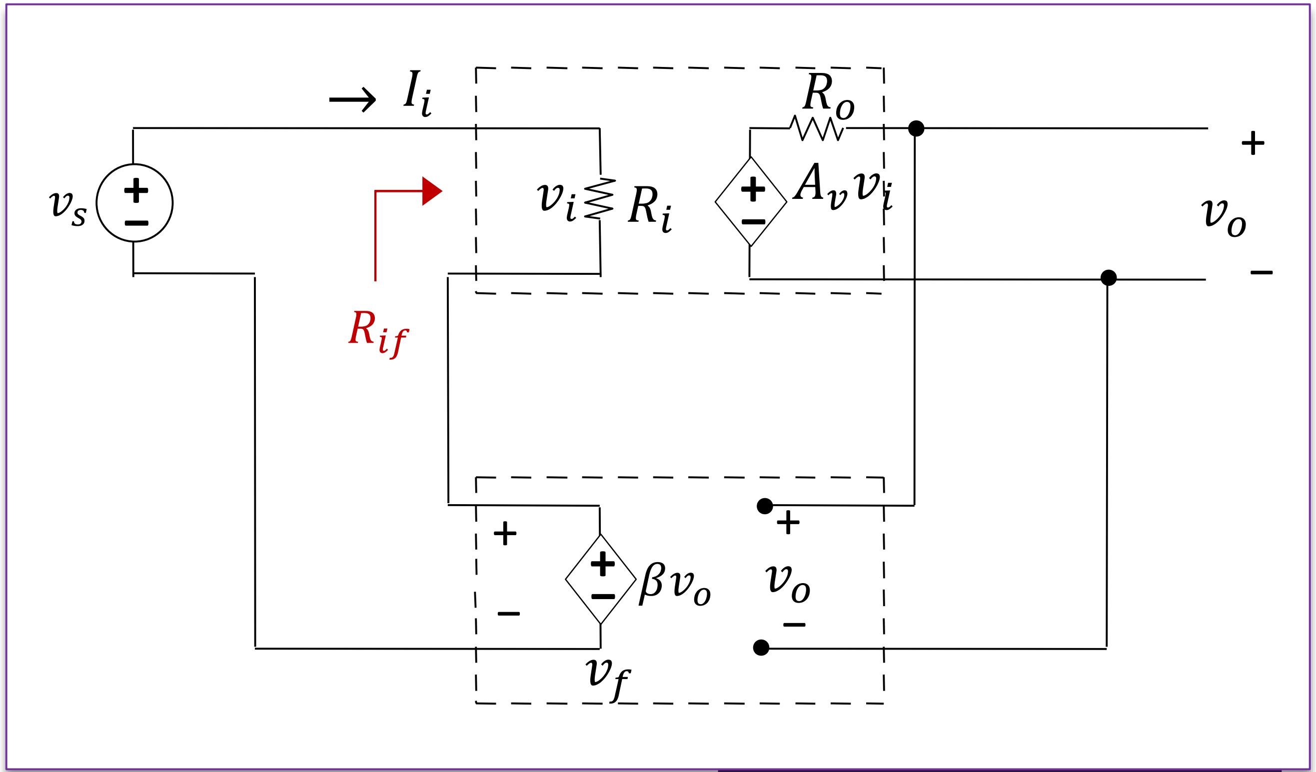
$$v_f = \beta v_o$$

Ideally

$$v_o = A_v v_i$$

$$\therefore \quad v_s = (1 + A_v\beta)v_i \qquad \text{- (1)}$$

$$I_i = \frac{v_i}{R_i} \qquad \text{- (2)}$$



$$\frac{(1)}{(2)}: \; R_{if} = \frac{v_s}{I_i} = R_i(1 + A_v\beta)$$ **(Series-Mixing)**

Output Resistance, R_{of}

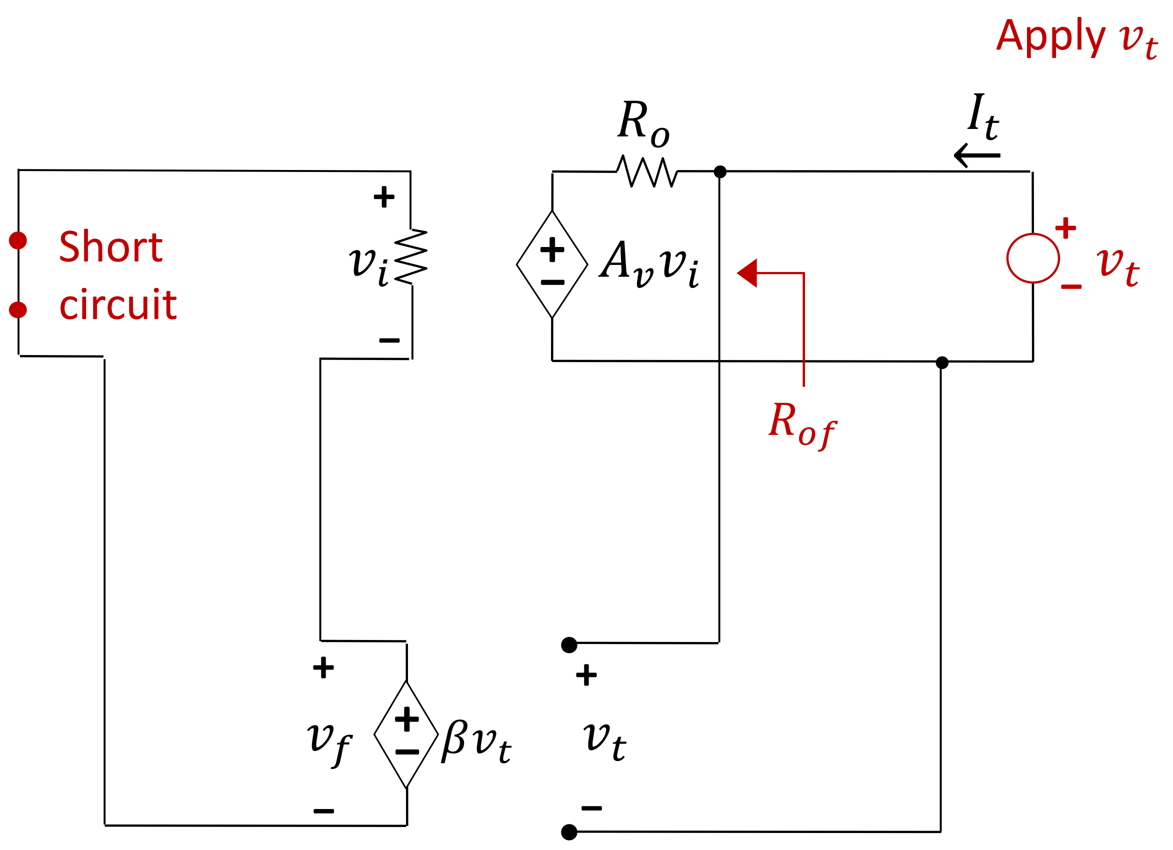
(Short v_s and apply v_t at output)

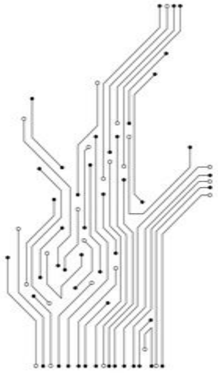
$$v_i = -v_f = -\beta v_t$$

$$v_t = I_t R_o + A_v v_i$$

$$\therefore \quad v_t = I_t R_o - A_v \beta v_t$$

or $v_t(1 + A_v\beta) = I_t R_o$

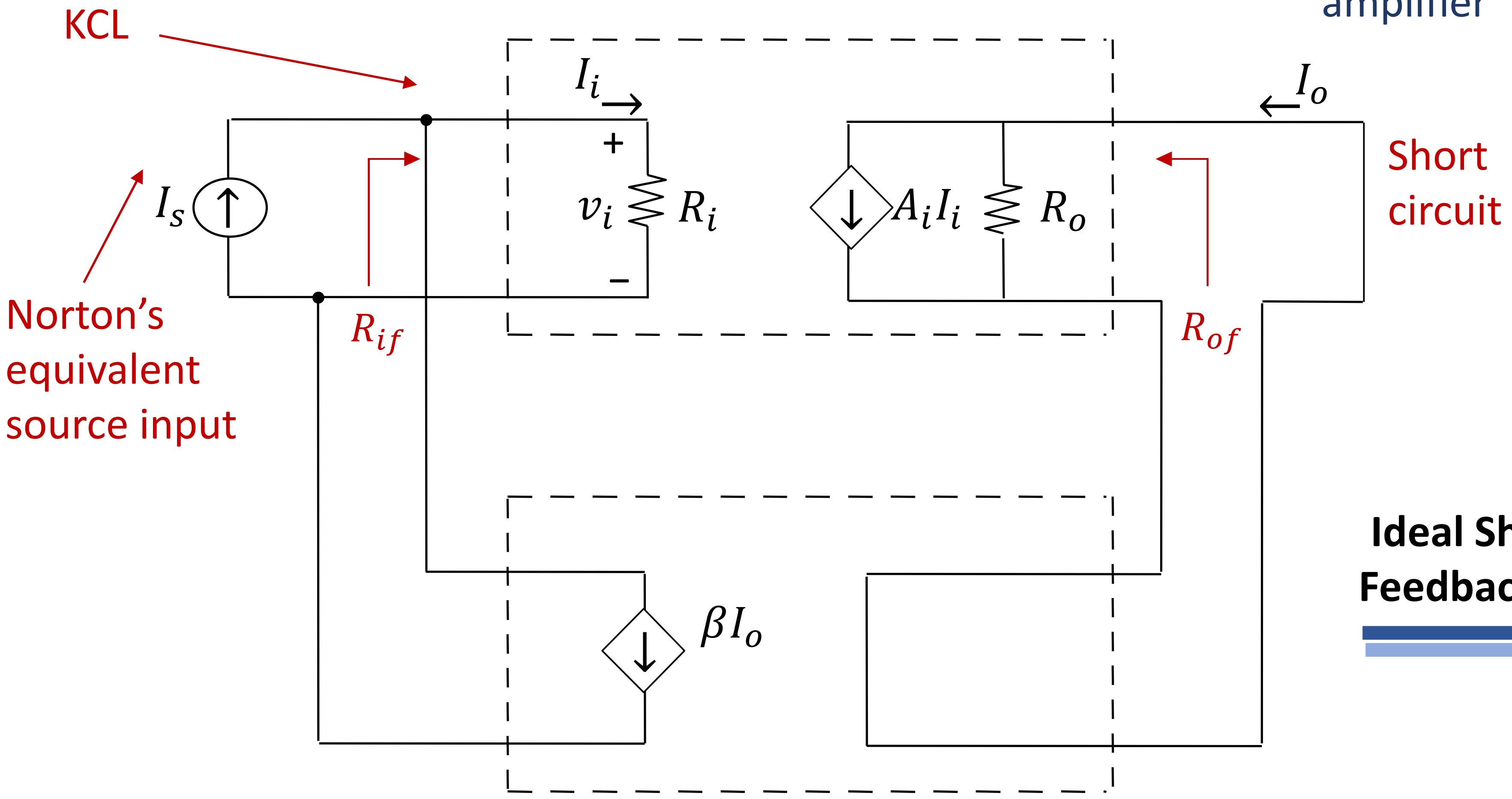




Hence $R_{of} = \dfrac{v_t}{I_t} = \dfrac{R_o}{(1 + A_v\beta)}$ **(Shunt-sampling)**

R_{if} and R_{of} of the Shunt-Series Feedback Amplifier

$I_i = I_s - I_f$



Ideal Shunt-Series Feedback Amplifier

Input Resistance, R_{if}

$I_i = I_s - I_f$

But ideally:

$I_f = \beta I_o$ and $I_o = A_i I_i$

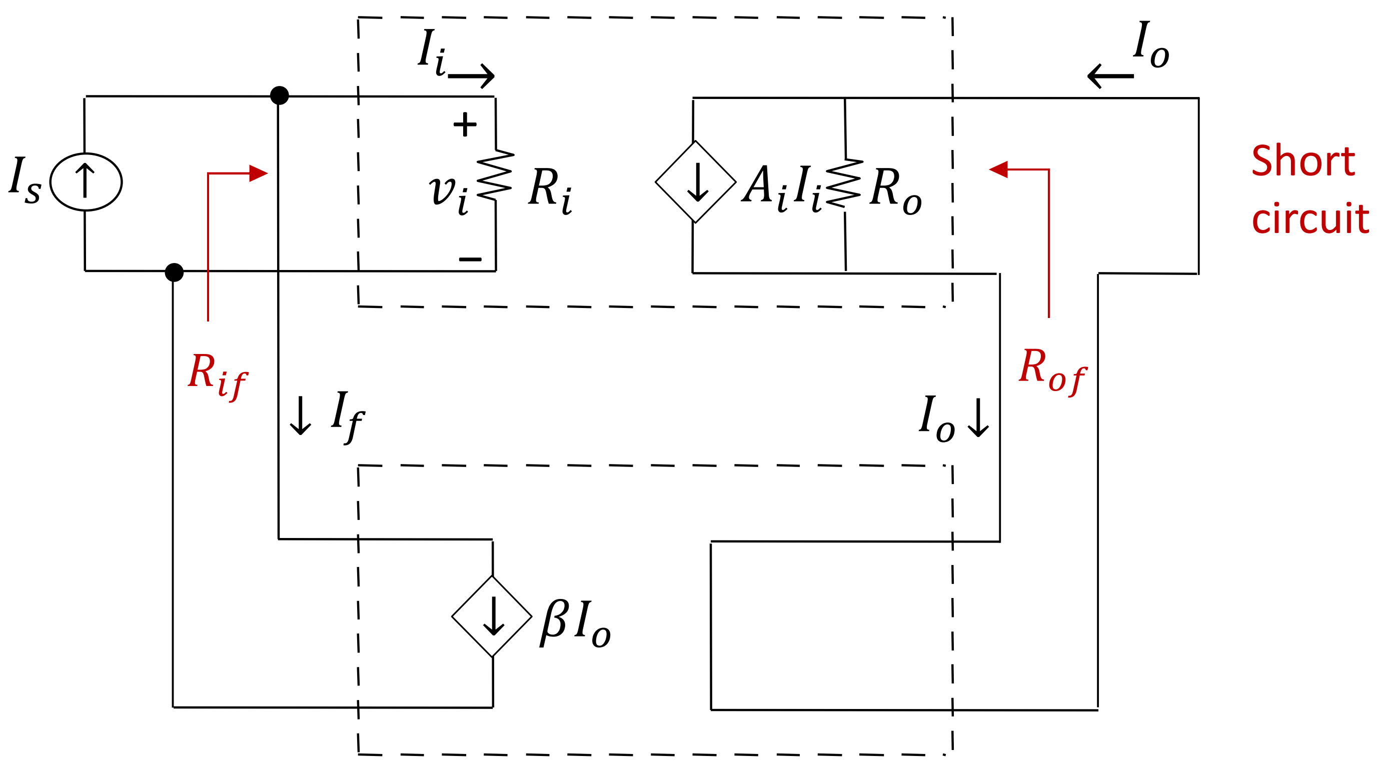
$$I_s = I_i(1 + A_i\beta) \quad \text{- (1)}$$

$$v_i = I_i R_i \quad \text{- (2)}$$

(2)/(1)

Hence $\quad R_{if} = \dfrac{v_i}{I_s} = \dfrac{R_i}{(1 + A_i\beta)}$ (Shunt-mixing)

Current amplifier: Shunt Series



Smaller R_{if} to extract more current from the source

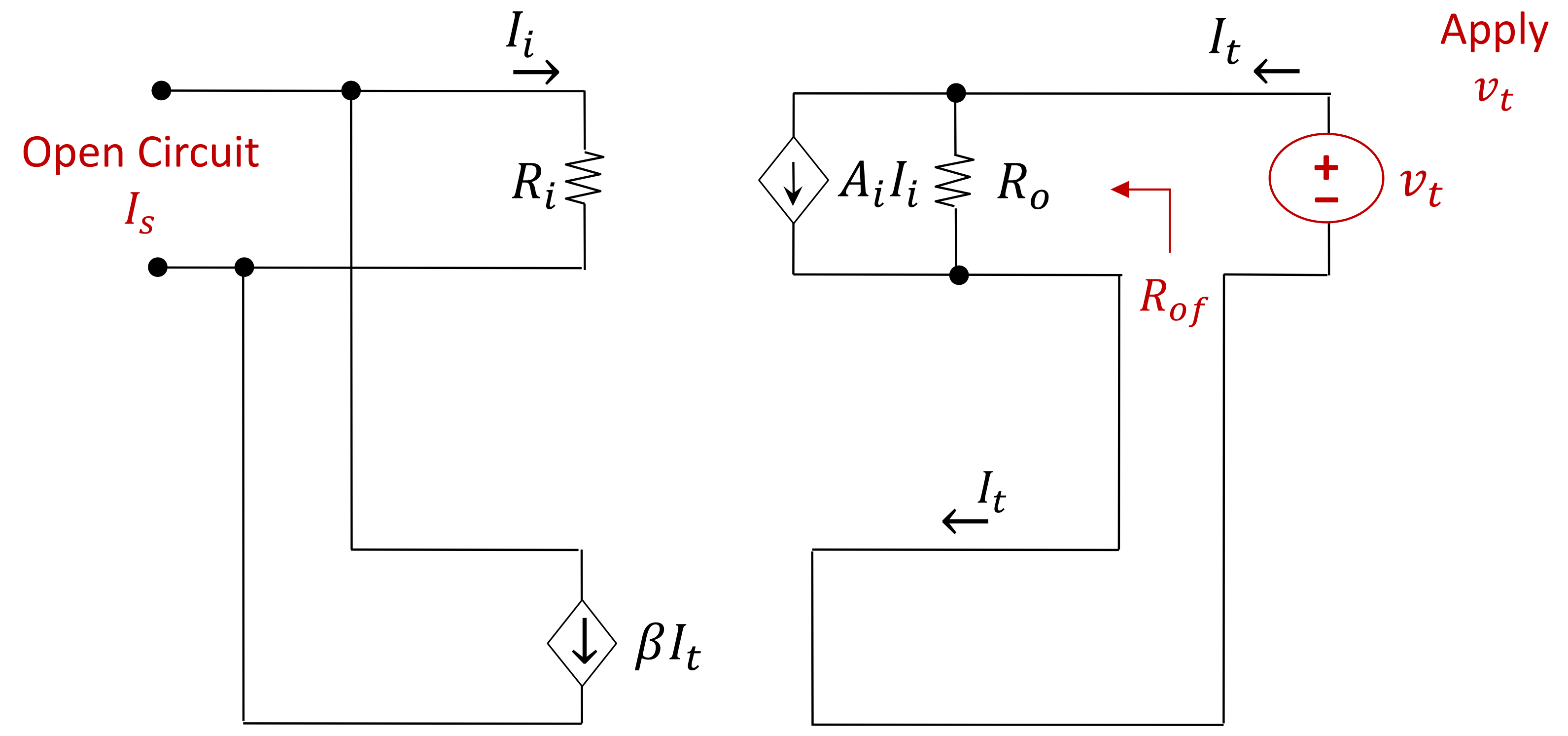
Output Resistance, R_{of}

Open Circuit I_s and
Apply V_t at output

$$I_i = -\beta I_t$$

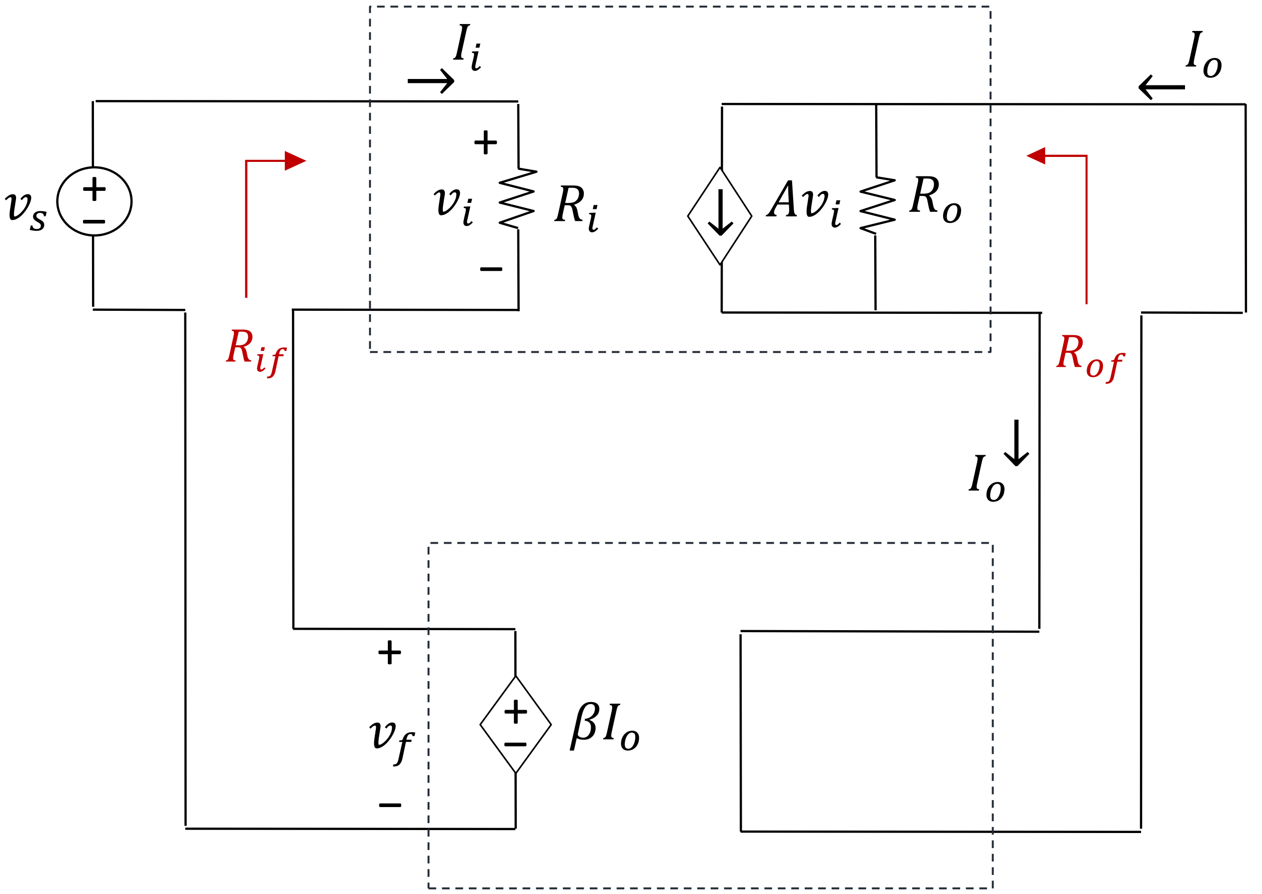
$$v_t = (I_t - A_i I_i)R_o$$

$$v_t = (I_t + A_i \beta I_t)R_o$$



Hence $R_{of} = \dfrac{v_t}{I_t} = (1 + A_i \beta)R_o$ **(Series-Sampling)**

R_{if} and R_{of} of the Series-Series Feedback Amplifier



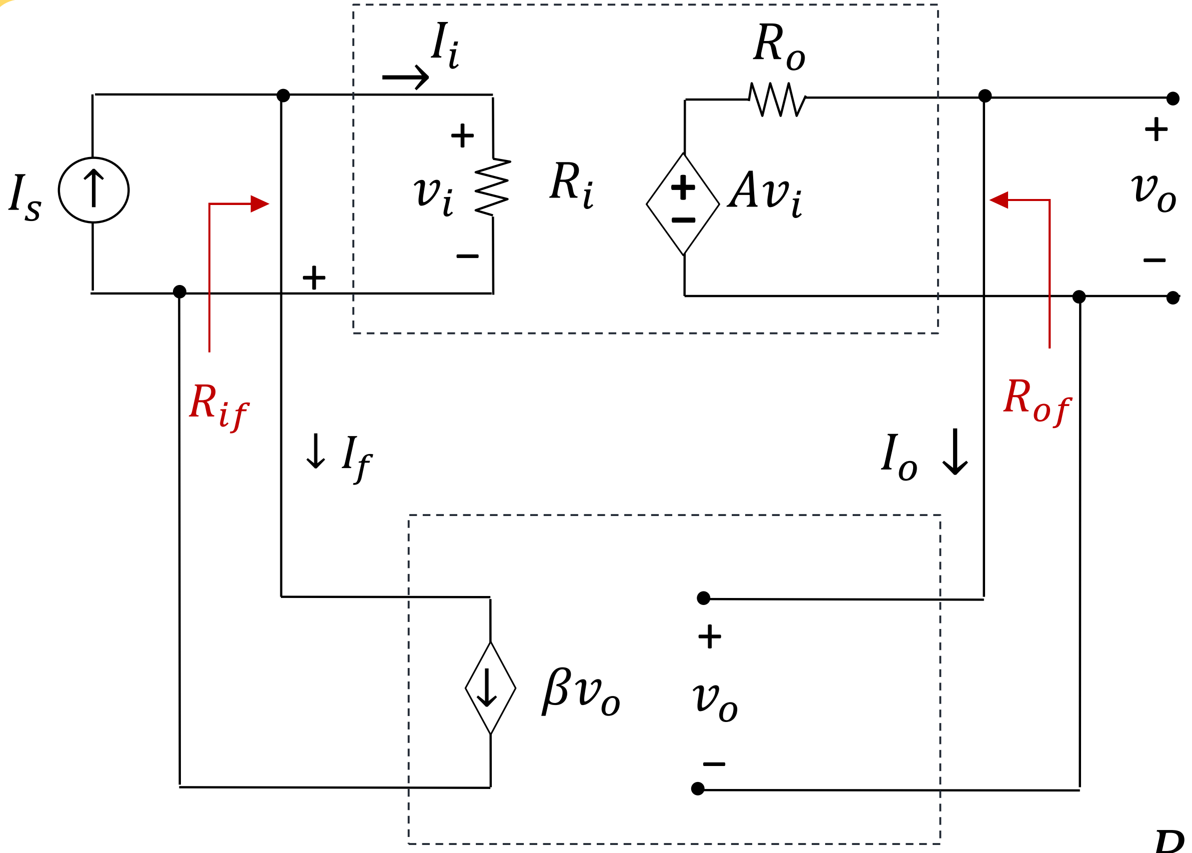
Series $R_f = R(1 + A\beta)$

Ideal Series-Series Feedback Amplifier

Input Resistance, $R_{if} = R_i(1 + A\beta)$

Output Resistance, $R_{of} = R_o(1 + A\beta)$

R_{if} and R_{of} of the Shunt-Shunt Feedback Amplifier



Shunt (Parallel)

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

Ideal Shunt-Shunt Feedback Amplifier

Input Resistance, $$R_{if} = \frac{R_i}{(1+A\beta)}$$

Output Resistance, $$R_{of} = \frac{R_o}{(1+A\beta)}$$

Summary of Feedback Topology

A_v : Voltage Gain

A_i : Current Gain

G_m : Trans-conductance

R_m : Trans-resistance

Type of Amplifier	**Voltage Amplifier**	**Current Amplifier**	**Trans-conductance Amplifier**	**Trans-resistance Amplifier**
Input Signal	v_i	I_i	v_i	I_i
Output Signal	v_o	I_o	I_o	v_o
Transfer Characteristics	$A_v v_s$	$A_i I_s$	$G_m v_s$	$R_m I_s$
Feedback Topology	Series-Shunt	Shunt-Series	Series-Series	Shunt-Shunt
Feedback Factor $\boldsymbol{\beta}$	v_f/v_o	I_f/I_o	v_f/I_o	I_f/v_o
Input Resistance $\boldsymbol{R_{if}}$	$R_i(1+A\beta)$	$\dfrac{R_i}{(1+A\beta)}$	$R_i(1+A\beta)$	$\dfrac{R_i}{(1+A\beta)}$
Output Resistance $\boldsymbol{R_{of}}$	$\dfrac{R_o}{(1+A\beta)}$	$R_o(1+A\beta)$	$R_o(1+A\beta)$	$\dfrac{R_o}{(1+A\beta)}$

4. Procedures of Feedback Amplifier Analysis

1. **Identify** the Topology:

(Mixing)

(a) Is the feedback signal X_f a **voltage** or a **current** signal? i.e., is X_f applied in **Series** or in **Shunt** with external excitation?

(b) Is the sampled signal X_o a **voltage** or a **current** signal? i.e., is X_o taken at the **output voltage node** or from the **output current loop**?

(Sampling)

2. **Separate** feedback network from basic amplifier, $\boldsymbol{A}$, and find Input and Output resistance, $\boldsymbol{R_{\beta i}}$ and $\boldsymbol{R_{\beta o}}$, of feedback circuit and also, feedback factor, $\boldsymbol{\beta}$, from the feedback circuit.

(Contd.)

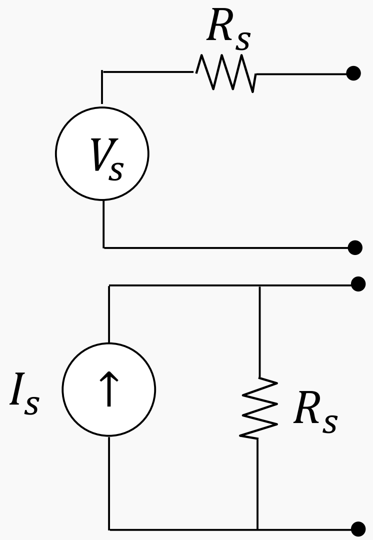
4. Procedures of Feedback Amplifier Analysis (Contd.)

3. **Draw** the basic amplifier circuit without feedback network but with $\boldsymbol{R_{\beta i}}$ and $\boldsymbol{R_{\beta o}}$obtained in step 2.
   This new basic amplifier is called ***A'***.

4. Use a **Thevenin's** equivalent source input if the feedback signal $\boldsymbol{X_f}$ is a **voltage** or a **Norton's** equivalent source if $\boldsymbol{X_f}$ is a **current**.

Thevenin's equivalent circuit

Norton's equivalent circuit



5. Replace each active device in $\boldsymbol{A'}$ circuit by a proper model (i.e. h-parameter or hybrid-π model) and evaluate amplifer gain ***A'*** of the $\boldsymbol{A'}$ circuit with $\boldsymbol{R_{\beta i}}$ and $\boldsymbol{R_{\beta o}}$included. Also, find the Input and Output resistance of the $\boldsymbol{A'}$ circuit ($\boldsymbol{R_i'}$ and $\boldsymbol{R_o'}$).

4. Procedures of Feedback Amplifier Analysis (Contd.)

6. From amplifier gain, $\boldsymbol{A'}$ with $\boldsymbol{R_{\beta i}}$ and $\boldsymbol{R_{\beta o}}$ and feedback factor, $\boldsymbol{\beta}$, find A_f, R_{if} and R_{of}.

$$R_{if} = (1 + A'\beta)R_i' \quad \text{(Series mixing - Voltage)}$$

$$R_{if} = R_i'/(1 + A'\beta) \quad \text{(Shunt mixing - Current)}$$

$$A_f = \frac{A'}{1 + A'\beta}$$

$$R_{of} = (1 + A'\beta)R_o' \quad \text{(Series sampling - Current)}$$

$$R_{of} = R_o'/(1 + A'\beta) \quad \text{(Shunt sampling - Voltage)}$$

New gain with $R_{\beta i}$ and $R_{\beta o}$ (Loading effect)

New I/P impedance

New O/P impedance

Feedback Network β

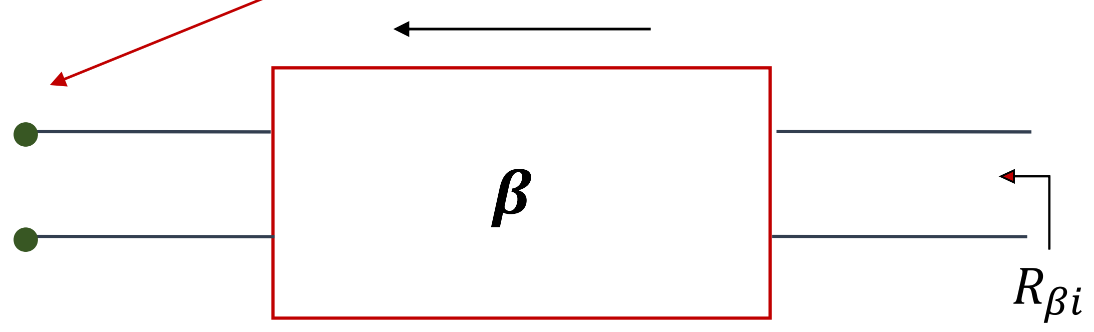
Input and Output Resistance ($R_{\beta i}$and $R_{\beta o}$) of the Feedback Network β

First, separate the whole **Feedback** Amplifier into **TWO** blocks, the basic amp ***A*** and the **Feedback** network. Apply the following rules to find $\boldsymbol{R_{\beta i}}$ and $\boldsymbol{R_{\beta o}}$.

Input resistance of Feedback circuit, $R_{\beta i}$

Open circuit

1. For Voltage (**Series**) mixing, **SEVER** the output node of the **Feedback** circuit.

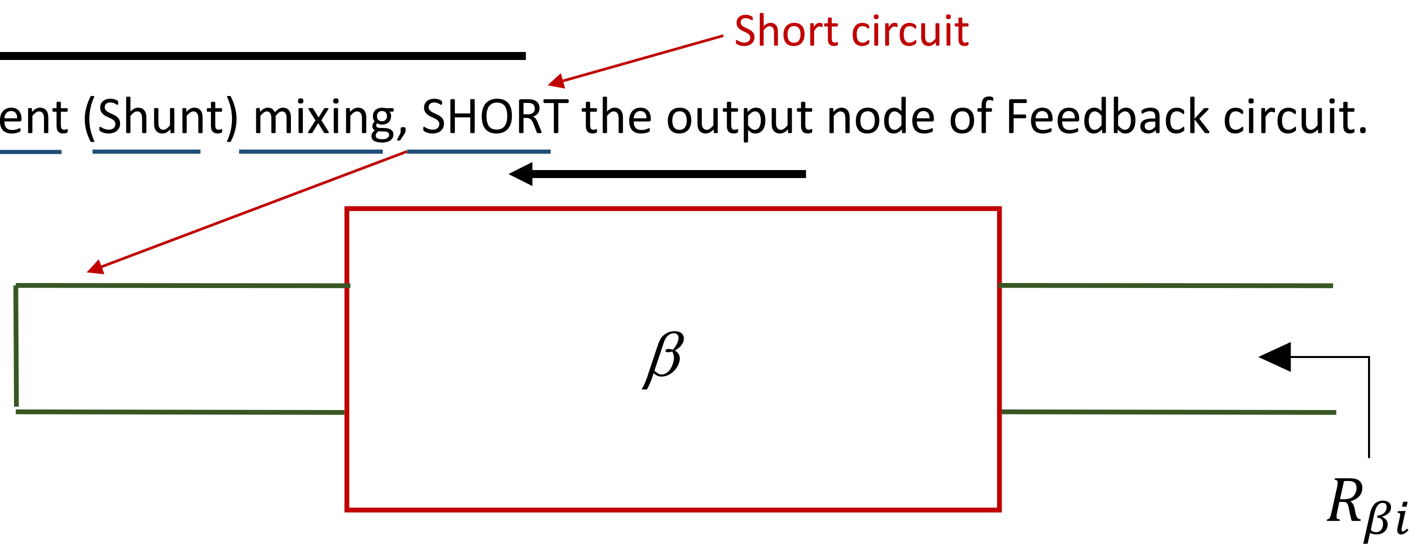


Series-Mixing

Feedback Network β

Input and Output Resistance ($R_{\beta i}$and $R_{\beta o}$) of the Feedback Network β

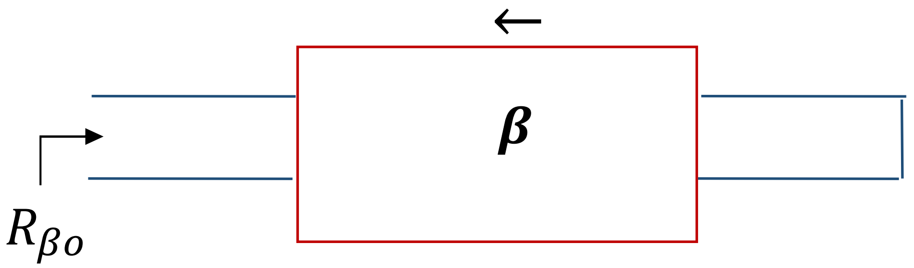
2. For Current (Shunt) mixing, SHORT the output node of Feedback circuit.



Shunt-Mixing

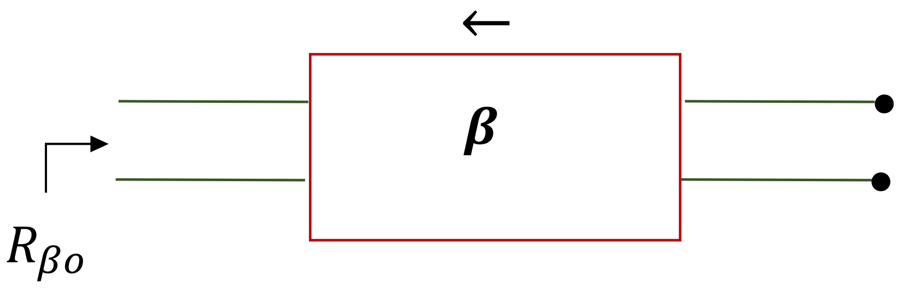
Output Resistance of Feedback Circuit, $R_{\beta o}$

1. For voltage (**Shunt**) sampling, **SHORT** the input node of **Feedback** circuit.



Shunt-Sampling

2. For current (**Series**) sampling, **SEVER** the input node of **Feedback** circuit.



Series-Sampling

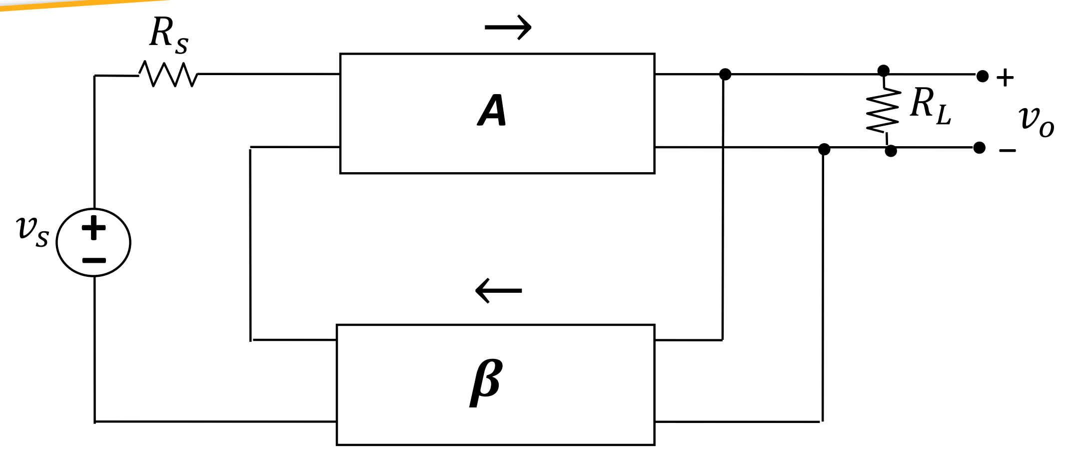
A simple rule to remember:

"If connection is SHunt, SHort it,
if connection is SEries, SEver it."

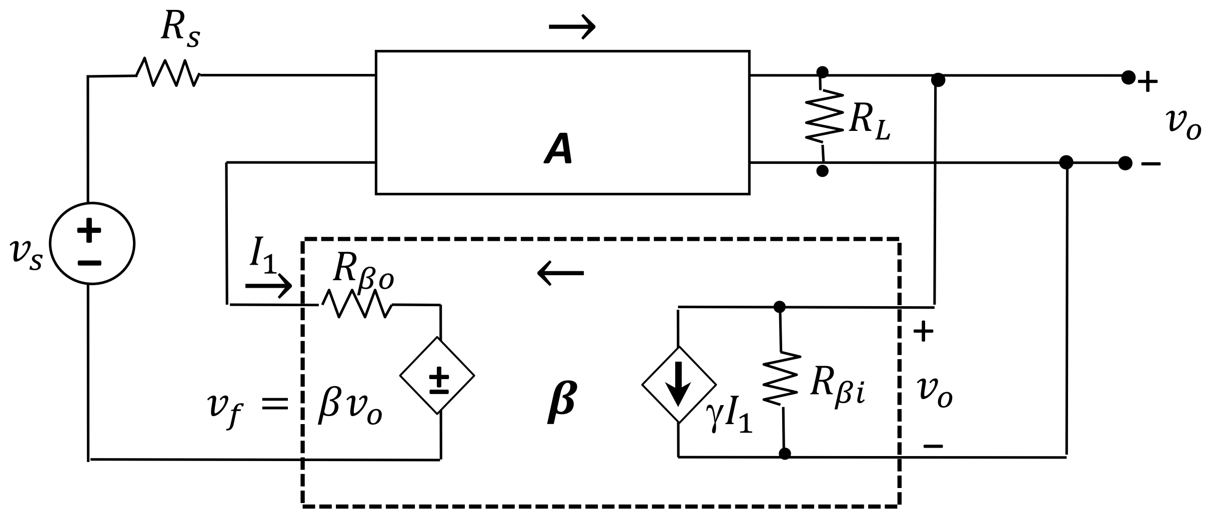
Practical Series-Shunt Feedback Amplifier

Example 7:

1 Separate the ***A*** block and the **Feedback** block:



2 Find $R_{\beta i}$ and $R_{\beta o}$ of **Feedback** block:

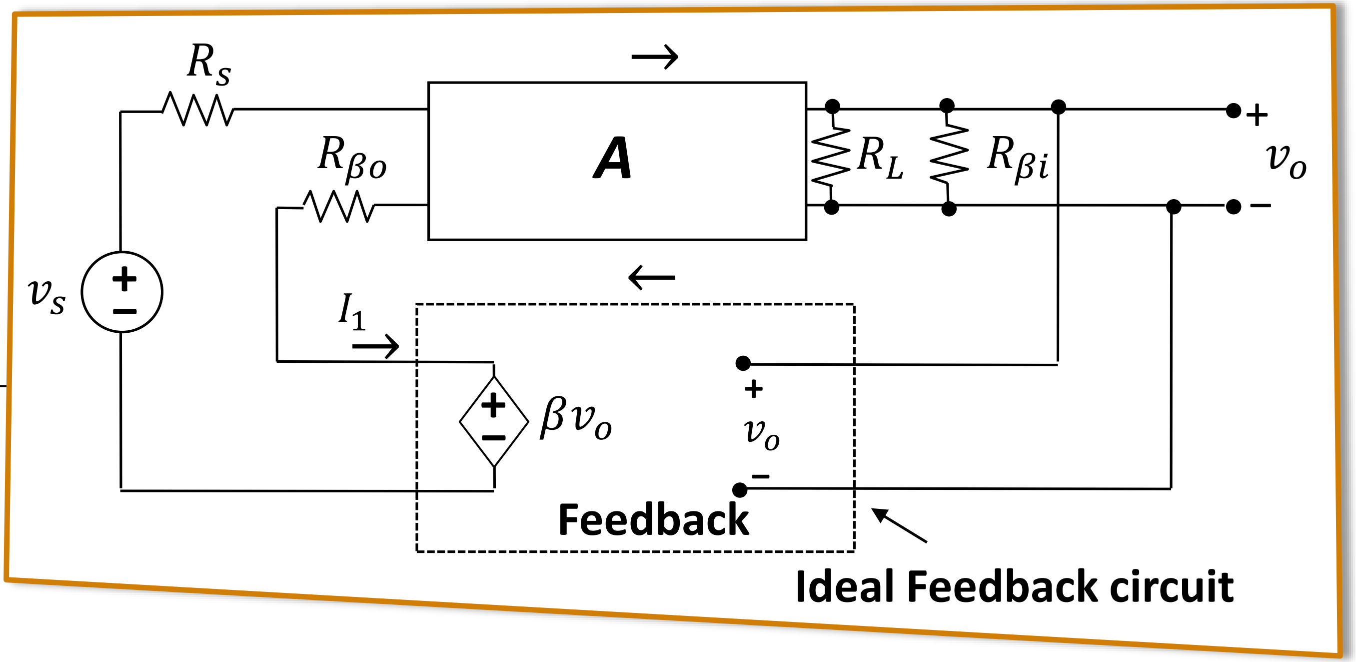


*Compare this with the ideal **Series-Shunt Feedback** amplifier structure.

Practical Series-Shunt Feedback Amplifier (Contd.)

Example 7:

3 Include $R_{\beta i}$ and $R_{\beta o}$ with the ***A*** Block:

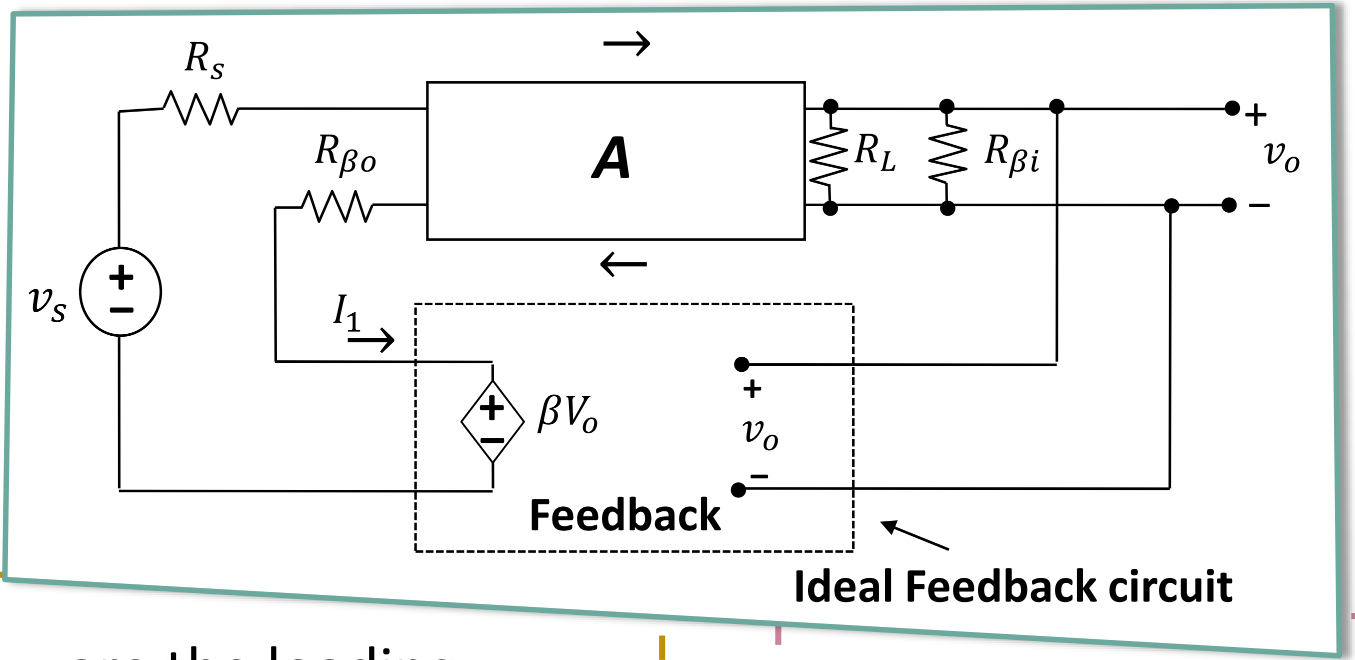


Note that the current dependent source γI_1 is neglected.
In fact, β is the forward transmission of the **Feedback** network and γ is the reverse transmission of the **Feedback** network.

This reverse transmission, in comparison to the much larger forward transmission of the basic amp ***A***, is very negligible.

Practical Series-Shunt Feedback Amplifier (Contd.)

Example 7:



$R_{\beta i}$ and $R_{\beta o}$ are the loading effects of the feedback network **Feedback** on the basic amplifier ***A***.

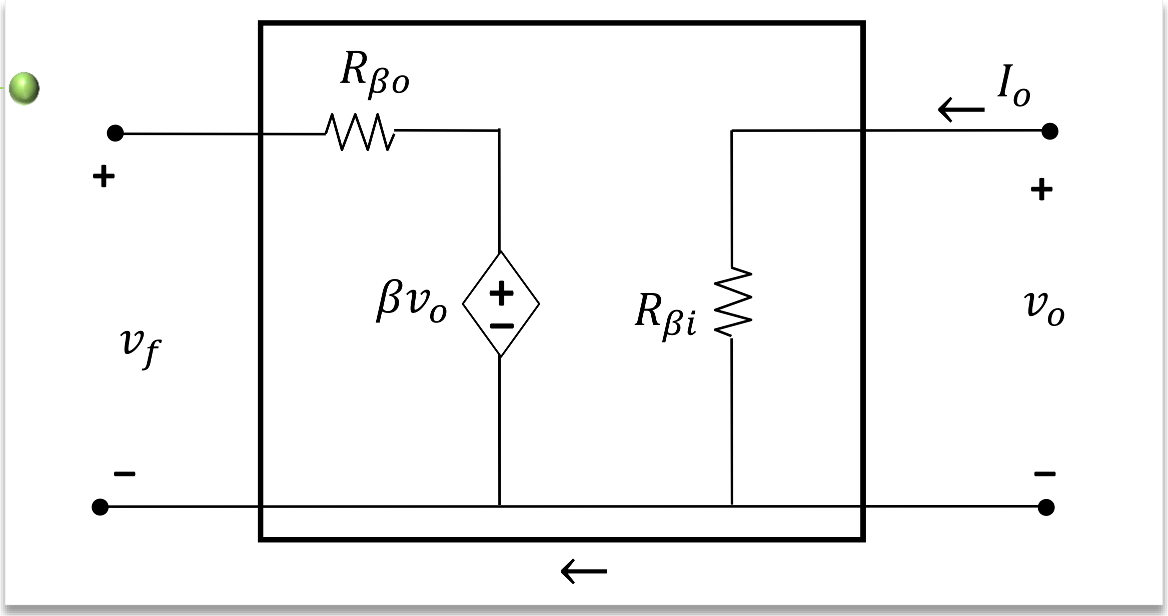
They are obtained by destroying the feedback, i.e. while looking into the appropriate port (input port for $R_{\beta i}$ and output port for $R_{\beta o}$), the other port is either sever or short so as to destroy the feedback.

Equivalent Circuit of Feedback Network with $R_{\beta i}$ and $R_{\beta o}$

1 Output of **Feedback** circuit is **voltage**

Thevenin's equivalent circuit.

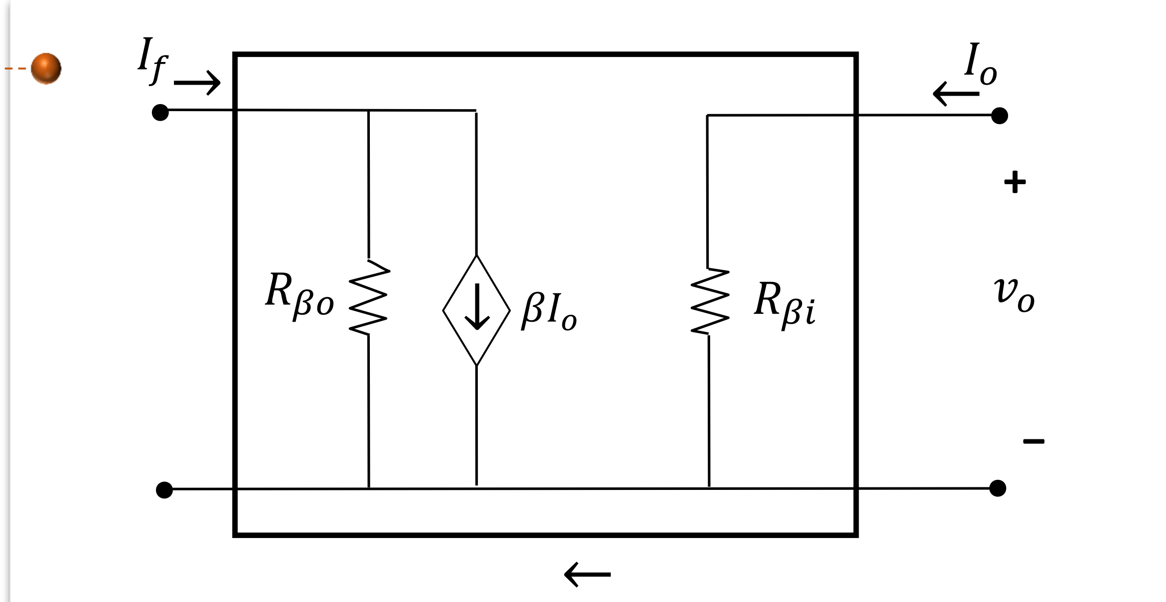
$$v_f = v_{R_{\beta o}} + \beta v_o$$



2 Output of **Feedback** circuit is **current**

Norton's equivalent circuit.

$$I_f = I_{R_{\beta o}} + \beta I_o$$

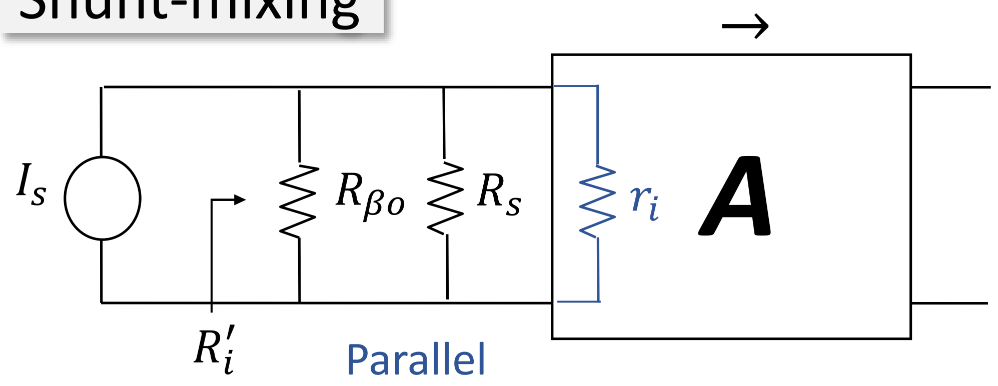


5. Loading Effect of Feedback Network on Basic Amplifier A

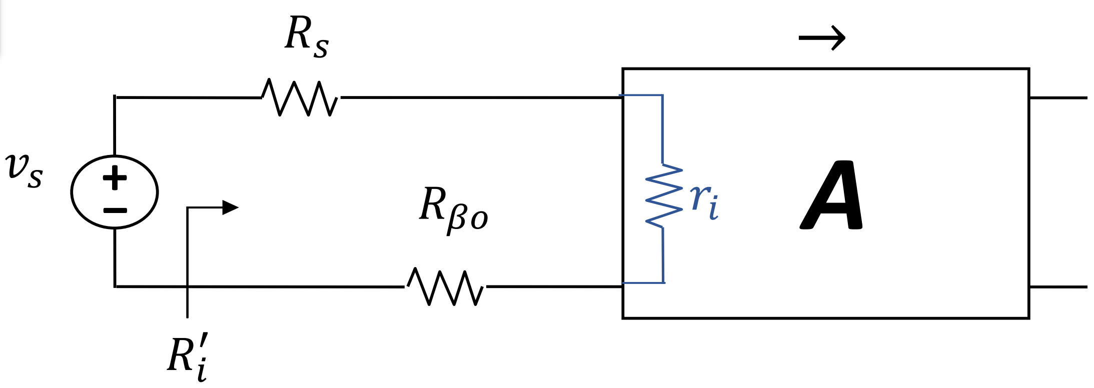
Basic Amplifier **A** with Feedback Network resistance $R_{\beta i}$ and $R_{\beta o}$

5.1 - Input of ***A*** circuit with $R_{\beta o}$

Shunt-mixing



Series-mixing

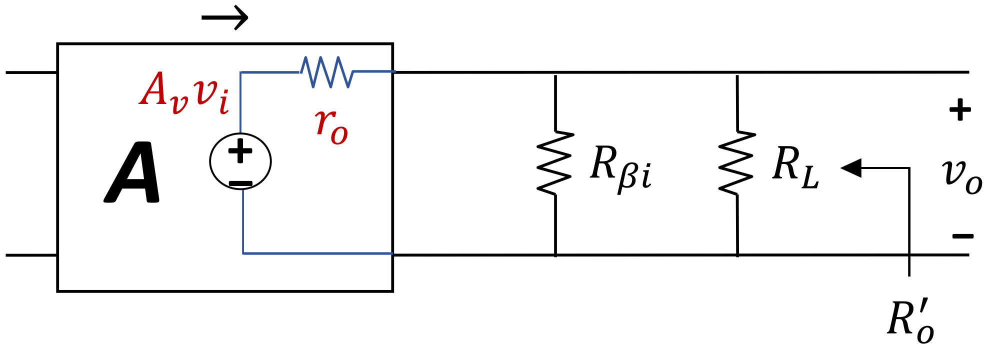


5. Loading Effect of Feedback Network on Basic Amplifier A

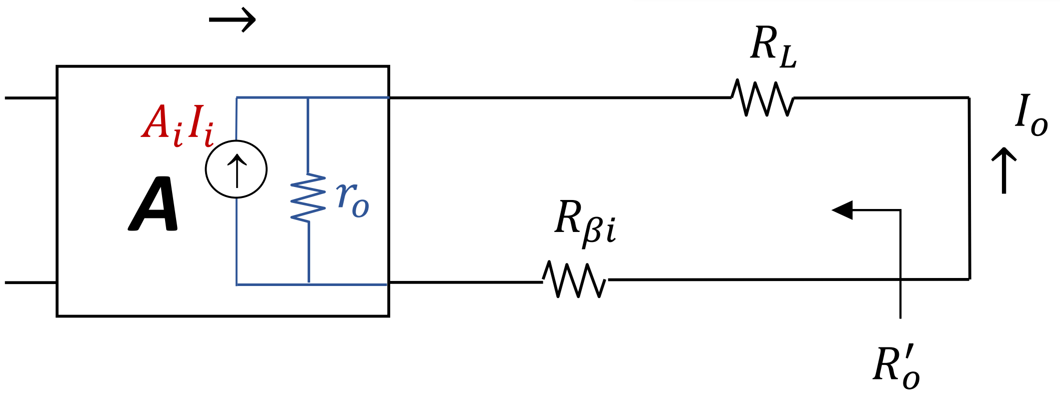
Basic Amplifier **A** with Feedback Network resistance $R_{\beta i}$ and $R_{\beta o}$

5.2 - Input of ***A*** circuit with $R_{\beta i}$

Shunt-sampling

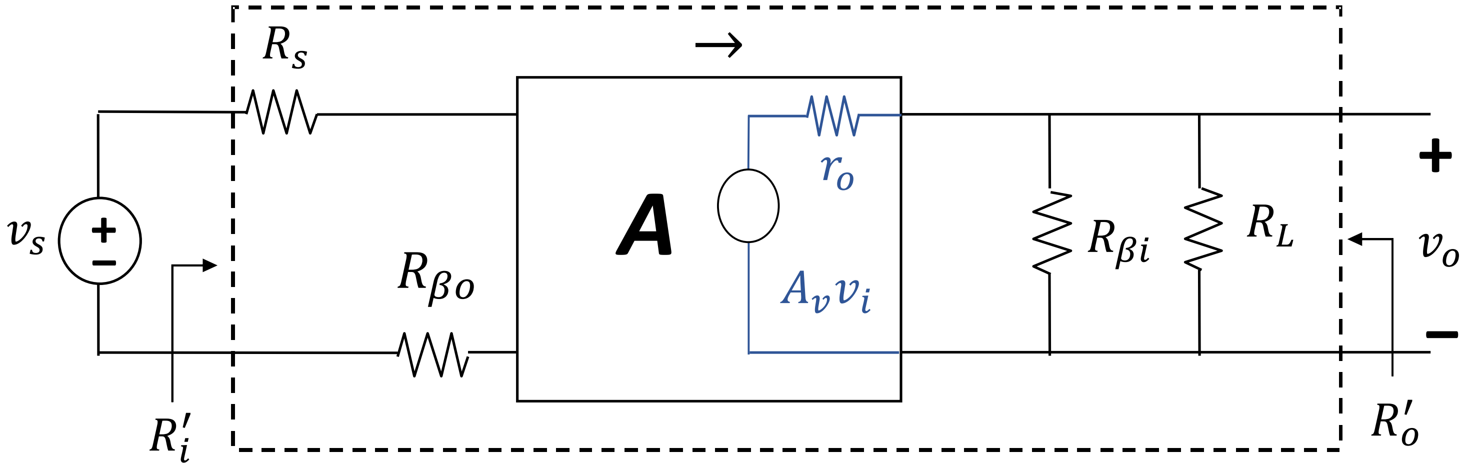


Series-sampling



Series-Shunt Feedback Amplifier

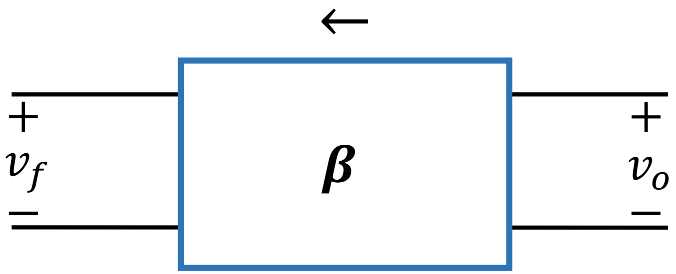
Basic Amplifier ***A*** with $R_{\beta i}$ and $R_{\beta o}$:



New gain, $A' = \dfrac{v_o}{v_s}$ New voltage gain with $R_{\beta o}$ and $R_{\beta i}$.

Loading effect

$\beta = \dfrac{v_f}{v_o}$



Feedback network $\boldsymbol{\beta}$ without $R_{\beta i}$ and $R_{\beta o}$

Series-Shunt Feedback Amplifier (Contd.)

New open-loop gain, A’, considering the loading effect $(R_{\beta i}, R_{\beta o})$

Closed-loop gain: $A_f = \dfrac{A'}{1 + A'\beta}$

Input-Output Resistance, R_{if} and R_{of}

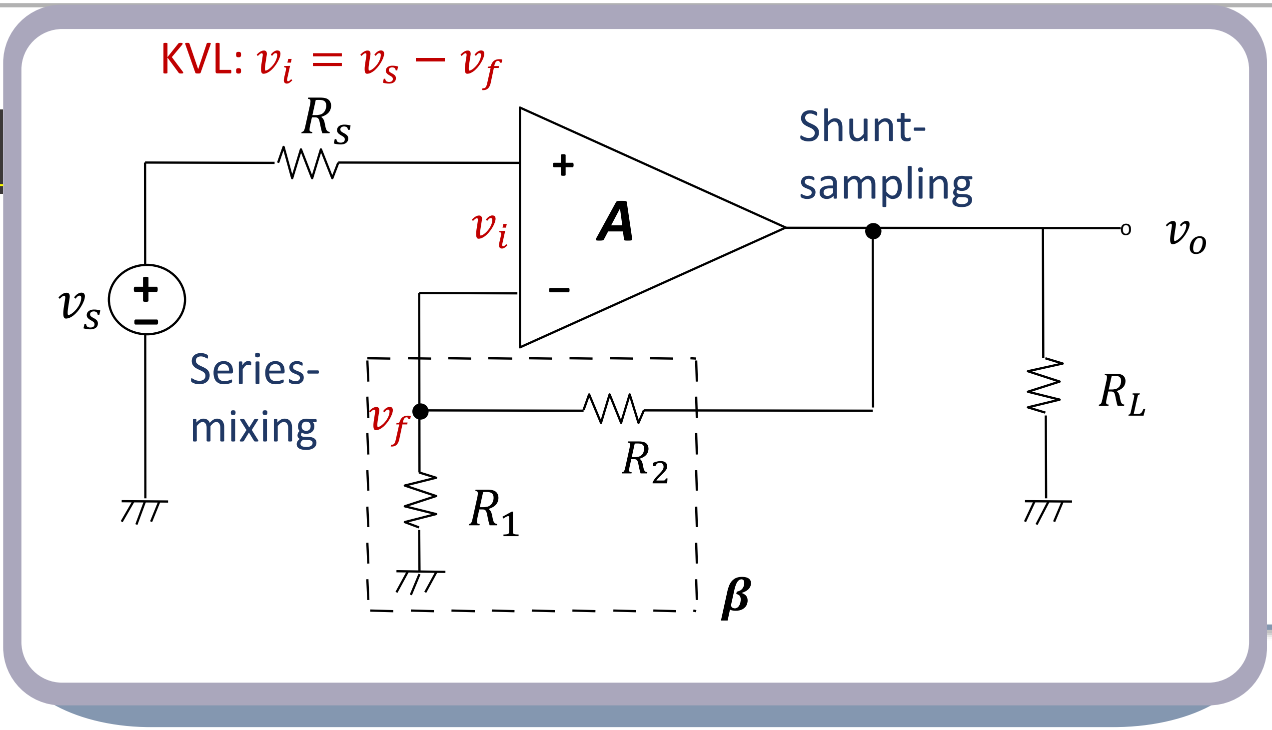
$R_{if} = (1 + A'\beta)R_i'$ (Series-mixing)

$R_{of} = \dfrac{R_o'}{(1 + A'\beta)}$ (Shunt-sampling)

The amount of feedback = $(1 + A'\beta)$

Analysis of a Feedback Amplifier

Example 8:



Topology check 1

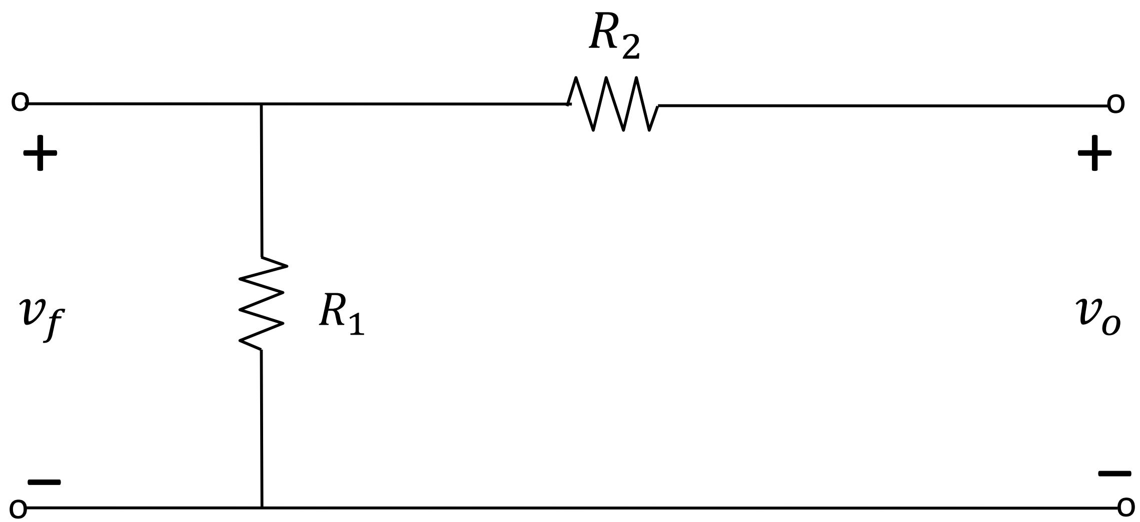
From **Feedback** circuit, sampling is taken from output node (v_o)=> Voltage sampling (Shunt-sampling).

Feedback signal is fed into Op-amp in series with external source, (v_s) => Voltage mixing (Series-mixing).

∴ This is a **Series-Shunt Feedback** amplifier.

Analysis of a Feedback Amplifier (Contd.)

Example 8:



Separate feedback circuit and find β, $R_{\beta i}$ and $R_{\beta o}$.

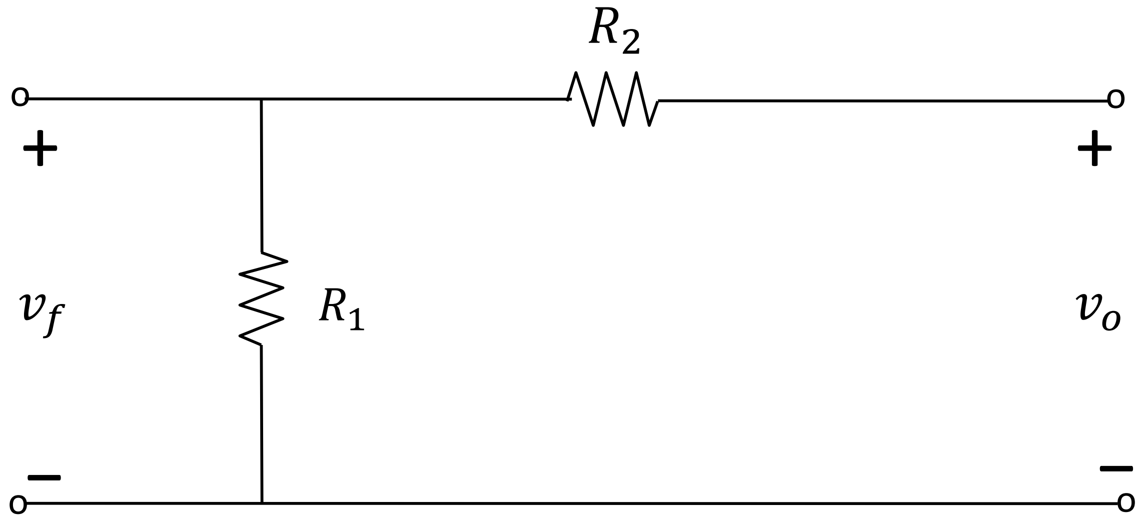
2

$$\beta = \frac{v_f}{v_o} = \frac{R_1}{R_1 + R_2}$$

$$v_f = \frac{R_1}{R_1 + R_2} v_o$$

Analysis of a Feedback Amplifier (Contd.)

Example 8:

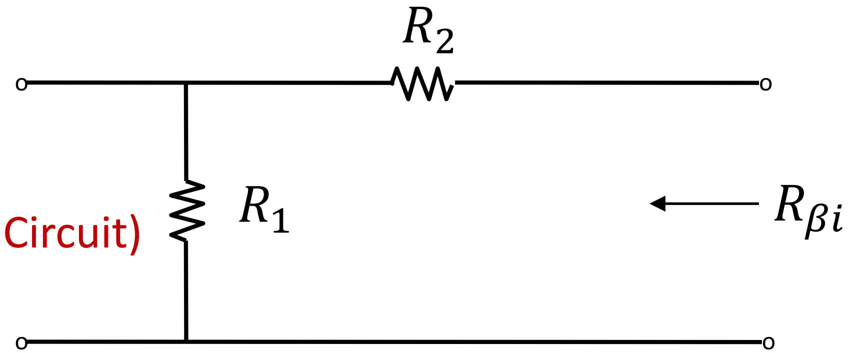


Separate feedback circuit and find $\boldsymbol{\beta}$, $\boldsymbol{R_{\beta i}}$ and $\boldsymbol{R_{\beta o}}$.

2

To find $\boldsymbol{R_{\beta i}}$, Sever O/P port of **Feedback** circuit (Series-mixing).

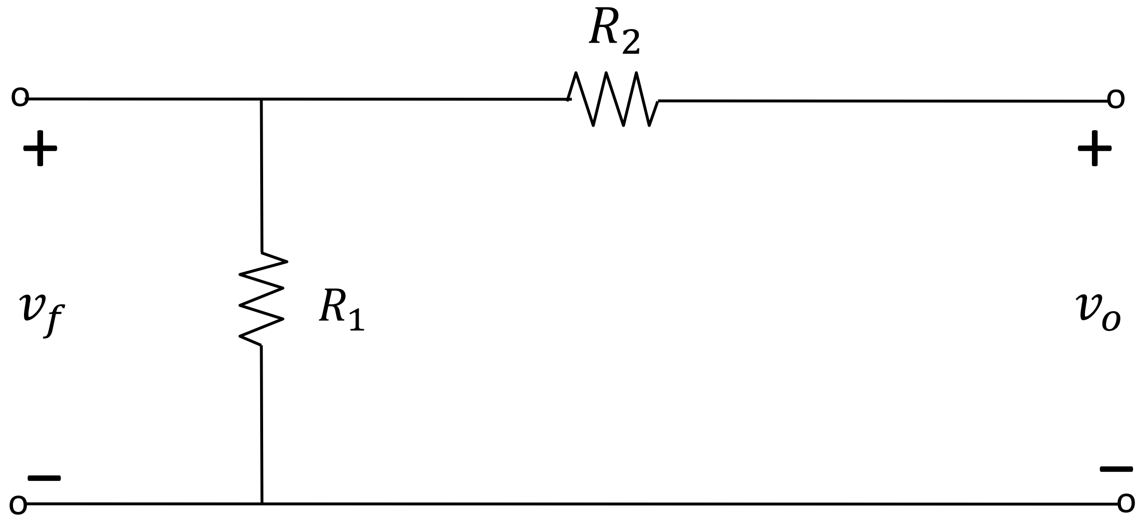
Series-mixing
(Sever: Open Circuit)



$$R_{\beta i} = R_1 + R_2$$

Analysis of a Feedback Amplifier (Contd.)

Example 8:

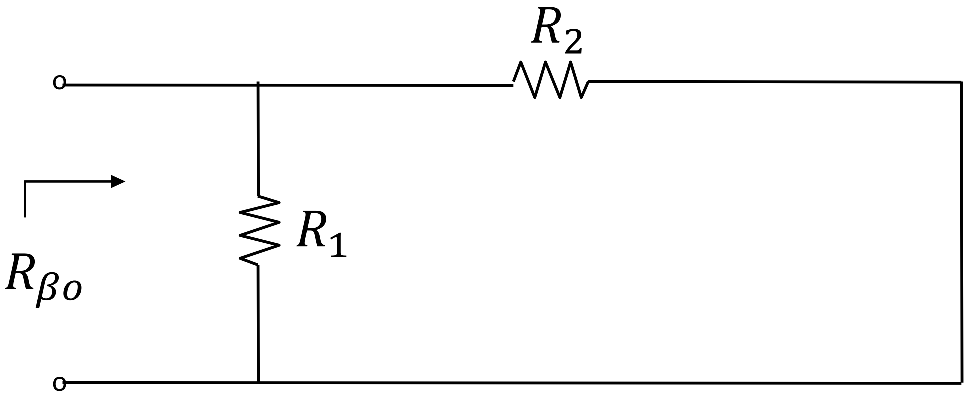


Feedback circuit

Separate feedback circuit and find $\boldsymbol{\beta}$, $\boldsymbol{R_{\beta i}}$ and $\boldsymbol{R_{\beta o}}$.

2

To find $\boldsymbol{R_{\beta o}}$, Short I/P port of **Feedback** circuit (Shunt-Sampling).



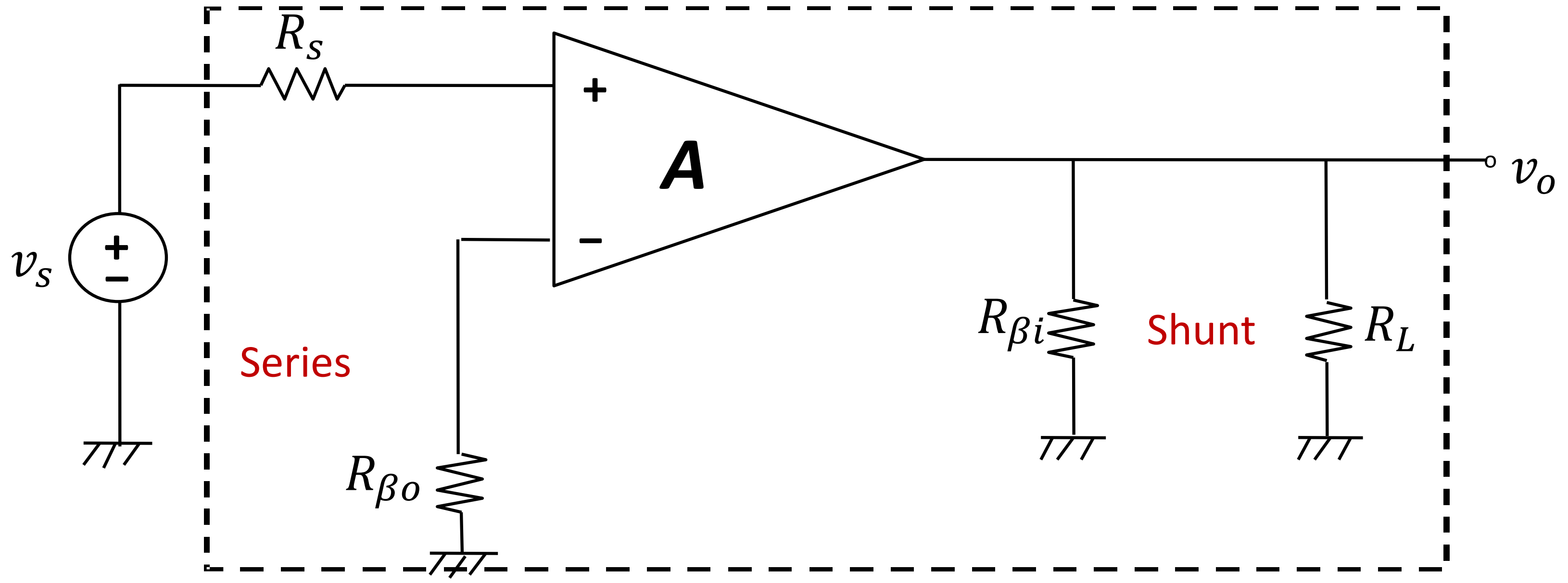
$$R_{\beta o} = R_1 // R_2$$

Shunt-sampling

(Short: Short circuit)

Analysis of a Feedback Amplifier (Contd.)

Example 8:



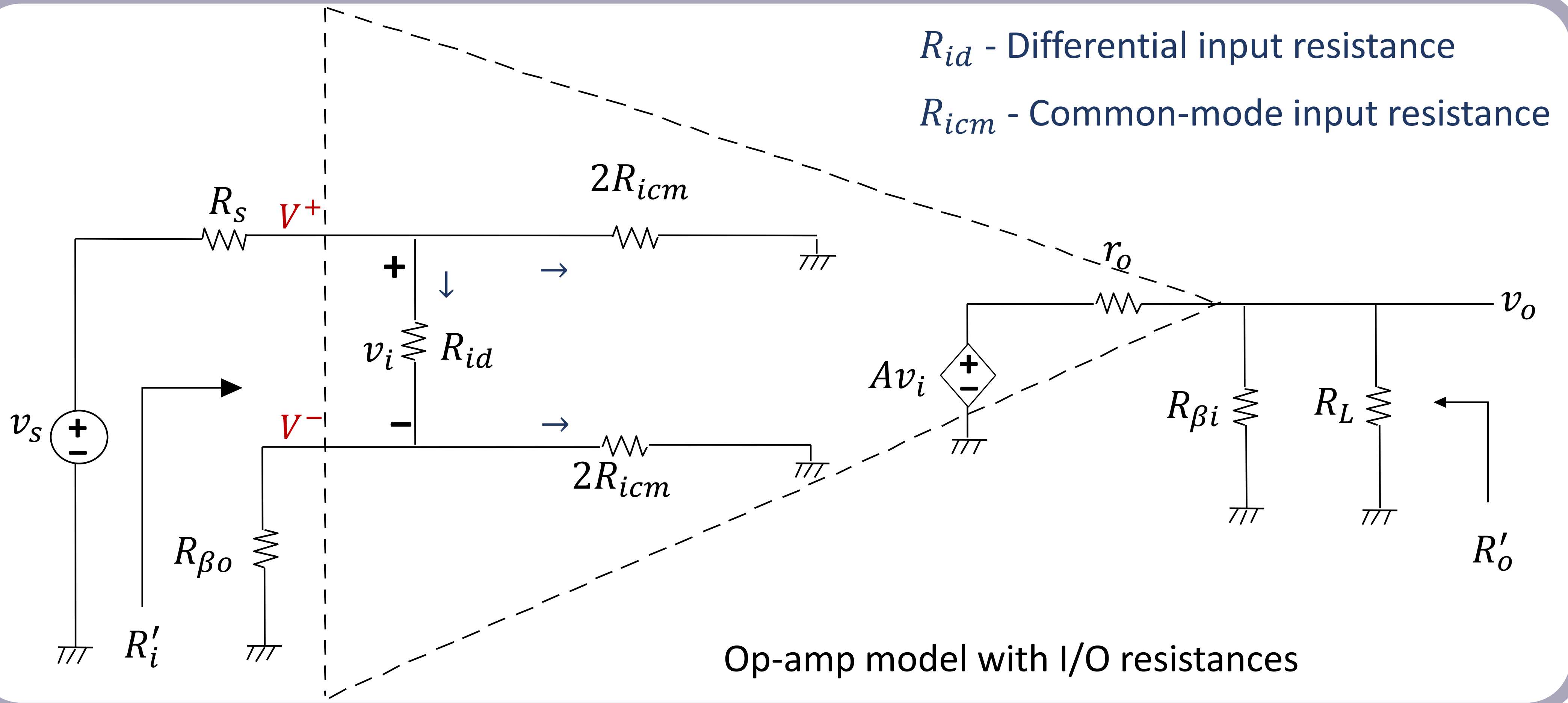
New A' circuit

Redraw basic amplifier with Feedback network I/O resistances, and apply Thevenin's equivalent source

3

Analysis of a Feedback Amplifier (Contd.)

Example 8:

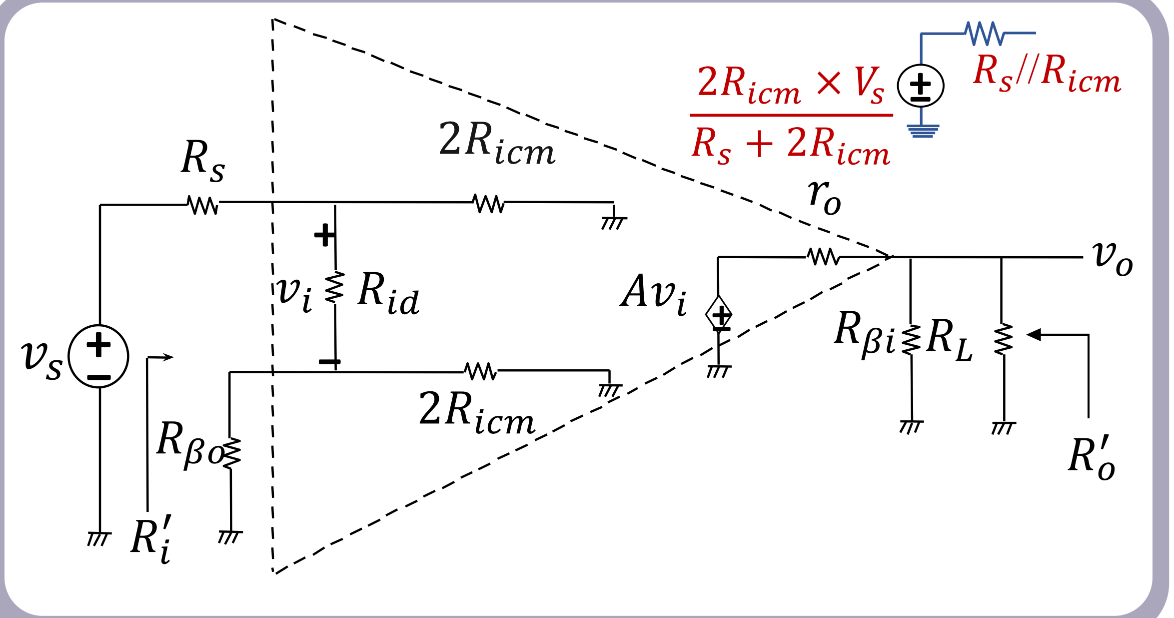


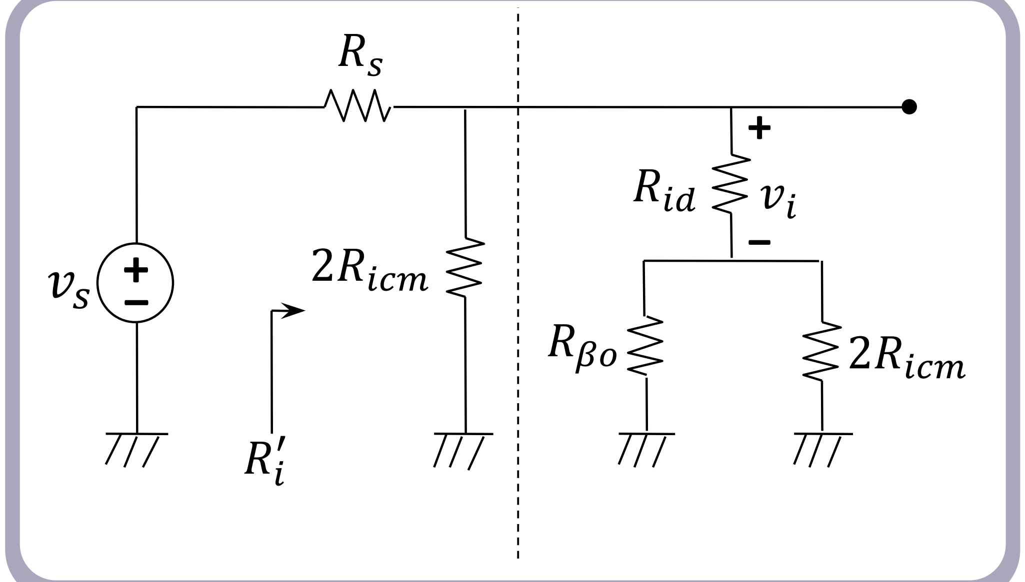
Find new gain A' and new I/O resistances R_i' and R_o' of new A' block.

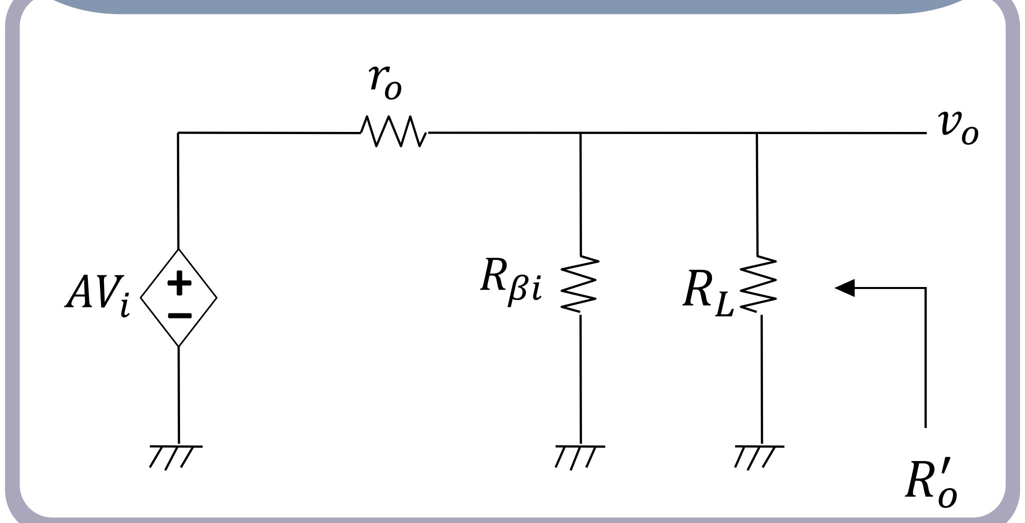
Analysis of a Feedback Amplifier (Contd.)

Example 8:

5 **Redraw Circuit**





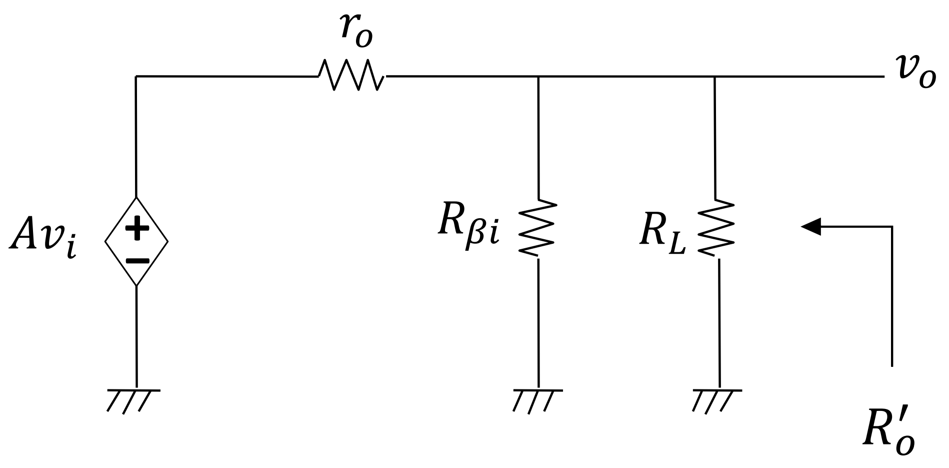


$$\frac{v_i}{v_s} = \frac{R_{id}}{(R_s//2R_{icm}) + R_{id} + (R_{\beta o}//2R_{icm})} \times \frac{2R_{icm}}{R_s + 2R_{icm}} \quad - (1)$$

Analysis of a Feedback Amplifier (Contd.)

Example 8:

5 **Redraw Circuit**



$$\frac{V_o}{V_i} = A \times \frac{(R_{\beta i}//R_L)}{r_o + (R_{\beta i}//R_L)} \quad - (2)$$

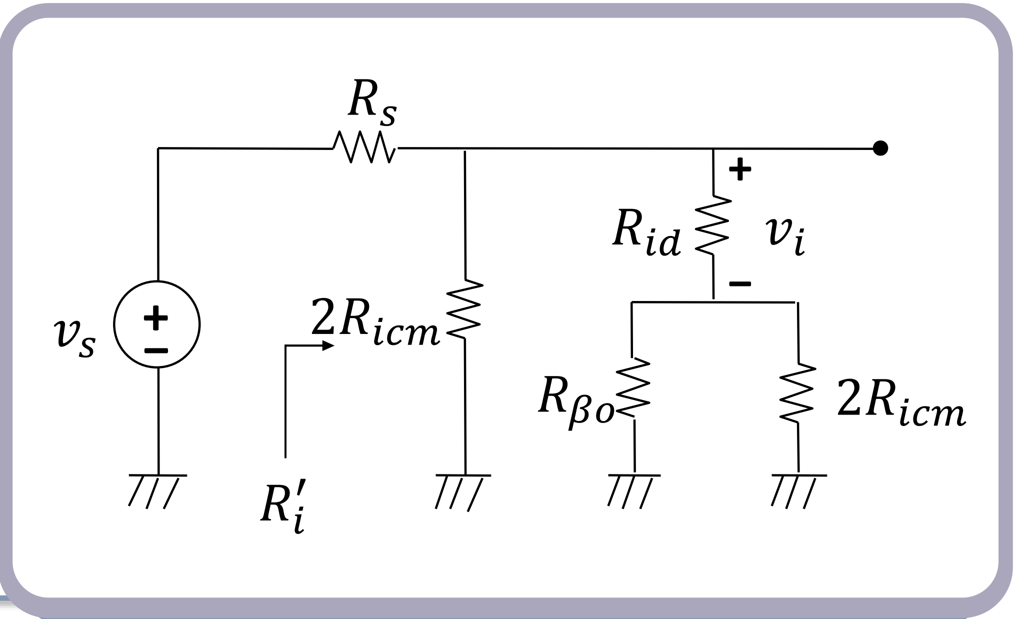
$\therefore$ New gain $A' = \frac{v_o}{v_s} = \frac{v_o}{v_i} \times \frac{v_i}{v_s}$

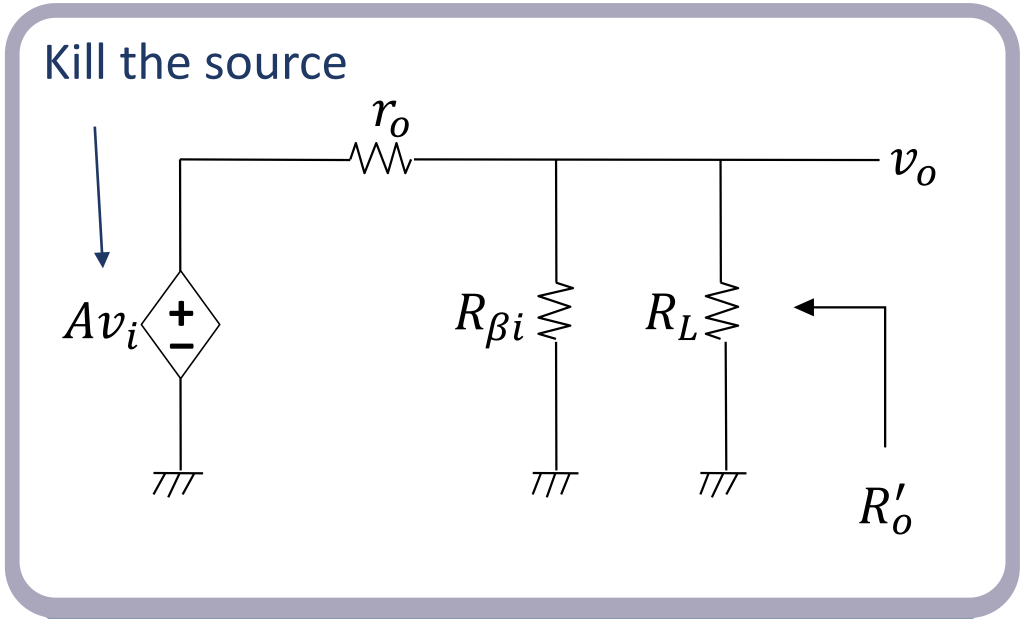
$$A' = \frac{A(R_{\beta i}//R_L)}{r_o + (R_{\beta i}//R_L)} \times \frac{R_{id}}{(R_s//2R_{icm} + R_{id} + R_{\beta o}//2R_{icm})} \times \frac{2R_{icm}}{(R_s + 2R_{icm})}$$

Analysis of a Feedback Amplifier (Contd.)

Example 8:

5 **Redraw Circuit**





Input resistance, R_i'

$$R_i' = \left[\left(R_{id} + R_{\beta o}//2R_{icm}\right)//2R_{icm}\right] + R_s$$

Output resistance, R_o'

$$R_o' = r_o//R_{\beta i}//R_L$$

Analysis of a Feedback Amplifier (Contd.)

Find closed-loop gain A_f and Input-Output resistance R_{if} and R_{of} 6

$$A_f = \frac{A'}{1 + A'\beta}$$

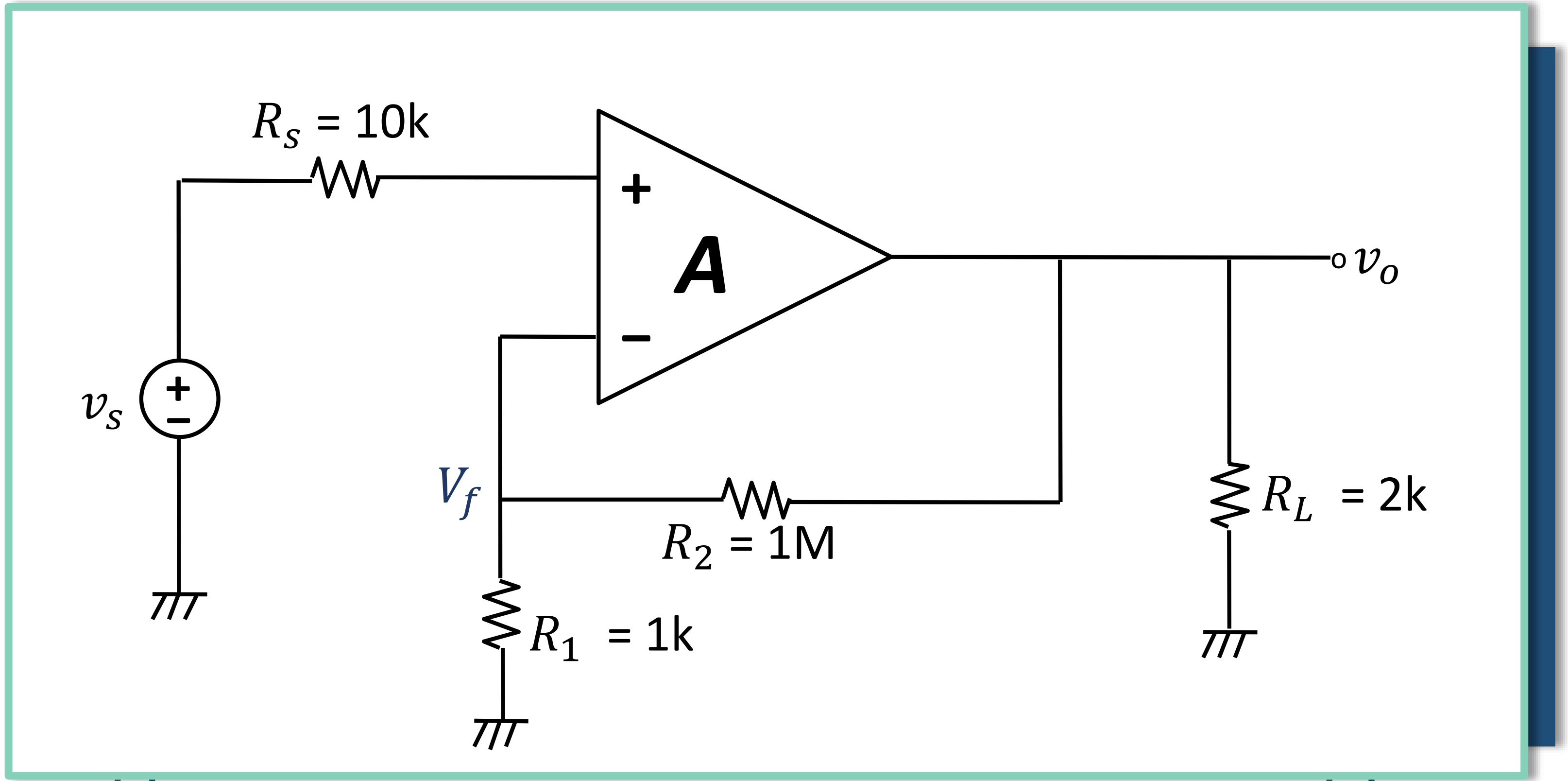
$$R_{if} = (1 + A'\beta)R_i' \quad \text{(Series-mixing)}$$

$$R_{of} = \frac{R_o'}{1 + A'\beta} \quad \text{(Shunt-sampling)}$$

Analysis of a Feedback Amplifier (Contd.)

Example 8A:

With numerical values



$A = 10^4$

$R_{id} = 100\text{k}\Omega$

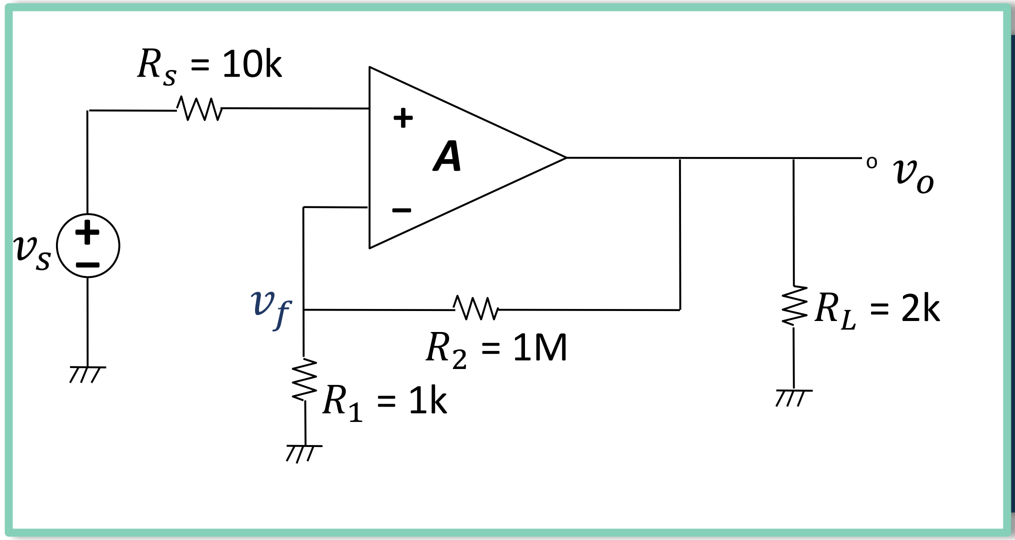
$R_{icm} = 5\text{k}\Omega$

$r_o = 1\text{k}\Omega$

Analysis of a Feedback Amplifier (Contd.)

Example 8A:

With numerical values



- $A = 10^4$
- $R_{id} = 100\text{k}\Omega$
- $R_{icm} = 5\text{k}\Omega$
- $r_o = 1\text{k}\Omega$

$$\beta = \frac{v_f}{v_o} = \frac{R_1}{R_1 + R_2} = \frac{1\text{k}}{1\text{k} + 1\text{M}} \approx 10^{-3}$$

$$R_{\beta i} = R_1 + R_2 = 1001\text{k}\Omega$$

$$R_{\beta o} = R_1 // R_2 = 1\text{k}//1\text{M} \approx 1\text{k}\Omega$$

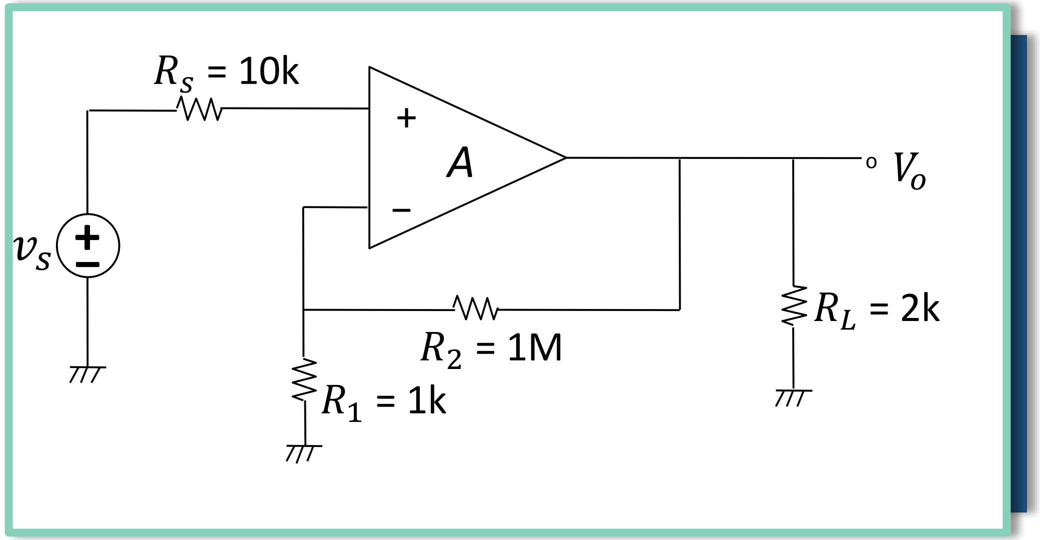
$$A' = \frac{A\left(R_{\beta i}//R_L\right)}{r_o + \left(R_{\beta i}//R_L\right)} \times \frac{R_{id}}{\left(R_s//2R_{icm} + R_{id} + R_{\beta o}//2R_{icm}\right)} \times \frac{2R_{icm}}{\left(R_s + 2R_{icm}\right)}$$

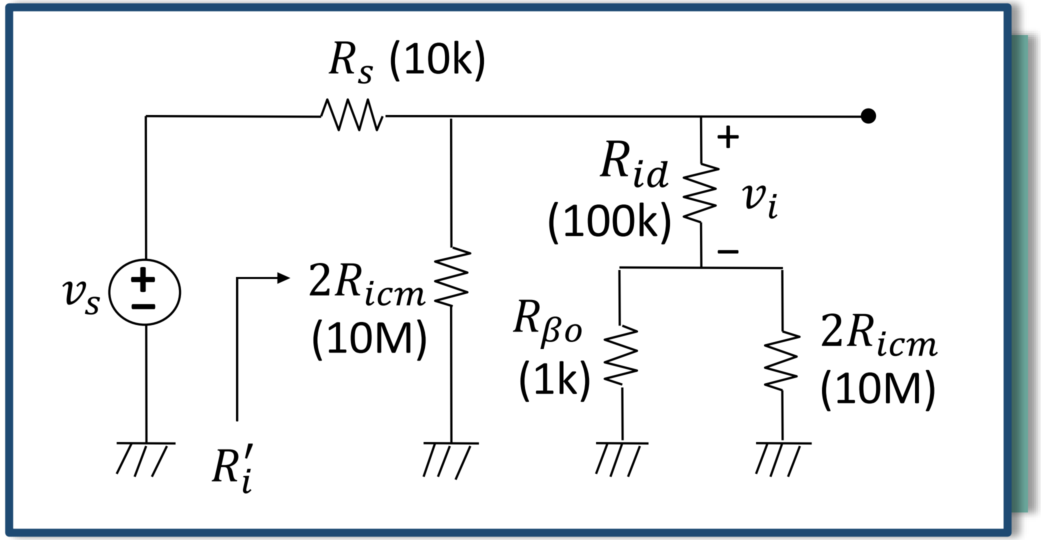
$$A' = \frac{10^4(1001\text{k}//2\text{k})}{1\text{k} + (1001\text{k}//2\text{k})} \times \frac{100\text{k}}{10\text{k}//10\text{M} + 100\text{k} + 1\text{k}//10\text{M}} \times \frac{10\text{M}}{10\text{k} + 10\text{M}} \approx 600\text{V/V}$$

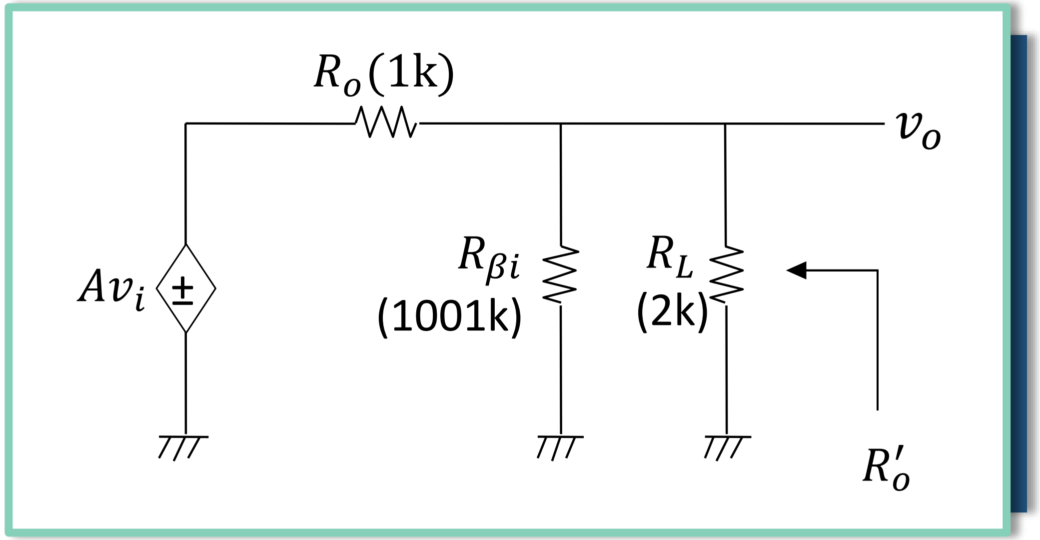
Analysis of a Feedback Amplifier (Contd.)

Example 8A:

With numerical values







$$R_i' = (100\text{k} + 1\text{k}//10\text{M})//10\text{M} + 10\text{k} \approx 111\text{k}\Omega$$

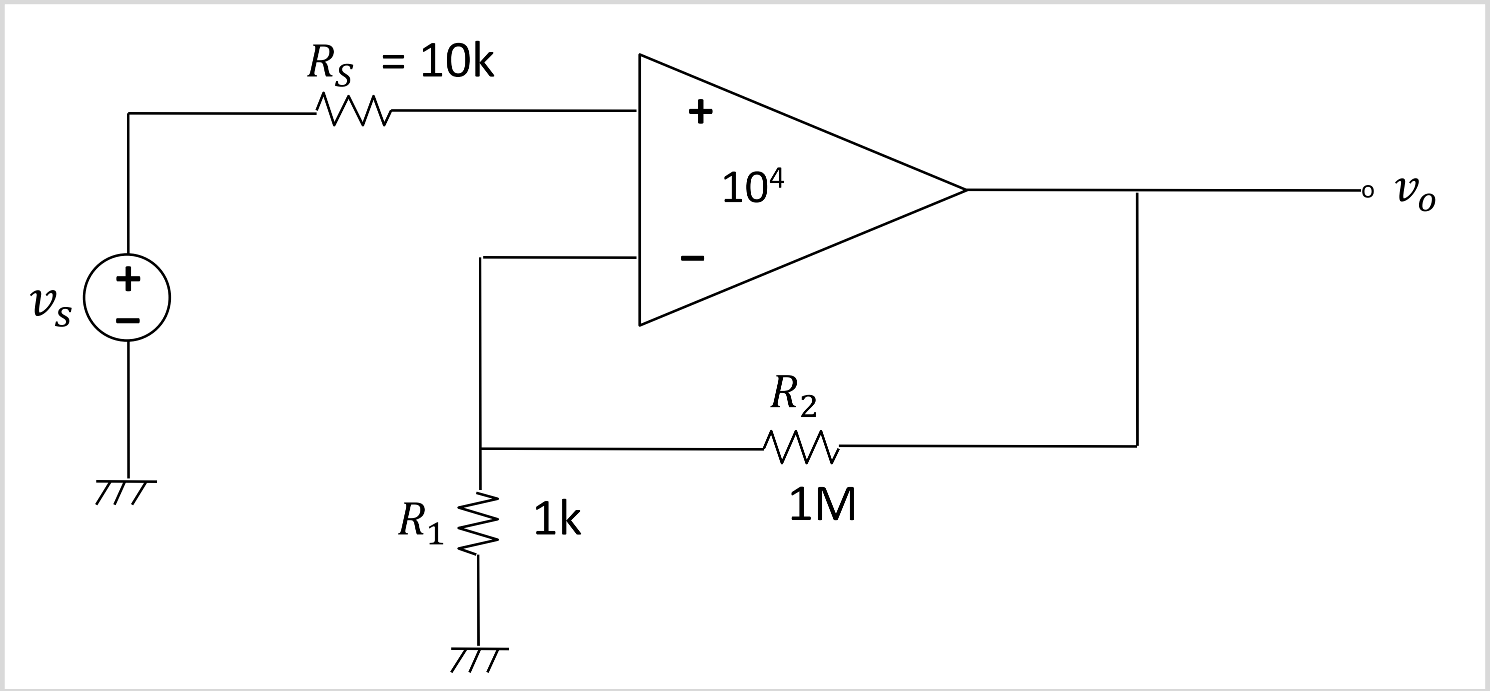
$$R_o' = 1\text{k}//1001\text{M}//2\text{k} \approx 0.67\text{k}\Omega$$

$$A_{f3} = \frac{A'}{1 + A'\beta} = \frac{6000}{1 + 6000 \times 10^{-3}} = 857\text{V/V}$$

$$R_{if} = R_i(1 + A'\beta) = 111\text{k}(1 + 6) = 777\text{k}\Omega$$

$$R_{of} = \frac{R_o}{(1 + A'\beta)} = \frac{0.67\text{k}}{1 + 6} 95.7k\Omega$$

Compare with Conventional Analysis of Op-amp



If $A = \infty$ (Ideal case)

$$A_{f1} = \frac{R_1 + R_2}{R_1} = 1 + \frac{1\text{M}}{1\text{k}}$$

$$= 1001$$

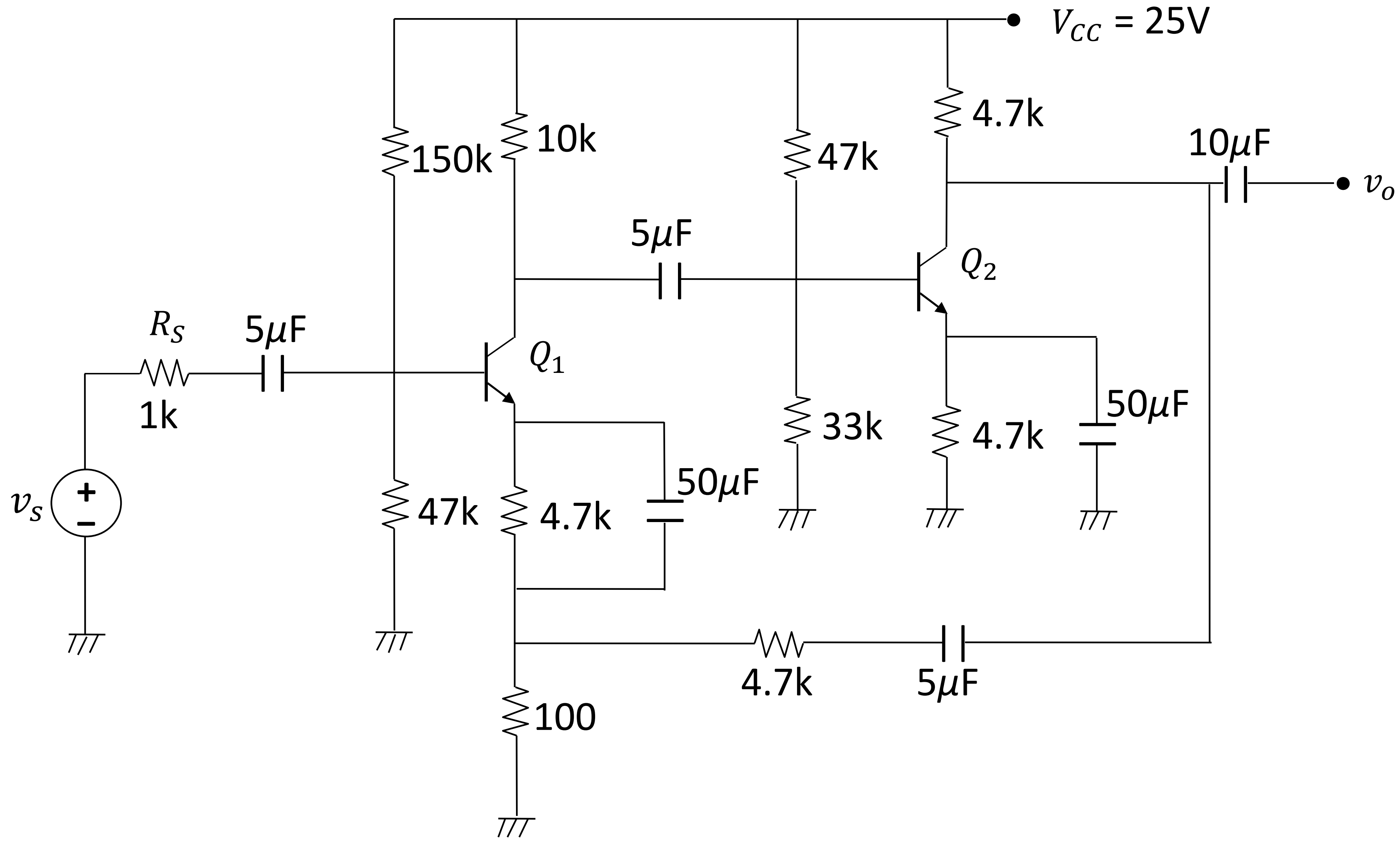
Input R, $R_i \approx \infty$

Output R, $R_o \approx 0$

If $A = 10{,}000$

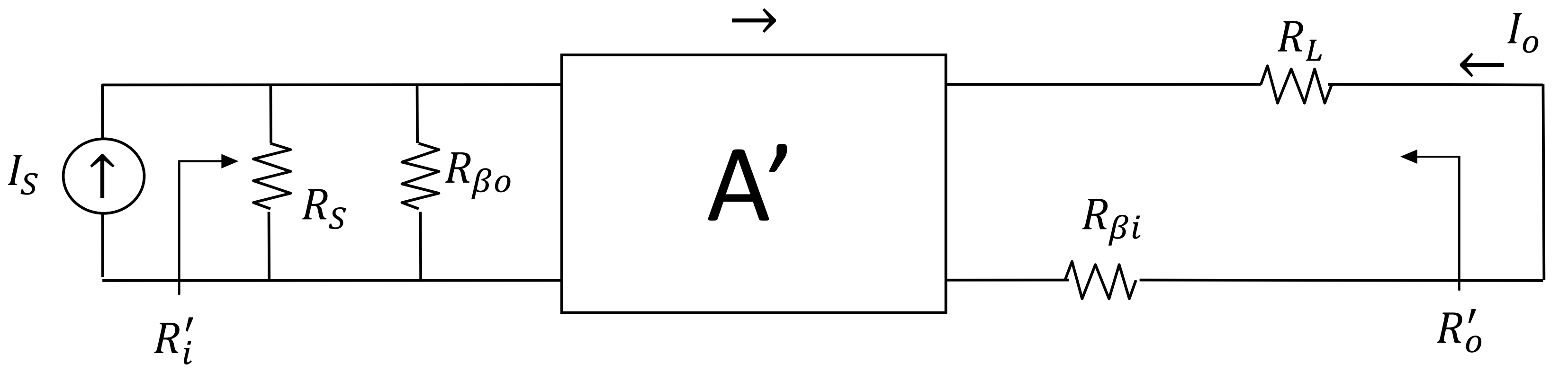
$$A_{f2} = \frac{A}{1 + A\beta} = \frac{10000}{1 + 10000\left(\frac{1}{1001}\right)} = 909.9$$

Example of Series-Shunt Feedback Amplifier



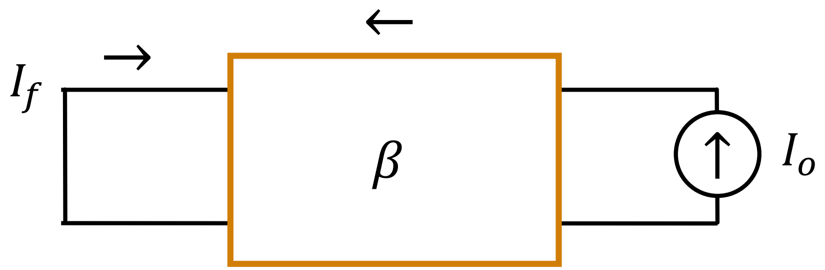
6. Examples of Feedback Amplifier Analysis: Shunt-Series

New Basic Amplifier - A’



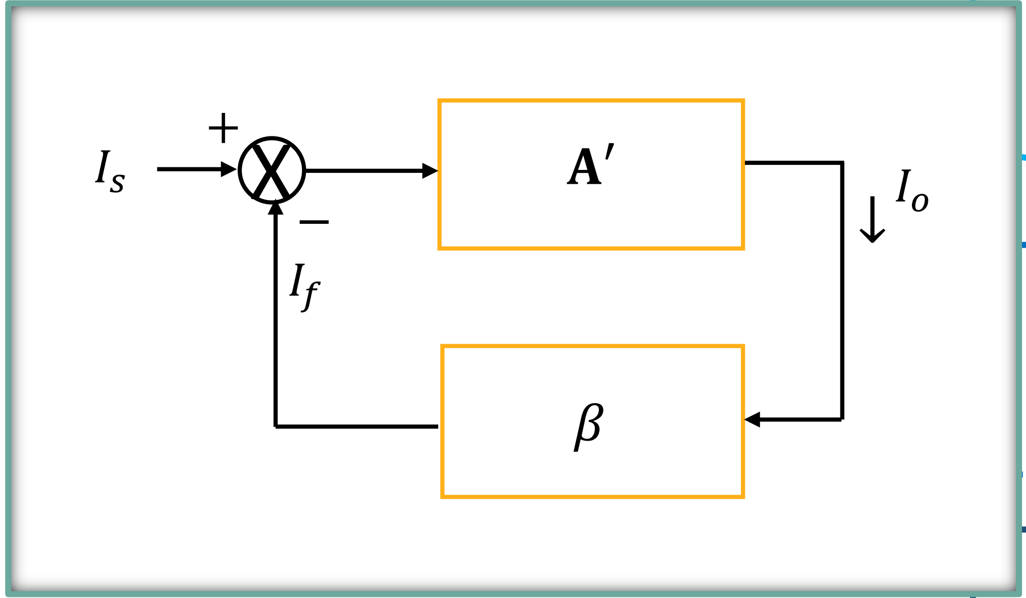
New gain, $A' = \frac{I_o}{I_s}$

$\beta = \frac{I_f}{I_o}$



Feedback circuit - β

Closed-loop gain A_f and I/O Resistance R_{if} and R_{of}

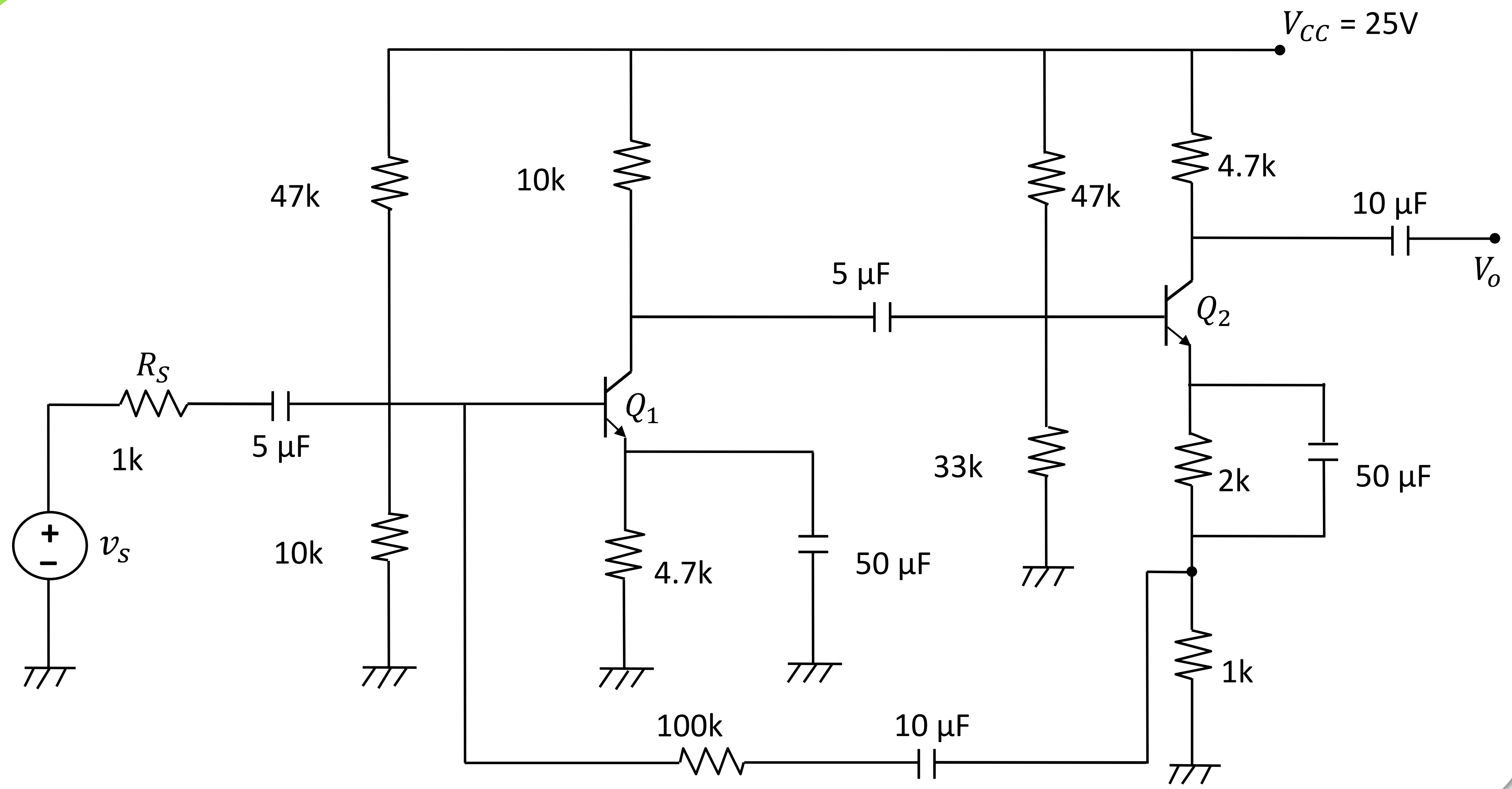


$$A_f = \frac{A'}{1 + A'\beta}$$

$$R_{if} = \frac{R'_i}{1 + A'\beta}$$ (Shunt-mixing)

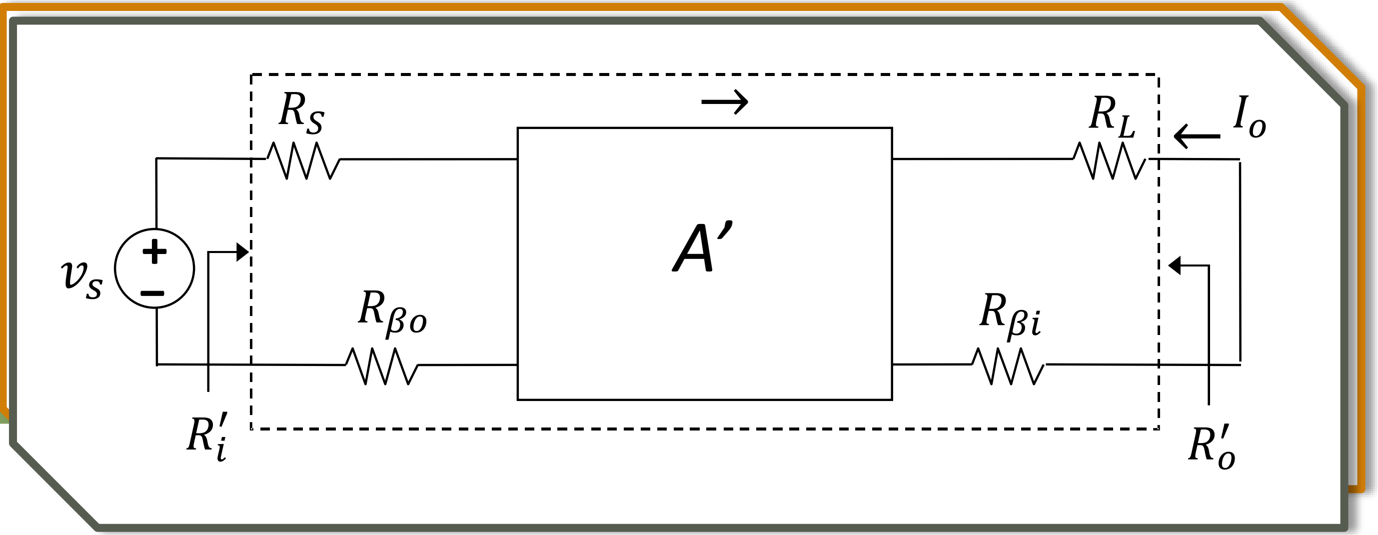
$$R_{of} = R'_o(1 + \mathrm{A}'\beta)$$ (Series-sampling)

Example of Shunt-Series Feedback Amplifier



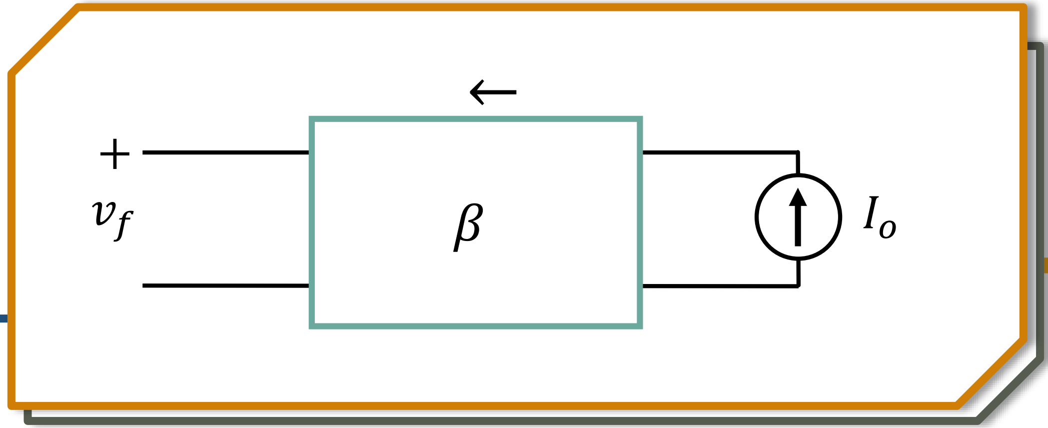
6. Examples of Feedback Amplifier Analysis: Series-Series

New Basic Amplifier - A’



New gain, $A' = \dfrac{I_o}{v_s}$

$\beta = \dfrac{v_f}{I_o}$



Feedback circuit - β

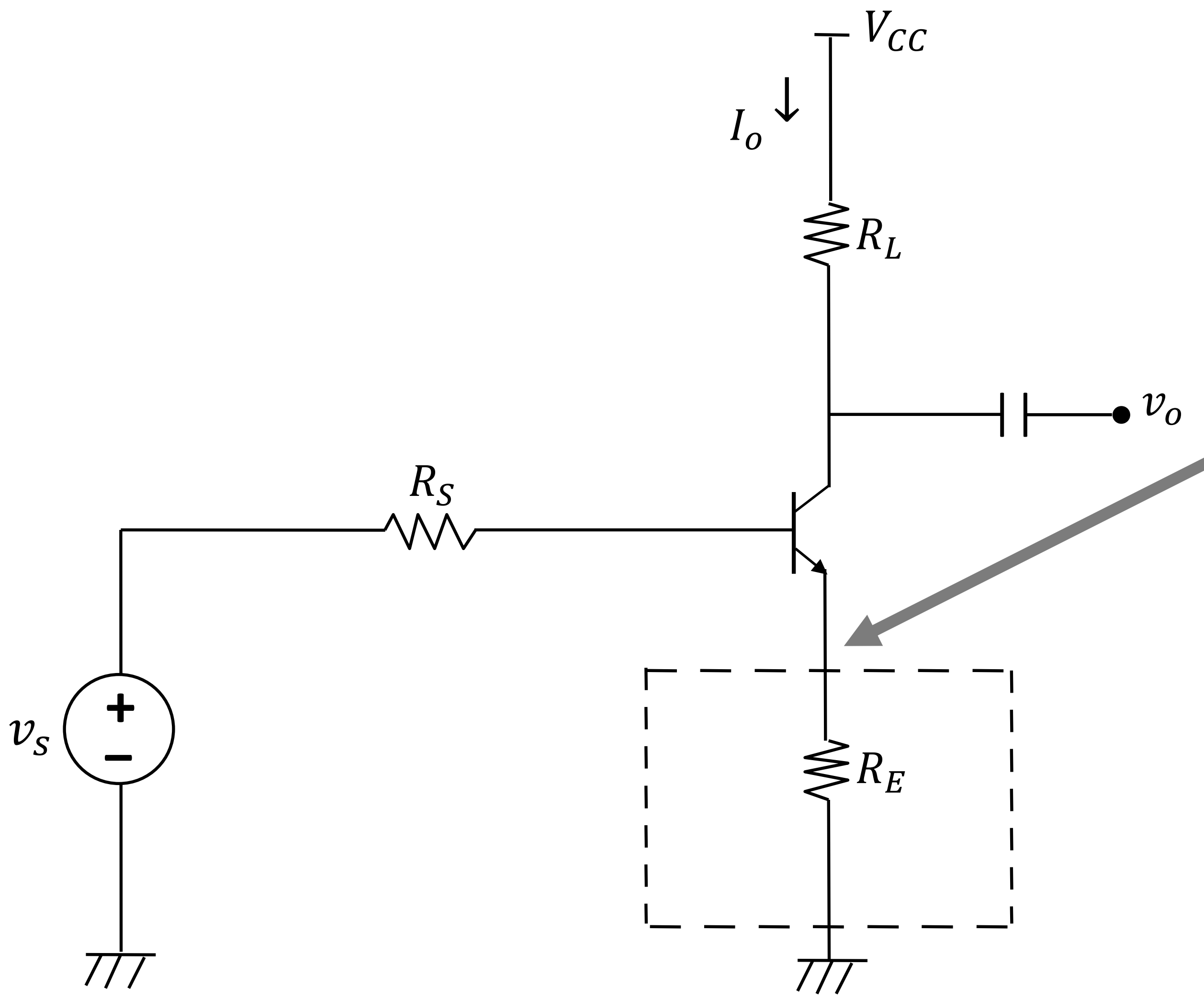
Closed-loop gain A_f and I/O Resistance R_{if} and R_{of}

$$A_f = \frac{A'}{1 + A'\beta}$$

$R_{if} = R_i'(1 + A'\beta)$ (Series-mixing)

$R_{of} = R_o'(1 + A'\beta)$ (Series-sampling)

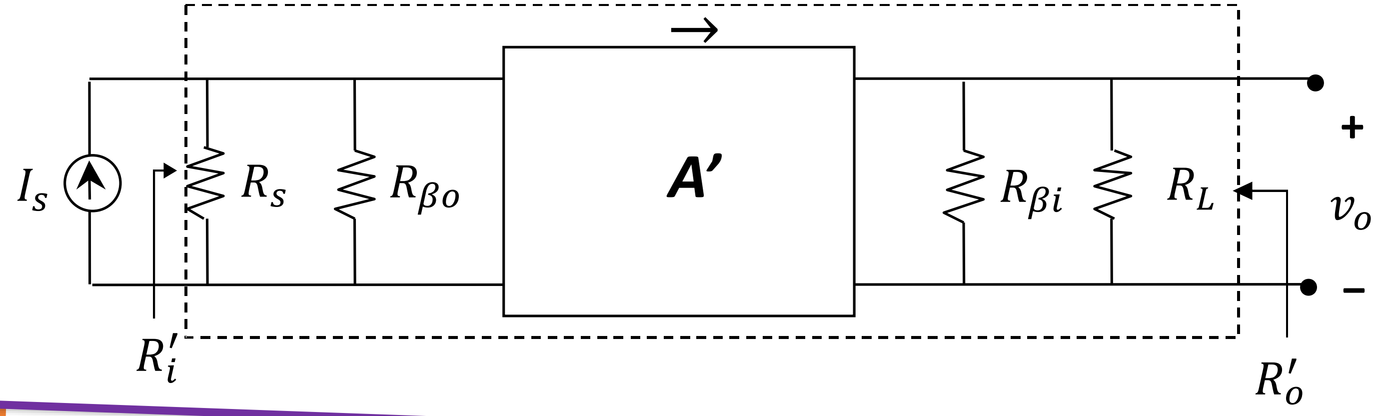
Example of Series-Series Feedback Amplifier



The current sampled at output current loop and emitter voltage is connected in series with input source.

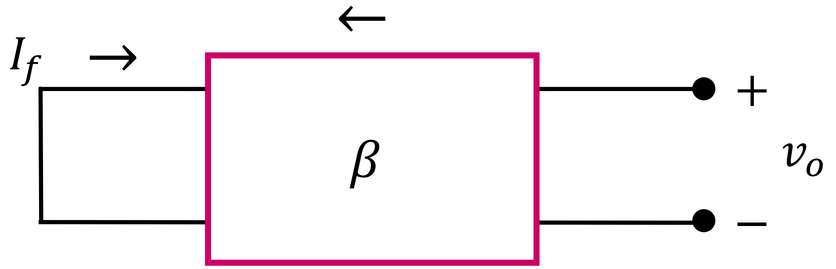
6. Examples of Feedback Amplifier Analysis: Shunt-Shunt

New Basic Amplifier - A’



New gain, $A' = \frac{v_o}{I_s}$

$\beta = \frac{I_f}{v_o}$



Feedback circuit - β

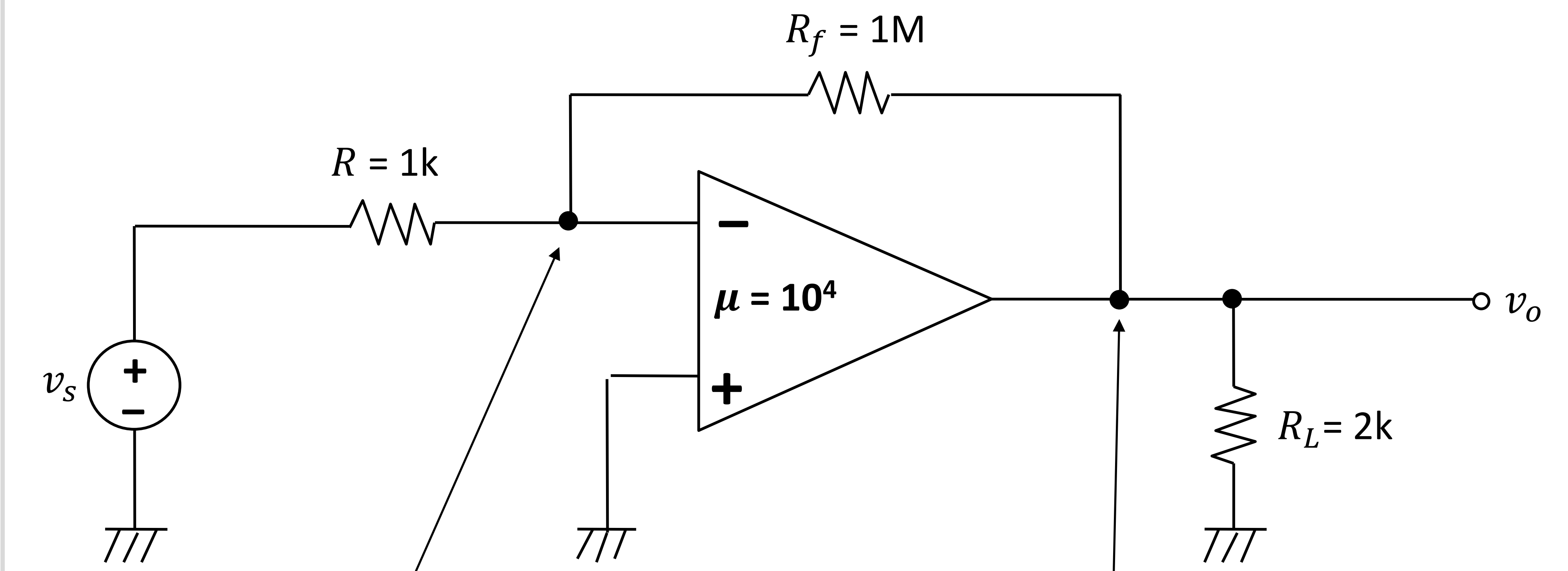
Closed-loop gain A_f and I/O Resistance R_{if} and R_{of}

$$A_f = \frac{A'}{1 + A'\beta}$$

$$R_{if} = \frac{R_i'}{1 + A'\beta}$$ (Shunt-mixing)

$$R_{of} = \frac{R_o'}{1 + A'\beta}$$ (Shunt-sampling)

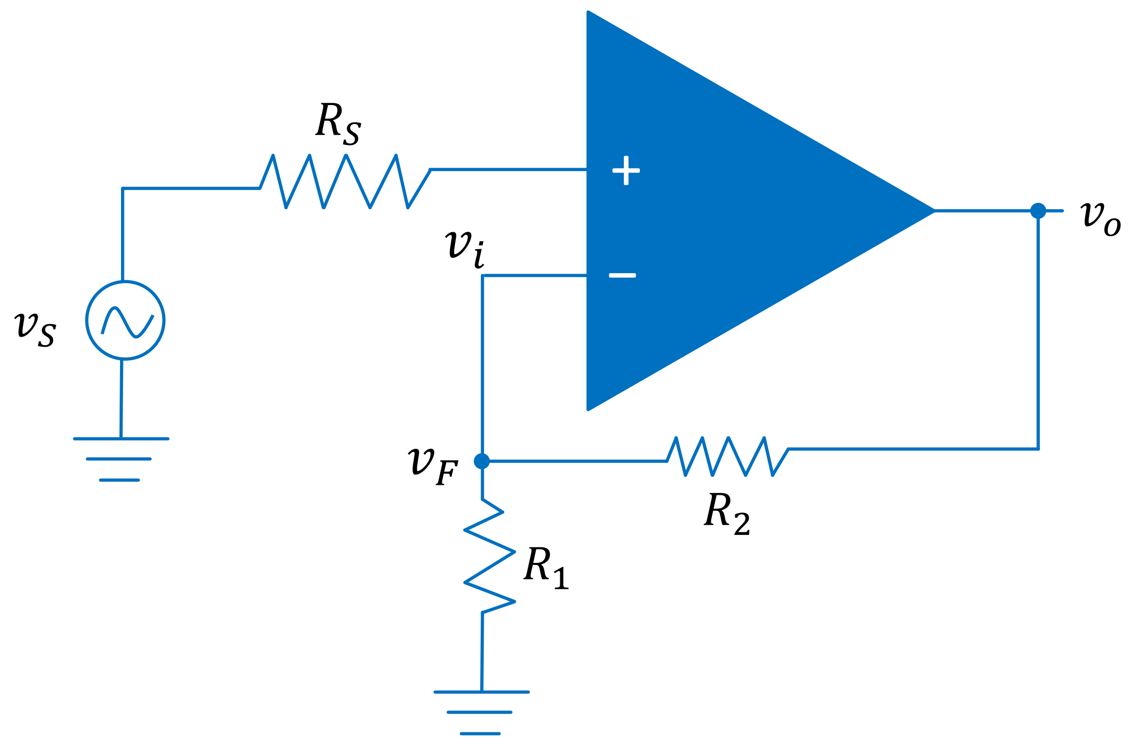
Example of Shunt-Shunt Feedback Amplifier



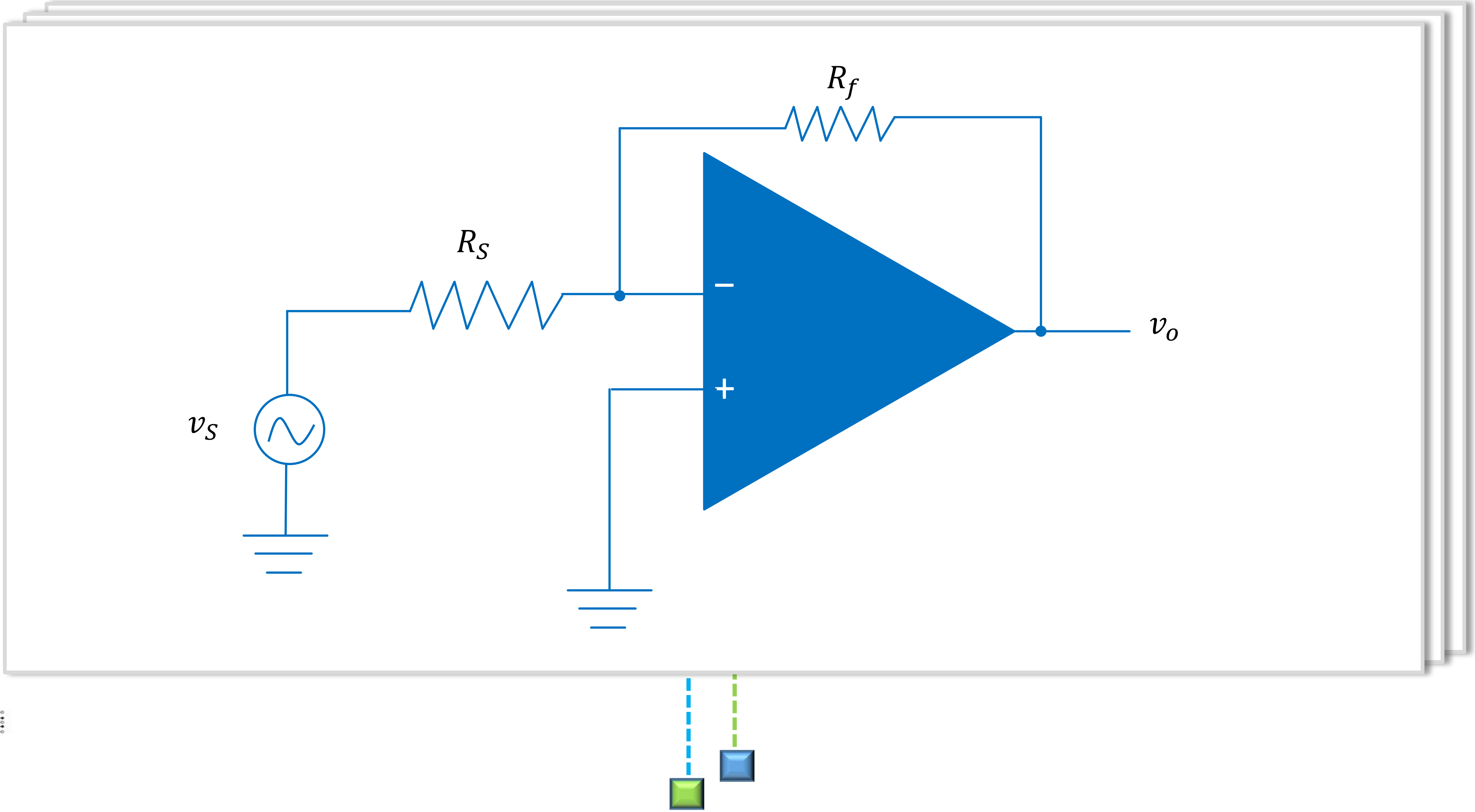
Feedback signal is current => Shunt mixing

Voltage sampling taken at output node => Shunt-sampling

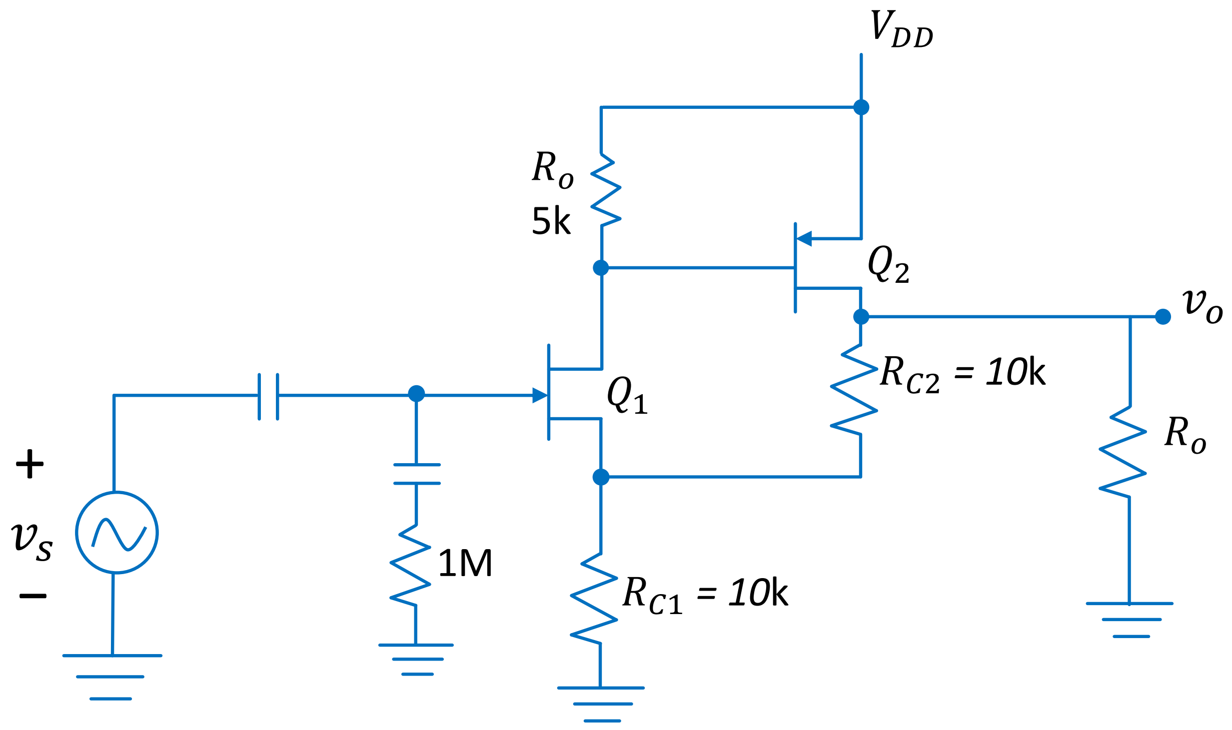
Case Study



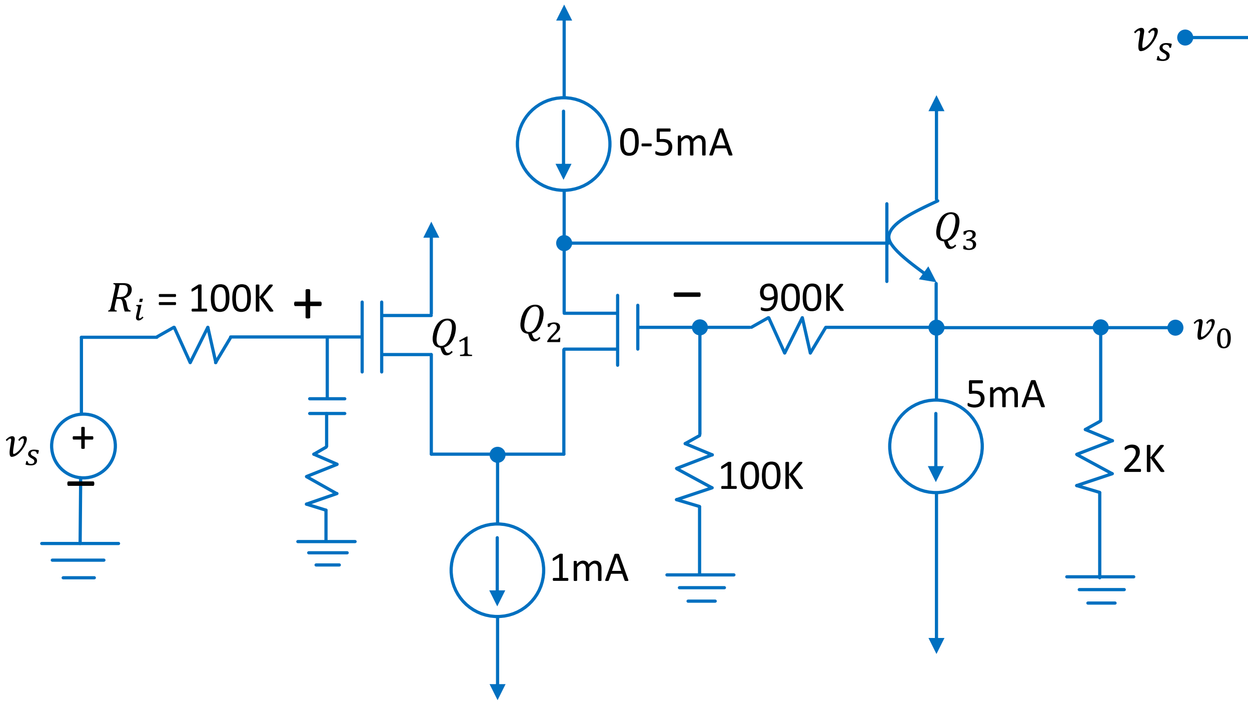
Case Study

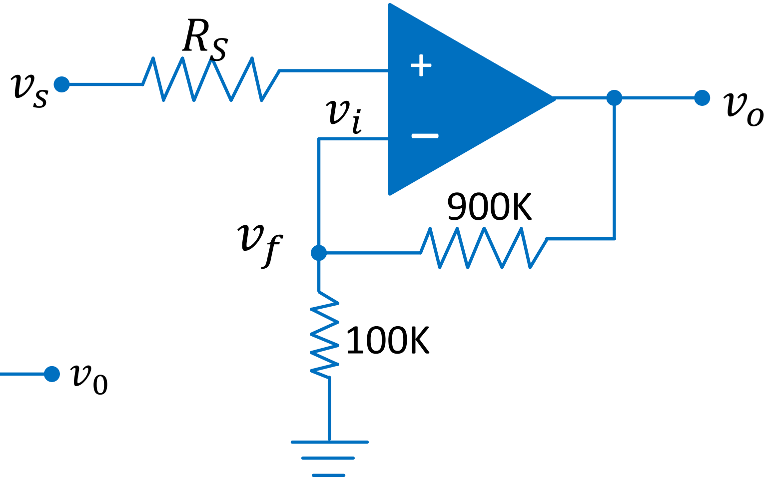


Case Study



Case Study





$v_f - v_o$

series - shunt

voltage amplifier

Summary

Here are the key takeaways from this lesson.

- The general feedback structure of the negative feedback amplifier consists of a basic amplifier A and a feedback network β.
- The characteristics of a negative feedback amplifier are gain de-sensitivity, reduced frequency distortion, noise reduction, reduced non-linear distortion, input and output impedance change which are obtained at the expense of gain reduction.
- There are four feedback topologies, Series-Shunt, Shunt-Series, Series-Series and Shunt-Shunt feedback topology.
  - There are six steps to analyse the feedback amplifier with the loading effect of $R_{\beta i}$ and $R_{\beta o}$.
    The steps are as follows:
    - Identify the topology.
    - Separate A and β.
    - Find $\beta, R_{\beta i}$ and $R_{\beta o}$.
    - Draw the basic amplifier with $R_{\beta i}$ and $R_{\beta o}$ to covert into a new basic amplifier A'.
    - Find A', R_i' and R_o'.
    - Determine the Gain (A_f), Input Impedance $\left(R_{if}\right)$and Output Impedance (R_{of}) of a feedback amplifier.

Thank You

Feedback Circuits