Choose **Two** of Three Measurements

- Open-Circuit Voltage \( v_{oc} \)
- Short-Circuit Current \( i_{sc} \)
- Resistance of the Dead Circuit

Never Turn Off Dependent Sources
Determine the Thevenin Equivalent Circuit
Electrical Signals

Analog - Continuous Range of Equally Likely Values

Digital - Discrete Values (0 or 1)

Mixed-Signal - Analog and Digital
Common Analog Signal Processes

Amplification

\[ A \, v_1 \]

Addition

\[ v_1 + v_2 \]

Subtraction

\[ v_1 - v_2 \]

Use an Operational Amplifier to Implement These Processes
Op-Amp Characteristics

Inputs

Supply Voltages

\[ v_{out} = A_{vd} (v^+ - v^-) \]

Differential Voltage Gain

Large! $\sim 300,000$

Circuit Model

\[ V^- \leq v_{out} \leq V^+ \]
Inside the Op-Amp

LM741
Demonstration Circuit: Analysis

Non-Inverting Amplifier

No $R_t$ or $R_L$ Dependence

\[ v_d = v_{in} - A_{vd} v_d \left( \frac{R_1}{R_1 + R_f} \right) \]
\[ v_d = \frac{v_{in}}{1 + A_{vd} \left( \frac{R_1}{R_1 + R_f} \right)} \]

\[ v_{out} = A_{vd} v_d = v_{in} \frac{A_{vd}}{1 + A_{vd} \frac{R_1}{R_1 + R_f}} \]
\[ A_{vd} \rightarrow \infty \approx v_{in} \left( \frac{R_f}{R_1} + 1 \right) \]
Subject to **Negative Feedback** …

\[ v^+ \approx v^- \]

\[ v^+ - v^- = \frac{v_{out}}{A_{vd}} \quad A_{vd} \to \infty \approx 0 \]

\[ i^+ \sim 0 \quad i^- \sim 0 \]
Demonstration Circuit: Analysis

Non-Inverting Amplifier

\[ v^+ = v_{in} \]
\[ v^- = v_{out} \left( \frac{R_1}{R_1 + R_f} \right) \]
\[ v^+ \approx v^- \quad v_{out} = v_{in} \left( \frac{R_f}{R_1} + 1 \right) \]
Negative Feedback

Let $v_{out} > v_{in} \left( \frac{R_f}{R_1} + 1 \right)$

$v^- = v_{out} \left( \frac{R_1}{R_1 + R_f} \right)$

$v_d = v_{in} - v^-$

$v_{out} = A_{vd} \cdot v_d$
Positive Feedback?

Let \( v_{out} > v_{in} \left( \frac{R_f}{R_1} + 1 \right) \)

\[ v^+ = v_{out} \left( \frac{R_1}{R_1 + R_f} \right) \]

\[ v_d = v^+ - v_{in} \]

\[ v_{out} = A_{vd} v_d \]
Unity-Gain Buffer

\[ i_{in} = 0 \quad \rightarrow \quad v^+ = v_{in} \quad | \quad v^- = v_{out} \quad \rightarrow \quad v_{out} = v_{in} \]

No \( R_t \) or \( R_L \) Dependence
Exercise 1

Determine $v_{\text{out}}$
\[ v_{out} = -i_{vg} R_f = -I_n R_f \]
\[ v_{out} = -i_{vg} R_f = -\frac{v_{in}}{R_1} R_f \]
Exercise 2

Determine $v_{out}$

Summing Amplifier
Differential Amplifier

\[ v^+ = v_1 \frac{R_1}{R_1 + R_2} \]

\[ v^- = v_2 \frac{R_1}{R_1 + R_2} + v_{out} \frac{R_2}{R_1 + R_2} \]

\[ v^+ \approx v^- \quad \rightarrow \quad v_{out} = \frac{R_1}{R_2} (v_1 - v_2) \]
Exercise 3

Build Me

Sinusoidal Input
1 V Peak-to-Peak
f = 1 kHz
Scope Ch. 1

Scope Ch. 2

LM741

Voltage Gain = 11 ?
Large Amplitudes ?

1 kΩ

10 kΩ

V_{in}

V_{out}
Little Black Box
- Breadboard
- Parts Box
- Wire Strippers

Write Team Names on Label
Use Throughout Semester
Boxes Remain in OHE 230
Breadboard Layout

5-Hole Columns
Multiple-Hole Rows
ICs Span Center
Wires When Needed

NOT Intended for High-Frequency Circuits
Breadboard Layout

Be Neat

Use Minimum Wire Lengths

Good Student

Bad Student
“Floating” Outputs
Need to Establish Circuit Ground

- COM = Ground
- GND = Chassis Ground (Do not Use)

Use Banana-to-Point Leads

- Red - Positive
- Black - Negative

Current Limited - Not for Welding, Toasting

Calibrators: Precision Voltages (Low Power)
50-Ω Output Impedance

Display Amplitude Assumes Particular Load

- Infinite Load \( V_{\text{out}} = V_t \) Default?
- \( 50 \, \Omega \) \( V_{\text{out}} = V_t / 2 \)
- System Menu Selects Load Setting

Always Check Output with Oscilloscope

Cables

- BNC to Point Leads
- BNC to “Clippy Thing”

Do Not Use SYNC Output
Learn to Use This Instrument!
Avoid the Auto-Set Button!

Channel 1
- Function Generator Output
- Route Signal to Circuit with BNC ”Tee”

Channel 2
- Circuit Output
Oscilloscope Triggering

Trigger on Channel 1

Adjust Trigger Level to Stabilize Displayed Waveform
Oscilloscope Probe

\[ R_1 C_1 = R_2 C_2 \]

\[ v_x = \frac{R_2}{R_1 + R_2} v_p \]

No Temporal Signal Corruption
Troubleshooting

Important for Efficient Experimentation
Important for Industrial Practice

Our Circuit Doesn’t Work, Mr. Duckman

Lab Team

Instructor

Think!
Expect the Unexpected (Murphy’s Rule)
Be Neat!
No Wire Clippings on the Floor
Don’t Abuse the Equipment
Don’t #%&$ With the Probes
Report Malfunctioning Equipment
Turn In Broken Cables
Return Cables to Drawers

Don’t Let Your Lab Partner Do All the Work
Exercise 3

Build Me

Sinusoidal Input
1 V Peak-to-Peak
f = 1 kHz
— Scope Ch. 1

Scope Ch. 2

Voltage Gain = 11 ?
Large Amplitudes ?