true

Chapter 1

Making Laboratory Measurements Worksheet

Measuring Resistance

- Record the colors of the bands on each resistor and determine the marked resistance value. Measure and record the actual value of the three resistors. Calculate and record the percentage error between the marked and measured values.

Resistor	Color Bands	Marked Value	Measured Value	Error [%]
Example	BN-BK-RD-GD	1.0 kΩ $\pm$5%	981 Ω	1.9%
R1				
R2				
R3				

Measuring Voltage

- Measure the voltage across each resistor, moving clockwise around the loop.

Voltage	Measured Value
V_{AD}	
V_{BA}	
V_{CB}	
V_{DC}	

- Calculate the sum of the four voltage measurements. Does it appear that Kirchhoff's Voltage Law is satisfied around this loop? Justify your answer.

  $V_{AD} + V_{BA} + V_{CB} + V_{DC} =$

- Measure the voltage across each resistor, moving counter-clockwise around the loop.

Voltage	Measured Value
V_{DA}	
V_{AB}	
V_{BC}	
V_{CD}	

- Calculate the sum of the four voltage measurements. Does it appear that Kirchhoff's Voltage Law is satisfied around this loop? Justify your answer.

  $V_{DA} + V_{CD} + V_{BC} + V_{AB} =$

Measuring Current

- Record I_{CW}, the current flowing clockwise around the circuit loop, measured between **R1** and **R2**.

- Record I_{CCW}, the current flowing counter-clockwise around the circuit loop, measured between **R1** and **R2**.

- Based on your understanding of how a current measurement is affected by the connections of the red and black probes, does it appear that the measurements of I_{CW} and I_{CCW} are *consistent*?

- Record I_{CW}, the current flowing clockwise around the circuit loop, measured between **R2** and **R3**.

- Based on your understanding of how current flows in a circuit, does it appear that the two measurements of I_{CW} (at nodes **B** and **C**) are consistent?

Chapter 2

Series & Parallel Circuits Worksheet

Series Circuits

- Record the colors of the bands on R1 and R2, then use the resistor color code to determine the marked resistance value and tolerance for each resistor. Measure the actual value of the resistors.

Resistor	Color Bands	Marked Value	Measured Value
R1			
R2			

- Measure and record V_{AC}, V_{BA}, and V_{BC}, the voltages across the voltage source, R1, and R2.

Voltage	Measured Value
V_{AC}	
V_{BA}	
V_{CB}	

- Calculate the sum of the three voltage measurements.

  $V_{AC} + V_{BA} + V_{CB} =$

- Does it appear that Kirchhoff's Voltage Law is satisfied when progressing clockwise around this loop? Justify your answer.

- Measure and record V_{CA}, V_{AB}, and V_{CB}, the voltages across the voltage source, R1, and R2.

Voltage	Measured Value
V_{CA}	
V_{AB}	
V_{BC}	

- Calculate the sum of the three voltage measurements.

  $V_{CA} + V_{AB} + V_{BC} =$

- Does it appear that Kirchhoff's Voltage Law is satisfied when progressing counter-clockwise around this loop? Justify your answer.

- Measure and record the current through each resistor.

Current	Measured Value
I_A	
I_B	
I_C	

- Are the three current measurements consistent with the electrical definition of **series elements**?

Parallel Elements

- Record the colors of the bands on R3, then use the resistor color code to determine its marked resistance value and tolerance. Measure the actual value of the resistor.

Resistor	Color Bands	Marked Value	Measured Value
R3			

- Measure the three currents **out of** (leaving) node **B**.

Current	Measured Value
I_{OB1}	

Current	Measured Value
I_{OB2}	
I_{OB3}	

- Calculate the sum of the three currents flowing out of node **B**.

  $I_{OB1} + I_{OB2} + I_{OB3} =$

- Does it appear that Kirchhoff's Current Law is satisfied at node **B**? Justify your answer.

- Measure the three currents **into** (entering) node **C**.

Current	Measured Value
I_{IC1}	
I_{IC2}	
I_{ICS}	

- Calculate the sum of the three currents flowing into node **C**.

  $I_{IC1} + I_{IC2} + I_{ICS} =$

- Does it appear that Kirchhoff's Current Law is satisfied at node **C**? Justify your answer.

- How does I_{OB3} compare to I_{ICS}? What would you expect to be the relationship between these two values?

Chapter 3

Resistors and Ohm's Law Worksheet

Series and Parallel Resistors

- Record the colors of the bands on the three resistors, including the band (if any) that indicates the resistor's tolerance. Use the resistor color code to determine the marked resistance value for each resistor and record these values. Use your multimeter to measure the actual value of the three resistors. Record these values with (at least) three significant digits.

Resistor	Color Bands	Marked Value	Measured Value
R1			
R2			
R3			

- Use the **measured** resistance values to calculate the equivalent resistance of R2 in parallel with R3, which we will refer to as R23.

  R23 =

- Use the **measured** resistance values to calculate the equivalent resistance of R1 in series with R23, which we will refer to as REQ.

  REQ =

- Measure and record the resistance between nodes **B** and **C**. How does the measured value compare to the calculated value of R23?

- Measure and record the resistance between nodes **A** and **C**. How does the measured value compare to the calculated value of REQ?

Ohm's Law

- Measure and record the supply voltage, V_{AC}, with at least three significant digits.

- Given the calculated value of REQ and the measured supply voltage, use Ohm's Law to calculate the value of I_{SRC}.

- Break the circuit connection at node **A**, between the voltage source and R1, and measure I_{SRC}. How does the measured value of I_{SRC} compare to the value you calculated above?

- Use Ohm's Law to calculate the voltage across R1 (V_{AB}) and the voltage across R23 (V_{BC}).

- Measure and record the voltages V_{AB} and V_{BC} with at least three significant digits. How do the measured values compare to the values you calculated using Ohm's Law above?

- Suppose we apply Kirchhoff's Voltage Law to the loop formed by the voltage source, R1, and R23. What can you say about the relationship between the supply voltage, V_{AC}, and the voltage drops across R1 and R23? Are your calculations and measurements consistent with your expectations?

- Use Ohm's Law to calculate the currents I_{R2} and I_{R3} using the measured value of V_{BC} and the measured values of R2 and R3.

- Considering the values you have calculated for I_{SRC}, I_{R2}, and I_{R3}, does it appear that Kirchhoff's Current Law is satisfied at node **B**? Explain your answer.

- Measure I_{R2} and I_{R3}. How do the calculated values of these currents compare to their measured values?

Chapter 4

Superposition Worksheet

Assembling & Verifying the Test Circuit

- Select four resistors with four different values between 1 kΩ and 10 kΩ.

Resistor	Color Bands	Marked Value	Measured Value
R1			
R2			
R3			
R4			

- Measure and record the voltage across each element.

Voltage	Measured Value
V_{V1}	
V_{V2}	
V_{R1}	
V_{R2}	
V_{R3}	
V_{R4}	

- Verify your voltage measurements using Kirchhoff's Voltage Law around the upper loop, which includes V1, R1, and R2.

  $V_{SUM} = V_{CA} + V_{AB} + V_{BC} =$

  Does it appear that Kirchhoff's Voltage Law is satisfied around this loop? Justify your answer.

- Verify the voltage measurements using KVL around the lower loop, which includes V2, R2, R3, and R4.

  $V_{SUM} = V_{EC} + V_{CB} + V_{BD} + V_{DE} =$

  Does it appear that Kirchhoff's Voltage Law is satisfied around this loop? Justify your answer.

- Verify the voltage measurements using KVL around the outer loop, which includes V1, V2, R1, R3, and R4.

  $V_{SUM} = V_{CA} + V_{AB} + V_{BD} + V_{DE} + V_{EC} =$

  Does it appear that Kirchhoff's Voltage Law is satisfied around this loop? Justify your answer.

Demonstrating superposition

- "Zero out" V2 and measure the voltages across the remaining elements.

Voltage	Measured Value
V_{V1}	
V'_{R1}	
V'_{R2}	
V'_{R3}	
V'_{R4}	

- "Zero out" V1 and measure the voltages across the remaining elements.

Voltage	Measured Value
V_{V2}	
V''_{R1}	
V''_{R2}	
V''_{R3}	
V''_{R4}	

- Calculate the sum of the single-prime and double-prime voltages for each resistor.

  $V'_{R1} + V''_{R1} =$

$V'_{R2} + V''_{R2} =$

$V'_{R3} + V''_{R3} =$

$V'_{R4} + V''_{R4} =$

- Compare the sums you calculated above to the measured resistor voltages from the original circuit (with both voltage sources present). Does it appear that the principle of superposition is satisfied for this circuit? Justify your answer.

Chapter 5

Thévenin Equivalent Circuits

Current and Voltage Measurements

Procedure

- Record the open-circuit voltage, V_{OC}.

- Record the measured load voltage value, V_{LOAD}.

- Record the measured load resistor value, R_{LOAD}.

- Calculate the current I_{LOAD} using your measured values for V_{LOAD} and R_{LOAD}.

- Calculate the equivalent Thévenin resistance of the linear circuit.

- Draw a sketch of the Thévenin equivalent circuit for the test circuit.

Thévenin Equivalent Circuit

- Measure and record the actual resistance of your chosen R_{TH}.

- Measure and record the open-circuit voltage of the equivalent circuit.

- Measure and record the voltage V_{LOAD} of the equivalent circuit.

Chapter 6

Operational Amplifier Circuits Worksheet

Inverting Amplifier

- Record the color bands for R_i and R_f, their marked values, and their measured values.

Resistor	Color Bands	Marked Value	Measured Value
R_1			
R_2			

- Calculate the expected gain, A_E, of the inverting amplifier circuit.

- Record the voltages at pins 2, 3, 4, and 7 of the operational amplifier. that you understand what the reasonable values for these voltages are and you can verify each of the voltages by measuring them. **Record** the measured voltage at each pin.

Pin	Function	Voltage
2	inverting input	
3	non-inverting input	
4	negative power supply	
7	positive power supply	

- For V_{in} values of approximately 0.25 V, 0.50 V, and 1.00 V, measure and record the actual voltages of V_{in} and V_{out}. Calculate the observed circuit gain, A_O, and the gain error, ΔA.

Approx. V_{in}	V_{in} (V)	V_{out} (V)	A_O (V/V)	ΔA (%)
0.25 V				
0.50 V				

Approx. V_{in}	V_{in} (V)	V_{out} (V)	A_O (V/V)	ΔA (%)
1.00 V				

- For V_{in} values of approximately 0.25 V, 0.50 V, and 1.00 V, measure and record V_{inv}, the voltage at the inverting operational amplifier input.

Approx. V_{in}	V_{in} (V)	V_{inv} (V)
0.25 V		
0.50 V		
1.00 V		

- Does the measured value of V_{inv} change significantly as you adjust the value of V_{in}?

- What can you say about the relationship between the voltages at the inverting and non-inverting inputs to the operational amplifier in this circuit?

- Measure and record the actual resistance of R_{load}.

- For V_{in} values of approximately 0.25 V, 0.50 V, and 1.00 V, measure and record the actual voltages of V_{in} and V_{out}. Calculate the observed circuit gain, A_O, and the gain error, ΔA.

Approx. V_{in}	V_{in} (V)	V_{out} (V)	A_O (V/V)	ΔA (%)
0.25 V				
0.50 V				
1.00 V				

  Did the observed gain change significantly when you added the load resistor?

- Calculate the currents I_{in} and I_f.

- Use Kirchhoff's Current Law to determine I_{inv}. Is I_{inv} large or small compared to I_{in} and I_f?

- Use Ohm's law to calculate I_{load}.

- Use Kirchhoff's Current Law to determine I_{out}.

- What is the source of the current that eventually appears at the output pin of the operational amplifier?

Non-inverting Amplifier

- Use the measured values of R_i and R_f to calculate the expected gain, A_E, of the non-inverting amplifier circuit.

- For V_{in} values of approximately 0.25 V, 0.50 V, and 1.00 V, measure and record the actual voltages of V_{in} and V_{out}. Calculate the observed circuit gain, A_O, and the gain error, ΔA.

Approx. V_{in}	V_{in} (V)	V_{out} (V)	A_O (V/V)	ΔA (%)
0.25 V				
0.50 V				
1.00 V				

- For V_{in} values of approximately 0.25 V, 0.50 V, and 1.00 V, measure and record V_{inv}, the voltage at the inverting operational amplifier input.

Approx. V_{in}	V_{in} (V)	V_{inv} (V)
0.25 V		
0.50 V		
1.00 V		

- How does the measured value of V_{inv} change as you adjust the value of V_{in}? What can you say about the relationship between the voltages at the inverting and non-inverting inputs to the operational amplifier in this circuit?

Voltage Follower

- Suppose that the non-inverting amplifier circuit is modified so that R_i is replaced with a resistor that is 100 times larger than R_f. What is the expected gain of the non-inverting amplifier?

- What is the value of the expected gain A_E if $R_i = 10000 \times R_f$?

- What happens to the expected gain value of the non-inverting amplifier as the value of R_i approaches infinity?

- For V_{in} values of approximately 0.25 V, 0.50 V, and 1.00 V, measure and record the actual voltages of V_{in} and V_{out}. Calculate the observed circuit gain, A_O, and the gain error, ΔA.

Approx. V_{in}	V_{in} (V)	V_{out} (V)	A_O (V/V)	ΔA (%)
0.25 V				
0.50 V				
1.00 V				

- What is the relationship between V_{inv} and V_{out} for this circuit?

- If the voltages at V_{inv} and V_{out} are equal, then what is the voltage **across** R_f? How much current flows through R_f?

- If there is no current flowing through a resistor then what must be the voltage across the resistor, **regardless of its resistance value**?

- Replace R_f with a wire connecting the inverting input and output pins of the operational amplifier. For V_{in} values of approximately 0.25 V, 0.50 V, and 1.00 V, measure and record the actual voltages of V_{in} and V_{out}. Calculate the observed circuit gain, A_O, and the gain error, ΔA.

Approx. V_{in}	V_{in} (V)	V_{out} (V)	A_O (V/V)	ΔA (%)
0.25 V				
0.50 V				
1.00 V				

- Can you discuss an important practical use for the voltage follower circuit? Is there a characteristic of the circuit, other than unity voltage gain, that might be advantageous in some circumstances?

Chapter 7

Operational Amplifier Application Worksheet

Circuit Design

Procedure

- With RF chosen to be 27 kΩ, determine the appropriate values of RA and RB.

- You need to use a voltage divider to create V_{OFF}, the 0.32 V constant offset voltage

  1. Determine the voltage values that you will use for VPS+ and VPS-.

  2. **Calculate** the desired value of current through R2.

  3. **Calculate** the voltage across R1.

  4. **Calculate** the resistance value for R1.

  5. **Specify** the standard resistor values that you can connect together to achieve an equivalent resistance that is within 5% of the desired value of R1.

Circuit Testing

- **Record** the final value of R1 that you used and the measured value of V_{OFF}. If you combined standard resistors to achieve the necessary value of R1, describe which standard values you selected and how you combined them (in series or in parallel).

- **Compute** the temperature in Celsius or Fahrenheit, as well as the corresponding voltage, to fill in the table below. Connect the DMM to measure the op-amp output voltage, V_{F}. **Set** V_{C} to the appropriate voltage corresponding to the Celsius temperature, then **measure and record** the resulting value of V_{F}, the amplifier output voltage. The difference between the desired value and the measured value should be less than 10%.

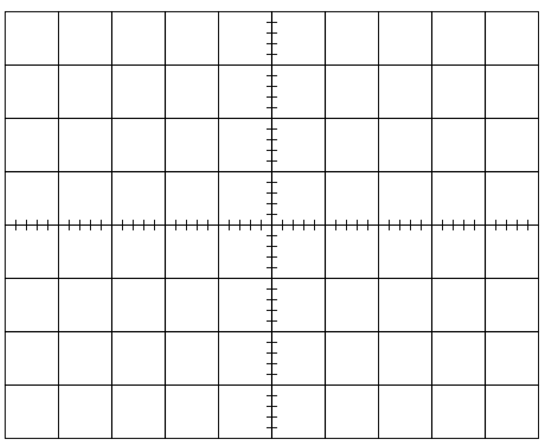
Temp (°C)	V_{C} (V)	Temp (°F)	Desired V_{F} (V)	Measured V_{F} (V)
100	1.00	212	-2.12	
38	0.38			
25	0.25			
0	0.00			

Chapter 8

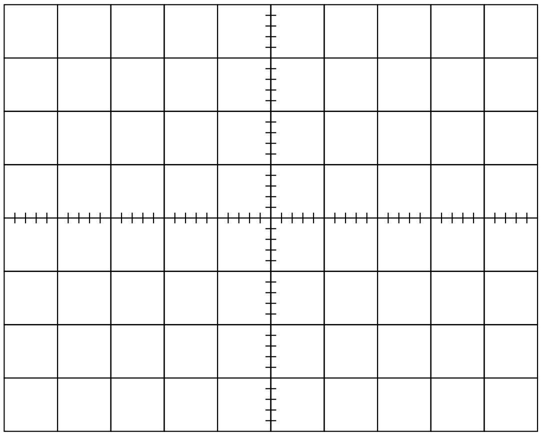
Transient Response of RC and RL Circuits Worksheet

RC Circuits

- Calculate the time constant, τ, of the RC circuit based on the marked component values.
- Sketch the capacitor voltage waveform for one complete cycle.



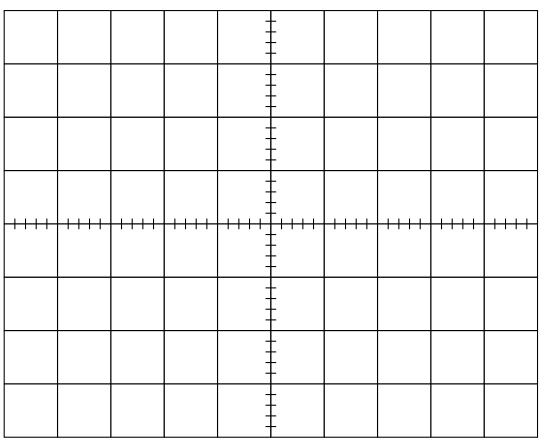
- Observe and record the actual time constant value. Is there reasonably good agreement between your calculated and observed values of τ?
- Sketch the resistor voltage waveform for one complete cycle below.

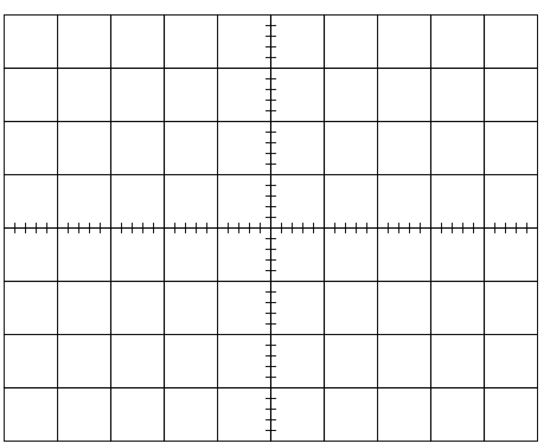


- Recalculate the time constant after replacing the 2.2 kΩ resistor with a 5.6 kΩ resistor.

- Observe and record the actual time constant value. Is there reasonably good agreement between your calculated and observed values of τ?

- Repeat your sketches for the capacitor voltage and the resistor voltage.



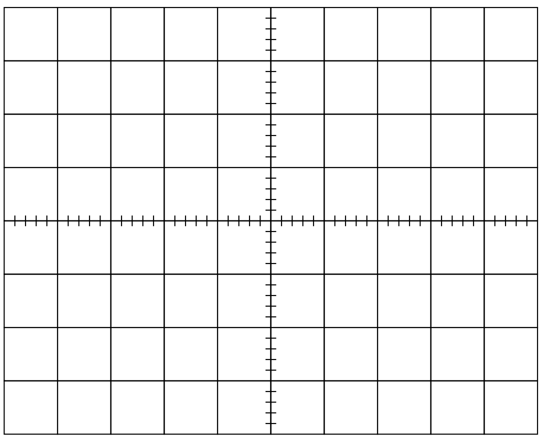


RL Circuits

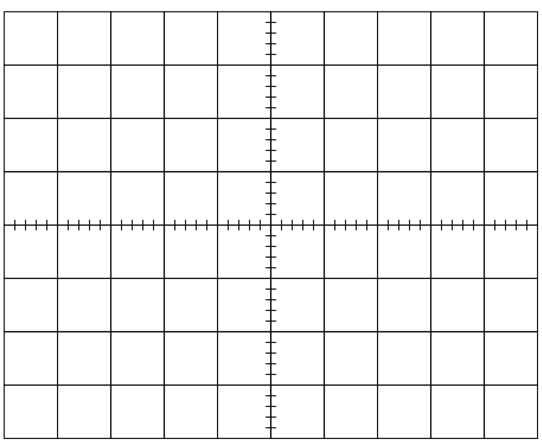
- Calculate and record the time constant of the RL circuit, based on the marked component values.

- Observe and record the actual time constant. Is there reasonably good agreement between your calculated and observed values?

- Sketch the inductor voltage waveform for one complete cycle below, recording the voltage scale and time scale values.



- Swap the positions of the resistor and inductor in your circuit, so that one end of the resistor is connected to ground. Sketch the resistor voltage waveform for one complete cycle below.



Chapter 9

Steady-state RC Circuits Worksheet

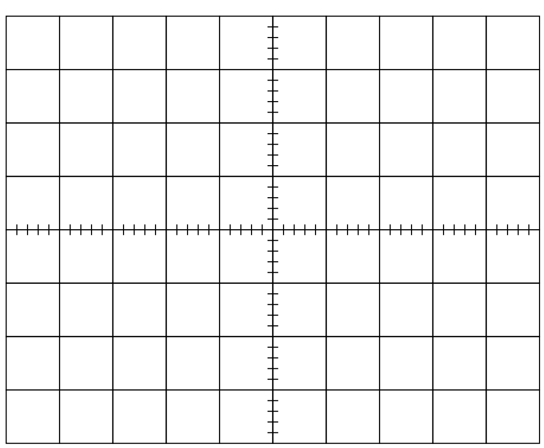
Procedure

- Compute and record the vertical scale of the computed resistor voltage waveform in volts per division.

- Compute and record the vertical scale of the corresponding resistor current waveform in amperes per division.

- Record the observed time difference between the capacitor voltage and capacitor current waveforms. Calculate and record the corresponding phase difference (in degrees) between the current and voltage.

- Sketch the capacitor voltage and current waveforms for at least one complete cycle.



- Record the RMS voltage of the function generator output, the voltage across the resistor, and the voltage across the capacitor.

- Based on the **voltmeter** measurements, does it appear that KVL is satisfied for this circuit? Explain your observations.

- After changing the function generator frequency, record the observed time difference between the capacitor voltage and capacitor current waveforms. Calculate and record the corresponding phase difference (in degrees) between the current and voltage.

- Record the RMS voltage of the function generator output, the voltage across the resistor, and the voltage across the capacitor.

- Describe how your measurements and observations were different at the two function generator frequencies, and how they were the same.

Chapter 10

Resonance in RLC Circuits

Procedure

- **Measure** and **record** the actual resistance values of the 100 Ω resistor (R_{100}), the 47 Ω resistor (R_{47}), and the inductor (R_L).

Element	Value
R_{100}	
R_{47}	
R_L	

- **Calculate** and **record** the resonant frequency, f_R, of the circuit in hertz.

- **Calculate** and **record** the total series resistance of the circuit.

- **Calculate** and **record** the quality factor, Q, of the circuit.

- **Calculate** and **record** the bandwidth BW, of the circuit.

- Slowly adjust the function generator frequency until the voltage across the 47 Ω resistor reaches a **maximum** value. **Record** the peak-to-peak output voltage of the function generator, the peak-to-peak voltage across the resistor, and the actual frequency of the signal.

- Is the observed resonant frequency within 10% of the calculated value? If not, resolve the discrepancy before moving on.

- Use the DMM to measure the RMS voltage across the capacitor and inductor. **Record** the measured values here. At resonance these voltages should have an equal magnitude but be 180° out of phase. **Explain** whether your observations are consistent with that expectation.

- Use the DMM to measure the RMS voltage across the 47 Ω resistor and the 100 Ω resistor. **Record** your measurements here.

- At d.c. the sum of the voltages across the capacitor, inductor, and 47 Ω resistor would equal the voltage across the 100 Ω resistor. Is that true for the a.c. steady-state resonant case here? **Explain** your answer.

- **Increase** the signal generator frequency (above the resonant frequency) until the voltage across the resistor falls to about 71% of its value at resonance. **Record** this frequency here.

- **Decrease** the signal generator frequency (below the resonant frequency) until the voltage across the resistor falls to about 71% of its value at resonance. **Record** this frequency here.

- The **difference** between the two frequencies where the resistor voltage falls to 70.7% of its value at resonance is defined to be the *bandwidth* of the resonant circuit. Calculate and **record** the measured bandwidth here.

- Is the observed bandwidth within 10% of the calculated value? **Record** your observations here.

Chapter 11

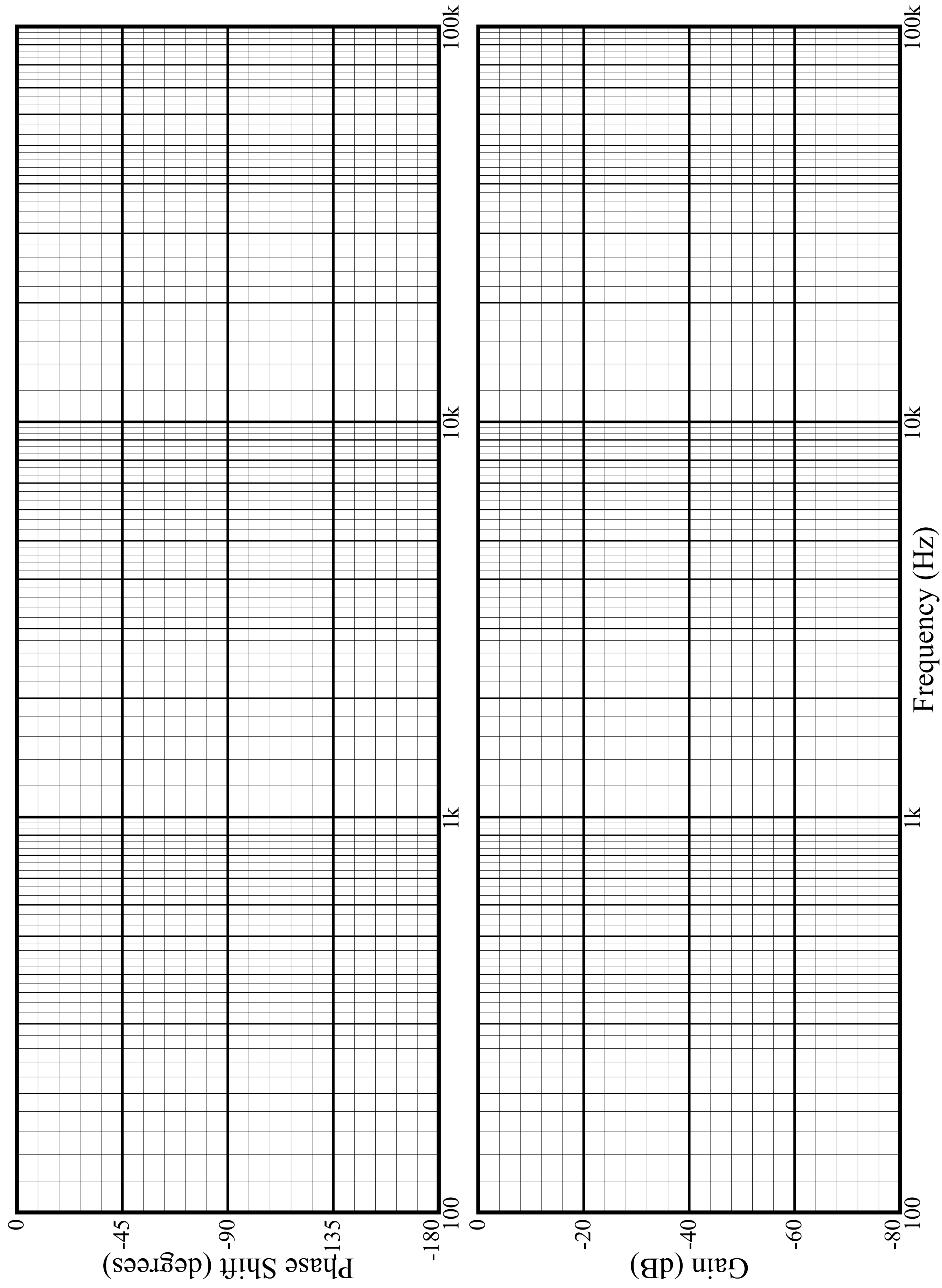
Bode Plots Worksheet

Procedure

- Based on your understanding of impedance for inductors and capacitors, is the LC filter a low-pass filter or a high-pass filter? **Justify** your answer.
- **Measure** and **record** the peak-to-peak amplitude and phase delay of the output voltage, V_{OUT}, with respect to V_{IN} at each test frequency. **Calculate** and **record** the gain of the circuit in both volts/volt and decibels for each test frequency. **Calculate** and **record** the period of each test frequency and the corresponding phase shift of the output, in degrees.

Freq. (Hz)	Period	V_{OUT}	Gain (V/V)	Gain (dB)	Phase Delay	Phase Shift (°)
100						
200						
500						
1k						
2k						
5k						
10k						
20k						
50k						
100k						

- Plot the gain and phase of the filter on semilog graph paper.
- This filter has two poles (i.e. a double pole) at the same frequency. **Calculate** and **record** the pole frequency in **hertz**.
- Is the shape of your plotted gain and phase data consistent with your understanding of how a Bode plot should look for this filter, given the number and frequency of its poles? **Explain** your answer.


Phase Shift (degrees)
0
-45
-90
-135
-180
Gain (dB)
0
-20
-40
-60
-80
100
1k
10k
100k
Frequency (Hz)

Chapter 12

Transformers

Finding the ratio of turns

Procedure

- **Calculate** and **record** the turns ratio, n, for the transformer based on the rated voltages.

- **Measure** and **record** the voltage that appears across the full secondary winding of the transformer.

- **Calculate** and **record** the turns ratio, n, for the transformer using the measured voltage values for the primary and secondary.

- **Discuss** how the calculated value for n using the rated voltages compares to the value calculated from the measured voltages. You should expect these values to be within about 10% of each other.

Finding the dotted connections

Procedure

- **Measure** and **record** the voltage from the *undotted* primary lead to the *unconnected* secondary lead.

- **Measure** and **record** the peak-to-peak voltages of both the primary and secondary. **Calculate** the turns ratio once again from the measured voltages and verify that it is essentially the same as the value you calculated from the RMS voltmeter measurements.

Behavior with loaded secondary

Procedure

- **Measure** and **record** the resistance of the load resistor provided to you, to the nearest ohm.

- **Measure** and **record** the primary current with nothing but the oscilloscope connected to the secondary.

- **Record** the RMS voltage across the secondary winding after connecting the load resistor. Using the measured resistance value, **calculate** and **record** the secondary current.

- With the resistor still connected across the secondary winding, **record** the RMS voltage across the primary winding as well as the primary current.

- **Calculate** and **record** the *increase* in the primary current caused by adding a load to the secondary.

- **Calculate** and **record** the turns ratio using the secondary current divided by the increase in primary current.