Concluding op-amps today. Start with clicker review:

(fast clicker Q's)

Look back at summing amplifier:

\[ V_1 \quad R_1 \quad I_1 \quad \Rightarrow \quad I \quad \Rightarrow \quad R_f \quad I \quad \Rightarrow \quad V_{\text{out}} \]

We considered the current \( I \) drawn past the virtual ground and through the feedback resistor \( R_f \).

We concluded from Golden Rule 2 that the same current \( I \) from the summing network went through \( R_f \), so \( V_{\text{out}} = -IR_f \).

But, can apply this to any current source connected to the

\[ I_{\text{in}} \quad \Rightarrow \quad V_{\text{out}} \quad \text{(clicker)} \]

So \( \frac{V_{\text{out}}}{I_{\text{in}}} = -R_f \) Current-to-voltage or "trans-impedance" amplifier. The "gain" is \( \frac{V_{\text{out}}}{I_{\text{in}}} \) so has units of ohms.

Will be used in two weeks when we do photometry. A case where you have small current sources you are trying to detect.
Final comments on op-amps: When the Golden Rules don't apply:

1) Gain-bandwidth product: frequency-dependent limit on gain
2) Maximum output voltage: Consider full diagram of op-amp:

\[ V_{cc}^+ \] and \[ V_{cc}^- \] power the op-amp, so \( V_{out} \) always stays between them. In practice, the \( V_{out} \) usually saturates at \(-1.2V\) below \( V_{cc}^+\), \(-1.2V\) above \( V_{cc}^-\).

3) Max output current: \( \approx 25mA \) for the LF356. Will be an issue if you connect output to a small load (like a speaker)
Concept very closely related to bandwidth is slew rate: how quickly output can change with time. Specified for LF356 as 12V/μs = \( \text{MAX} \frac{dV_{\text{out}}}{dt} \).

Slew rate results in distortion of output, especially for large signals near \( f_B \).

Sine wave slewing:
- Small output: no distortion
- Same frequency
- Larger output: more distortion

Square wave:

For sine wave \( V_{in} = V_0 \sin \omega t \), \( V_{out} = G V_0 \sin \omega t \)

\[
\frac{dV_{\text{out}}}{dt} = G V_0 \omega \cos \omega t,
\]

\[
\left| \frac{dV_{\text{out}}}{dt} \right|_{\text{max}} = GV_0 \omega \text{ if } \omega \leq S \text{ to avoid distortion.}