Op-amp review: negative feedback; golden rules

The “golden rules” for op-amp operation encode this idea in two simple rules that are sufficient to analyze the behavior of most op-amp circuits:

Golden rules:

1). No current flows into the inputs, i.e.,
   \[ I_+ = 0 \quad \& \quad I_- = 0 \]
   This follows from the FET inputs.

2). The op-amp output will do whatever it can to force the inputs to be equal, i.e.,
   \[ V_+ = V_- \]
   Rule 2 can only work when there is some sort of feedback from \( V_{out} \) to \( V_- \). Otherwise, \( V_{out} \) is “at a rail” if \( V_+ \neq V_- \).

Relies on enormous gain to apply "force back to equilibrium position", through negative feedback.
Op-amp review: non-inverting amplifier

Using the golden rules we can analyze the circuit for a non-inverting amplifier.

Rule 1 means high impedance. Rule 2 means that $V_{\text{out}}$ relates to $V_{\text{in}}=V_+=V_-$ through a simple voltage divider relationship.

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

Solving for $V_{\text{out}}$ in terms of $V_{\text{in}}$ gives

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

$$V_{\text{out}} = V_{\text{in}} (1+R_2/R_1)$$

$$G = 1+R_2/R_1$$

Limits on $R_1$ and $R_2$. 
Non-inverting amplifier

What would we get if we added a capacitor in the non-inverting amplifier?

\[ G = \frac{1}{R_1} \]

becomes

\[ G = \frac{1}{R_1 + \frac{1}{\omega C}} = \frac{1}{R_1 + X_C} \]
Op-amp review: inverting amplifier

Using the golden rules we can analyze the circuit for an inverting amplifier.

Rule 2 means $V_\text{-} = \text{ground}$. Called a “virtual ground”.

Rule 1 means that no current flows into inverting input. So, $I_1 = I_2$

$V_{\text{in}} = I_1 R_1$

$V_{\text{out}} = -I_2 R_2 = -I_1 R_2 = -V_{\text{in}} R_2 / R_1$

$G = -R_2 / R_1$
Package

You will use an LM741 in an 8-pin DIP
Input biasing

We need to bias the input because AC coupling gives no ground reference.
Power supply by-passing

What would we get if we added a capacitor to the positive feed-back loop?

This would feed the signal back to the input, with a small delay.

That would be amplified, and that would feedback further causing a growing oscillation.

Parasitic capacitance and inductance can cause oscillation even when there is not input.
Power supply by-passing

What would we get if we added a capacitor to the **positive** feed-back loop?

We can also get "ground bounce" or power supply sag from current surges when the output signal changes.

The power supplies can't provide that current fast enough through long (inductive) wires.
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Comparator

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Comparator problem from noise

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A fast comparator can fire on noise.

If we are counting pulses going over threshold, this will over count.

We can fix this…
Schmitt trigger to fix comparator noise problem

We can fix this by changing the threshold for rising and falling transitions.

Note the opposite polarity of inputs!

- $V_{\text{out}}$ is low when $V_{\text{in}} > V_{\text{thr}}$
- $V_{\text{out}}$ is high when $V_{\text{in}} < V_{\text{thr}}$

When $V_{\text{out}}$ is low, the threshold is 0 V.
When $V_{\text{out}}$ is high, the threshold is higher; here $V_{\text{Thr}} = 5 \times 1k/(101k) = 50$ mV.

$V_{\text{out}}$ stays high until $V_{\text{in}}$ goes above 50 mV. $V_{\text{out}}$ stays low until $V_{\text{in}}$ goes below 0 V.

This adds hysteresis, hence the symbol for this “Schmitt trigger”.
Integrate, sample, hold, and compare
Comparator with "open-collector" output

Often comparator chips differ from standard op-amps in that they have a special output stage with the output connected to a transistor’s collector. This allows optimization for speed, and external control of logic levels.

\[ V_{\text{out}} = \begin{cases} +5 \text{ V}, & V_{\text{in}} < 0 \\ 0 \text{ V}, & V_{\text{in}} > 0 \end{cases} \]

This requires a pull-up resistor.
Note the opposite polarity of the comparator response.
Without a pull-up, it goes high impedance, aka tri-state.
Differential amplifier

The op-amp is a huge gain differential amplifier. We can get controlled differential amplification with negative feedback using…
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\[ V_B = \frac{V_+ R_2}{R_1 + R_2} = V_A \]

\[ I = \frac{V_+ - V_A}{R_1} \]

\[ V_{\text{out}} = V_A - I R_2 \]
Differential amplifier

The op-amp is a huge gain differential amplifier. We can get controlled differential amplification with negative feedback using this circuit.

\[
V_B = \frac{V_+ R_2}{(R_1+R_2)} = V_A
\]

\[
I = \frac{(V_- - V_A)}{R_1}
\]

\[
V_{out} = V_A - I R_2
\]

\[
V_{out} = \frac{V_+ R_2}{(R_1+R_2)} - (V_- - V_A)\frac{R_2}{R_1}
\]

\[
= R_2 \left[ \frac{V_+}{(R_1+R_2)} - \frac{V_-}{R_1} + \frac{V_+ R_2}{R_1(R_1+R_2)} \right]
\]

\[
= R_2 \left[ \frac{V_+(1+R_2/R_1)}{(R_1+R_2)} - \frac{V_-}{R_1} \right]
\]

\[
= R_2 \left[ \frac{V_+(R_1/R_1+R_2/R_1)}{(R_1+R_2)} - \frac{V_-}{R_1} \right]
\]

\[
= R_2 \left[ \frac{V_+/R_1 - V_-/R_1} \right]
\]

\[
= (V_+ - V_-) \frac{R_2}{R_1}
\]
Design of a smoke alarm

We have enough tools to start designing things.

Learning the electronics design process is part of our goal here.

As we design, we might need to learn some new tools.

So, let’s go through the design of a smoke alarm.
In lab next week you will make a “burglar alarm”.
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Start with an overview of the required stages:

Sense smoke $\rightarrow$ Process information $\rightarrow$ Generate alarm
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Sense

We can sense smoke as a decrease in the transparency of air.
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Sense

We can sense smoke as a decrease in the transparency of air.

Adjust $R_1$ until $V_{out}$ is in the desired range for smoke vs no-smoke
Process

We might want to add another amplifier, and a low pass filter, but this amp does most of what we need.
Alarm

We need to alarm if the voltage gets below some threshold

\[ V_{\text{out}} = V_{\text{CC}} \text{ if } V_{\text{in}} \text{ above } V_{\text{Thr}}. \]
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And an LED is a wimpy alarm.
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And an LED is a wimpy alarm

But a DC level on a speaker isn’t going to cause a sound!
We need to alarm if the voltage gets below some threshold

We need to drive the speaker with a time dependent, oscillating signal.

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Smoke alarm

Safety checks:
- Battery warning
- Test feature
Oscillator

We can make an oscillator with any positive feedback

\[
R_1 \approx 10R_2 \\
\omega_0 \approx \frac{1}{RC}
\]

"CMOS inverters"
Oscillator

We can make an oscillator with an op-amp

The $I_+ = I_- = 0$ golden rule means we can calculate $V_+$ and $V_-$ in terms of $V_1$.

$V_+ = \frac{V_1}{2}$

$V_2 = V_- = V_1 - I R$
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![Oscillator Circuit Diagram]

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where $I = C \frac{dV_2}{dt}$
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$T \approx 2.2RC$
555 timer

Oscillators and other timing applications are common, so there is a timer chip
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