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Reading Assignment:
   Agarwal and Lang, Ch. 15 (§ § 15.1-15.3)

Handouts:
   Lecture 6 notes

Announcements:
   Please do pre-lab 4 before going to the lab…
0.1 Dependent Sources

• Types of dependent current sources:
  – Voltage-controlled current source:

\[
i_o = f(v_I)
\]

• Current-controlled current source:

\[
i_o = f(i_I)
\]
• Dependent voltage sources:
  – Voltage-controlled voltage source:

\[
\begin{align*}
  i_I &\quad \text{control port} \\
v_I &\quad \quad \quad \quad \\
  v_O &\quad \text{output port} \\
  \quad \quad \quad f(v_I) \\
\end{align*}
\]

\[v_O = f(v_I)\]

– Current-controlled voltage source:

\[
\begin{align*}
  i_I &\quad \text{control port} \\
v_I &\quad \quad \quad \quad \\
  i_O &\quad \text{output port} \\
  \quad \quad \quad f(i_I) \\
\end{align*}
\]

\[v_O = f(i_I)\]
How to build amplifiers?
0.2 Building an amplifier with a voltage-controlled current-source:

- Consider the following circuit:
• Analyzing the circuit:

\[ v_O = V_S - R_L G v_I \]

• \( v_O \) linearly proportional to \( v_I \) \(\rightarrow\) no distortion

• Notice minus sign: output is out of phase from input \(\rightarrow\) not generally a problem

• In order to have amplification, need:

\[ R_L G > 1 \]
How to build dependent sources?
0.3 Transistors... The MOSFET

- MOSFET = Metal-Oxide-Semiconductor Field-Effect Transistor
- MOSFET = three terminal semiconductor device
- In the MOSFET: Current through two terminals (source and drain) controlled by voltage in third terminal (gate).
- A modern microprocessor contains $\sim 10^8 - 3 \times 10^9$ MOSFETs
• i-v characteristics of 2N7000
Operational amplifiers

(The “logic gates” of the analog world)
1. Operational amplifier: Intro

Ideal op-amp is a *voltage-controlled voltage source*:

Equivalent circuit of ideal op-amp:
Properties of \textit{ideal} op-amp:

- Differential input
- Single-ended output
- Very large and constant voltage gain
- Infinite input resistance $\rightarrow$ zero input current
- Zero output resistance $\rightarrow$ can deliver or sink infinite output current at any output voltage
- No saturation (i.e. it can produce any voltage)
- Infinite bandwidth (i.e. it is infinitely fast)
Real op-amp:
- Gain is non linear
- Output signal limited by power supply voltages (saturation)
- Offset in output voltage
- Input and output resistances less than ideal
- Bandwidth limited
- Gain and offset are temperature dependent

A better model:
The op-amp we will use in the lab: LF356
Op-amp can be used to enable numerous circuits, with applications in fields such as:

- Signal processing
- Instrumentation
- Control
- Power
- Etc.

![Integrator](image1)

![Inverting amplifier](image2)

![Sample-and-hold circuit](image3)

![Current-to-Voltage converter](image4)

![Band-pass filter](image5)
2. An op-amp-based amplifier

- Consider a simple amplifier configuration:

  ![Op-amp diagram](image)

  Very large gain, but...
  - Output offset results in output even if no input signal
  - Output can easily saturate
  - Temperature sensitivity corrupts output voltage

  “Open loop” configuration has large gain but it is unstable.

Need to find a way to “pin” the output to ground when there is no signal at the input.
• Consider the following circuit:

![Circuit Diagram]

How does it work?

- Suppose with \( v_{IN} = 0 \) there is output offset \( v_O > 0 \)
  \( \rightarrow \) \( R_1/R_2 \) voltage divider results in \( v_+ > 0 \)
  \( \rightarrow \) \( v_+ - v_- < 0 \) drives \( v_O \) to zero

- Now assume no output offset.
  If \( v_{IN} > 0 \), then \( v_O > 0 \) such that \( v_O \) causes \( v_+ = v_- \)
  \( \rightarrow \) \( v_O/v_{IN} \) gain of this amplifier is less than \( A! \)

“Closed loop” configuration \( \rightarrow \) feedback path mitigates problems
How do we calculate the amplifier gain?

Equivalent circuit model:
\[ v_+ = v_{in} \]

\[ v_- = \frac{R_2}{R_1 + R_2} v_o \]

Then:

\[ v_o = A(v_+ - v_-) = A(v_{IN} - \frac{R_2}{R_1 + R_2} v_o) \]

Solving for \( v_o \):

\[ v_o = \frac{A}{1 + A \frac{R_2}{R_1 + R_2}} v_{IN} < A v_{IN} \]
Op-amp itself has “open-loop gain”: $A$
Op-amp amplifier has “closed loop gain”: $G$

Why would anybody do this?
→ Traded-off gain for robustness!

Amplifier gain is set by ratio of two resistance values:
→ gain largely independent of temperature
→ also corrected output offset problem
3. Methodology to analyze op-amp circuits

- Look again at non-inverting amplifier:

\[ v_+ - v_- = \frac{v_O}{A} \approx \frac{G}{A} v_{IN} \]

Since \( A \) is very large, then \( v_+ - v_- \ll v_{IN}, v_O \)

In the scale of \( v_{IN}, v_O \),

\[ v_+ \approx v_- \]

As \( A \to \infty \)

\[ v_+ \to v_- \]
Method to analyze op-amp circuits:

- assume that $A \rightarrow \infty$
- assume that $v_+ = v_-$ $\Rightarrow i_+ = i_- = 0$
- work in large-signal domain

• Example: **non-inverting amplifier**

Voltage divider at output:

$$v_- = \frac{R_2}{R_1 + R_2} v_O$$

At input:

$$v_- = v_+ = v_{IN}$$

Combine these two equations and solve:

$$\frac{v_O}{v_{IN}} = 1 + \frac{R_1}{R_2}$$
• Interesting limit of non-inverting amplifier when $R_1=0$ and $R_2=\infty$:

$$v_o = v_{IN}$$

This is called “buffer” or voltage follower. Used to buffer stages in a system.

Assembly of a complete system much easier with adequate buffering of individual stages.
4. Another example: inverting amplifier

Consider:

\[ v_- = 0 \Rightarrow i_1 = \frac{v_{IN}}{R_1} \]

\[ i_- = 0 \Rightarrow i_2 = i_1 = \frac{v_{IN}}{R_1} \]

Then:

\[ v_O = -i_2 R_2 = -\frac{R_2}{R_1} v_{IN} \]

And:

\[ \frac{v_O}{v_{IN}} = -\frac{R_2}{R_1} \]
Summary

- **Op-amp =** device with:
  - Differential input
  - Single-ended output
  - Very large but unstable voltage gain
  - Very high input resistance
  - Very low output resistance
- “Open-loop” use of op-amp results in unstable operation
- In op-amp use, close loop and trade gain against stability
- **Analysis of op-amp circuits:**
  - Assume negligible voltage difference between two inputs
  - Assume negligible input currents