Analogue Electronics 8: Feedback and Op Amps

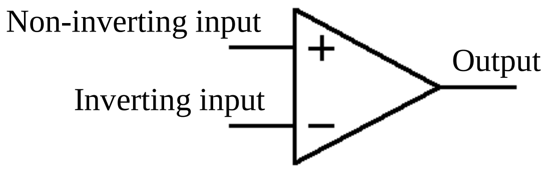
Last lecture we introduced *diodes* and *transistors* and an outline of the semiconductor physics was given to understand them on a fundamental level. We use transistors a great deal, but in most cases we don't work with them directly. Instead we deal with *"black box" devices* such as logic gates which contain many transistors. Now we are going to introduce another "black box" device: a generic form of amplifier called an **Operational Amplifier** (or **Op Amp**). This will also need an introduction to the important phenomenon of **feedback.**

Introduction to an Op Amp: (H&H, 4.02, p. 176)

What is an **Operational Amplifier** (or short **Op Amp**)? An Op Amp is an amplifier circuit with two input terminals (+ and -, called **non-inverting** and **inverting input**) and one output. An Op Amp performs the operation:

$$V_{out} = A(V_+ - V_-)$$

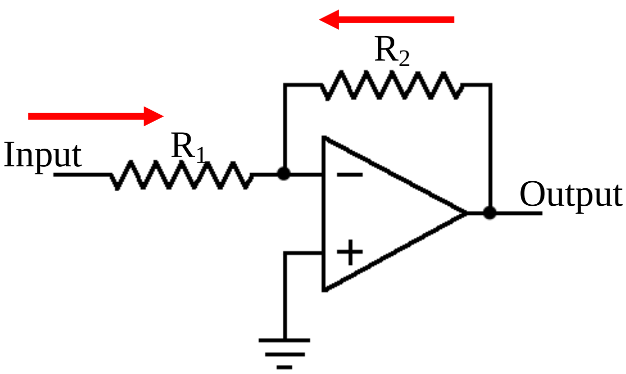
i.e. the device amplifies the *voltage difference* between the two inputs by a factor A. The symbol for an Op Amp is shown here:



Inside Op-Amps are quite complicated. They have more than 20 transistors plus additional circuitry around them for control and stabilisation. In addition to the connections shown (as with logic gates) the Op Amp must be supplied with power.

Often either V_+ or V_- is *attached to ground*. In these cases the device is used either as a non-inverting or as an inverting amplifier of a voltage signal. "A" is called the **open-loop gain** and is usually very large (> 100,000). But the Op Amps cannot be operated in a stable way at these large gains, and they cannot sustain to feed the output current into any real load. The desired stability and output capabilities *can be achieved at the expense of the gain* by the introduction of feedback.

Op-Amp with feedback: (H&H, 4.04, p. 177)



Here you see the Op Amp with some external circuitry. The signal is put in through the inverting input while the non-inverting input is tied to ground, i.e. the signal at the output will have the *opposite sign* of the signal at the input. The resistor R_1 adds to the *input impedance* of the amplifier. This may not be optimal for signal reception, i.e. e.g. reflections may occur. We will come back to this later. **Feedback** of the output back to the input of the amplifier is introduced via the resistor R_2. The red arrows indicate the signal flow.

Since the amplifier is configured to be *inverting* the feedback at the input is *negative*, i.e. a fraction of the output is being "fed back" and *subtracted* from the input.

We will first determine how this specific circuit work. Later on we will return and think about why negative feedback is more broadly useful.

We need some additional terminology: **Open-loop gain** is the amount of amplification created if there is **no** feedback network, i.e. $R_2 = \infty$. **Closed-loop gain** is the amplification created with finite feedback, i.e. $0\Omega \leq R_2 < \infty$.

The open-loop gain of an Op-Amp is *very large*, typically $10^5 - 10^6$. Op Amps are almost never used without feedback. An amplifier cannot supply more voltage than that of the power supply used to drive it. A difference of several tens of micro-volts between the amplifier inputs will result in an output which exceeds the power supply. The closed-loop gain is typically much smaller, i.e. adapted to the **dynamic range** of the Op Amp and the requirements for the output signal, and therefore no problem.

The golden rules: (H&H, 4.03, p. 177)
We are not dealing with the 20-odd internal transistors directly. Instead we are going to deal with this amplifier as a "black box" device, i.e. we are not going to worry about how it actually works. Op-Amps with external (negative) feedback can be understood in terms of a model with *two simple* **Golden Rules**:

1. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.

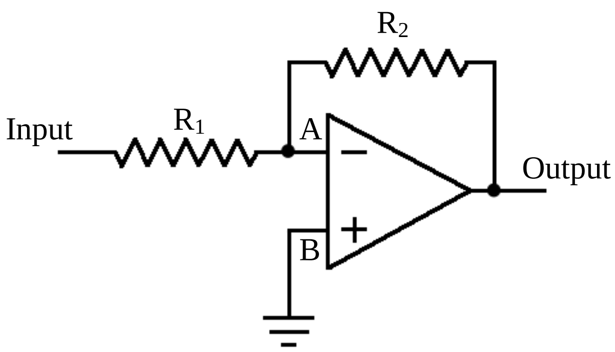
The op-amp does not, and *cannot*, change its inputs. Instead, based on the voltage at the input terminals, it changes its output such that the *feedback network removes the voltage difference between the inputs*.

2. The inputs draw no current.

In practice an op-amp draws less than 1nA and for most practical purposes this can be ignored.

We will look at a handful of op-amp circuits using these rules to understand them. The first is the inverting amplifier. We will use this as the context for taking a slightly more profound look at what is achieved by negative feedback.

The Inverting Amplifier: (H&H, 4.04, p. 178)



Using the golden rules we get:

- Rule 1: Since point B is at ground then point A must be too.
  Consequence: the voltage across R_2 is V_{out} and the voltage across R_1 is V_{in}

- Rule 2: Since no current flows into the inverting input, all current flowing through the feedback must flow towards the input.

$$\frac{V_{out}}{R_2} = \frac{-V_{in}}{R_1} \quad \Leftrightarrow \quad \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

This circuit amplifies the input. The value of the closed-loop gain is R_2/R_1. Interestingly enough the open-loop gain "A" does not even appear in this relation. In real applications the closed-loop gain will typically be of order 10, i.e. in any case very much less than A.

Step back a moment – *what actually is feedback*?

Feedback is a problem solving technique. It involves *comparing* the output of a system with the output that was required. Steps are then taken to *eliminate any discrepancy* between the two. It is a very powerful idea in electronics. You get a *self-regulating* system and you can design the *stable point* (or the potential minimum if you care to see it that way) to be where you want it.

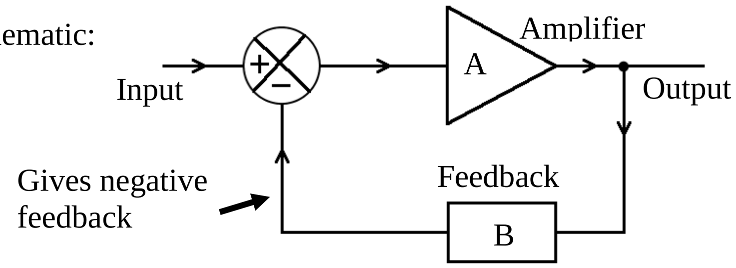
Negative feedback – is when the output is used to reduce the input.
Positive feedback – makes a vaguely positive response emphatic.

Why is *negative feedback useful*?

Negative feedback reduces the gain of an amplifier. This is not obviously useful... However, at the same time it *eliminates distortion* and *non-linearity* from the amplifier performance. And that is high in demand.

An ideal amplifier provides an output that is some multiple of the input. Hence negative feedback can be implemented by comparing an *attenuated version* of the output with the input. This is shown schematically below. Some fraction of the output is fed back and *subtracted* from the input. If there is a difference then the output is not this multiple of the input. The difference signal is amplified, appears at the output and a fraction of the amplified difference is fed back to the input, adjusting the amount subtracted from the input so that the *difference becomes smaller*.

Schematic:



Let's have a look at a quantitative account of negative feedback. The triangle shaped symbol represents an amplifier with gain A. The rectangle is a network of components that sends back a fraction B of the output. The circular symbol subtracts the feedback from the input. So:

$$A(V_{in} - BV_{out}) = V_{out}$$

which gives

$$V_{out} = \left(\frac{A}{1 + AB}\right) V_{in}$$

Therefore the closed-loop gain is:

$$G = {}^{A}/_{(1+AB)}$$

and for the case A = ∞ this gives:

$$G = {}^{1}/_{B}$$

i.e. if the open-loop gain is very high then the closed-loop gain of the circuit becomes independent of the properties of the amplifier.

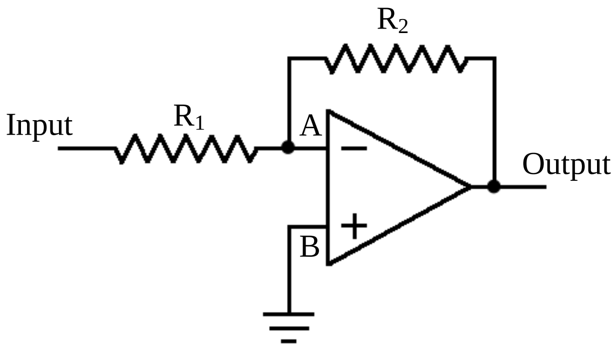
A non-uniform frequency response of without feedback would greatly distort signals. Imagine an amplifier with a gain of 10000 at intermediate frequencies and a gain of 1000 at high frequencies. When introducing negative feedback, e.g. for B = 0.1, this would give:

when A = 10000 then G = 9.90
when A = 1000 then G = 9.99

i.e. the variation in gain becomes only 1%.

You are now supposed to have some understanding of the role of negative feedback in amplification.

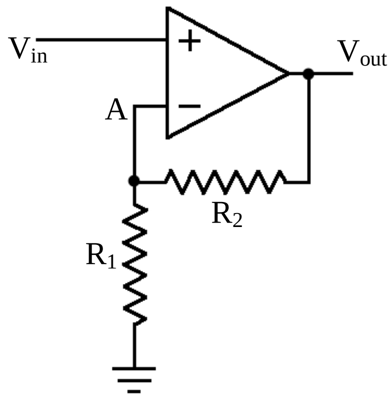
A disadvantage of the Inverting Amplifier:



What is the input impedance for this circuit? It depends on R_1, R_2 and the output circuit and may be rather low. What do we typically want the input impedance of measuring devices such as voltmeters and oscilloscopes to be? It should be large to not draw current and ideally to observe the signal without altering it. This is the *first major disadvantage* with this circuit design.

We are now going to go through a couple of approaches to solving this problem. We need to keep all of the advantages of the op-amp with negative feedback while using a circuit with better input characteristics.

Solution 1 – The non-inverting amplifier: (H&H, 4.05, p. 178)



Using the golden rules:

- Rule 1: $V_A = V_{in}$
- Rule 2: V_A is from a voltage divider $V_A = V_{out}\left({}^{R_1}/_{(R_1+R_2)}\right)$

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

Again we have amplification depending on the relative sizes of the resistors, and not depending on the open-loop gain. Good.

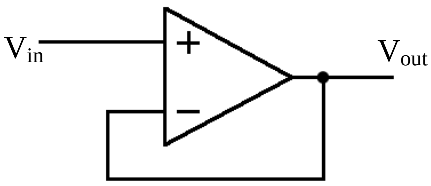
With the non-inverting amplifier the input voltage goes straight into the op-amp. Hence the input impedance is that of the first transistor inside the integrated circuit:

- for BJT inputs this could be $10^8\Omega$,
- for FET inputs this could be $10^{12}\Omega$

i.e. *very* large. Hence, this solves the input impedance problem of the inverting amplifier.

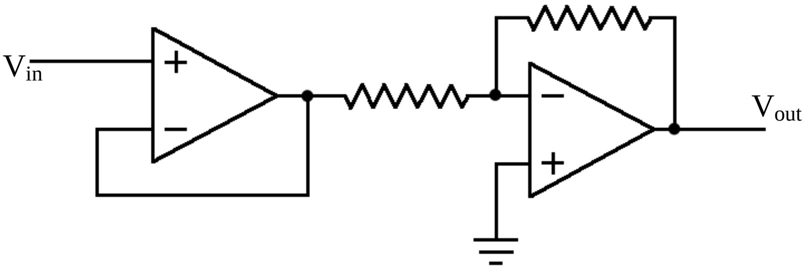
However it is not the best solution. One reason is that the "virtual ground" of the inverting amplifier is actually useful. In the non-inverting amplifier there is *no direct connection from the inputs to ground*. If you are trying to work with input signals relative to ground this can be a disadvantage.

Solution 2 – The source follower: (H&H, 4.06, p. 179)



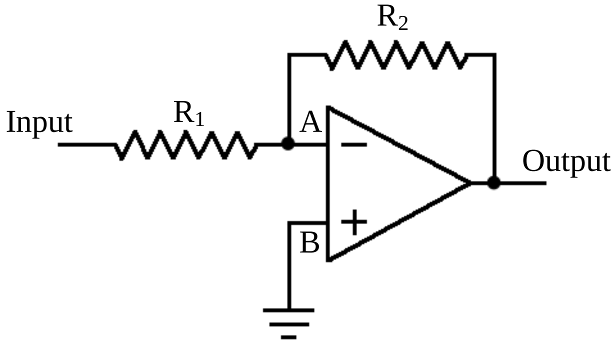
We don't need any separate analysis of this arrangement, because it is a non-inverting amplifier with $R_2 = 0$ and $R_1 = \infty$. Putting these numbers into the above equation we find that the *closed-loop gain of the* **source follower** *is 1*.

At first glance this looks like a pointless circuit, if ever there was one. It turns out it is actually quite useful. Because it provides the impedance behaviour we are looking for (*high input impedance and low output impedance*), and it just leaves the amplification to the subsequent circuit, which e.g. could be an inverting amplifier.



So, by separating the circuit into two stages of op-amps we have solved our input impedance problem. This is a good solution because op-amps are cheap.

Unfortunately there remains *one more irritation to think about* with the inverting amplifier. This is going to be the only time when we stray from the Golden Rules. And it is something that you need to bring under control in the lab: the input B actually will draw a small **input bias current**, I_B, which will offset the circuit and its output from the common ground,



This is the *second major disadvantage* with this circuit design.

If the op-amp has BJT input transistors then there will be a *small but significant* bias current I_B flowing into the input. To the inverting input, A, the resistors R_1 and R_2 make up the output impedance of the previous part of the circuit. So, instead of being a held at "virtual ground" the inverting input is held at a voltage:

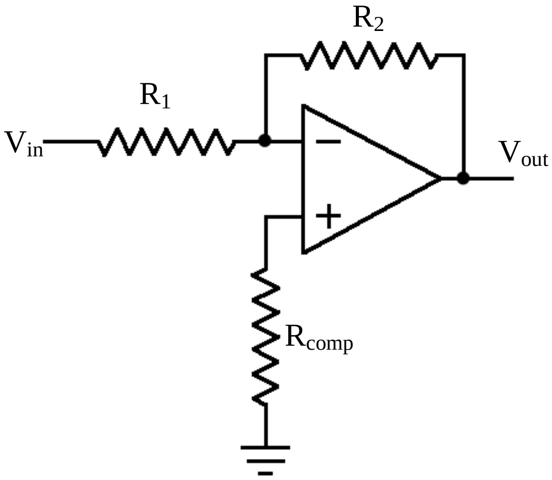
$$V_{in} = I_B \left({R_1 R_2}/{(R_1 + R_2)} \right)$$

For some op-amps this bias can be a large fraction of a volt. This bias at the input will create an offset in the output. In the lab you will need to deal with this in checkpoint A2.

The first possible solution is to keep the resistances in the feedback network as small as possible. That may contradict your needs for the absolute values of R_1 and R_2.

The second and better solution is to add another component, a compensation resistor R_{comp}:

$$R_{comp} = {R_1 R_2}/{(R_1 + R_2)}$$



This has the same value as the resistance that the inverting input is "looking at". Placed between the non-inverting input and ground it will ensure that the two inputs to sit at the same voltage and, thus, no offset is generated in the output.

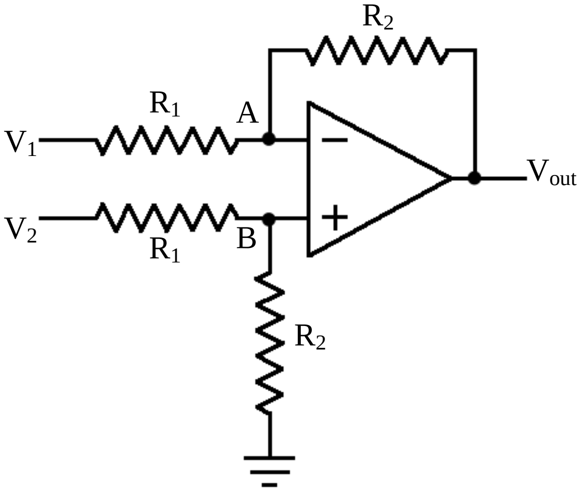
Compensation is usually unnecessary for FET input op-amps as the input impedance of the first transistor is so high that the input bias current I_B is so small that it can be neglected.

Sum & difference amplifiers: (H&H, 4.09, p. 184-5)

Next we are going to deal with op-amp circuits with multiple inputs. These can be used to carry out marginally more complicated operations on the input voltages.

The difference amplifier:

This makes use of the inverting and non-inverting inputs in a fairly obvious way in order to perform a subtraction of two voltages.



Rule 1: $V_A = V_B$

Rule 2: $V_B = V_2 \frac{R_2}{R_1 + R_2}$

Rule 2: $\frac{V_{out} - V_B}{R_2} = -\frac{V_1 - V_B}{R_1}$

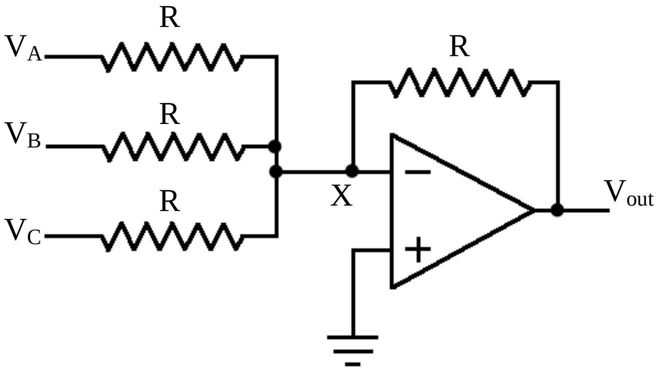
$$V_{out} = \left(\frac{R_2}{R_1}\right)\left(\left(1 + \frac{R_1}{R_2}\right)V_B - V_1\right) = \left(\frac{R_2}{R_1}\right)\left((R_2 + R_1)\frac{V_B}{R_2} - V_1\right)$$

$$V_{out} = \left(\frac{R_2}{R_1}\right)(V_2 - V_1)$$

The performance of this circuit *depends on having identically matching resistors*. Consequently this is not an ideal design.

The summing amplifier:

The example below shows adding voltages with no particular weighting on them. By changing the relative sizes of the left-hand resistors it is possible to add two V_A to three V_B and one V_C.



Using the golden rules:

Rule 1: Point X is a virtual ground

Rule 2: The feedback current flowing into point X balances the sum of the input currents entering that point.

$$\frac{V_{out}}{R} = -\left(\frac{V_A}{R} + \frac{V_B}{R} + \frac{V_C}{R}\right)$$
$$V_{out} = -(V_A + V_B + V_C)$$

As mentioned above making the input resistors different leads to a *weighted sum* of the input voltages. The voltages are added *in proportion to the ratio of the input resistor to the feedback resistor*.

We will next be combining op-amps and complex numbers to make filters that work much better than those based on passive linear components.