Op-amps, positive feedback, the `Golden Rules’ and a few devices

READING: Art of Electronics, 4.01-4.09
& Harold S. Black, IEEE Spectrum 1977 (on wiki)
Why not turn it up to 11?

At the end of last week’s lab, we used feedback to make an 11 x amplifier. The 11 x gain with the feedback significantly reduced the gain of the amplifier without feedback – the so-called ‘open-loop’ gain.

Why would one wish to do this? Doesn’t this throw away gain that we worked very hard to incorporate into our amplifier?

The short answer is – yes, it does ‘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.

Next week, we’ll learn what happens when you use these devices with their incredible gain to make circuits with positive feedback; this week, we’ll only focus on negative feedback and the amazing properties it has.

Point for discussion on Piazza: 1. What problem did Harold S. Black solve by inventing negative feedback amplifiers? 2. Harold Black wrote his idea for the negative feedback amplifier on the newspaper – why might he have done this?
Now, on to 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 many wires?
The `golden rules’ for op-amp behavior assuming it is operating with 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?
Basic op-amp circuits & their analysis

An op-amp follower:

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 to $\Delta V_+$; second, GRII: $V_-=V_{out}$.

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

Also called a buffer.

On pizza:

On pizza.
Basic op-amp circuits & their analysis

non-inverting amplifier: (might look familiar from last week’s lab):

- From GRI, \( V_A = V_{in} \)
- But, \( V_A \) comes from a \( V \)-divider:
  \[
  V_A = \frac{V_{out} \cdot R_2}{R_1 + R_2}
  \]
  this is our gain:

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

\[
G = 1 + \frac{1k}{1k} = 11
\]
Basic op-amp circuits & their analysis

Inverting amplifier:

\[ R_2 \]

\[ \text{Point } B \text{ is a "virtual ground".} \]

\[ \text{GRI: Point } A \text{ is also at } V=0. \]

\[ \Delta V_{\text{in-a}} = I_{R_3} \cdot R_1 = V_{\text{in}} \]

\[ \text{GRII: } I_{R_1} = I_{R_2} = I \]

\[ \Rightarrow \Delta V_{\text{o-a}} = I \cdot R_2 = V_{\text{out}} \]

Thus, \[ \frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{R_2}{R_1} = G. \]

Note: gain is negative here: if \( V_{\text{in}} > 0 \), \( V_{\text{out}} < 0 \).
Current Sources: A basic design, with a glaring problem.

$V_m = V$  
$V_n = V$

$$\text{GRI: } V_n = V_{in} \quad \text{Thus, by GRI, } I = \frac{V_m}{R}$$

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 $1V/\mu A$ 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. You’ll have feedback.

• 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.

See e.g. lab.

See e.g. exercises this week.

LF411 has >20 transistors. Some will burn if overdriven.