

EE3122: Analogue Circuit Fundamentals

Feedback

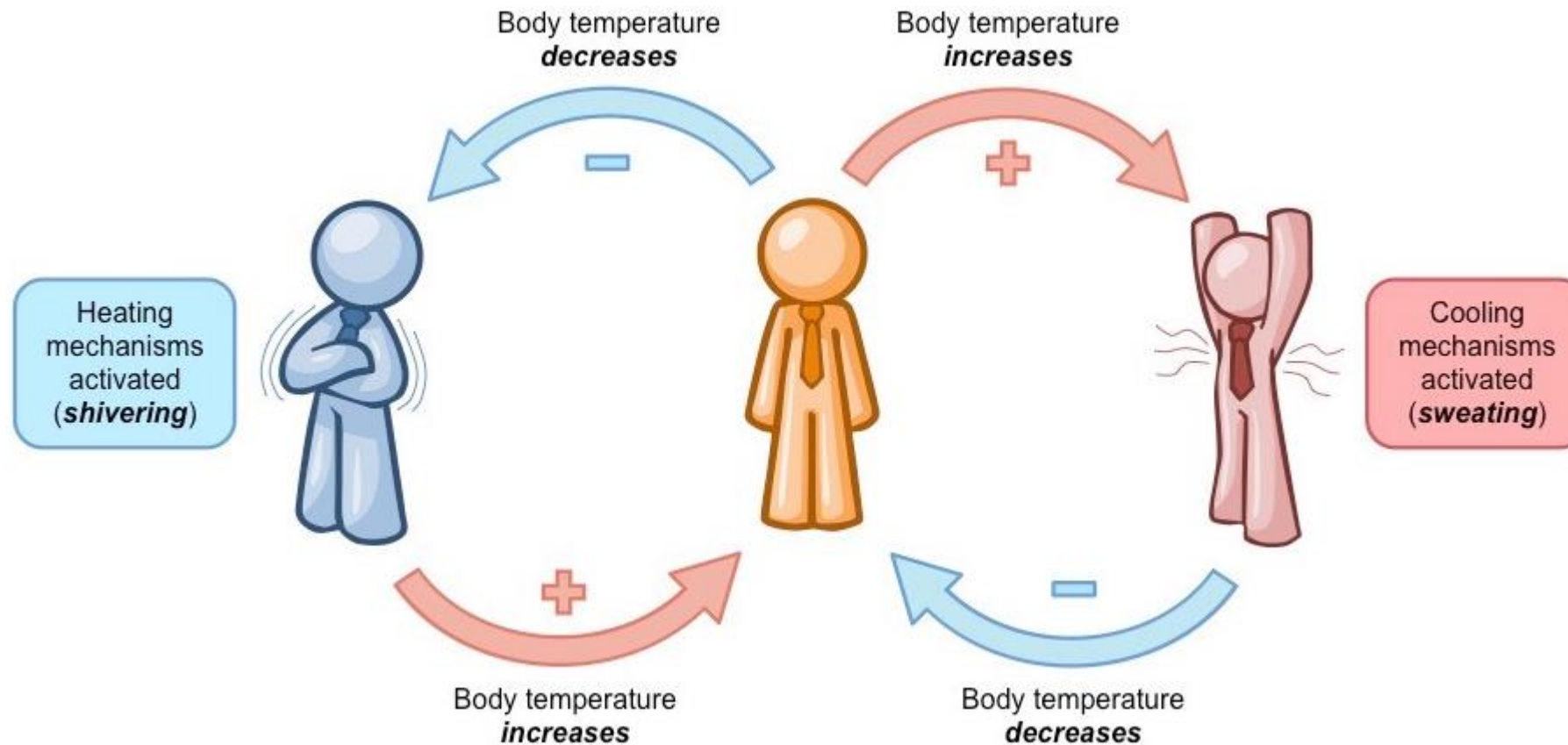
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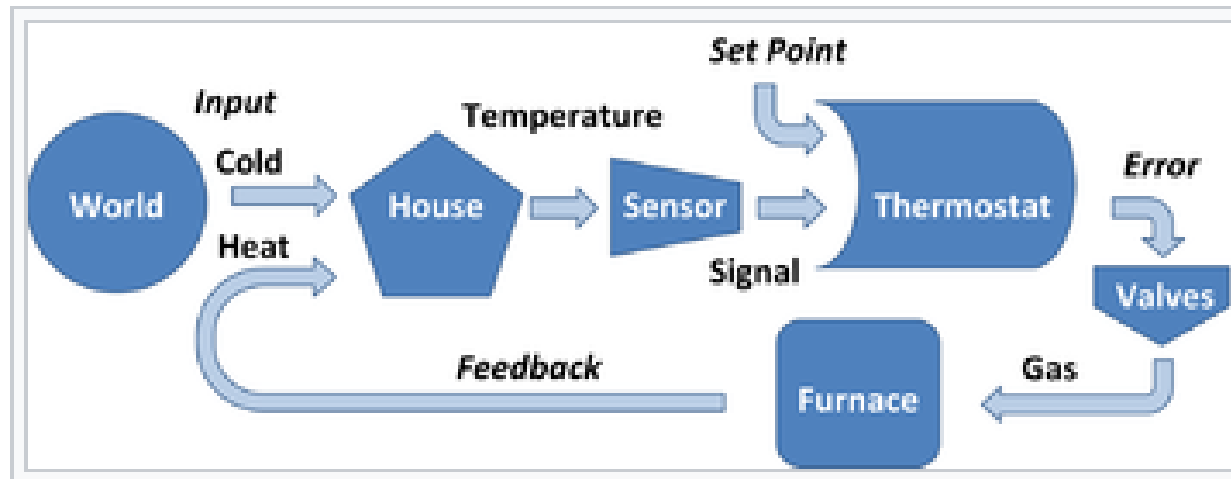
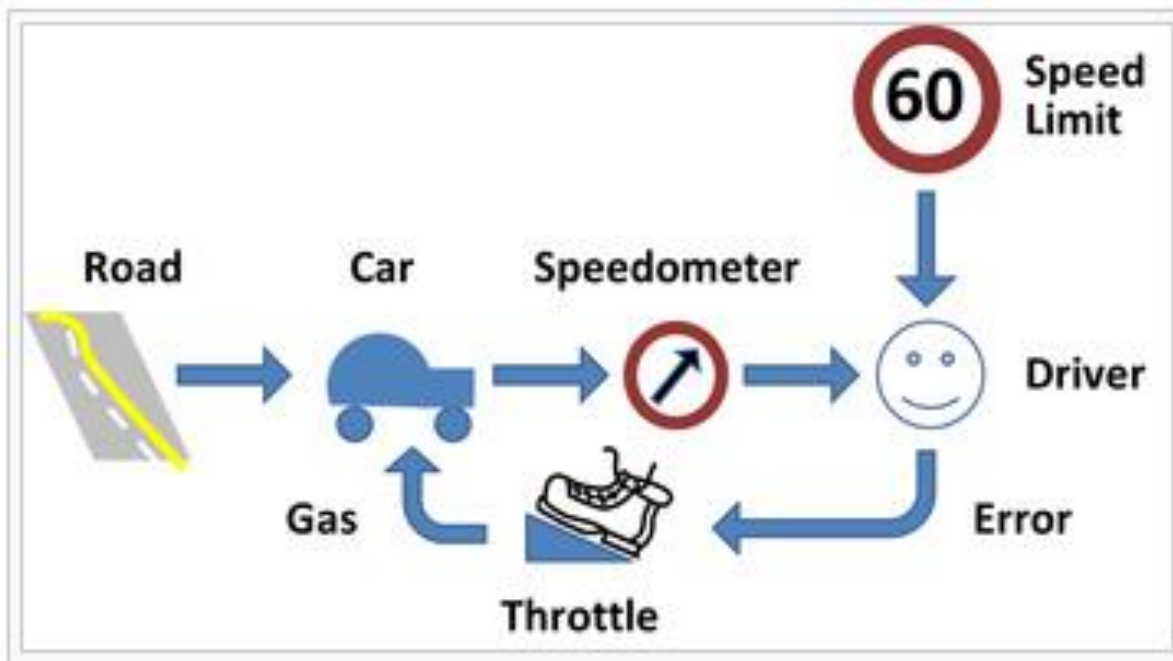
Introduction

Feedback is everywhere in real life!



Introduction

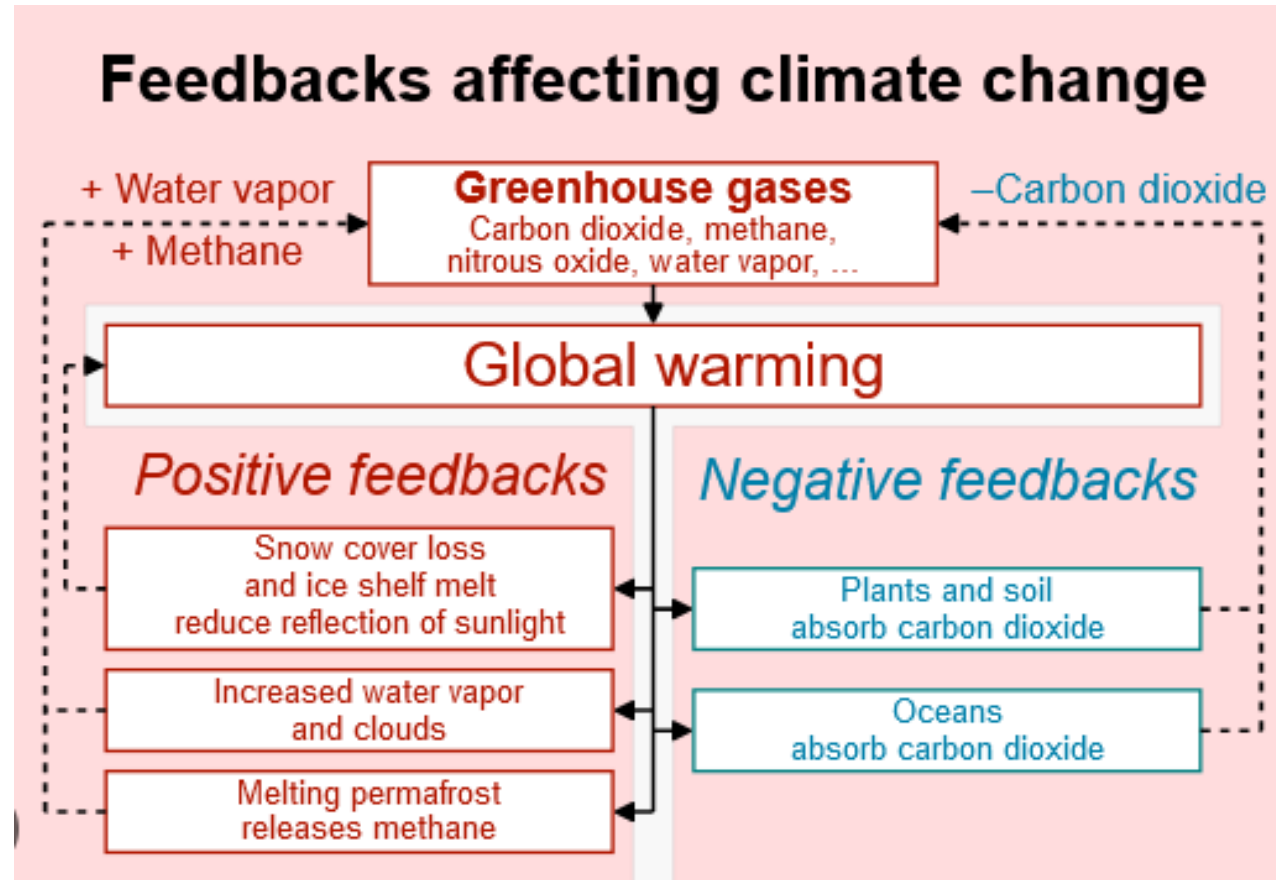
Feedback is everywhere in real life!



Negative Feedback

Introduction

Feedback is everywhere in real life!



Positive Feedback

Revisiting the Op-amp

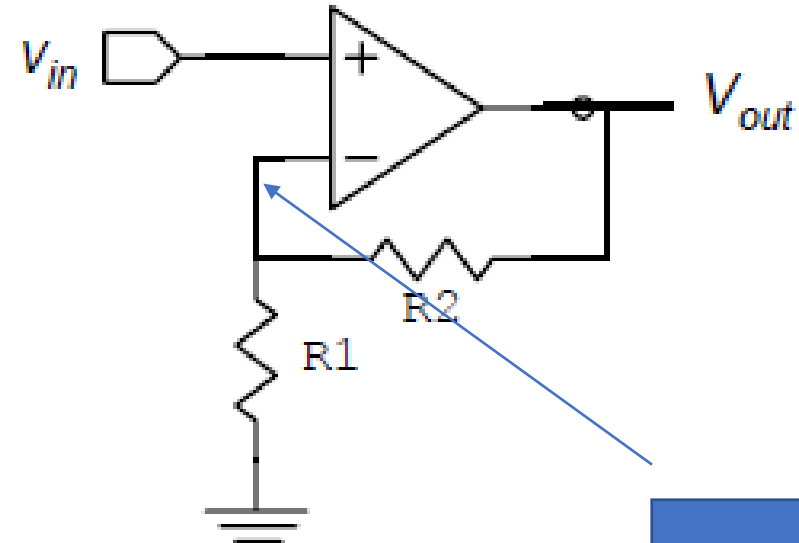
An ideal op-amp is a voltage amplifier with

- infinite voltage gain
- zero input admittance
- zero output impedance
- Zero reverse gain

This definition results in the “golden rules”:

- $v_+ = v_-$
- $i_+ = i_- = 0$

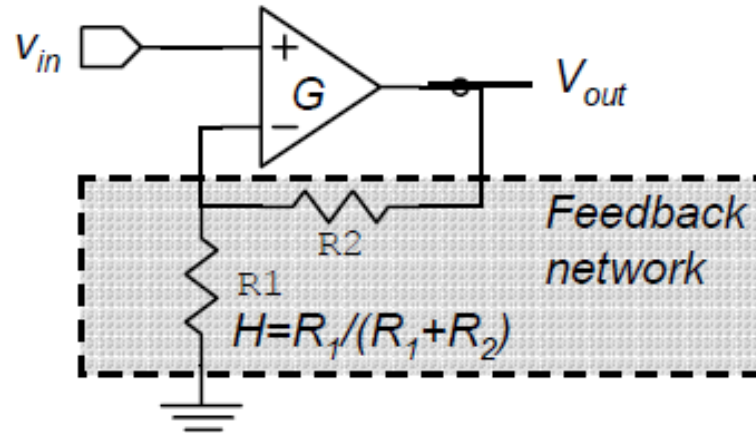
Result: $A_v = 1 + R2/R1$



Negative feedback

What if Op-amp does not have infinite voltage gain?

Op-amp with finite gain



- Keep all the properties of the ideal op-amp except that the op-amp now has a finite gain G . (G may be complex, or a function of frequency!)
- The network connecting the output and the input is an ideal voltage divider (since both $Y_{in}=0$ and $Z_{in}=0$) with gain $H=R_1/(R_1+R_2)$ from output to input.
- The amplifier must amplify its input by G : $V_{out}=G(V_+-V_-)$
- We can now solve the circuit :

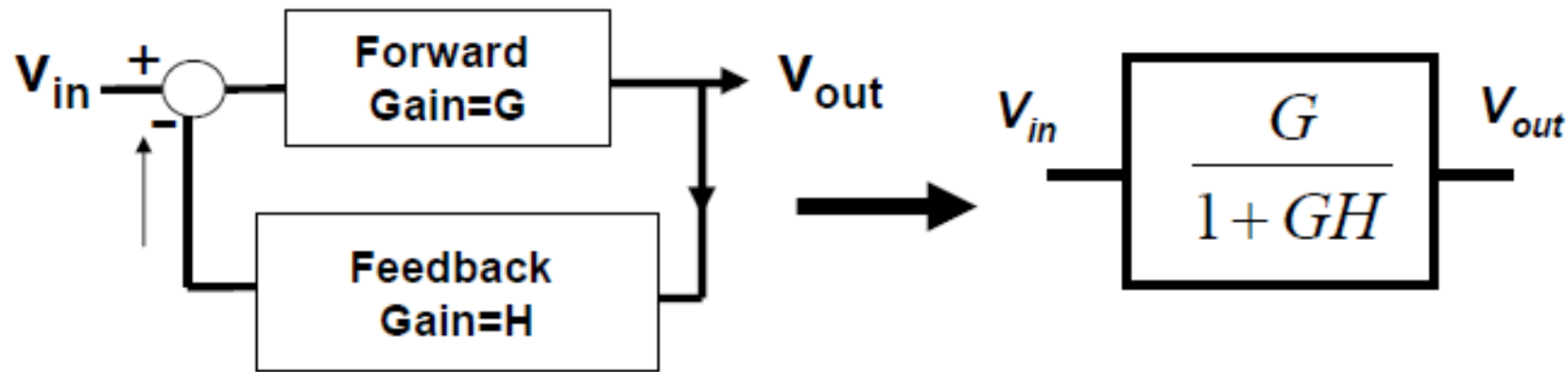
$$v_{out} = G(v_{in} - v_-) \Rightarrow v_{out} = G(v_{in} - Hv_{out}) \Rightarrow v_{out} = \frac{G}{1+GH} v_{in}$$

- Notice that if G is infinite we recover the familiar result:

$$\lim_{G \rightarrow \infty} v_{out} = \lim_{G \rightarrow \infty} \frac{G}{1+GH} v_{in} = \frac{1}{H} v_{in}$$

Op-amp with finite gain

The non-inverting amp is functionally equivalent to the following block diagram:



The signals on the network must be self-consistent, so, as before

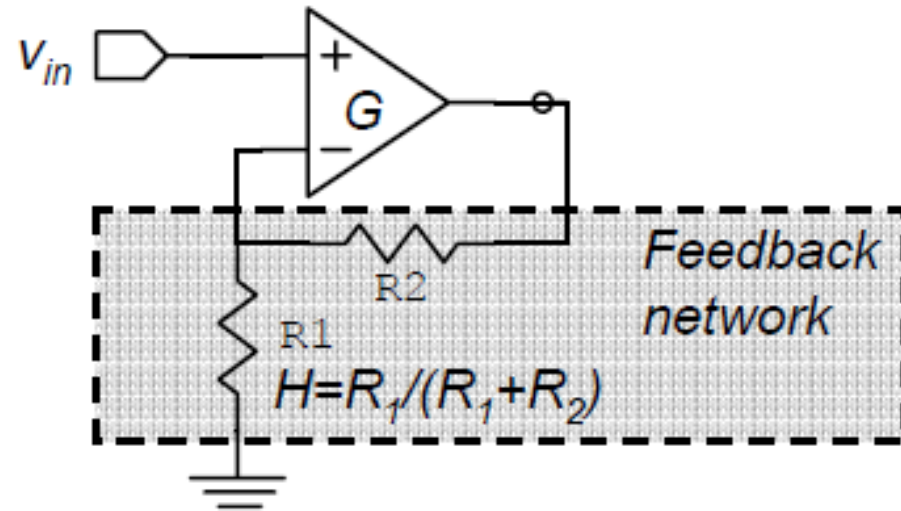
$$v_{out} = G(v_{in} - v_{out}H) \Rightarrow v_{out} = \frac{v_{in}G}{1 + GH}$$

If GH is large, a Taylor expansion gives: $\frac{v_{out}}{v_{in}} = \frac{1}{H} \left(1 - \frac{1}{GH} + \frac{1}{(GH)^2} - \dots \right)$

- GH is called the **loop gain** G_L

(G & H could be function of frequency)

Approximating the Non-inverting gain Amp



We found that the closed loop gain is:

$$v_{out} = G(v_{in} - v_{out}H) \Rightarrow v_{out} = \frac{v_{in}G}{1 + GH} \simeq \frac{v_{in}}{H} \left(1 - \frac{1}{GH} + \dots \right)$$

The loop gain GH is usually big when working with monolithic op-amps, so the

gain is approximately the ideal op-amp gain multiplied by: $1 - \frac{1}{GH}$

Approximating the Non-inverting gain Amp

Example

Suppose you want to create a non-inverting amplifier with a gain of 10. What should be the minimum gain of the Op-amp so that the gain error is less than 1%?

$1 + R_2/R_1 = 10$ for non-inverting amplifier $\rightarrow 1/H = 10$ or $H = 0.1$

Acceptable error is $< 1\%$ $\rightarrow$ error/ideal value < 0.01

For feedback system with finite opamp gain G , actual gain $\sim 1/H * (1 - 1/GH)$ $\rightarrow$ error = $1/H * 1/GH$

Error / ideal value = $1/GH < 0.01$

Hence, $G > (1/H) * 100 = 1000$

Effect of feedback on Bandwidth

Consider a non-inverting amplifier circuit, using a dominant pole amplifier in the forward path. Apply the feedback theory to get the **closed loop gain**:

$$A_v = \frac{G}{1+GH} = \frac{\frac{A_{DC}}{1+j\omega/\omega_p}}{1+\frac{A_{DC}H}{1+j\omega/\omega_p}} = \frac{A_{DC}}{j\omega/\omega_p + 1 + A_{DC}H} = \frac{A_{DC}\omega_p}{j\omega + (\omega_p + A_{DC}\omega_p H)}$$

The DC gain is: $A_{v0} = A_v(\omega = 0) = \frac{A_{DC}\omega_p}{\omega_p + A_{DC}\omega_p H}$

The pole (break frequency) of this amplifier is at: $\omega_0 = \omega_p + A_{DC}\omega_p H$

It follows that the product of gain and bandwidth is insensitive to the DC gain:

$$A_{v0}\omega_0 = A_{DC}\omega_p$$

Gain bandwidth product is constant!
(= Unity Gain Frequency (UGF))

Effect of feedback on Bandwidth

Example

Suppose you want to create a non-inverting amplifier with a gain of 10 using a non-ideal opamp with finite unity-gain frequency (UGF) = 1 MHz. What will be the closed-loop bandwidth of the non-inverting amplifier?

$$UGF = \text{Gain} * BW = \text{constant}$$

The gain for closed-loop system is 10.

Hence, $10 * BW = UGF = 1 \text{ MHz} \rightarrow BW = 100 \text{ kHz}$

Feedback in Electronics

- There is **both** a voltage and a current at every terminal
- Precise definitions of measurements at the output:
 - **Voltage** is measured with **voltmeters**. Voltmeters are:
 - *connected in parallel to the circuit*
 - *have infinite input resistance (Voltage meters draw no current).*
 - **Current** is measured with **amperometers**. Amperometers are:
 - *connected in series to the circuit*
 - *have zero input resistance (current meters develop no voltage).*
- *Precise definitions of adding the error signal at the input*
 - Voltages are added by connecting voltage sources in series
 - Currents are added by connecting current sources in parallel (“shunt”)

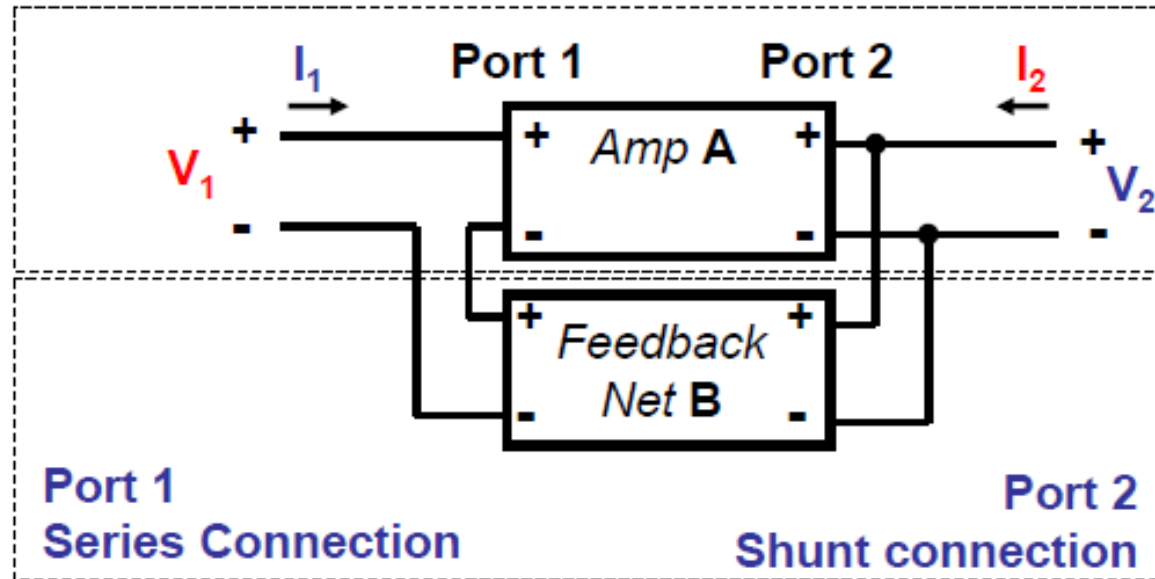
Types of Feedback

- There are 4 ways to implement electronic feedback:
 - **measure** the output:
 - **Voltage**, by connecting the input (port 2!) of the FB network in **shunt** (parallel)
 - **Current**, by connecting the input (port 2!) of the FB network in **series**
 - “**mix**” (feed back) the signal to the input as:
 - **Voltage**, by connecting the output (port 1!) of the FB network in **series**
 - **Current** by connecting the output (port 1!) of the FB network in **shunt** (parallel)
- Feedback topologies are named according to the connections: eg “series-shunt feedback” means series connection at the input and shunt connection at the output

Feedback also changes impedance →

- Series results in increase ($Z_F = Z_{OL} * (1+GH)$)
- Shunt results in decrease ($Z_F = Z_{OL} / (1+GH)$)

Series-Shunt Connection



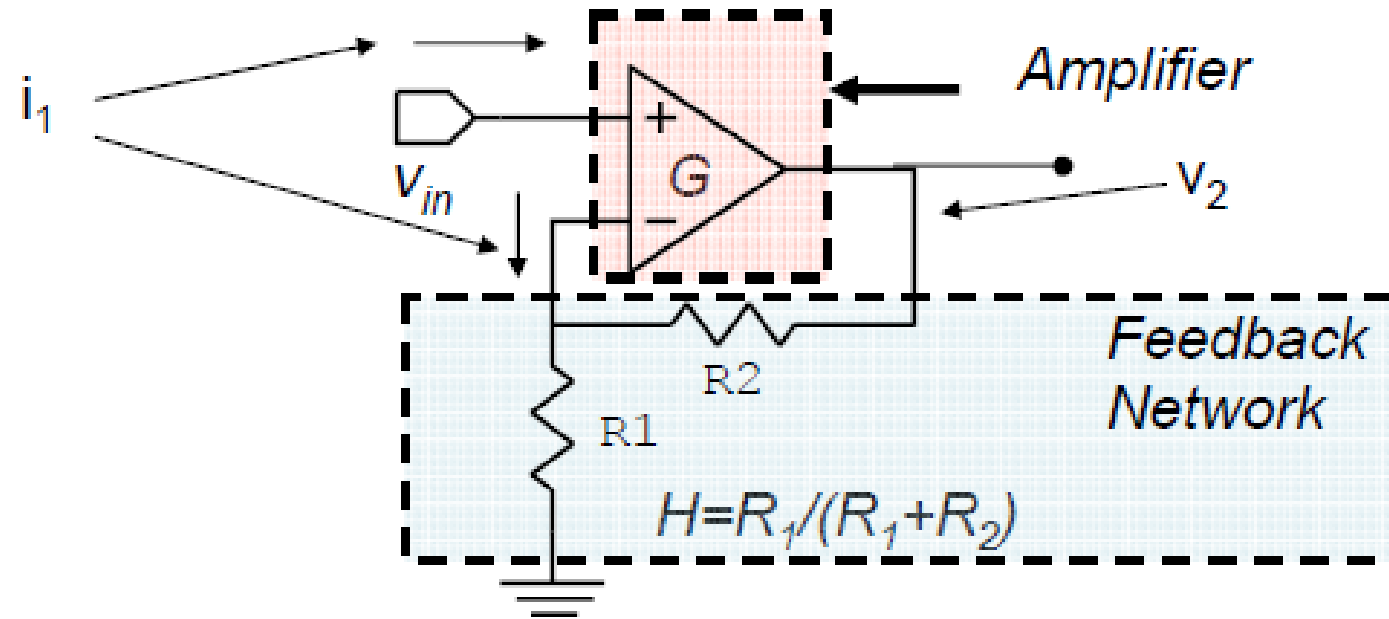
Function of the feedback path network:

- Measures the output **Voltage**
- Feeds back a correction to the input **Voltage** of the forward amplifier

This connection improves the terminal characteristics of a voltage amplifier (VCVS):

- Increases the input impedance (bigger voltage for same current)
- Decreases the output impedance (bigger current for same voltage)

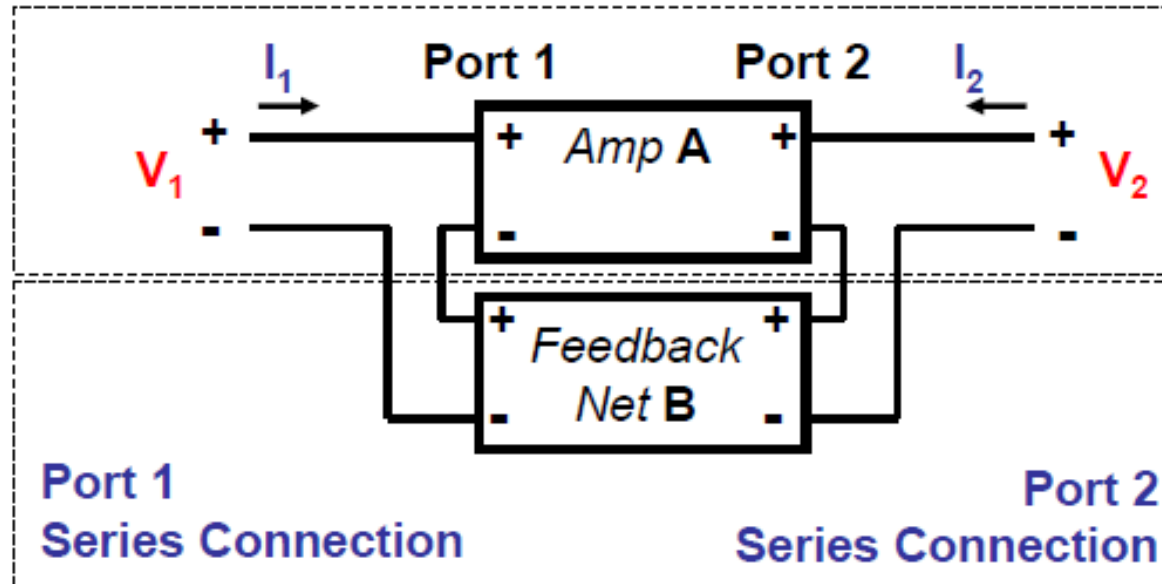
Series-Shunt Connection: Example



The op-amp acts like a voltage amplifier

The feedback network samples the output voltage, voltage divides it and feeds back a voltage into the input, so that v_{in} is the sum of input and fed-back v .

Series-Series Connection



Function of the feedback path network:

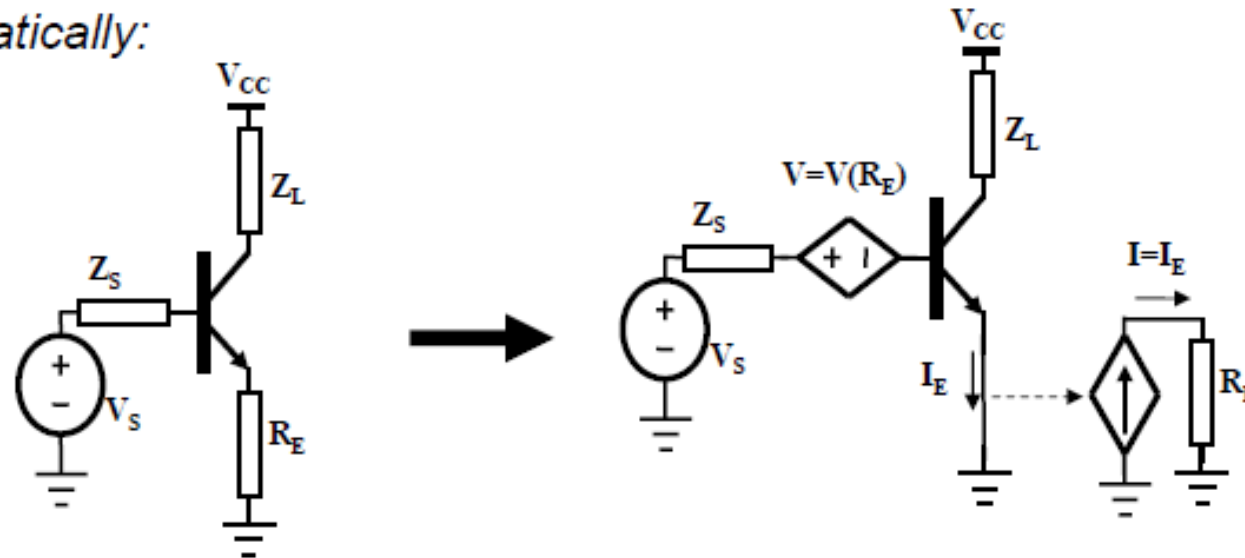
- Measures the output **current**
- Feeds back a correction to the input **Voltage** of the forward amplifier

This connection improves the terminal characteristics of a transconductance amplifier (VCCS):

- Increases the input impedance (bigger voltage for same current)
- Increases the output impedance (bigger voltage for same current)

Series-Series Connection: Example

- Add a Z_E to the common emitter amplifier
- Schematically:



- The feedback network samples the emitter current. Since emitter current is almost equal to the collector current we can say that the feedback network (R_E) samples the output current.
- The voltage developed on the feedback resistor is in series with V_{BE} so the feedback voltage is mixed into the input voltage.
- This is an example of series-series feedback.

Negative feedback: Summary

We are given a negative feedback network with forward gain G and feedback path gain H .

The system has a loop gain GH and a feedback factor $F=1+GH$

1. The amplifier gain and its sensitivity to the gain G are both reduced by a factor F
2. For large G the closed loop response approaches the inverse function of H .
3. The closed loop amplifier has input and output impedances related to those of the high gain block G as follows:
 - A series connection (S) at a port multiplies the port impedance by a factor F
 - A parallel connection (P) at a port multiplies the port admittance by a factor F
 - These 2 rules apply both to the input and the output ports.

Connection	Forward path gain	Reverse path gain
Series-Shunt	Voltage gain	Voltage gain
Shunt-Series	Current gain	Current gain
Series-series	Transconductance	Transimpedance
Shunt-Shunt	Transimpedance	Transconductance

Positive Feedback

Same analysis as negative feedback, apart for $H \rightarrow -H$

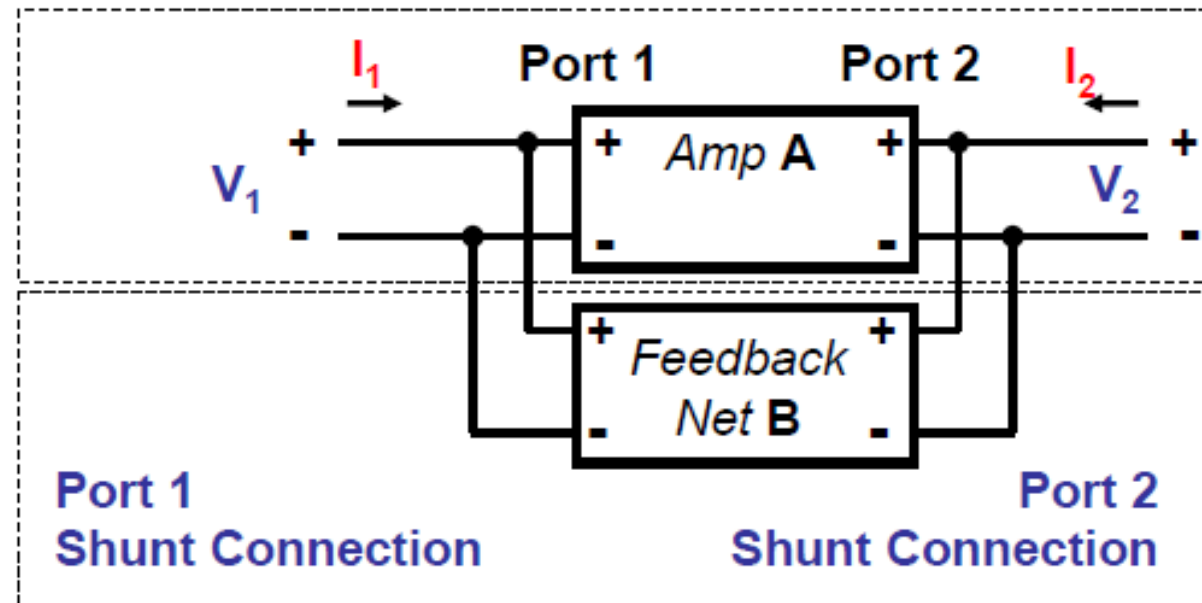
Positive feedback can be used to do things negative feedback cannot do:

- Introduce hysteresis (e.g. Schmitt Trigger)
- Generate negative impedances
- Invert an impedance
- Under positive feedback we can have $F=1-GH=0$. If $F=0$ we (in theory) can turn an amplifier into an ideal version by a suitable feedback connection and $GH=1$.
- However, $F=0$ at a non-zero frequency is the Barkhausen condition for oscillation.
- Positive feedback is used to make oscillators.

Look at oscillators next!

Appendix

Shunt-Shunt Connection



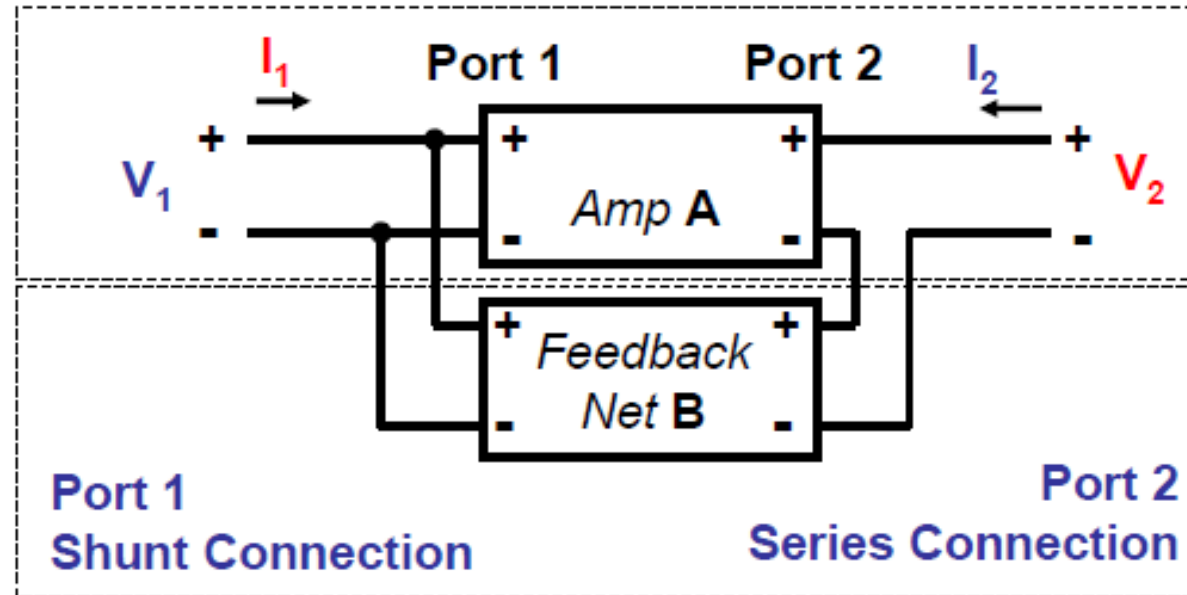
Function of the feedback network:

- Measures the output **Voltage**
- Feeds back a correction to the input **Current** of the forward amplifier

This connection improves the terminal characteristics of a transimpedance amplifier (a CCVS):

- Decreases the input impedance (bigger current for same voltage)
- Decreases the output impedance (bigger current for same voltage)

Shunt-Series Connection



Function of feedback network:

- Measures the output **Current**
- Feeds back a correction to the input **Current** of the forward amplifier

This connection improves the terminal characteristics of a Current Amplifier (CCCS)

- Decreases the input impedance (bigger current for same voltage)
- Increases the output impedance (bigger voltage for same current)