1. For the op-amp circuit below, derive $V_o$ for $R_F = \infty \Omega$ (open), $V_c(0) = 0V$ (capacitor initially uncharged). Sketch $V_o$ for $V_i = a$ square wave which varies between $+10V$ and $-10V$ at a $f = 1KHz$. Be certain to label, with numerical values, peak voltage and period.

2. For the op-amp circuit above, $V_i = \sqrt{2} \sin (\omega t)$ Volts and $R_F = 10K\Omega$. Derive the closed-loop gain ($V_o / V_i$). In addition, determine the magnitude of $V_o$ in $V_{RMS}$ at the following frequencies: 0, 20, 40, 70, 100, 200, 300, 400, 700 1K and 2K Hz. Also, calculate cut-off frequency in Hertz.
3. The circuit shown is a comparator op-amp circuit used as a continuity tester.
   Note: +V = 9V and –V = 0V
   The test resistance is connected between nodes X and Y.
   Prove $V_o = 9V$ (LED does not light) when there’s an open between X, Y.
   Also, prove $V_o = 0V$ (LED does light) when there’s a short between X, Y.

Note: Replace 2KΩ resistor with 2.2KΩ
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

General Closed-Loop Gain Equation for Integrator / Low-Pass Filter

\[ \frac{V_i - V_A}{R_1} = \frac{V_A - V_o}{R_F} + j(V_A - V_o)\omega C_F \]  \hspace{1cm} (5-2)

\[ \text{KCL at node A of Figure 5-1: } i_{R1} = i_{RF} + i_{CF} \]  \hspace{1cm} (5-1)

\[ V_A = 0\text{V since non-inverting input grounded and voltage across op-amp inputs equal zero.} \]
\[
\frac{V_i}{R_1} = -\frac{V_o}{R_f} - j(V_o)\omega C_F
\]  
(5-3)

General Closed-Loop Gain:
\[
\frac{V_o}{V_i} = -\frac{\frac{R_f}{R_1}}{1 + j\omega R_F C_F}
\]  
(5-4)

When \(\omega = 0\) (DC input):
\[
\frac{V_o}{V_i} = -\frac{R_f}{R_1}
\]  
(5-5)

Equation 5-5 is the closed-loop gain of an inverting amplifier since capacitor acts like an open to DC current.

Magnitude of equation 5-4:
\[
\left| \frac{V_o}{V_i} \right| = \frac{R_f}{R_1} \frac{1}{\sqrt{1 + (\omega R_F C_F)^2}}
\]  
(5-6)

Writing equation 5-4 as:
\[
\frac{V_o}{V_i} = -\frac{1}{\frac{R_1}{R_f} + j\omega C_F}
\]  
(5-7)

If \(R_F\) is large, equation 5-7 reduces to:
\[
\frac{V_o}{V_i} = -\frac{1}{j\omega C_F}
\]  
(5-8)

Using Laplace transform:
\[
V_o = -\frac{1}{R_1 C_F} \int V_i dt
\]  
(5-9)

Equation 5-9 shows when \(R_F\) is large, ideally infinite, op-amp circuit is an integrator. In a practical integrator, \(R_F\) is a high resistance (for example 1 Meg \(\Omega\) as used in this experiment). This feedback resistor is necessary to prevent output from saturating due to large DC gain.

Cut-off frequency, \(\omega_{co}\), is the frequency where magnitude of
\[
\frac{V_o}{V_i} = \frac{R_f}{\sqrt{2}}
\]  
(5-10)

As can be seen from equation 5-6:
\[
\omega_{co} = \frac{1}{R_F C_F}
\]  
(5-11)

**Comparator**
An op-amp without feedback can be used as a comparator. A comparator outputs one of two possible voltages dependant on the comparison of two input voltages.
Figure 5-2 is an example of a comparator.

The output voltage of an ideal comparator equals either the positive rail voltage or the negative rail voltage. Which rail voltage the output equals depends on the input voltages ($V_i$ and $V_R$ in Figure 5-2). If the non-inverting input voltage ($V_i$) is $>$ the inverting input voltage ($V_R$), then $V_o$ equals the positive supply voltage (+12V). If the inverting input voltage ($V_R$) is $>$ the non-inverting input voltage ($V_i$), then $V_o$ equals the negative supply voltage (-12V).

**Procedure 1: Integrator (prelab #1 circuit with $R_F = 1$Meg$\Omega$)**
- Measure $C_F$ on an impedance bridge.
  
  $$C_F = \text{______________ Farads}$$

- Measure both resistors with ohmmeter.
  
  $$R_F = \text{______________} \Omega \quad R_1 = \text{______________} \Omega$$

- Build the circuit of prelab #1.
- Use a function generator (Hi Z mode) to apply a square wave 10Vpp 500Hz at $V_i$.
- Observe $V_o$ on scope, carefully measure $V_{pp}$ of output with cursors and capture both $V_o$ and $V_i$.
  
  o $V_{pp}$ measurement of $V_o$ is important for a postlab question.

**Procedure 2: Low-Pass Filter (prelab #1 circuit with $R_F = 10K\Omega$)**
- Measure 10K$\Omega$.
  
  $$R_F = \text{______________} \Omega$$

- Remove square wave input and replace $R_F$ with a 10K$\Omega$ resistor.
- Calculate and record the magnitude of $V_o/V_i$ for each frequency listed in Table 5-1.
  
  o Use measured values for calculated magnitude of $V_o/V_i$.
- Apply a 1V RMS 20Hz sinusoid at $V_i$ then measure and record $V_o$ in RMS volts.
  
  o Use an AC voltmeter to measure $V_o$, an AC voltmeter displays RMS volts.
- Keep $V_i$ at 1V RMS and change only frequency to each of the values listed in Table 5-1, record $V_o$.
- Plot magnitude of $\frac{V_o}{V_i}$ versus frequency for both experimental and calculated using Excel.
  
  o Plot both curves on one graph.
- Find cut-off frequency in Hertz from plot & compare to calculated $f_{co}$.
  
  o Use measured values to calculate $f_{co}$. 

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f_{co} plot = ___________  \hspace{2cm} f_{co} \text{ calc} = ___________  \hspace{2cm} \%\text{Error} = ___________

| f (Hz) | V_{\text{rms}} \text{ (V)} | \text{Experimental} \hspace{2cm} V_{o}/V_{i} \hspace{2cm} \text{Calculated} \hspace{2cm} V_{o}/V_{i} |
|--------|----------------|---------------------|---------------------|---------------------|
| 20     | ____________ | ____________ | ____________ | ____________ |
| 40     | ____________ | ____________ | ____________ | ____________ |
| 70     | ____________ | ____________ | ____________ | ____________ |
| 100    | ____________ | ____________ | ____________ | ____________ |
| 200    | ____________ | ____________ | ____________ | ____________ |
| 300    | ____________ | ____________ | ____________ | ____________ |
| 400    | ____________ | ____________ | ____________ | ____________ |
| 700    | ____________ | ____________ | ____________ | ____________ |
| 1000   | ____________ | ____________ | ____________ | ____________ |
| 2000   | ____________ | ____________ | ____________ | ____________ |

Table 5-1 Low-Pass Filter Plot Data

**Procedure 3: Comparator Application – Continuity Tester**

- Build the comparator (continuity tester) circuit of prelab #3.
  - **NOTE:** Use op-amp LM311 not LM741.
- Connect a wire between nodes X and Y, does the LED light?
- Does the LED light if there is an open between nodes X and Y?
- Obtain instructor verification of proper circuit operation.

Instructor Initials: __________

**Discussion**

1. Use equation 5-9 to calculate the peak-to-peak output voltage of the integrator circuit. How does it compare (%error) with the experimental output Vpp?
2. How well do the experimental and theoretical values in Table 5-1 compare? What are the significant causes of discrepancies?