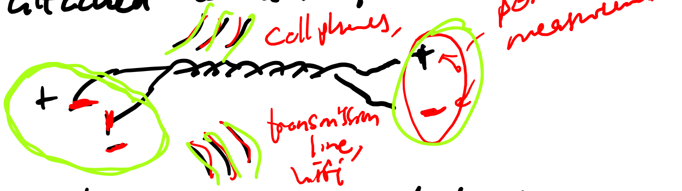
Active circuit elements: the transistor (`**trans**fer resis**tor**’) and the op-amp

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:

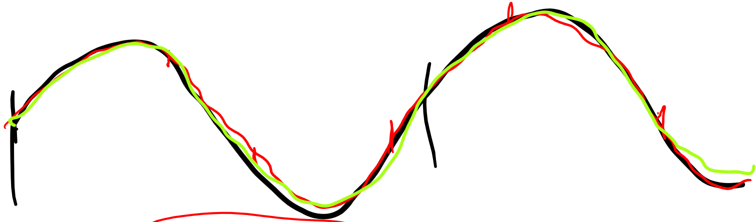


And there is ambient electrical noise:

Note that both leads, + Δ - carry this noise!

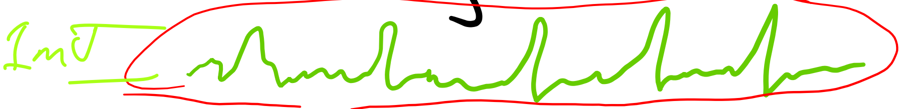
- you can easily see this from the 50 Hz signal carried on power lines.

Often, your signal will look like this:

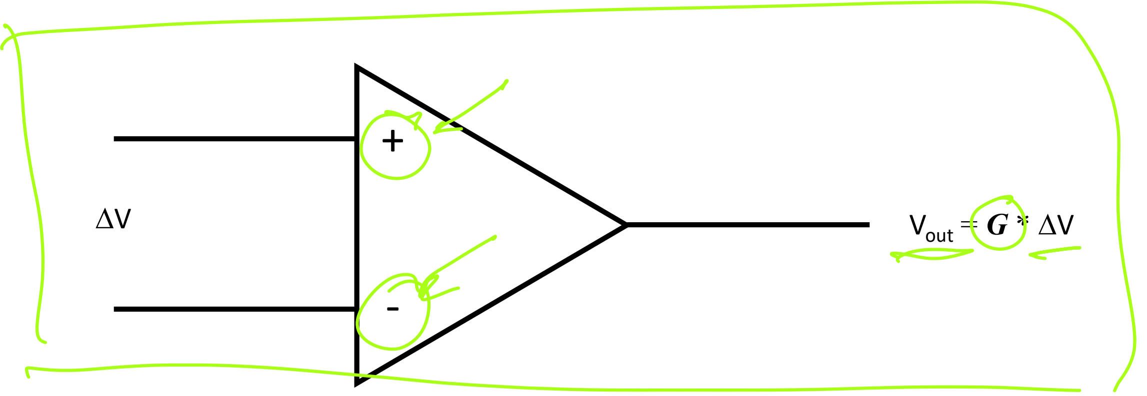


$$\Delta T = \frac{1}{50}$$

While expecting this:



The `ideal amplifier:'



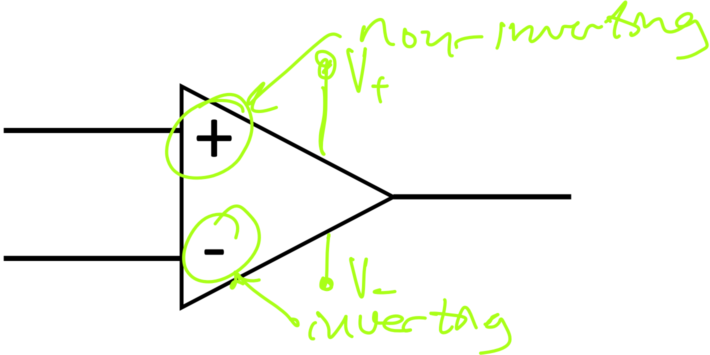
- Gain, ***G*** can be arbitrary, and very large if needed
- Bandwidth is infinite
- No load on the input signal (infinite input impedance)
- Perfect rejection of common-mode
- Perfect rejection of power-supply noise

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.

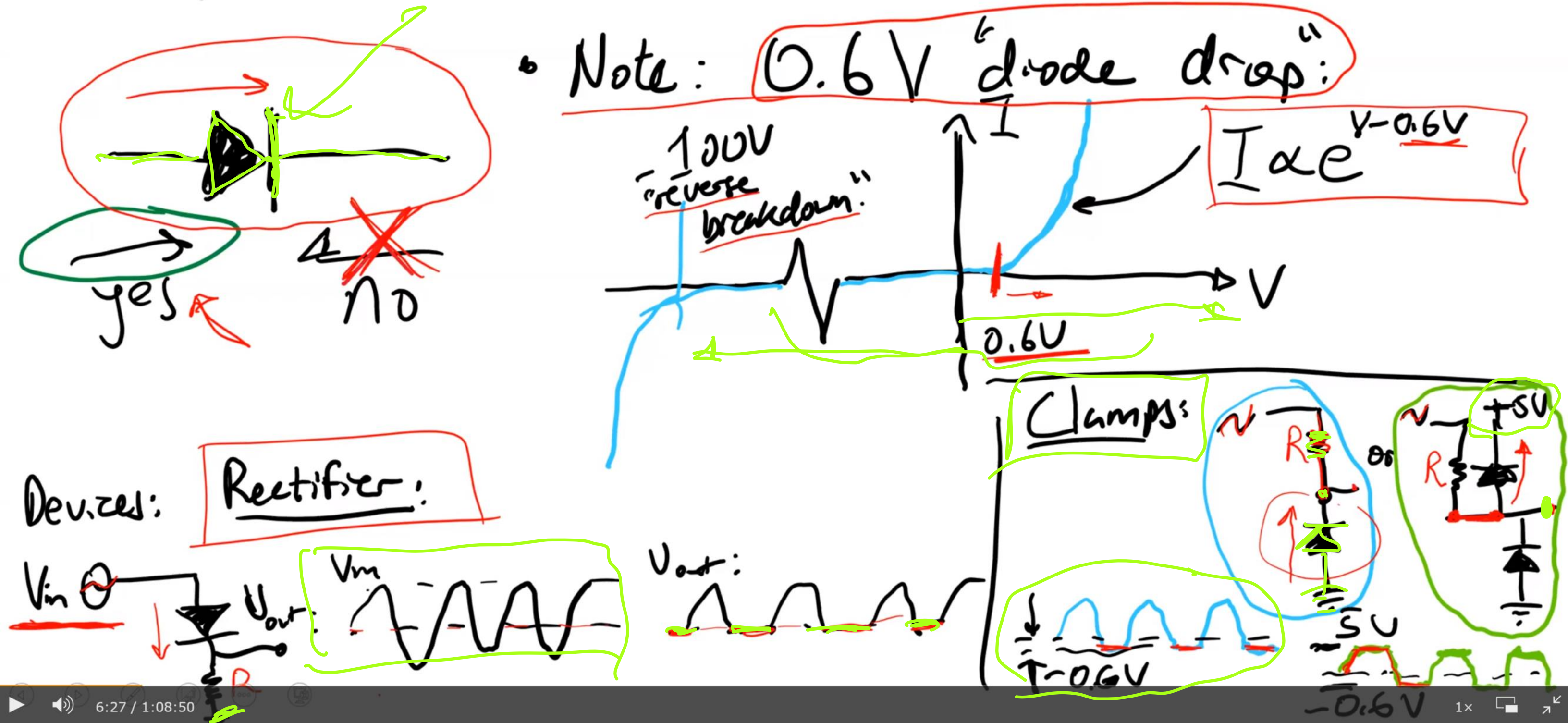


* The typical op-amp (e.g. the LF411) has an open-loop gain of 10^5 - 10^6

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...

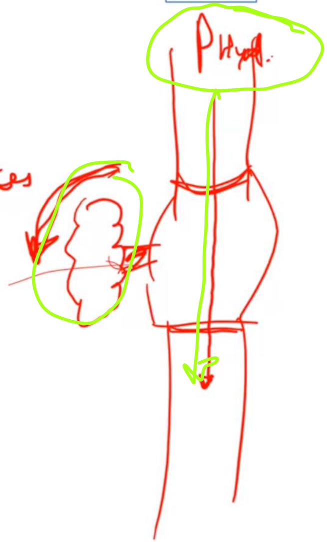


Onward with transistors: We'll work with BJTs (bipolar junction transistors)

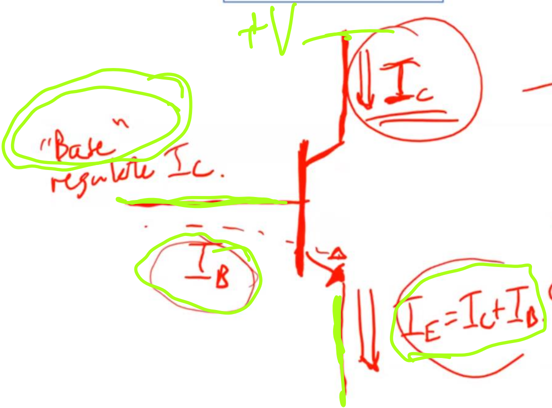
Think of it like a valve:

valve

wheel regulates flow



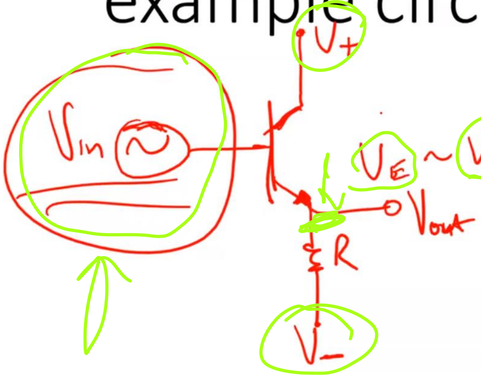
npn - transistor



– A little bit of base current I_B $\Rightarrow$ a lot of collector current.

$$I_C = \beta I_B$$

Understanding transistor behavior through example circuits: *a follower*



$V_E \sim V_{in}$ $(= V_{in} - 0.6)$.

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:

$\Delta V_{in} = \Delta V_{BASE}$

$\Rightarrow$ ~~small ΔI~~

Small ΔI_b

Same ΔV's

$\dfrac{(V_{out} - V_-)}{R_E} = I_E \sim I_C$

$\Delta V_{out} = \Delta V_E \sim \Delta V_{BASE}$

Large $\Delta I_E \sim \Delta I_C$

V. different ΔI's

* Looking into base of the transistor, I see a v. large impedance.

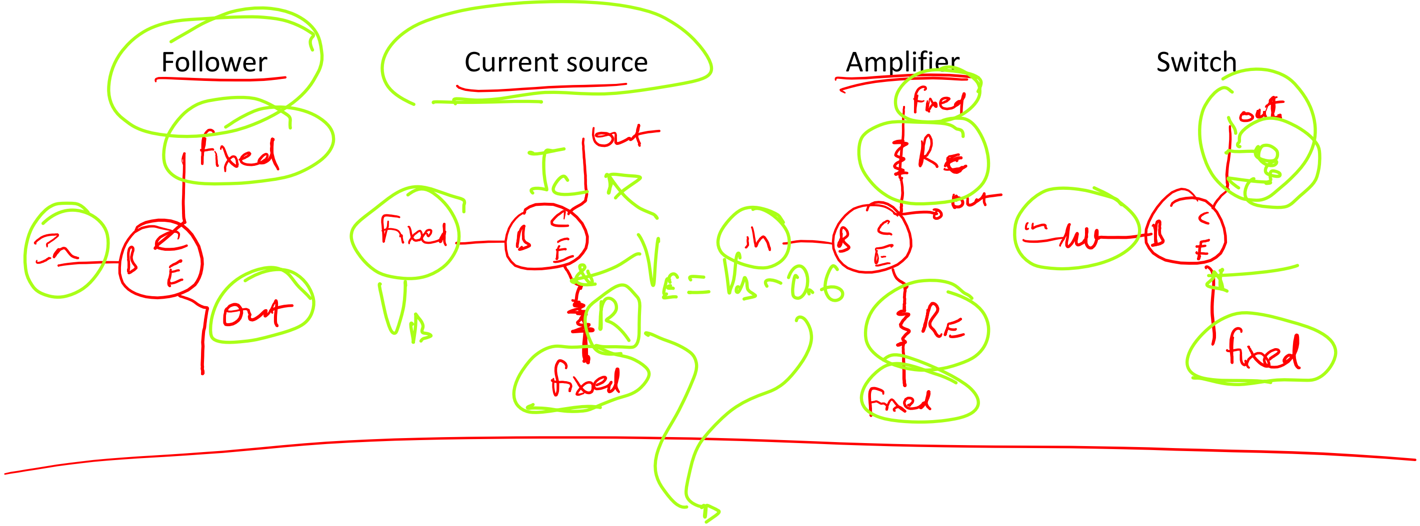
* Look into the emitter from output, we see a v. low impedance:

$\dfrac{\Delta V}{\Delta I}$

measuring Z_{out} of transistor:

1. we measure V_E w/out load, with ~33k on base
2. we connect a 1k load to ground; measure ΔV_E again

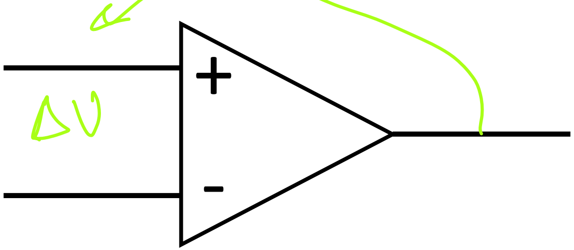
A summary of our transistor circuits:



$$I_E = \frac{V_E}{R}$$

Back to *the op-amp:*

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



The `golden rules’ for op-amp behavior

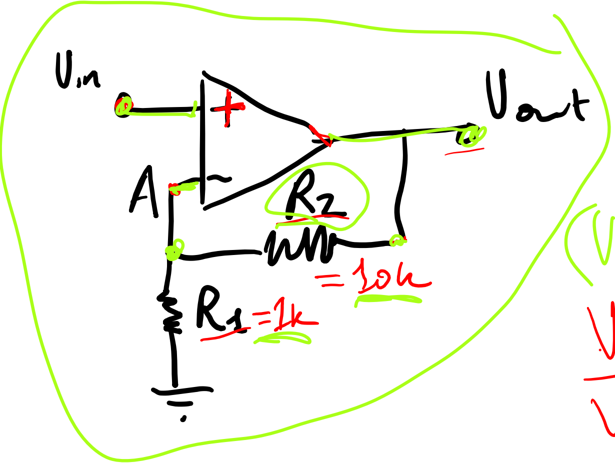
assuming it is operating with negative feedback

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:



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

$$(V_{in} =)\; V_A = V_{out}\frac{R_1}{R_1+R_2}$$ this is our gain!

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

$$G = 1 + \frac{10k}{1k} = 11.$$

Turn it up to 11!

A note on negative feedback

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?

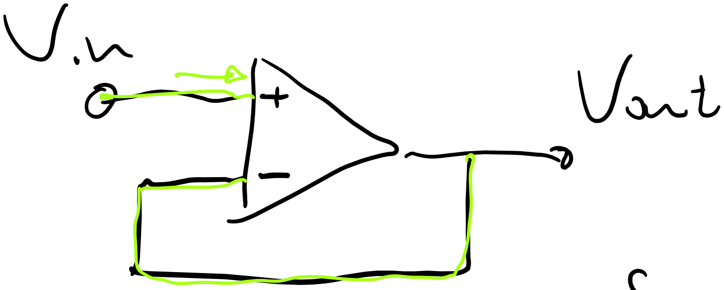
Indeed, we do `throw away' gain - but not without redeeming merit! Keep in mind, we now have *feedback* in our circuit. This is the key advantage. When the open-loop gain vastly exceeds the gain attained via feedback, we refer to this as *negative feedback* – not like a news-cycle, where bad news begets 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****ΔV' behavior.

Basic op-amp circuits & their analysis

An op-amp follower:



Also called a buffer.

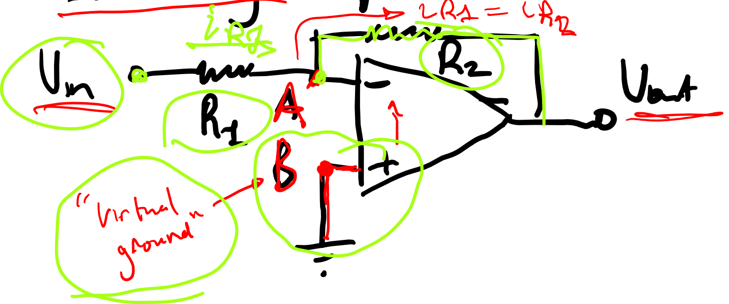
1. V_{in} increases
2. $\Delta V_{\pm}$ increases
3. Amp drives output up until $V_{out} = V_{in}$.

Simple! At step 3, both Golden Rules apply – first GR I: the output responds to $\Delta V_{\pm}$; Second, GR II: $V_{-} = V_{out}$.

What is the benefit of this circuit – e.g. why would one want to use it?

Basic op-amp circuits & their analysis

Inverting amplifier:



→ • Point B is a "virtual ground".

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

• $\Delta V_{in-A} = I_{R1} \cdot R_1 = V_{in}$

• GRII: $I_{R1} = I_{R2} = I$

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

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

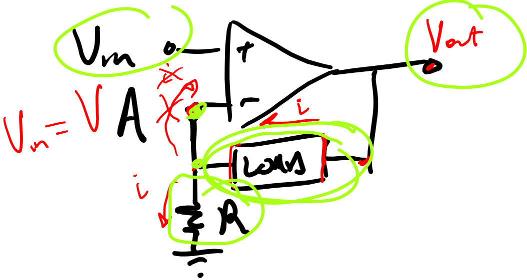
Note: gain is negative here: if $V_{in} > 0$, $V_{out} < 0$.

What is the input impedance of this amplifier? (hint: it is not the input impedance of the op-amp!)

Basic op-amp circuits & their analysis

Current sources:

A basic design, with a glaring problem:



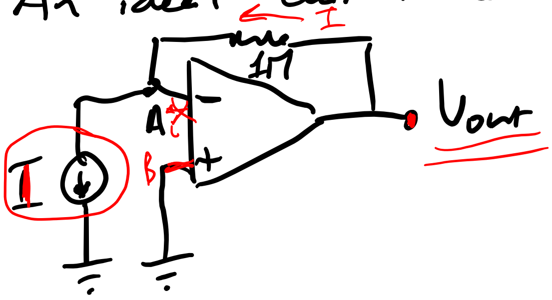
GRI: $V_A = V_{IN}$; Thus, by GRII, $\boxed{I = \frac{V_{in}}{R}}$

• I passes through the load.

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?

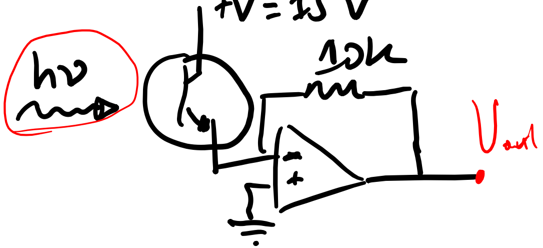
Basic op-amp circuits & their analysis

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



This circuit produces an output of $\boxed{1V/\mu A}$ of current: useful for e.g. a photodiode, 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.