1. **Prove** the closed-loop gain \( V_o / V_i \) for the op-amp circuit below equals 1.

![Op-Amp Circuit Diagram](image)

2. **Derive** the closed-loop gain \( V_o / V_i \) for the op-amp circuit below. Also, can this op-amp circuit “attenuate” a signal? Why or why not?

![Op-Amp Circuit Diagram with Resistors](image)
3. The op-amp circuit below is an inverting amplifier. Sketch $V_o$ if $R_A = 1\, \text{K}\Omega$, $R_B = 10\, \text{K}\Omega$ and $V_1 = \cos (628t)$ Volts. Be certain to label, with numerical values, peak voltage and period.

![Inverting Amplifier Circuit](image)

4. For the summing amplifier, derive $V_o$ with $R_2 = 2R_1$, $R_3 = 2R_2$ and $R_F = R_3$. Also, if input voltages $V_1$, $V_2$ and $V_3$ are digital signals (bits) with only two possible values, 0V or -1V, calculate all possible $V_o$ values. Hint: There are eight possible $V_o$ values.
Objective
Examine the characteristics and limitations of op-amps and to observe the operation of common op-amp circuits.

Workbench Equipment
- Digital Oscilloscope, Agilent 54621A
- Function Generator, Agilent 33120A
- Digital Multimeter, Agilent 34401A
- DC Power Supply, Agilent E3640A
- Dual-tracking DC Power Supply, TPS-4000

Check-out Equipment, 20-111 window
- Large Breadboard
- Scope Probe (10:1), 2
- Banana to grabber 4 pair, 4red / 4black
- BNC to grabber lead
- Banana to Banana lead, 3

Background
Ideal Op-Amp
An ideal op-amp has the following characteristics:

\[ R_{\text{in}} \text{ (input resistance)} = \infty \Omega \]
\[ A \text{ (open-loop gain)} = \infty \]
\[ R_{\text{out}} \text{ (output resistance)} = 0\Omega \]

Since input resistance is equal to infinity (an open) the current at either input of an op-amp is zero. Also, since output resistance is zero (a short) thereby \( V_o = AV_{\text{in}} \) (refer to Figure 4-1) and since open-loop gain ideally equals infinity; for any finite \( V_o, V_{\text{in}} = 0V \).

![Op-Amp Model](image)

**Fig. 4-1** Op-Amp Model
The term “virtual short” refers to both current and voltage equal to zero at the input of an ideal op-amp. A virtual short exists when an op-amp has negative feedback. Negative feedback is an electrical path between the op-amp output and the inverting input (input labeled with a minus sign), see Figure 4-2.

![Fig. 4-2 Op-Amp Circuit Symbol](image)

The op-amp output is limited by the voltage supply values (or “rails”) which power the op-amp. The output signal $V_{out}$ can never be more positive than $V^+$ and $V_{out}$ can never be more negative than $V^-$. $V_{out}$ will distort if any portion of its waveform contacts either limit.

An op-amp can be connected into a circuit to provide useful operations. Depending on the components connected to the op-amp; op-amp circuits can provide amplification or attenuation with inversion, amplification without inversion, loading prevention and digital to analog conversion, as well as, many other useful applications such as filtering, integration and threshold detection. These half dozen or so op-amp circuits are only a small sample of common op-amp applications. There are many other common and custom applications of op-amps than those demonstrated in this experiment, the usefulness of an op-amp is only limited by one’s imagination.

741 Op-Amp IC Important Information

Pin Diagram: Note: Offset Null will not be used.

![Pin Diagram](image)

Maximum Ratings:

Supply voltage $\pm 18$ volts

Input voltage $\pm 15$ volts$^*$

$^*$Note: The input voltage must be less than the actual supply voltage.
Operational Notes:

A dc path must exist from each input to ground to allow for the necessary input biasing current to flow.

A resistor or some other feedback element must be provided.

A dual power supply providing + and - voltages must be used. These connections are not often shown on op amp diagrams.

Procedure 1: Voltage Follower

- Build op-amp circuit of prelab #1. Use TPS-4000 Dual Power Supply for +12V and -12V to power op-amp IC.
  - Make certain connect +12V to pin 7 of 741IC and -12V to pin 4. If these supply voltages are reversed, the op-amp will fry!!
  - Measure +12V and -12V with DVM, do not rely on supply analog meters.
- Use function generator (Hi Z mode) to apply a 1Vpp 200Hz sinusoidal signal at V1.
- Observe both V1 and V0 on scope, capture scope image.
  - V1 and V0 should be very close to identical, if not consult instructor.
- Change input signal to a 10Vpp 200Hz square wave.
- Observe V0 on scope and verify output signal matches closely to input signal.
  - Increase frequency of square wave to 20,000Hz. Observe output signal on scope, it should be severely distorted (trapezoidal). Capture scope image.
  - Note: There is a postlab question on this observation.

Procedure 2: Non-inverting Amplifier

- Build op-amp circuit of prelab #2.
- Use function generator (Hi Z mode) to apply a 0.5Vpp 200Hz sinusoidal signal at V1.
- For RA = 10KΩ, complete Table 4-1.
  - Make certain output and input are approximately in-phase. If not, consult instructor.

<table>
<thead>
<tr>
<th>RB (KΩ)</th>
<th>V_o p-p (V)</th>
<th>( \frac{V_o}{V_i}^{TH} )</th>
<th>( \frac{V_o}{V_i}^{EXP} )</th>
<th>%Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>___________</td>
<td>___________</td>
<td>___________</td>
<td>_______</td>
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<td>100</td>
<td>___________</td>
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</tr>
</tbody>
</table>

Table 4-1 Non-Inverting Amplifier Close-Loop Gain

- For RB = 100KΩ, increase amplitude of V1 until V0 distorts by hitting both limits.
- Measure with cursors V_{omax} and record below. Capture scope image.

V_{omax} = ___________
Procedure 3: Inverting Amplifier

- Build op-amp circuit of prelab #3.
- Use function generator (Hi Z mode) to apply a 1Vpp 200Hz sinusoidal signal at V1.
- For RA = 10KΩ, complete Table 4-2.
  - Make certain output and input are approximately out-of-phase by 180°. If not, consult instructor.

<table>
<thead>
<tr>
<th>RB (KΩ)</th>
<th>V_o p-p (V)</th>
<th>( \frac{V_o}{V_{TH}} )</th>
<th>( \frac{V_o}{V_i} ) EXP</th>
<th>%Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tbody>
</table>

Table 4-2 Inverting Amplifier Close-Loop Gain

- For RB = 100KΩ, increase amplitude of V1 until V_o distorts by hitting both limits.
- Measure with cursors V_{omax} and record below. Capture scope image.

- V_{omax} = __________

Procedure 4: DAC (Digital-to-Analog Converter)

- Build the circuit of Figure 4-3. Inside the diagram box is a summing amplifier. Outside box is a 74163 IC, a binary counter which provides digital inputs to the summing amplifier. Pin diagram and basic operation of 74163 follows Discussion section of this experiment.
  - Suggestion: Build summing amplifier and counter IC circuits separately and test separately before connecting together.

Fig. 4-3 DAC Circuit

- Calculate V_o for all possible input values (use 0V for ‘0’ and use +3.5V for ‘1’) and record in Table 4-3.
- Ground Clear input of 74163 to ensure summing amplifier inputs start at 0000.
- Use a DVM to measure V_o, record in Table 4-3.
• Apply a pulse at Clock input of 74163, counter outputs should increment to next binary count in Table 4-3, measure $V_o$ with DVM and record.
• Repeat previous step until Table 4-3 is complete.
• Use function generator (Hi Z mode) to apply a 0V to 5V 1KHz square wave signal at the 74163 Clock input.
  o Observe square wave on scope and make certain square wave does not go below zero volts (ground).
• Observe $V_o$ with scope. Capture staircase-like waveform.

<table>
<thead>
<tr>
<th>Count</th>
<th>$V_o$ (V)</th>
<th>$V_o$ (V)</th>
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<tbody>
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<td></td>
</tr>
<tr>
<td>0001</td>
<td></td>
<td></td>
</tr>
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</tbody>
</table>

Table 4-3 DAC Data

Discussion
1. What is the primary application of a voltage follower? Illustrate its importance with a numerical example.
2. Why did the 20,000Hz input square wave produced a trapezoidal distorted output signal in procedure 1?
3. What is the primary reason for any differences between $\frac{V_o}{V_{th}}$ and $\frac{V_o}{V_{EXP}}$ in the non-inverting and inverting amplifier procedures?
4. How is the output signal distorted when the input voltage is increased in the last step of procedures 2 and 3?
5. Under what circumstances would a 1 MΩ internal input resistance of an op-amp affect circuit operation?
6. Explain how a linear ramp function can be obtained by smoothing out the staircase waveform output of the digital-to-analog converter.