Learning Objectives:

Understand the use of op-amps as analog devices for performing mathematical operations.

Laboratory Equipment:

- Agilent Oscilloscope Model 54622A
- Agilent Function Generator Model HP33120A
- Agilent Power Supply Model E3631A
- Multimeter

Supplies and Components:

- Breadboard
- 1 KΩ Resistor
- 2 KΩ Resistor (2 each)
- 10 KΩ Resistor (4 each)
- 100 KΩ Resistor (2 each)
- 10 MΩ Resistor
- 1 μF Capacitor
- 100 pF Capacitor
- Op-Amp 741 or 1458
- LED

Pre-Lab Questions

1. Write the gain equation for an inverting op-amp.
2. Reference: Summing Amplifier (Figure A) - Calculate $V_{out}$ with respect to $V_1$, $V_2$, $V_3$.
3. Reference: Difference Amplifier (Figure B) - Calculate $V_{out}$ with respect to $V_1$, $V_2$.

Post-Lab Questions

1. Reference: Figure A, what is the reason for the second op-amp in the summing amplifier?
2. Reference: Figure B, predict the output if $V_1 = +5$ volts and $V_2 = -3$ volts.
3. Reference: Figure C, describe the output in response to a step input signal, if capacitor $C$ were replaced with a diode.
4. Reference: Figure E, describe the output in response to a step input signal, if capacitor $C$ were replaced with a diode.
Laboratory Seven - Operational Amplifiers (Arithmetic Applications)

Operational amplifiers (op-amps) are incredibly useful, high-performance devices that can be employed in a number of exciting ways. Typical op-amps have a non-inverting input, an inverting input, two DC power supply leads (positive and negative), an output terminal, as well as a few other specialized control leads. Operational amplifiers were first used as analog devices for computing mathematical expressions. For this lab, you will configure the op-amps into summing amplifiers, difference amplifiers, integrators, and differentiators.

1) **Summing Amplifier** (Figure A)
   a) Select resistors such that: $R_f, R_1, R_2, R_3 = 10 \, \text{K}\Omega$ each and $R_4, R_5 = 2 \, \text{K}\Omega$ each.
   b) Measure and record each of the resistive values.
   c) Construct the circuit below, be careful to correctly place the resistors in their respective locations.
   d) Connect the two supply voltages (+15 volts and -15 volts DC).
   e) Apply the following voltages:
      $$ V_1 = 1.0 \, \text{volts} $$
      $$ V_2 = 3.0 \, \text{volts} $$
      $$ V_3 = 5.0 \, \text{volts} $$
   f) Calculate $V_{out}$ based on your prelab derived summation formula.
   g) Measure $V_{out}$, compare to your predicted value, explain any discrepancies.

![Figure A. Summing Amplifier](image-url)
2) **Difference Amplifier** (Figure B)
   
a) Select resistors such that: $R_f$ & $R_3 = 100 \, \text{K}\Omega$ each and $R_1$ & $R_2 = 10 \, \text{K}\Omega$ each.
   
b) Measure and record each of the resistive values.
   
c) Construct the circuit below, be careful to correctly place the resistors in their respective locations.
   
d) Connect the two supply voltages (+15 volts and -15 volts DC).
   
e) Apply the following voltages:
      
      $V_1 = 7.0 \, \text{volts}$
      
      $V_2 = 5.0 \, \text{volts}$
      
   f) Calculate $V_{out}$ based on your prelab derived summation formula.
   
g) Measure $V_{out}$, compare to your predicted value, explain any discrepancies.

![Difference Amplifier Circuit](image-url)
3) **Integrating Amplifier** (Figure C)

The ideal integrating amplifier in Figure C depicts a theoretically perfect integrator. However, for real op-amp amplifiers, the output tends to drift due to non-ideal characteristics such as voltage offsets and bias currents. Two compensating resistors (see Figure D), R1 in parallel with the feedback capacitor provides for stable biasing, and R2 helps correct for voltage offset errors caused by input bias currents.

To demonstrate the integration operation, consider a rectangular waveform. The integral of this waveform is a sawtooth wave with the same basic frequency. If the input is a square wave, the output is a triangular wave whose amplitude depends on the gain characteristic of the amplifier, but with the same frequency as the input signal.

a) Construct the circuit below (Figure D).
b) Select components such that: $C = 1 \text{ uF}$, $R = 10 \text{ K}\Omega$, $R1 = 10 \text{ M}\Omega$, $R2 = 10 \text{ K}\Omega$.
c) Connect the two supply voltages (+15 volts and -15 volts DC).
d) Apply an 400 Hz, 500 millivolt square wave input signal.
e) Monitor the input signal on channel 1 of the oscilloscope and observe the output signal on channel 2.
f) Capture/record both waveforms to an electronic file and include a printout in your report.
g) Explain any differences in the output waveform that depart from expectations.
4) **Differentiating Amplifier** (Figure E)

The ideal differentiating amplifier in Figure E depicts a theoretically perfect differentiator. However, for real op-amp amplifiers the circuit is not practical. It is extremely susceptible to noise due to the op-amp's high AC gain. The feedback network also acts as a low pass filter that causes phase shift and stability problems. Both problems can be corrected by the addition of a feedback capacitor C1 and an input resistor R1. An additional input bias compensation resistor R2, helps correct for voltage offset errors caused by input bias currents (see Figure F).

At very high frequencies, the additional components affect performance; the differentiator acts as an integrator!

To demonstrate the differentiating operation, consider a triangular waveform. The derivative of this waveform is a rectangular wave with the same basic frequency whose amplitude depends on the gain characteristic of the amplifier.

a) Construct the circuit below (Figure F).

b) Select components such that: $C = 0.1 \, \text{uF}$, $R = 100 \, \text{K}\Omega$, $C = 100 \, \text{pF}$, $R1 = 1 \, \text{K}\Omega$, $R2 = 100 \, \text{K}\Omega$.

c) Connect the two supply voltages ($+15$ volts and $-15$ volts DC).

d) Apply an 400 Hz, 500 millivolt, triangular wave input signal.

e) Monitor the input signal on channel 1 of the oscilloscope and observe the output signal on channel 2.

f) Capture/record both waveforms to an electronic file and include a printout in your report.

g) Explain any differences in the output waveform that depart from expectations.

![Figure E. Ideal Differentiating Amplifier](image)

![Figure F. Compensated Differentiating Amplifier](image)
Grading Rubric: Operational Amplifiers (Arithmetic Application) (Lab 7)

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**I) Circuit Diagrams (Circuit Maker Only)**

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a. Experiment 1 – Summing Amplifier  
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b. Experiment 2 – Difference Amplifier  
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c. Experiment 3 – Integrating Amplifier  
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d. Experiment 4 – Differentiating Amplifier  
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**II) Data and Results**

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1) **Experiment 1 – Summing Amplifier**

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a. All Measured Values of R and C  
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b. Equation and Calculation for Predicted $V_{OUT}$ (Based on Resistors)  
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c. Measured Value of $V_{OUT}$  
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2) **Experiment 2 – Difference Amplifier**

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a. All Measured Values of R and C  
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b. Equation and Calculation for Predicted $V_{OUT}$ (Based on Resistors)  
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c. Measured Value of $V_{OUT}$  
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3) **Experiment 3 – Integrating Amplifier**

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a. All Measured Values of R and C  
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b. Graph(s) of $V_{IN}$ and $V_{OUT}$ (On the same plot!! Make sure you properly label!)  
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4) **Experiment 4 – Differentiating Amplifier**

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a. All Measured Values of R and C  
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b. Graph(s) of $V_{IN}$ and $V_{OUT}$ (On the same plot!! Make sure you properly label!)  
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**III) Discussion**

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1) **Arithmetic Application – Error in Predicted Output (Experiments 1 and 2)**

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a) In general, there are two major contributors to the variation in the values for the measured $V_{OUT}$ versus the predicted $V_{OUT}$ (from the resistor equation):

(1) varying resistor values (including unmatched resistors in Experiment 2,  
(2) real behavior (as opposed) to ideal behavior) of the op-amps. **Briefly discuss both of these contributors and how they could potentially influence the difference between the measured $V_{OUT}$ and the predicted $V_{OUT}$.**  
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2) **Integrating and Differentiating Amplifiers (Experiments 3 and 4)**

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a) Discuss the results you obtained in Experiments 3 and 4. Do the output signals make sense based on the type of amplifier and the input signal? Also, discuss how Experiments 3 and 4 are related to each other.  
**Hint: Experiment 3 is an Integrator and Experiment 4 is a differentiator!**  
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**IV) Post-Lab Questions**

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Post-Lab Question #1: The “second op-amp” is the op-amp where $R_5$ is the feedback resistor and $R_4$ is connected to the negative input terminal.  
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**V) References**

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