Physics 160
Lecture 14

Fun with Op Amps

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Ideal Op-Amp

Differential gain, of course. Common-mode gain is ideally zero.

1. Gain--infinite
2. Input impedance--infinite
3. Output impedance--zero
4. Bandwidth--infinite
5. Voltage out--zero (when voltages into each other are equal)
6. Current entering the amp at either terminal--extremely small

Such an ideal op-amp of course does not exist, but a first analysis of op-amp circuits can be done to a good approximation usually by ignoring the non-ideal behavior.
A Real Op-Amp: LF411

Differential voltage gain at low frequency is >100,000!

A current source, instead of resistor, is used as a load on the JFET drain, to produce high voltage gain.

Deliberate capacitor enhances the Miller effect to cause the gain to decrease at higher frequencies, for stability.

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(Note: many 741 versions have been made and sold, with varying detailed designs.)

A Real Op-Amp (famous 741)

Several current mirrors provide bias current to the various stages.

Unusual input stage: we hold the base constant and wiggle the emitter.

Sets the reference current.

Unequal current mirror; see Fig. 2.53.

2nd stage active load

Current source in diff-amp tail

Increases Miller effect to kill gain at high frequency (for stability)

Diodes to bias the output, to reduce crossover distortion

Short-circuit over-current protection for output stage (~25 mA)

Current-mirror active load

Second amplification stage. Common-emitter amp with an emitter-follower on the input

Temperature stabilized push-pull output stage.

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Op-Amp Example (Single Supply)

High Gain DC-coupled differential amp.

LM324

Details of the current references and mirrors are not shown.

Increases Miller effect to kill gain at high frequency (for stability)

Short-circuit protection

2nd stage amp (common-emitter)

2 emitter followers

Helps to pull the output all the way to ground.

Push-pull output
Non-Inverting Amplifier

Note: $Z_{in}$ is very large (transistor base or gate).

This is good!

Simplified analysis of an op-amp with negative feedback:

- Assume infinite gain, so the negative feedback always has to keep the two inputs equal in order to have a finite output.
- Assume zero current flow into the op-amp inputs.
- Then calculate the relationship between input and output from the feedback network.

$$G = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1} = 1 + 9 = 10$$
The amp without feedback is very high gain and non-linear. With negative feedback we get a gain that depends only on the feedback network, and we get excellent linearity. This is the principle behind op-amps.

Example from Lecture 10. This is a crude op-amp, since it is DC coupled, differential, high gain.

Gain is \( \frac{(10k+90k)}{10k} = 10 \)
Gain=10 with excellent linearity!

From Lecture 10
Inverting Amp

Note: $Z_i = R_1 = 1 \text{kohm}$

This is a distinct disadvantage of this configuration.

$I_{in} = \frac{V_{in}}{R_1}$

$V_{out} = -I_{in} \cdot R_2 = -\frac{V_{in}}{R_1} \cdot R_2$

Simplified analysis of an op-amp with negative feedback:

- Assume infinite gain, so the negative feedback always has to keep the two inputs equal in order to have a finite output.

- Assume zero current flow into the op-amp inputs.

- Then calculate the relationship between input and output from the feedback network.

$$G = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} = -100$$
Differential Amplifier

\[ V_{out} + (V_1 - V_{out}) \cdot \frac{R_2}{R_1 + R_2} \]

\[ V_1 \quad \text{R1} \]
\[ \text{equal} \]
\[ V_2 \quad \text{R1} \]

\[ V_2 \cdot \frac{R_2}{R_1 + R_2} \]

\[ V_{out} = \frac{R_2}{R_1} (V_2 - V_1) \]

Beware that the CMRR depends almost entirely on the matching of the resistors, so high precision resistors are essential in order to make this work well.

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Simple Current Source

This design works extremely well but is usually inconvenient, because the load does not connect directly to ground.

No current flows in or out of the inputs, and the inputs will be at the same voltage, so clearly the current through the load is $V/R$.

(As long as the op-amp output doesn’t try to exceed the supply voltage!)
Current Sources

\[ I_{\text{out}} = \frac{V_{CC} - V_{\text{in}}}{R} \]

No base current error if MOSFET is used.

Here the control voltage is relative to VCC.

Here the control voltage is relative to ground.

\[ I_{\text{out}} = \frac{V_{\text{in}}}{R_1} \cdot \frac{R_2}{R_3} \]

Figure 4.11. Current sources for grounded loads that don’t require a floating power supply.
Example Current Sink

Load would go here

“Base current error”
Current Sink Performance

The output impedance is completely dominated by the base current error and the Early effect.

\[ Z_{\text{out}} = \frac{14 - 9}{(4.9711 - 4.9694) \times 10^{-3}} = 2.94 M\Omega \]
Substitute a MOSFET for the BJT

This is the only place in your lab course where you will use a MOSFET (IRL510).

Notice how the programmed current is completely determined by the resistors and voltage supplies, and completely independent of any transistor characteristics!
Current Sink Performance

The output impedance is so high now that I cannot see any difference in the simulated current over this 7 volt range! Practically a perfect current source, as long as the compliance range is not exceeded.

JFET input op amp working together with a MOSFET
High-Current Sink

This also has the advantage of essentially zero error from the base current, since the JFET gate draws negligible current.

Note, using the IRL510 N-channel power MOSFET as in the previous slide is also a high-current option, as that device is rated up to about 4 to 5 amperes of current.

Q2 starts to turn on when $I_{\text{drain}}$ is about 0.6 mA.

Q1 can put at least 4 mA into the base of Q2, so Q2 can sink at least 100 mA.
Correcting Cross-Over Distortion

Note that the feedback path is from the output of the push-pull stage!
f = 100 Hz

The op-amp slews fast enough to eliminate most of the distortion!
$f = 1000 \text{ Hz}$

The op-amp cannot slew fast enough to completely correct the distortion here.
The op-amp cannot slew fast enough to make any significant correction here.

However, a combination of other techniques (diodes) plus negative feedback will cure crossover distortion.