Active circuit elements: the transistor (‘transfer resistor’) and the op-amp

And some useful circuits with transistors & amplifiers
The dreaded *common-mode*: how to handle a signal that is susceptible to ambient electrical noise?

Suppose you have a transducer attached to a sample:

And there is ambient electrical noise; note that both leads carry this noise!

- You can easily see this from the 50 Hz signal carried on power lines.

Often, your signal will look like this:

\[ \Delta T = \frac{1}{50} \]

While expecting this:
The `ideal amplifier:`

- Gain, $G$ can be arbitrary, and very large if needed
- Bandwidth is infinite
- No load on the input signal (infinite input impedance)
- Perfect rejection of common-mode
- Perfect rejection of power-supply noise

Clearly, we cannot get all of these things in one...

But we can get close!
Enter *the op-amp*:

An op-amp is a very high-gain* dc-coupled differential amplifier with a single-ended output.

* The typical op-amp (e.g. the LF411) has an open-loop gain of $10^5 - 10^6$

Why would we call the non-inverting input *the non-inverting input*? Isn’t it much easier just to call it the ‘positive input?’ How many leads would be necessary for such an amplifier?

How is such an amazing device constructed? => transistors!
A quick interlude on diodes...

- Note: 0.6V diode drop:

100V "reverse breakdown"
Onward with transistors: We’ll work with BJT
(bipolar junction transistors)

Think of it like a valve:

\[ I_C = \beta I_B \]
Understanding transistor behavior through example circuits: *a follower*

Why would we do this?

- Incredible behavior of the transistor in changing impedances
Transistor impedance: *not* the V-divider view; `rose-colored lens’ effect

A second look at the follower:

\[ \Delta V_{in} = \Delta V_{we} \]

\[ \Delta V_{out} = \Delta V_{be} \approx \Delta V_{base} \]

\[ \Delta I_e \approx \Delta I_c \]

\[ \frac{\Delta V}{\Delta I} \approx R_e \]

\[ E_c \]

\[ E_b \]

\[ E_e \]

\[ E_f \]

1. We measure \( V_e \) with load, with \( 33k \) on base
2. We connect a \( 1k \) load to ground; measure \( \Delta V_{c} = \Delta I_c \)
A summary of our transistor circuits:
An op-amp is a very high-gain* dc-coupled differential amplifier with a single-ended output.

The `golden rules’ for op-amp behavior assuming it is operating with negative feedback

I. The output *attempts to do* whatever is necessary to make the *voltage difference between the inputs 0*.

II. The inputs draw no current.

Can the op-amp dictate the voltage at the inputs? Why or why not?
A typical op-amp non-inverting amplifier – operating with negative feedback:

\[ V_{in} \quad + \quad \frac{R_2}{R_1} = 10k \quad \text{Vout} \quad \]

- From GRI, \( V_A = V_{in} \)
- But, \( V_A \) comes from a V-divider:

\[ V_A = \frac{V_{out}}{R_1 + R_2} \quad \text{this is our gain:} \]

\[ \frac{V_{out}}{V_{in}} = G = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1} \]

\[ G = 1 + \frac{10k}{1k} = 11 \]
Today, we’ll build an amplifier using the LF411 op-amp with a gain of about 10. Recall that op-amps have enormous open-loop gain … why would we want to throw away all of the amazing open-loop gain?

Indeed, we do ‘throw away’ gain - but not without redeeming merit! Keep in mind, we now have feedback in our circuit. This is the key advantage. When the open-loop gain vastly exceeds the gain attained via feedback, we refer to this as negative feedback – not like a news-cycle, where bad news begets bad news (this is positive feedback by our definition. If you’re not confused, just wait a moment…)

Negative feedback essentially consists of throwing away the ‘bad’ while keeping the ‘good.’ The output of the amplifier is attenuated, and compared with another input to the amplifier, and the deviation from the input then ‘directs’ the amplifier to move in the correct direction – thus suppressing noise, for example.

Consider an amplifier without feedback – any time it is exposed to noise, that noise is also amplified, and can drive the output away from the intended \( G \Delta V \) behavior.
Basic op-amp circuits & their analysis

An op-amp follower:

\[ V_{in} \]

Also called a buffer.

1. \( V_{in} \) increases
2. \( \Delta V_+ \) increases
3. Amp drives output up until \( V_{out} = V_{in} \).

Simple! At step 3, both Golden Rules apply—first, GRI: the output responds by \( \Delta V_+ \)Second, GRII: \( V_+ = V_{out} \).

What is the benefit of this circuit—e.g. why would one want to use it?
Basic op-amp circuits & their analysis

Inverting amplifier:

$V_{in}$

$R_1$

$A$

$B$

$R_2$

$V_{out}$

Input impedance is not $V_{in}$!

Point $B$ is a "virtual ground."

GRI: Point $A$ is also at $V=0$.

$\Delta V_{in-a} = I_{R_1} \cdot R_1 = V_{in}$

GR II: $I_{R_1} = I_{R_2} = I$

$\Rightarrow \Delta V_{o-a} = I \cdot R_2 = V_{out}$

Thus, $\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} = G$.

Note: gain is negative here: if $V_{in} > 0$, $V_{out} < 0$.

What is the input impedance of this amplifier? (hint: it is not the input impedance of the op-amp!)
What is the `glaring problem’ with this design? E.g. Why might it not be ideal for use in pushing a current through a resistive load?
Basic op-amp circuits & their analysis

An ideal current-to-voltage converter (a "trans-impedance" amp)

This circuit produces an output of
\[ \frac{1V}{\mu A} \]
of current: useful for e.g. a photo diode, which makes current when exposed to light.

Alternatively, suppose your current source requires power for e.g. a PMT

The devices we’ve review thus far do not constitute a comprehensive list of useful op-amp circuits. Find another circuit that uses negative feedback to do something useful!
Cautionary notes for application of the GRs

- Golden rules only apply if the op-amp is in the `active region’ (i.e. not saturated at $V_+$ or $V_-$ of the supply)
- Feedback *must be negative* – be careful not to mix up the inverting and non-inverting inputs
- There must always be feedback at DC – otherwise, you’re guaranteed to saturate. Alternatively, apply a high-pass filter to the input to eliminate concerns about DC offset driving the amp into saturation.
- Beware the maximum differential input voltage – if overdriven, the amp can fail catastrophically.