

Performance-based assessments for AC circuit competencies

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The purpose of these assessments is for instructors to accurately measure the learning of their electronics students, in a way that melds theoretical knowledge with hands-on application. In each assessment, students are asked to predict the behavior of a circuit from a schematic diagram and component values, then they build that circuit and measure its real behavior. If the behavior matches the predictions, the student then simulates the circuit on computer and presents the three sets of values to the instructor. If not, then the student then must correct the error(s) and once again compare measurements to predictions. Grades are based on the number of attempts required before all predictions match their respective measurements.

You will notice that no component values are given in this worksheet. The *instructor* chooses component values suitable for the students' parts collections, and ideally chooses different values for each student so that no two students are analyzing and building the exact same circuit. These component values may be hand-written on the assessment sheet, printed on a separate page, or incorporated into the document by editing the graphic image.

This is the procedure I envision for managing such assessments:

1. The instructor hands out individualized assessment sheets to each student.
2. Each student predicts their circuit's behavior at their desks using pencil, paper, and calculator (if appropriate).
3. Each student builds their circuit at their desk, under such conditions that it is impossible for them to verify their predictions using test equipment. Usually this will mean the use of a multimeter only (for measuring component values), but in some cases even the use of a multimeter would not be appropriate.
4. When ready, each student brings their predictions and completed circuit up to the instructor's desk, where any necessary test equipment is already set up to operate and test the circuit. There, the student sets up their circuit and takes measurements to compare with predictions.
5. If any measurement fails to match its corresponding prediction, the student goes back to their own desk with their circuit and their predictions in hand. There, the student tries to figure out where the error is and how to correct it.
6. Students repeat these steps as many times as necessary to achieve correlation between all predictions and measurements. The instructor's task is to count the number of attempts necessary to achieve this, which will become the basis for a percentage grade.
7. (OPTIONAL) As a final verification, each student simulates the same circuit on computer, using circuit simulation software (Spice, Multisim, etc.) and presenting the results to the instructor as a final pass/fail check.

These assessments more closely mimic real-world work conditions than traditional written exams:

- Students cannot pass such assessments only knowing circuit theory or only having hands-on construction and testing skills – they must be proficient at both.
- Students do not receive the “authoritative answers” from the instructor. Rather, they learn to validate their answers through real circuit measurements.
- Just as on the job, the work isn't complete until *all errors* are corrected.
- Students must recognize and correct their own errors, rather than having someone else do it for them.
- Students must be fully prepared on exam days, bringing not only their calculator and notes, but also their tools, breadboard, and circuit components.

Instructors may elect to reveal the assessments before test day, and even use them as preparatory labwork and/or discussion questions. Remember that there is absolutely nothing wrong with “teaching to

the test" *so long as the test is valid*. Normally, it is bad to reveal test material in detail prior to test day, lest students merely memorize responses in advance. With performance-based assessments, however, there is no way to pass without truly understanding the subject(s).

Version: _____

Competency: Analog oscilloscope set-up

Schematic

Given conditions

V_{signal} = Set by instructor without student's knowledge

f_{signal} = Set by instructor without student's knowledge

Parameters

Between two and five cycles of waveform displayed, without exceeding either top or bottom edge of screen.

file 01674

Competency: Digital oscilloscope set-up	Version:
Schematic	
Given conditions	
<p>$V_{\text{signal}} =$ Set by instructor without student's knowledge</p> <p>$f_{\text{signal}} =$ Set by instructor without student's knowledge</p>	
Parameters	
<p>Between two and five cycles of waveform displayed, without exceeding either top or bottom edge of screen.</p>	

Competency: **RMS versus peak measurements** Version:

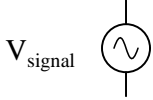
Schematic

Given conditions

V_{signal} = Set by instructor without student's knowledge

Parameters

		Measured	
	$V_{\text{signal(peak)}}$		(Measured with oscilloscope)
	Predicted	Measured	
$V_{\text{signal(RMS)}}$			(Measured with true-RMS multimeter)

Competency: Measuring frequency	Version:
Schematic	
	
Given conditions	
$V_{\text{signal}} =$	
$f_{\text{signal}} =$ Set by instructor without student's knowledge	
Parameters	
Measured with oscilloscope	
t_{period} <input type="text"/>	
Measured with counter Measured with oscilloscope	
f_{signal} <input type="text"/> <input type="text"/>	

file 01660

Competency: **Probe compensation adjustment** Version:

Schematic

Given conditions

(Use the built-in square wave signal source in your oscilloscope, and use a $\times 10$ probe to measure it)

Parameters

Between two and five cycles of waveform displayed, without exceeding either top or bottom edge of screen.

Measured

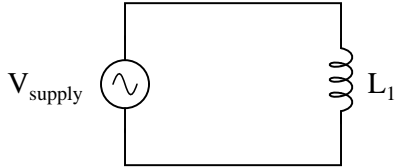
V_{signal}

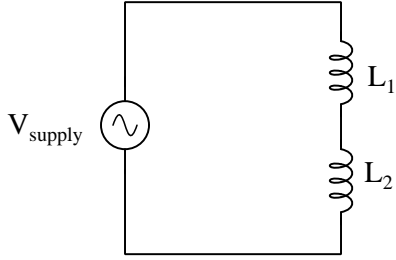
f_{signal}

Properly compensated probe waveform

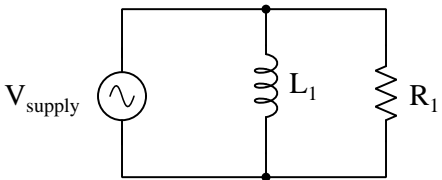
Overcompensated probe waveform

Undercompensated probe waveform

Competency: Inductive reactance and Ohm's Law for AC Version:				
Schematic				
				
Given conditions				
$V_{\text{supply}} =$	$L_1 =$			
$f_{\text{supply}} =$				
Parameters				
	<table style="margin-left: auto; margin-right: auto;"> <tr> <td style="padding: 5px;">Predicted</td> <td style="padding: 5px;">Measured</td> </tr> </table>	Predicted	Measured	
Predicted	Measured			
I_{total}	<table style="margin-left: auto; margin-right: auto;"> <tr> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> </tr> </table>			
V_{L1}	<table style="margin-left: auto; margin-right: auto;"> <tr> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> </tr> </table>			
<p><i>Qualitative answers only: Increase, decrease, or same</i></p>				
	<table style="margin-left: auto; margin-right: auto;"> <tr> <td style="padding: 5px;">Predicted</td> <td style="padding: 5px;">Measured</td> </tr> </table>	Predicted	Measured	
Predicted	Measured			
I_{total}	<table style="margin-left: auto; margin-right: auto;"> <tr> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> </tr> </table>			as frequency increases
I_{total}	<table style="margin-left: auto; margin-right: auto;"> <tr> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> </tr> </table>			as frequency decreases

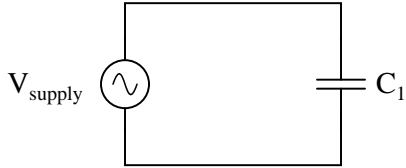
Competency: Series AC inductive reactances	Version:		
Schematic			
			
Given conditions			
$V_{\text{supply}} =$	$L_1 =$	$L_2 =$	$f_{\text{supply}} =$
Parameters			
X_{L1} Predicted	X_{L2} Predicted	X_{total} Predicted	
<input type="text"/>	<input type="text"/>	<input type="text"/>	
I_{total} Predicted	Measured	Derived ($X = V/I$)	
<input type="text"/>	<input type="text"/>	X_{total} <input type="text"/>	
Analysis			
Do series inductive reactances <i>add</i> or <i>diminish</i> ?			
Fault analysis			
Suppose component <input type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____			
<input type="checkbox"/> shorted			
<i>What will happen in the circuit?</i> <small>Write "increase", "decrease", or "no change" for each parameter:</small>			
V_{L1} <input type="text"/>	I_{L1} <input type="text"/>	I_{total} <input type="text"/>	
V_{L2} <input type="text"/>	I_{L2} <input type="text"/>		

Competency: Series LR circuit	Version:		
Schematic			
Given conditions			
$V_{\text{supply}} =$	$L_1 =$	$R_1 =$	$f_{\text{supply}} =$
Parameters			
	Predicted	Measured	
V_{L1}	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>	
V_{R1}	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>	
I_{total}	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>	
Calculations			
Fault analysis			
Suppose component <input style="width: 40px; height: 20px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted			
<i>What will happen in the circuit?</i> <small>Write "increase", "decrease", or "no change" for each parameter:</small>			
V_{L1}	<input style="width: 80px; height: 20px;" type="text"/>	I_{L1}	<input style="width: 80px; height: 20px;" type="text"/>
V_{R1}	<input style="width: 80px; height: 20px;" type="text"/>	I_{R1}	<input style="width: 80px; height: 20px;" type="text"/>
I_{total}	<input style="width: 80px; height: 20px;" type="text"/>		

Competency: Parallel LR circuit	Version:		
Schematic			
			
Given conditions			
$V_{\text{supply}} =$	$L_1 =$	$R_1 =$	$f_{\text{supply}} =$
Parameters			
	Predicted	Measured	
I_{L1}	<input type="text"/>	<input type="text"/>	
I_{R1}	<input type="text"/>	<input type="text"/>	
I_{total}	<input type="text"/>	<input type="text"/>	
Calculations			
Fault analysis			
Suppose component <input type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted			
<i>What will happen in the circuit?</i> <small>Write "increase", "decrease", or "no change" for each parameter:</small>			
I_{L1}	<input type="text"/>	V_{L1}	<input type="text"/>
I_{R1}	<input type="text"/>	V_{R1}	<input type="text"/>
I_{total}	<input type="text"/>		

Competency: **Capacitive reactance and Ohm's Law for AC** Version:

Schematic



Given conditions

$V_{\text{supply}} =$ $C_1 =$

$f_{\text{supply}} =$

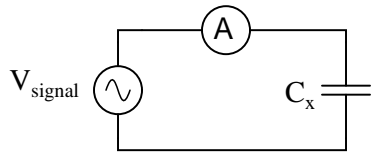
Parameters

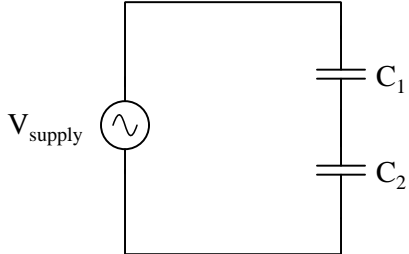
	Predicted	Measured
I_{total}	<input type="text"/>	<input type="text"/>
V_{C_1}	<input type="text"/>	<input type="text"/>

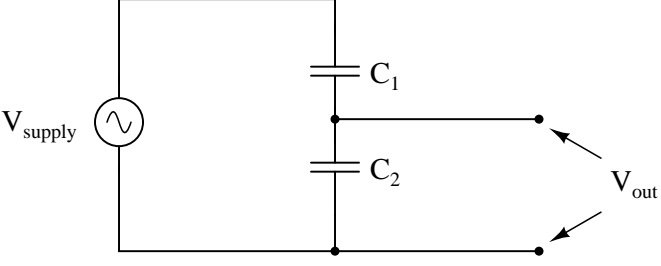
*Qualitative answers only:
Increase, decrease, or same*

	Predicted	Measured	
I_{total}	<input type="text"/>	<input type="text"/>	as frequency increases
I_{total}	<input type="text"/>	<input type="text"/>	as frequency decreases

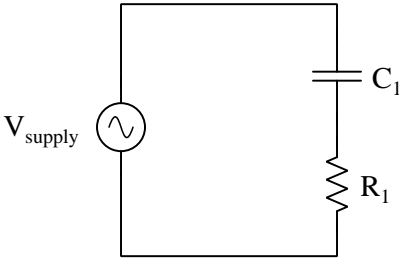
file 01617

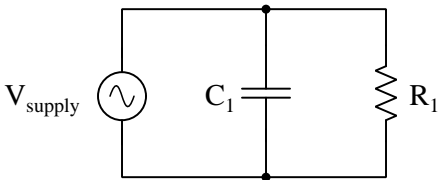
Competency: Measuring capacitance by AC reactance	Version:
Schematic	
	
Given conditions	
$V_{\text{signal}} =$	
Parameters	
Measured I_C <input style="width: 80px; height: 25px;" type="text"/> at $f =$	$\longrightarrow C_x$ <input style="width: 80px; height: 25px;" type="text"/>
I_C <input style="width: 80px; height: 25px;" type="text"/> at $f =$	$\longrightarrow C_x$ <input style="width: 80px; height: 25px;" type="text"/>
I_C <input style="width: 80px; height: 25px;" type="text"/> at $f =$	$\longrightarrow C_x$ <input style="width: 80px; height: 25px;" type="text"/>
C_x <input style="width: 80px; height: 25px;" type="text"/> (With C meter)	C_x <input style="width: 80px; height: 25px;" type="text"/> (Average)

Competency: Series AC capacitive reactances	Version:		
Schematic			
			
Given conditions			
$V_{\text{supply}} =$	$C_1 =$	$C_2 =$	$f_{\text{supply}} =$
Parameters			
X_{C1}	Predicted	X_{C2}	Predicted
I_{total}	Predicted		Measured
			Derived ($X = V/I$)
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Analysis			
Do series capacitive reactances <i>add</i> or <i>diminish</i> ?			
Fault analysis			
Suppose component <input type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____			
<input type="checkbox"/> shorted			
<i>What will happen in the circuit?</i> Write "increase", "decrease", or "no change" for each parameter:			
V_{C1}	I_{C1}	I_{total}	
V_{C2}	I_{C2}		
<input type="text"/>	<input type="text"/>	<input type="text"/>	
<input type="text"/>	<input type="text"/>		

Competency: Capacitive AC voltage divider	Version:					
Schematic						
						
Given conditions						
$V_{\text{supply}} =$	$C_1 =$	$C_2 =$				
$f_{\text{supply}} =$						
Parameters						
V_{out}	<table style="margin: auto;"> <tr> <td style="padding: 5px;">Predicted</td> <td style="padding: 5px;">Measured</td> </tr> <tr> <td style="padding: 5px;"><input style="width: 80px; height: 25px;" type="text"/></td> <td style="padding: 5px;"><input style="width: 80px; height: 25px;" type="text"/></td> </tr> </table>	Predicted	Measured	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	at specified frequency
Predicted	Measured					
<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>					
<i>Qualitative answers only: Increase, decrease, or same</i>						
V_{out}	<table style="margin: auto;"> <tr> <td style="padding: 5px;">Predicted</td> <td style="padding: 5px;">Measured</td> </tr> <tr> <td style="padding: 5px;"><input style="width: 80px; height: 25px;" type="text"/></td> <td style="padding: 5px;"><input style="width: 80px; height: 25px;" type="text"/></td> </tr> </table>	Predicted	Measured	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	as frequency increases
Predicted	Measured					
<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>					
V_{out}	<table style="margin: auto;"> <tr> <td style="padding: 5px;">Predicted</td> <td style="padding: 5px;">Measured</td> </tr> <tr> <td style="padding: 5px;"><input style="width: 80px; height: 25px;" type="text"/></td> <td style="padding: 5px;"><input style="width: 80px; height: 25px;" type="text"/></td> </tr> </table>	Predicted	Measured	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	as frequency decreases
Predicted	Measured					
<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>					

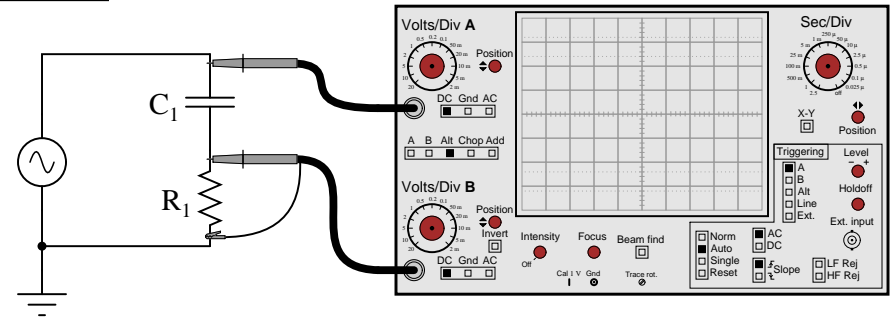
file 01662

Competency: Series RC circuit	Version:		
Schematic			
			
Given conditions			
$V_{\text{supply}} =$	$C_1 =$	$R_1 =$	$f_{\text{supply}} =$
Parameters			
	Predicted	Measured	
V_{C1}	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>	
V_{R1}	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>	
I_{total}	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>	
Calculations			
Fault analysis			
Suppose component <input style="width: 40px; height: 20px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted			
<i>What will happen in the circuit?</i> <small>Write "increase", "decrease", or "no change" for each parameter:</small>			
V_{C1}	<input style="width: 80px; height: 20px;" type="text"/>	I_{C1}	<input style="width: 80px; height: 20px;" type="text"/>
V_{R1}	<input style="width: 80px; height: 20px;" type="text"/>	I_{R1}	<input style="width: 80px; height: 20px;" type="text"/>
I_{total}	<input style="width: 80px; height: 20px;" type="text"/>		

Competency: Parallel RC circuit	Version:												
Schematic													
													
Given conditions													
$V_{\text{supply}} =$ $C_1 =$ $R_1 =$ $f_{\text{supply}} =$													
Parameters													
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 30%; text-align: center;">Predicted</th> <th style="width: 35%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td>I_{C1}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> <tr> <td>I_{R1}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> <tr> <td>I_{total}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> </tbody> </table>			Predicted	Measured	I_{C1}			I_{R1}			I_{total}		
	Predicted	Measured											
I_{C1}													
I_{R1}													
I_{total}													
Calculations													
Fault analysis													
<p>Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted</p> <p><i>What will happen in the circuit?</i> <small>Write "increase", "decrease", or "no change" for each parameter:</small></p> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 30%;">I_{C1}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="width: 30%;">V_{C1}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> <tr> <td>I_{R1}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td>V_{R1}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> <tr> <td>I_{total}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td></td> <td></td> </tr> </table>		I_{C1}		V_{C1}		I_{R1}		V_{R1}		I_{total}			
I_{C1}		V_{C1}											
I_{R1}		V_{R1}											
I_{total}													

Competency: **Time-domain phase shift measurement** Version:

Schematic



Given conditions

$f_{\text{supply}} =$ $C_1 =$ $R_1 =$

Parameters

Predicted

θ

Measured

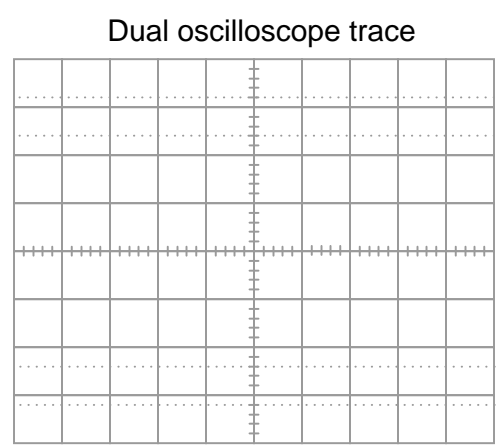
Shift (divisions)

Period (divisions)

θ

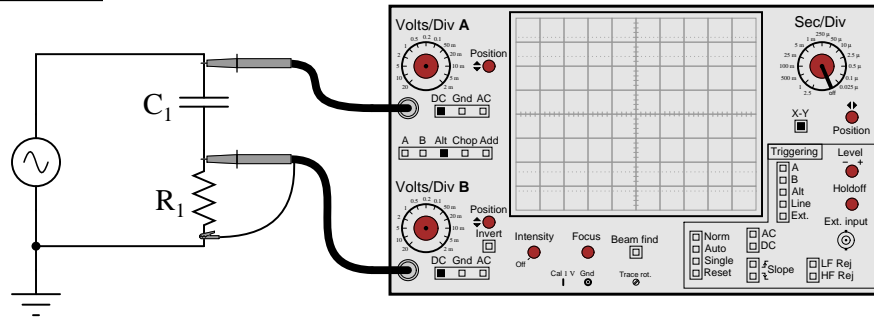
→ | | ← Period

→ | | ← Shift



Competency: **Lissajous figures for phase shift measurement** Version:

Schematic



Given conditions

$f_{\text{supply}} =$ $C_1 =$ $R_1 =$

Parameters

Predicted

θ

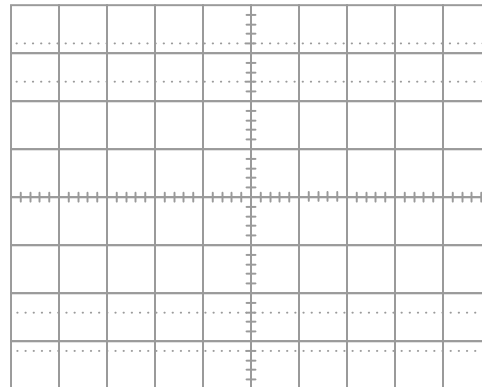
Measured

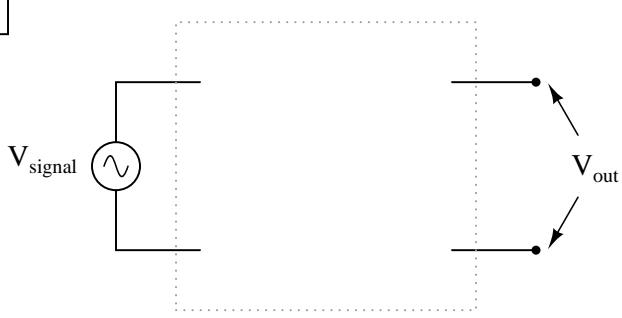
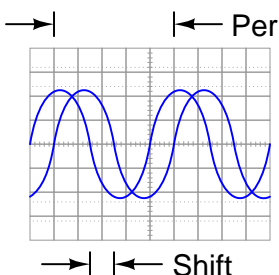
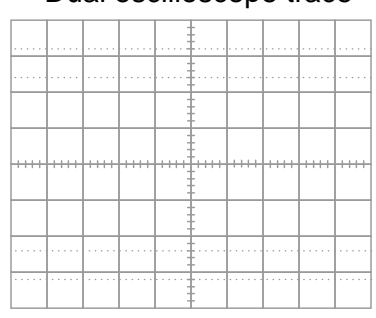
n (Divisions)

m (Divisions)

θ

Lissajous figure (measured)

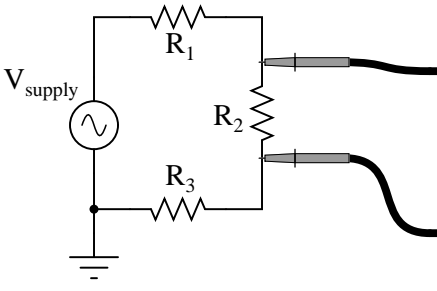
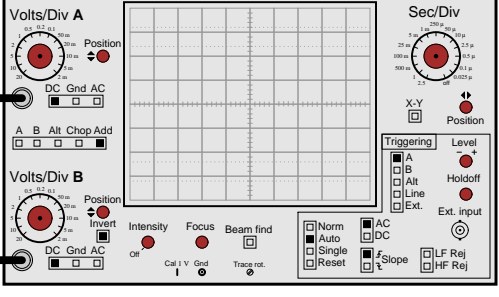


Competency: Phase shift circuit	Version:
Description	
Build an RC circuit to produce the specified phase shift from input to output, and measure this shift with an oscilloscope.	
Given conditions	
$\theta =$	Leading <input type="checkbox"/>
	<i>(instructor checks one)</i>
$f_{\text{supply}} =$	Lagging <input type="checkbox"/>
Schematic	
	
Parameters	
Shift (divisions) <input style="width: 100px;" type="text"/>	Measured
Period (divisions) <input style="width: 100px;" type="text"/>	
θ <input style="width: 100px;" type="text"/>	
	Predicted
	C_1 <input style="width: 100px;" type="text"/>
	R_1 <input style="width: 100px;" type="text"/>
	

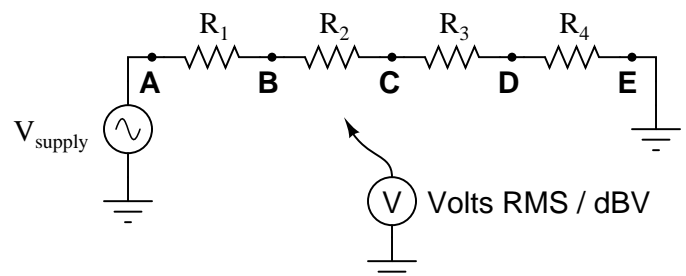
file 02170

Competency: Variable phase shift bridge circuit		Version:				
Schematic						
Given conditions						
$V_{\text{signal}} =$	$R_1 = R_2 =$	<i>Recommendations</i> $R \approx \frac{1}{2\pi fC}$ $R_{\text{pot}} \gg R_1, R_2$				
$f_{\text{signal}} =$	$C_1 = C_2 =$					
	$R_{\text{pot}} =$					
Parameters						
$\theta_{V_{\text{out}}}$	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="height: 20px;"></td> <td style="height: 20px;"></td> </tr> </tbody> </table>	Predicted	Measured			<i>Potentiometer at full-left position</i>
Predicted	Measured					
$\theta_{V_{\text{out}}}$	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="height: 20px;"></td> <td style="height: 20px;"></td> </tr> </tbody> </table>	Predicted	Measured			<i>Potentiometer at full-right position</i>
Predicted	Measured					
V_{out}	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="height: 20px;"></td> <td style="height: 20px;"></td> </tr> </tbody> </table>	Predicted	Measured			<i>Potentiometer at full-left position</i>
Predicted	Measured					
V_{out}	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="height: 20px;"></td> <td style="height: 20px;"></td> </tr> </tbody> </table>	Predicted	Measured			<i>Potentiometer at full-right position</i>
Predicted	Measured					

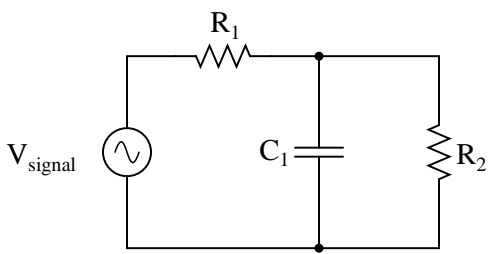
file 03468

Competency: Differential voltage measurement		Version:	
Schematic			
			
Given conditions			
$V_{\text{supply}} =$	$R_1 =$	$R_2 =$	$R_3 =$
Parameters			
V_{R2}	Predicted <input style="width: 80px; height: 25px;" type="text"/>	Measured <input style="width: 80px; height: 25px;" type="text"/>	
Fault analysis			
Suppose component <input style="width: 40px; height: 20px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted What will happen in the circuit?			

file 01822

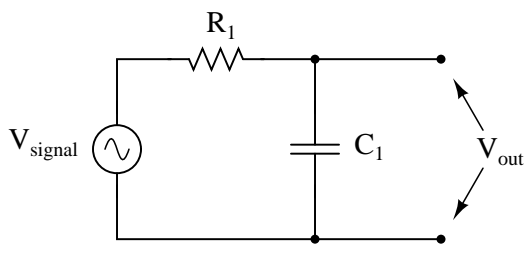
Competency: Measuring decibels	Version:																														
<div style="border: 1px solid black; padding: 2px; display: inline-block; margin-bottom: 5px;">Schematic</div> 																															
<div style="border: 1px solid black; padding: 2px; display: inline-block; margin-bottom: 5px;">Given conditions</div> <p> $V_{\text{supply}} = 1 \text{ volt RMS}$ $R_1 =$ $R_2 =$ $R_3 =$ $R_4 =$ $= 0 \text{ dBV}$ </p>																															
<div style="border: 1px solid black; padding: 2px; display: inline-block; margin-bottom: 5px;">Parameters</div> <table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 10%;"></th> <th style="width: 20%;">Measured (V)</th> <th style="width: 20%;">Measured (dBV)</th> <th colspan="2"></th> </tr> </thead> <tbody> <tr> <td>V_A</td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td colspan="2" style="text-align: right;"><i>(Establishing reference voltage)</i></td> </tr> <tr> <td>V_B</td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> </tr> <tr> <td>V_C</td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> </tr> <tr> <td>V_D</td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> </tr> <tr> <td>V_E</td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> <td><input style="width: 100%;" type="text"/></td> </tr> </tbody> </table>			Measured (V)	Measured (dBV)			V_A	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<i>(Establishing reference voltage)</i>		V_B	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	V_C	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	V_D	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	V_E	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>
	Measured (V)	Measured (dBV)																													
V_A	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<i>(Establishing reference voltage)</i>																												
V_B	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>																											
V_C	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>																											
V_D	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>																											
V_E	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>																											

file 03456

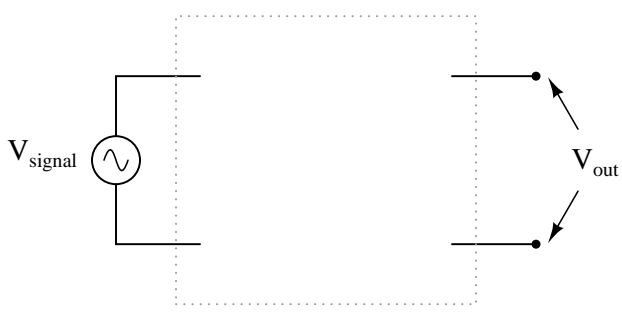
Competency: Series-parallel RC circuit	Version:		
Schematic			
			
Given conditions			
$V_{\text{signal}} =$	$C_1 =$	$R_1 =$	$R_2 =$
$f_{\text{signal}} =$			
Parameters			
	Predicted	Measured	
V_{R1}			
I_{C1}			
I_{R2}			
I_{total}			
Fault analysis			
Suppose component fails		<input type="checkbox"/> open	<input type="checkbox"/> other _____
<i>What will happen in the circuit?</i>		<input type="checkbox"/> shorted	

Competency: Series-parallel RC circuit	Version:	
Schematic		
Given conditions		
$V_{\text{signal}} =$	$R_1 =$	$R_2 =$
$f_{\text{signal}} =$	$C_1 =$	$C_2 =$
Parameters		
	Predicted	Measured
V_{R1}		
V_{R2}		
V_{C2}		
I_{C1}		
I_{total}		
Fault analysis		
Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted What will happen in the circuit?		

Competency: Passive filter circuit	Version:	
Schematic		
Given conditions		
$V_{\text{signal}} =$	$C_1 =$	$R_1 =$
Parameters		
	Predicted	Measured
Filter type (hp, lp, bp, bs)	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>
$f_{-3\text{dB}}$	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>
$\theta_{-3\text{dB}}$	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>
Calculations		
Fault analysis		
Suppose component <input style="width: 40px; height: 20px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted <i>What will happen in the circuit?</i>		

Competency: Passive filter circuit	Version:	
Schematic		
		
Given conditions		
$V_{\text{signal}} =$	$C_1 =$	$R_1 =$
Parameters		
	Predicted	Measured
Filter type (hp, lp, bp, bs)	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>
$f_{-3\text{dB}}$	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>
$\theta_{-3\text{dB}}$	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>
Calculations		
Fault analysis		
Suppose component <input style="width: 50px; height: 20px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted <i>What will happen in the circuit?</i>		

file 01614

Competency: Passive RC filter circuit design	Version:									
Description										
Design and build an RC filter circuit, either high pass or low pass, with the specified cutoff frequency.										
Given conditions										
<i>(instructor checks one)</i>										
$f_{-3dB} =$	High-pass <input type="checkbox"/> Low-pass <input type="checkbox"/>									
Parameters										
	<table style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th style="padding: 5px;"></th> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="padding: 5px;">f_{-3dB}</td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> </tr> <tr> <td style="padding: 5px;">θ_{-3dB}</td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> </tr> </tbody> </table>		Predicted	Measured	f_{-3dB}			θ_{-3dB}		
	Predicted	Measured								
f_{-3dB}										
θ_{-3dB}										
Schematic										
										

file 02095

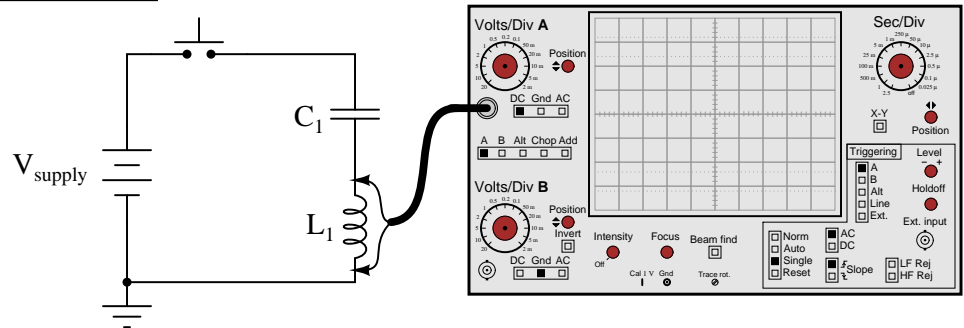
Competency: Passive twin-tee filter circuit		Version:
Schematic		
Given conditions		
$V_{\text{signal}} =$	$C_1 =$	$R_1 =$
	$C_2 =$	$R_2 =$
	$C_3 =$	$R_3 =$
Parameters		
Filter type (hp, lp, bp, bs)	Predicted <input style="width: 100px; height: 20px;" type="text"/>	Measured <input style="width: 100px; height: 20px;" type="text"/>
f_{center}	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
Fault analysis		
Suppose component <input style="width: 50px; height: 20px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted What will happen in the circuit?		

file 02580

Competency: Series resonance	Version:						
Schematic							
Given conditions							
$R_1 =$	$C_1 =$	$L_1 =$					
Parameters							
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 35%; text-align: center;">Predicted</th> <th style="width: 35%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td style="padding: 5px;">f_{resonant}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> </tbody> </table>		Predicted	Measured	f_{resonant}			
	Predicted	Measured					
f_{resonant}							
Calculations							
Fault analysis							
<p>Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____</p> <p><input type="checkbox"/> shorted</p> <p><i>What will happen in the circuit?</i></p>							

Competency: **Dampened resonant oscillations**
Version:

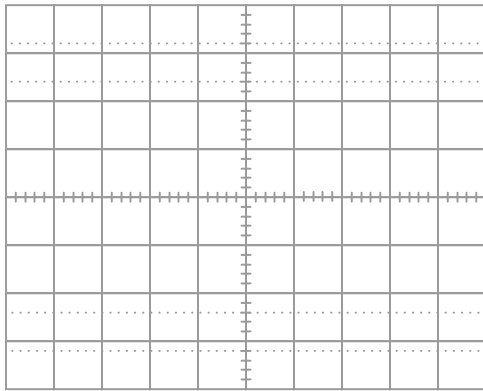
Schematic



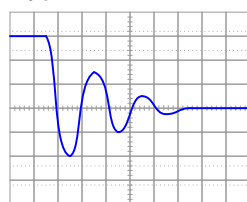
Given conditions

$L_1 =$ $C_1 =$

Parameters

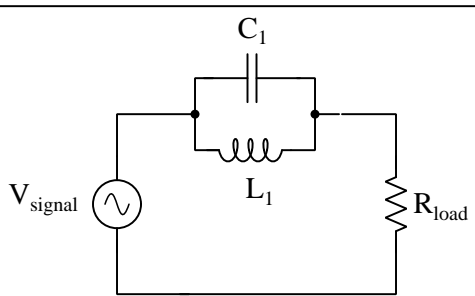
	Predicted	Measured	
f			<div style="border: 1px solid black; padding: 5px; margin-bottom: 10px;"> <div style="text-align: center; font-weight: bold;">Captured waveform</div>  </div>

Typical waveform

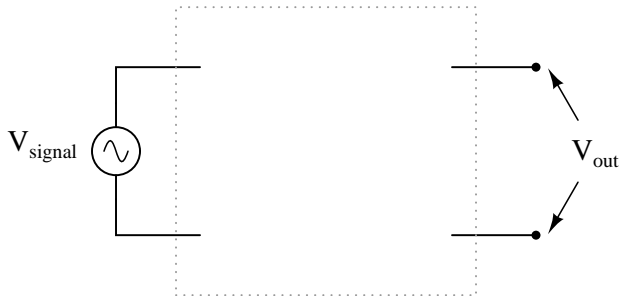


Competency: Measuring inductance by series resonance Version:	
Schematic	
Given conditions	
$R_1 =$	$C_1 =$
Parameters	
f_{resonant}	Measured <input style="width: 100px; height: 20px;" type="text"/>
Inferred from f_{resonant}	Measured with LCR meter
L_x <input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
Calculations	

Competency: Passive resonant filter circuit	Version:												
Schematic													
Given conditions													
$V_{\text{signal}} =$	$C_1 =$												
$L_1 =$	$R_{\text{load}} =$												
Parameters													
	<table style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th style="padding: 5px;"></th> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="padding: 5px;">Filter type (hp, lp, bp, bs)</td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> </tr> <tr> <td style="padding: 5px;">f_{resonant}</td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> </tr> <tr> <td style="padding: 5px;">θ_{resonant}</td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> </tr> </tbody> </table>		Predicted	Measured	Filter type (hp, lp, bp, bs)			f_{resonant}			θ_{resonant}		
	Predicted	Measured											
Filter type (hp, lp, bp, bs)													
f_{resonant}													
θ_{resonant}													
Calculations													
Fault analysis													
Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted <i>What will happen in the circuit?</i>													

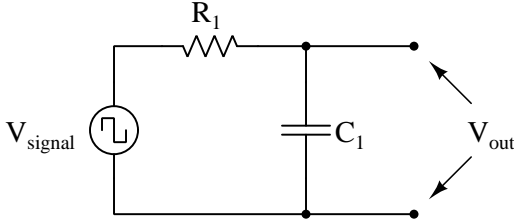
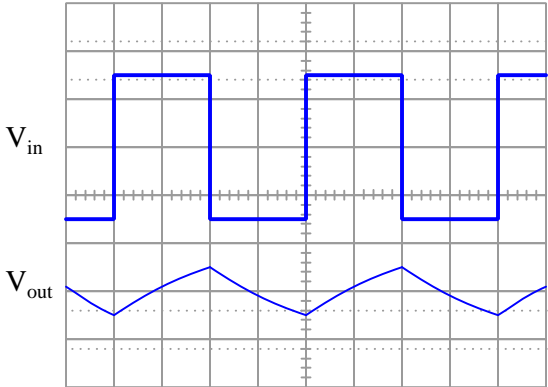
Competency: Passive resonant filter circuit	Version:				
Schematic					
					
Given conditions					
$V_{\text{signal}} =$	$C_1 =$				
$L_1 =$	$R_{\text{load}} =$				
Parameters					
	<table style="width: 100%; border: none;"> <tr> <td style="width: 50%;"></td> <td style="width: 25%; text-align: center;">Predicted</td> <td style="width: 25%; text-align: center;">Measured</td> </tr> </table>		Predicted	Measured	
	Predicted	Measured			
Filter type (hp, lp, bp, bs)	<table style="width: 100%; border: none;"> <tr> <td style="width: 50%; border: 1px solid black; height: 20px;"></td> <td style="width: 25%; border: 1px solid black; height: 20px;"></td> <td style="width: 25%; border: 3px double black; height: 20px;"></td> </tr> </table>				
f_{resonant}	<table style="width: 100%; border: none;"> <tr> <td style="width: 50%; border: 1px solid black; height: 20px;"></td> <td style="width: 25%; border: 3px double black; height: 20px;"></td> <td style="width: 25%;"></td> </tr> </table>				
Calculations					
Fault analysis					
Suppose component <input style="width: 50px;" type="text"/> fails <table style="display: inline-table; vertical-align: middle; margin-left: 20px;"> <tr> <td><input type="checkbox"/> open</td> <td><input type="checkbox"/> other _____</td> </tr> <tr> <td><input type="checkbox"/> shorted</td> <td></td> </tr> </table>		<input type="checkbox"/> open	<input type="checkbox"/> other _____	<input type="checkbox"/> shorted	
<input type="checkbox"/> open	<input type="checkbox"/> other _____				
<input type="checkbox"/> shorted					
<i>What will happen in the circuit?</i> <small>Identify changes in filtering type and frequency, if any</small>					
Filter type (hp, lp, bp, bs) <input style="width: 100px;" type="text"/>					
f_{resonant} <input style="width: 100px;" type="text"/>					

file 01658

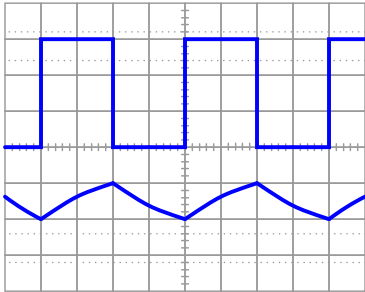
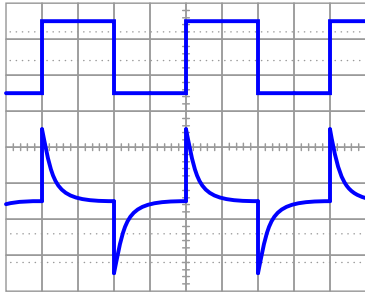
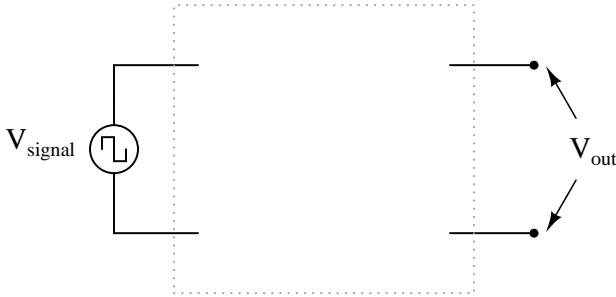
Competency: Passive LC filter circuit design	Version:
Description	
Design and build a passive LC filter circuit with a resonant frequency specified by the instructor.	
Given conditions	
<i>(instructor checks one)</i>	
$f_r =$	Band-pass <input type="checkbox"/> Band-stop <input type="checkbox"/>
Parameters	
	Predicted Measured
f_r	<input type="text"/> <input type="text"/>
Schematic	
	

file 02097

Competency: Passive differentiator circuit		Version:
Schematic		
Given conditions		
$f_{\text{signal}} =$	Required V_{out} waveshape	
Parameters		
Predicted		
C_1		R_1
Fault analysis		
Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____		
<input type="checkbox"/> shorted		
<i>What will happen in the circuit?</i>		
<small>Identify changes to the output voltage waveshape, if any</small>		

Competency: Passive integrator circuit	Version:
Schematic	
	
Given conditions	
$f_{\text{signal}} =$	<p style="text-align: center;">Required waveshapes</p> 
Parameters	
Predicted	
C_1 <input style="width: 60px; height: 25px;" type="text"/>	R_1 <input style="width: 60px; height: 25px;" type="text"/>
Fault analysis	
Suppose component <input style="width: 40px; height: 20px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted	
What will happen in the circuit? <small>Identify changes to the output voltage waveshape, if any</small>	

file 01687

Competency: Passive integrator/differentiator circuit Version:	
Description	
Build either a passive integrator or a passive differentiator circuit to produce the desired waveforms given a square-wave input.	
Given conditions	
$f_{\text{signal}} =$	
Integrator <input type="checkbox"/>	Differentiator <input type="checkbox"/>
(instructor checks one)	
	
$V_{\text{out}} = \frac{1}{3}V_{\text{in}}$	5τ in each pulse width
Schematic	
	
Parameters	
Predicted	
C_1	<input style="width: 100px; height: 20px;" type="text"/>
R_1	<input style="width: 100px; height: 20px;" type="text"/>

Competency: Tone balance control circuit		Version:
Schematic		
Given conditions		
$L_1 =$	$C_1 =$	$R_{pot1} = R_{pot2} =$
$R_1 = R_2 =$		$Z_{headphones} =$
(Use audio source for signal, voltage adjusted for ample volume)		
Parameters		
	Predicted	Measured
Bass control	<input style="width: 80px; height: 30px;" type="text"/>	<input style="width: 80px; height: 30px;" type="text"/>
Treble control	<input style="width: 80px; height: 30px;" type="text"/>	<input style="width: 80px; height: 30px;" type="text"/>
(Identify which pot is which)		
Frequency response (maximum bass, minimum treble)		Frequency response (minimum bass, maximum treble)
V_{out}		
	f	f

Note: when testing the frequency response of the tone control circuit, you may need to replace the headphones with a non-inductive resistor of equivalent impedance, and measure V_{out} across it.

[file 02022](#)

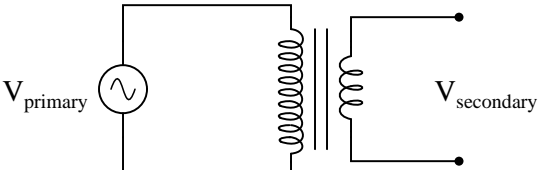
Competency: Tone balance control circuit		Version:																																																		
Schematic																																																				
Given conditions																																																				
$L_1 =$	$C_1 =$	$R_{pot1} = R_{pot2} =$																																																		
$R_1 = R_2 =$	$Z_{speaker} =$	$T_1 =$																																																		
(Use audio source for signal, voltage adjusted for ample volume)																																																				
Parameters																																																				
	Predicted	Measured																																																		
Bass control																																																				
Treble control																																																				
(Identify which pot is which)																																																				
Frequency response (maximum bass, minimum treble)		Frequency response (minimum bass, maximum treble)																																																		
V_{out}	<table border="1" style="width: 100%; height: 100%; border-collapse: collapse;"> <tr><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td></tr> <tr><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td></tr> <tr><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td></tr> <tr><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td></tr> <tr><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td><td style="width: 20px; height: 20px;"></td></tr> </table>																																																			V_{out}
f		f																																																		

Note: when testing the frequency response of the tone control circuit, you may need to replace the transformer/speaker assembly with a non-inductive resistor of equivalent impedance, and measure V_{out} across it.

file 02023

Competency: Noise coupling and decoupling	Version:								
Schematic									
Given conditions									
$C_{\text{decoupling}} =$	Cable length =								
Parameters									
<i>Predicted values are qualitative only (least, greatest, little bit less than . . .)</i>									
$V_{\text{noise (1b-2b)}}$	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> </tbody> </table>	Predicted	Measured						
Predicted	Measured								
$V_{\text{noise (2b-3b)}}$	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> </tbody> </table>	Predicted	Measured						
Predicted	Measured								
$V_{\text{noise (3b-4b)}}$	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> </tbody> </table>	Predicted	Measured						
Predicted	Measured								
} Without $C_{\text{decoupling}}$									
$V_{\text{noise (1b-2b)}}$	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> </tbody> </table>	Predicted	Measured						
Predicted	Measured								
$V_{\text{noise (2b-3b)}}$	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> </tbody> </table>	Predicted	Measured						
Predicted	Measured								
$V_{\text{noise (3b-4b)}}$	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> <tr> <td style="width: 60px; height: 25px;"></td> <td style="width: 60px; height: 25px;"></td> </tr> </tbody> </table>	Predicted	Measured						
Predicted	Measured								
} With $C_{\text{decoupling}}$ connected across test points									

file 01692

Competency: Transformer voltage ratio	Version:						
Schematic							
							
Given conditions							
Transformer winding (turns) ratio =							
$V_{\text{primary}} =$							
$f =$							
Parameters							
<table><thead><tr><th></th><th>Predicted</th><th>Measured</th></tr></thead><tbody><tr><td>V_{sec}</td><td><input type="text"/></td><td><input type="text"/></td></tr></tbody></table>			Predicted	Measured	V_{sec}	<input type="text"/>	<input type="text"/>
	Predicted	Measured					
V_{sec}	<input type="text"/>	<input type="text"/>					
Calculations							

file 03655

Competency: **Transformer voltage/current ratios** Version:

Schematic

There must be no exposed line power conductors!

Given conditions

Transformer step-down ratio =

$V_{\text{line}} =$

$R_{\text{load}} =$

Parameters

Procedure for ensuring no shock hazard when connecting meter:

Description (written by student)		Observed (written by instructor)	

	Predicted	Measured		Predicted	Measured
V_{pri}	<input style="width: 80%; height: 20px;" type="text"/>	<input style="width: 80%; height: 20px;" type="text"/>	V_{sec}	<input style="width: 80%; height: 20px;" type="text"/>	<input style="width: 80%; height: 20px;" type="text"/>
I_{pri}	<input style="width: 80%; height: 20px;" type="text"/>	<input style="width: 80%; height: 20px;" type="text"/>	I_{sec}	<input style="width: 80%; height: 20px;" type="text"/>	<input style="width: 80%; height: 20px;" type="text"/>

file 01675

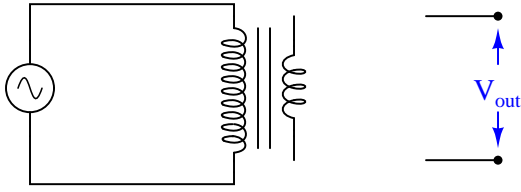
Competency: Transformer voltage/current ratios Version:																			
Schematic																			
<p style="text-align: center;">Audio transformer</p> <p style="text-align: center;">V_{source} R_{load}</p> <p style="text-align: center;">Terminal block connections 1000:8 Ω</p>																			
Given conditions																			
<p>Transformer winding (turns) ratio =</p> <p>$V_{source} =$ $R_{load} =$</p> <p>$f_{source} =$</p>																			
Parameters																			
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 20%;">Predicted</th> <th style="width: 20%;">Measured</th> <th style="width: 15%;"></th> <th style="width: 20%;">Predicted</th> <th style="width: 20%;">Measured</th> </tr> </thead> <tbody> <tr> <td style="vertical-align: middle;">V_{pri}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="vertical-align: middle;">V_{sec}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> <tr> <td style="vertical-align: middle;">I_{pri}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="vertical-align: middle;">I_{sec}</td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> </tbody> </table>			Predicted	Measured		Predicted	Measured	V_{pri}			V_{sec}			I_{pri}			I_{sec}		
	Predicted	Measured		Predicted	Measured														
V_{pri}			V_{sec}																
I_{pri}			I_{sec}																
Calculations																			

Competency: Auto-transformers	Version:												
Description													
Connect a step-down power transformer in the "buck" auto-transformer configuration, and use it to power a low-resistance load. <i>There must be no exposed line power conductors!</i>													
Given conditions													
$V_{\text{supply}} =$	$R_{\text{load}} =$ Transformer step-down ratio =												
Parameters													
	<table><thead><tr><th></th><th>Predicted</th><th>Measured</th></tr></thead><tbody><tr><td>I_{supply}</td><td><input type="text"/></td><td><input type="text"/></td></tr><tr><td>V_{load}</td><td><input type="text"/></td><td><input type="text"/></td></tr><tr><td>I_{load}</td><td><input type="text"/></td><td><input type="text"/></td></tr></tbody></table>		Predicted	Measured	I_{supply}	<input type="text"/>	<input type="text"/>	V_{load}	<input type="text"/>	<input type="text"/>	I_{load}	<input type="text"/>	<input type="text"/>
	Predicted	Measured											
I_{supply}	<input type="text"/>	<input type="text"/>											
V_{load}	<input type="text"/>	<input type="text"/>											
I_{load}	<input type="text"/>	<input type="text"/>											

file 01611

Competency: Auto-transformers		Version:
Description		
<p>Connect a step-down power transformer in the "boost" auto-transformer configuration, and use it to power a low-resistance load.</p> <p><i>There must be no exposed line power conductors!</i></p>		
Given conditions		
$V_{\text{supply}} =$	$R_{\text{load}} =$	Transformer step-down ratio =
Parameters		
	Predicted	Measured
I_{supply}	<input type="text"/>	<input type="text"/>
V_{load}	<input type="text"/>	<input type="text"/>
I_{load}	<input type="text"/>	<input type="text"/>

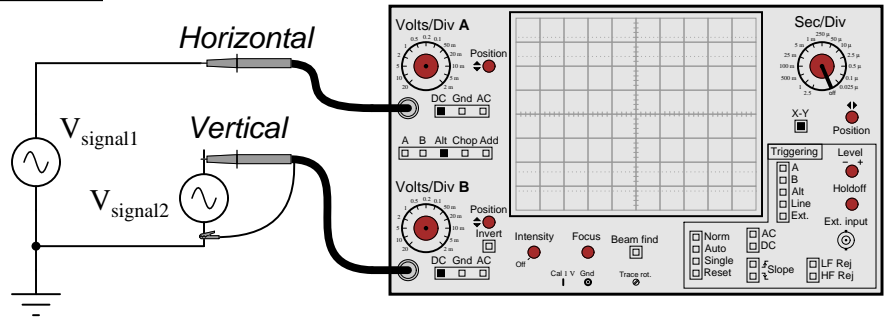
file 01612

Competency: Auto-transformers	Version:						
<div data-bbox="310 212 472 254" style="border: 1px solid black; padding: 2px;">Description</div> <p data-bbox="440 296 1138 369" style="text-align: center;">Connect a step-down transformer as an auto-transformer, to either boost or buck the input voltage.</p> <p data-bbox="440 394 1154 432" style="text-align: center;"><i>There must be no exposed line power conductors!</i></p>							
<div data-bbox="310 495 542 537" style="border: 1px solid black; padding: 2px;">Given conditions</div> <p data-bbox="402 583 509 625">$V_{\text{supply}} =$</p> <p data-bbox="342 653 574 716">Transformer step-down ratio =</p> <p data-bbox="927 558 1073 600" style="text-align: right;">Boost <input type="checkbox"/></p> <p data-bbox="938 653 1073 695" style="text-align: right;">Buck <input type="checkbox"/></p>							
<div data-bbox="310 779 472 821" style="border: 1px solid black; padding: 2px;">Schematic</div> <div data-bbox="532 863 1049 1052" style="text-align: center;">  </div> <p data-bbox="367 1087 1211 1125" style="text-align: center;">(Be sure to note the transformer's polarity using dot convention)</p>							
<div data-bbox="310 1167 472 1209" style="border: 1px solid black; padding: 2px;">Parameters</div> <table data-bbox="334 1230 789 1325" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 35%; text-align: center;">Predicted</th> <th style="width: 35%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td style="vertical-align: middle;">V_{output}</td> <td style="text-align: center;"><input style="width: 80%; height: 20px;" type="text"/></td> <td style="text-align: center;"><input style="width: 80%; height: 20px;" type="text"/></td> </tr> </tbody> </table>			Predicted	Measured	V_{output}	<input style="width: 80%; height: 20px;" type="text"/>	<input style="width: 80%; height: 20px;" type="text"/>
	Predicted	Measured					
V_{output}	<input style="width: 80%; height: 20px;" type="text"/>	<input style="width: 80%; height: 20px;" type="text"/>					

file 02131

Competency: **Lissajous figures for frequency ratio measurement** Version:

Schematic

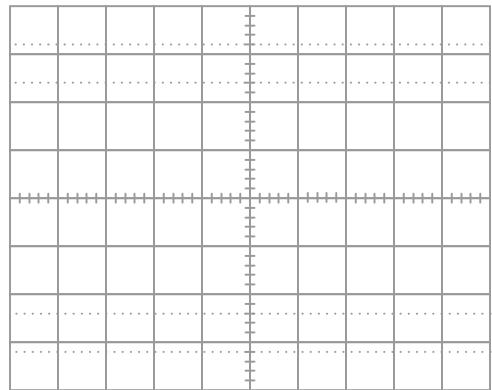


Given conditions

(Voltage specified by instructor, frequencies set by student)

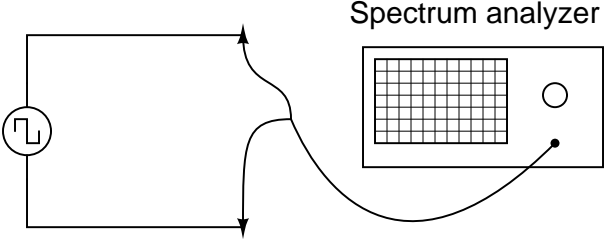
V_{signal1} and $V_{\text{signal2}} =$

Lissajous figure

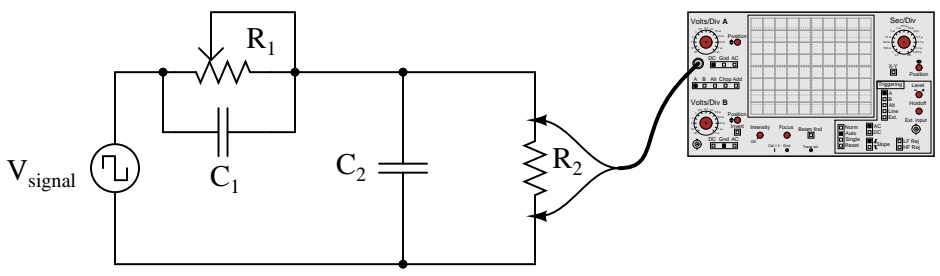


Parameters

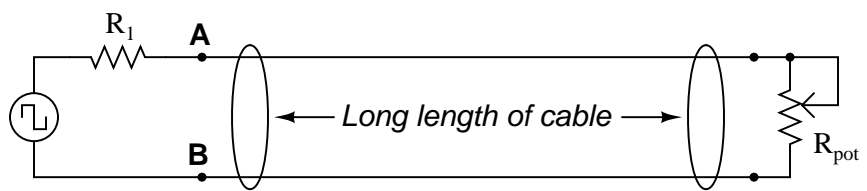
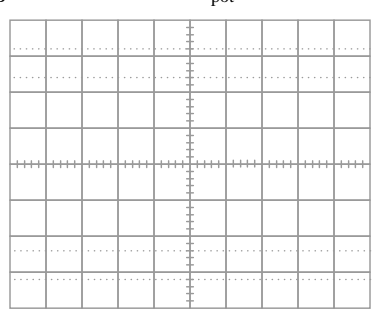
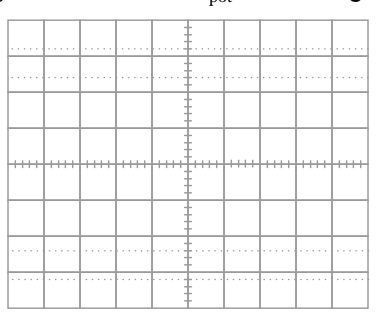
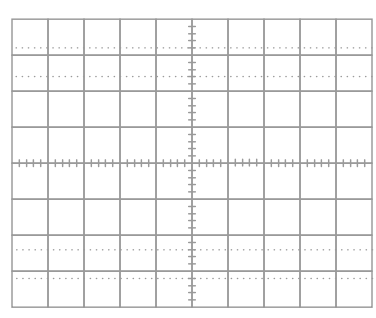
	Predicted	Measured
$\frac{f_{\text{signal2}}}{f_{\text{signal1}}}$	<input type="text"/>	<input type="text"/>

Competency: Fourier analysis of a square wave	Version:	
Schematic		
		
Given conditions		
$V_{\text{supply}} =$	Duty cycle = 50%	
$f_{\text{fundamental}} =$		
Parameters		
	Predicted	Measured
1st "overtone" amplitude	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>
1st "overtone" frequency	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>
2nd "overtone" amplitude	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>
2nd "overtone" frequency	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>
3rd "overtone" amplitude	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>
3rd "overtone" frequency	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>

[file 01684](#)

Competency: Balanced attenuator circuit	Version:						
Schematic							
							
Given conditions							
$V_{\text{signal}} =$	$R_2 =$						
$f_{\text{signal}} =$	$C_1 =$						
	$C_2 =$						
Parameters							
<table border="1" style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th></th> <th style="padding: 5px;">Predicted</th> <th style="padding: 5px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="text-align: center; padding: 5px;">R_1</td> <td style="width: 60px; height: 20px;"></td> <td style="width: 60px; height: 20px;"></td> </tr> </tbody> </table>		Predicted	Measured	R_1			
	Predicted	Measured					
R_1							
(necessary to achieve undistorted square-wave output)							
Fault analysis							
Suppose component fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted What will happen in the circuit?							

file 01661

Competency: Characteristic cable impedance		Version:	
Schematic			
			
Given conditions			
$f_{\text{supply}} =$	$R_1 =$	$R_{\text{pot(max)}} =$	
Velocity factor =			
Parameters			
	Predicted	Measured	Measured
Length of cable	<input type="text"/>	<input type="text"/>	Z_0 <input type="text"/>
V_{AB} waveform with R_{pot} set too low		V_{AB} waveform with R_{pot} set too high	
			
V_{AB} waveform with $R_{\text{pot}} = Z_0$			
			

file 01915

(Template)

Competency:	Version:
Schematic	
Given conditions	
Parameters	
Predicted	Measured
<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>

file 01602

Answers

Answer 1

You may use circuit simulation software to set up similar oscilloscope display interpretation scenarios, for practice or for verification of what you see in this exercise.

Answer 2

You may use circuit simulation software to set up similar oscilloscope display interpretation scenarios, for practice or for verification of what you see in this exercise.

Answer 3

You may use circuit simulation software to set up similar oscilloscope display interpretation scenarios, for practice or for verification of what you see in this exercise.

Answer 4

You may use circuit simulation software to set up similar oscilloscope display interpretation scenarios, for practice or for verification of what you see in this exercise.

Answer 5

There really isn't much you can do to verify your experimental results. That's okay, though, because the results are qualitative anyway.

Answer 6

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 7

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 8

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 9

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 10

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 11

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 12

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 13

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 14

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 15

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 16

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 17

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 18

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 19

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 20

The predicted value should be easy enough to figure out, given this is nothing more than a resistive voltage divider. If you are not configuring the oscilloscope properly, you will not get the correct measurement value!

Answer 21

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 22

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 23

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 24

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 25

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 26

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 27

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 28

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 29

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 30

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 31

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 32

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 33

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 34

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 35

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 36

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 37

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 38

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 39

Use circuit simulation software to verify your predicted and measured parameter values, using an AC current source as the motor, and a multi-conductor transmission line as the cable. Note: this may be quite complicated to set up in simulation!

Answer 40

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 41

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 42

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 43

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 44

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 45

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 46

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 47

Use circuit simulation software to verify your predicted and measured parameter values.

Answer 48

Use circuit simulation software to verify your predicted and measured parameter waveforms.

Note: this circuit works on the same basic principle as the compensation adjustment on high-quality oscilloscope probes, except that here the resistor is variable and not the capacitor.

Answer 49

The meter measurements you take will constitute the “final word” for validating your predictions.

Answer 50

The oscilloscope display will conclusively show when $R_{pot} = Z_0$.

Answer 51

Here, you would indicate where or how to obtain answers for the requested parameters, but not actually give the figures. My stock answer here is “use circuit simulation software” (Spice, Multisim, etc.).

Notes 1

An oscilloscope is nothing more than a graphical voltmeter, having the ability to represent fast-changing voltages over time in the form of a graph. It is very important for all students of electronics to learn how to use an oscilloscope well!

Use a sine-wave function generator for the AC voltage source, and be sure set the frequency to some reasonable value (well within the capability of both the oscilloscope and counter to measure).

If this is not the first time students have done this, be sure to “mess up” the oscilloscope controls prior to them making adjustments. Students *must* learn how to quickly configure an oscilloscope’s controls to display any arbitrary waveform, if they are to be proficient in using an oscilloscope as a diagnostic tool.

General concepts and principles to emphasize

- Basic oscilloscope operation (vertical sensitivity, coupling, timebase, triggering)
- Location of “ground” connections on both the oscilloscope and signal generator
- Relationship between the *period* of a wave and its *frequency*

Suggestions for Socratic discussion and experimentation

- What is the distinction between a waveform’s *peak* voltage value and its *peak-to-peak* voltage value?
- Demonstrate how to make the waveform appear taller (i.e. each cycle extending farther along the vertical axis) on the oscilloscope’s display.
- Demonstrate how to make the waveform appear longer (i.e. each cycle extending farther along the horizontal axis) on the oscilloscope’s display.
- Demonstrate how to set the *triggering* value for the oscilloscope, and what difference that makes in the displayed waveform.

An oscilloscope is nothing more than a graphical voltmeter, having the ability to represent fast-changing voltages over time in the form of a graph. It is very important for all students of electronics to learn how to use an oscilloscope well!

Use a sine-wave function generator for the AC voltage source, and be sure set the frequency to some reasonable value (well within the capability of both the oscilloscope and counter to measure).

Some digital oscilloscopes have “auto set” controls which automatically set the vertical, horizontal, and triggering controls to “lock in” a waveform. Be sure students are learning how to set up these controls on their own rather than just pushing the “auto set” button!

General concepts and principles to emphasize

- Basic oscilloscope operation (vertical sensitivity, coupling, timebase, triggering)
- Location of “ground” connections on both the oscilloscope and signal generator
- Relationship between the *period* of a wave and its *frequency*

Suggestions for Socratic discussion and experimentation

- What is the distinction between a waveform’s *peak* voltage value and its *peak-to-peak* voltage value?
- The standard unit of measurement for period is *seconds* (s). The standard unit of measurement for frequency is *Hertz* (Hz), which means “cycles per second.” However, an alternate unit of measurement for frequency is *inverse seconds*, or s^{-1} . Explain why $\text{Hz} = s^{-1}$.
- If you change the *voltage* level of the AC source, does this affect its frequency? Why or why not?
- Demonstrate how to make the waveform appear taller (i.e. each cycle extending farther along the vertical axis) on the oscilloscope’s display.
- Demonstrate how to make the waveform appear longer (i.e. each cycle extending farther along the horizontal axis) on the oscilloscope’s display.
- Demonstrate how to set the *triggering* value for the oscilloscope, and what difference that makes in the displayed waveform.

Use a sine-wave function generator for the AC voltage source, and be sure set the frequency to some reasonable value (well within the capability of a multimeter to measure). It is very important that students learn to convert between peak and RMS measurements for sine waves, but you might want to mix things up a bit by having them do the same with triangle waves and square waves as well! It is vital that students realize the rule of $V_{RMS} = \frac{V_{peak}}{\sqrt{2}}$ only holds for *sinusoidal* signals.

An important point to note in this exercise is that the “variable” adjustment on the vertical sensitivity for the input channel must be turned fully so that the knob “clicks” into its calibrated position. If this fine-adjustment is not set in the calibrated position, your voltage measurements will be inaccurate!

If you do choose to challenge students with non-sinusoidal waveshapes, be very sure that they do their voltmeter measurements using *true-RMS* meters! This means no analog voltmeters, which are “miscalibrated” so their inherently average-responding movements register (sinusoidal) RMS accurately. Your students must use true-RMS digital voltmeters in order for their non-sinusoidal RMS measurements to correlate with their calculations.

Incidentally, this lab exercise also works well as a demonstration of the importance of true-RMS indicating meters, comparing the indications of analog, non-true-RMS digital, and true-RMS digital on the same non-sinusoidal waveform!

General concepts and principles to emphasize

- The concept of “Root-Mean-Square” (RMS) measurement
- Basic oscilloscope operation (vertical sensitivity, coupling, timebase, triggering)
- Location of “ground” connections on both the oscilloscope and signal generator

Suggestions for Socratic discussion and experimentation

- Explain what the “RMS” (Root-Mean-Square) value means for any AC waveform.
- If you change the *frequency* of the AC source, does this affect its RMS or peak voltage value? Why or why not?
- A common misconception among students is that the RMS value of any waveform is *always* equal to 0.707 times the waveform’s peak value. Refute this misconception with a demonstrated example!

Notes 4

Use a sine-wave function generator for the AC voltage source, and be sure set the frequency to some reasonable value (well within the capability of both the oscilloscope and counter to measure).

An important point to note in this exercise is that the “variable” adjustment on the horizontal timebase must be turned fully so that the knob “clicks” into its calibrated position. If this fine-adjustment is not set in the calibrated position, your time measurements (and therefore your frequency calculations) will be inaccurate!

General concepts and principles to emphasize

- Relationship between the *period* of a wave and its *frequency*
- Basic oscilloscope operation (vertical sensitivity, coupling, timebase, triggering)

Suggestions for Socratic discussion and experimentation

- The standard unit of measurement for period is *seconds* (s). The standard unit of measurement for frequency is *Hertz* (Hz), which means “cycles per second.” However, an alternate unit of measurement for frequency is *inverse seconds*, or s^{-1} . Explain why $\text{Hz} = s^{-1}$.
- If you change the *voltage* level of the AC source, does this affect its frequency? Why or why not?

Notes 5

If the oscilloscope does not have its own internal square-wave signal source, use a function generator set up to output square waves at 1 volt peak-to-peak at a frequency of 1 kHz.

If this is not the first time students have done this, be sure to “mess up” the oscilloscope controls prior to them making adjustments. Students *must* learn how to quickly configure an oscilloscope’s controls to display any arbitrary waveform, if they are to be proficient in using an oscilloscope as a diagnostic tool.

General concepts and principles to emphasize

- Basic oscilloscope operation (vertical sensitivity, coupling, timebase, triggering)
- Relationship between the *period* of a wave and its *frequency*

Suggestions for Socratic discussion and experimentation

- Demonstrate how to make the waveform appear taller (i.e. each cycle extending farther along the vertical axis) on the oscilloscope’s display.
- Demonstrate how to make the waveform appear longer (i.e. each cycle extending farther along the horizontal axis) on the oscilloscope’s display.
- Explain why changes in the *triggering* level don’t seem to affect the displayed waveform at all.

In this exercise you will explore the concept of *reactance*, which is a form of opposition to the flow of electric current that is similar to but not identical to resistance. The distinction between reactance and resistance is a consequence of energy flow in an electrical component: components which *transfer* electrical energy out of the circuit and into some other form (such as heat in the case of a resistor or mechanical work in the case of an electric motor) exhibit *resistance*; components which have the ability to *absorb* energy from the circuit and *return* energy back into the circuit (e.g. inductors and capacitors) exhibit *reactance*.

In order to achieve results closely approximating ideal, you need to use an inductor that has very little wire resistance (the less, the better!). Your multimeter will be useful here to measure the DC resistance of the inductor – which is strictly a function of wire resistance and not inductance – and allow you to identify the most suitable inductor for this exercise. The problem with resistance is that it is a fundamentally different kind of opposition to electric current. If your inductor happens to possess a lot of resistance (in addition to inductive reactance), the results will be skewed by the presence of this resistance.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit).

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

General concepts and principles to emphasize

- Self-induction (i.e. how a single coil is able to experience induction as a consequence of a changing current passing through it)
- The concept of *reactance*, and how it differs from *resistance*
- The relationship between inductance, frequency, and inductive reactance

Suggestions for Socratic discussion and experimentation

- Identify ways the inductor could be modified so as to possess more inductance.
- Explain how *reactance* differs from *resistance*, even though they are both quantified using the same unit of measurement: *ohms* (Ω).
- Explain why current changes as source frequency changes, despite voltage remaining the same.
- A technique used in making wire-wound resistors is something called a *bifilar winding*. Bifilar windings have nearly zero inductance. Research how a bifilar winding is made, and then explain how it works to minimize induction and also why this might be important for making resistors.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard inductor values. If the inductors are not well shielded, be sure to keep them adequately separated so as to avoid mutual inductance!

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

In order to achieve results closely approximating ideal, you need to use an inductor that has very little wire resistance (the less, the better!). Your multimeter will be useful here to measure the DC resistance of the inductor – which is strictly a function of wire resistance and not inductance – and allow you to identify the most suitable inductor for this exercise. The problem with resistance is that it is a fundamentally different kind of opposition to electric current. If your inductor happens to possess a lot of resistance (in addition to inductive reactance), the results will be skewed by the presence of this resistance.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and inductor values.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- The concept of *reactance*, and how it differs from *resistance*
- The concept of *impedance*, and how it relates to both *resistance* and *reactance*
- The relationship between inductance, frequency, and inductive reactance

Suggestions for Socratic discussion and experimentation

- Explain how *reactance* differs from *resistance*, even though they are both quantified using the same unit of measurement: *ohms* (Ω).
- What will happen to the amount of current in this circuit if the source frequency is increased (assuming a constant source voltage)?
- What will happen to the amount of current in this circuit if the inductor is replaced by another having greater inductance?
- What will happen to the amount of current in this circuit if the resistor is replaced by another having greater resistance?
- Explain why the sum of the resistor's voltage and the inductor's voltage does *not* equal the source voltage.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and inductor values, and select a frequency that results in the inductor having a high Q value, so that its parasitic resistance does not become a significant factor in the calculations.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Notes 10

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify a standard capacitor value.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

Notes 11

In this exercise you will explore the concept of *reactance*, which is a form of opposition to the flow of electric current that is similar to but not identical to resistance. The distinction between reactance and resistance is a consequence of energy flow in an electrical component: components which *transfer* electrical energy out of the circuit and into some other form (such as heat in the case of a resistor or mechanical work in the case of an electric motor) exhibit *resistance*; components which have the ability to *absorb* energy from the circuit and *return* energy back into the circuit (e.g. inductors and capacitors) exhibit *reactance*.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify a standard capacitor value.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

General concepts and principles to emphasize

- The concept of *reactance*, and how it differs from *resistance*
- The relationship between capacitance, frequency, and capacitive reactance
- How to interpret numerical capacitor value codes

Suggestions for Socratic discussion and experimentation

- Identify ways the capacitor could be modified so as to possess more capacitance.
- How well would this experiment work if the source was DC instead of AC?
- Explain why current changes as source frequency changes, despite voltage remaining the same.
- If two identical capacitors were connected in series, what would happen to total capacitance in the circuit? What would happen to total capacitive reactance in the circuit?
- If two identical capacitors were connected in parallel, what would happen to total capacitance in the circuit? What would happen to total capacitive reactance in the circuit?

Notes 12

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard capacitor values.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

Students often become confused when learning about series and parallel capacitive reactances, because many think capacitors are inherently "opposite" of inductors and resistors in all respects. In other words, they first learn that *capacitance* (measured in Farads) adds in parallel and diminishes in series, and that this is just the opposite of resistance (Ohms) and inductance (Henrys), and they mistakenly carry this thinking on through capacitive *reactance* (Ohms) as well. The real lesson of this exercise is that reactances add in series, regardless of their nature.

Notes 13

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard capacitor values.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and capacitor values.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- The concept of *reactance*, and how it differs from *resistance*
- The concept of *impedance*, and how it relates to both *resistance* and *reactance*
- The relationship between capacitance, frequency, and capacitive reactance

Suggestions for Socratic discussion and experimentation

- Explain how *reactance* differs from *resistance*, even though they are both quantified using the same unit of measurement: *ohms* (Ω).
- What will happen to the amount of current in this circuit if the source frequency is increased (assuming a constant source voltage)?
- What will happen to the amount of current in this circuit if the capacitor is replaced by another having greater capacitance?
- What will happen to the amount of current in this circuit if the resistor is replaced by another having greater resistance?
- Explain why the sum of the resistor's voltage and the capacitor's voltage does *not* equal the source voltage.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and capacitor values.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- The concept of *reactance*, and how it differs from *resistance*
- The concept of *impedance*, and how it relates to both *resistance* and *reactance*
- The relationship between capacitance, frequency, and capacitive reactance

Suggestions for Socratic discussion and experimentation

- Explain how *reactance* differs from *resistance*, even though they are both quantified using the same unit of measurement: *ohms* (Ω).
- What will happen to the total amount of current in this circuit if the source frequency is increased (assuming a constant source voltage)?
- What will happen to the total amount of current in this circuit if the capacitor is replaced by another having greater capacitance?
- What will happen to the total amount of current in this circuit if the resistor is replaced by another having greater resistance?
- Explain why the sum of the resistor's current and the capacitor's current does *not* equal the source current.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and capacitor values.

I recommend using components that produce a phase shift of approximately 45 degrees within the low audio frequency range (less than 1 kHz). This allows most multimeters to be used for voltage measurement in conjunction with the oscilloscope.

One way for students to do this assessment is to have them predict what the sine waves will look like, based on circuit component values. They sketch the predicted waveforms on the grid provided before actually hooking up an oscilloscope, then the instructor assesses them based on the conformity of the real oscilloscope display to their prediction.

General concepts and principles to emphasize

- Basic oscilloscope operation (vertical sensitivity, coupling, timebase, triggering)
- Location of “ground” connections on both the oscilloscope and signal generator
- How to properly configure an oscilloscope for dual-trace operation

Suggestions for Socratic discussion and experimentation

- Explain why the “ground” clip of the oscilloscope must be connected to the same point in the circuit as the grounded terminal of the signal generator.
- Does it matter which input channel on the oscilloscope is used for triggering the sweep? Why or why not?
- Explain what will happen if you set the oscilloscope’s triggering to “line”. What exactly does “line” mean with regard to triggering, and why would an oscilloscope have such a setting?

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and capacitor values.

I recommend using components that produce a phase shift of approximately 45 degrees within the low audio frequency range (less than 1 kHz). This allows most multimeters to be used for voltage measurement in conjunction with the oscilloscope.

Something to suggest that students do is use their oscilloscopes' *ground* position on the coupling switch, to help center the dot on the screen before they set up their Lissajous figures for phase shift measurement.

One way for students to do this assessment is to have them predict what the Lissajous figure will look like, based on circuit component values. They sketch the predicted Lissajous figure on the grid provided (working the math "backward" to arrive at n and m values before actually hooking up an oscilloscope), then the instructor assesses them based on the conformity of the real oscilloscope display to their prediction.

General concepts and principles to emphasize

- Basic oscilloscope operation (vertical sensitivity, coupling, timebase, triggering)
- Location of "ground" connections on both the oscilloscope and signal generator

Suggestions for Socratic discussion and experimentation

- Based on the position of the oscilloscope's ground clip, identify the voltage being sensed by each of the two input channels. Remember that voltage is always measured between *two* points!
- Explain what you must do to the oscilloscope in order that the Lissajous figure has the same overall height and width (i.e. that the two n dimensions are identical), since the two channels clearly do not read the same amount of voltage.
- Identify some way that the oscilloscope could be connected to the circuit to achieve a 90° phase shift between the two channels. Note that this may require some creativity to work around the problem of ground connections between the signal generator and the oscilloscope!

Here, students must choose the right type of series RC circuit configuration to provide the requested phase shift. This, of course, also involves choosing proper values for C_1 and R_1 , and being able to successfully measure phase shift with an oscilloscope.

I recommend selecting a phase shift angle (Θ) somewhere between 15° and 75° . Angles too close to 90° will result in small output voltages that are difficult to measure through the noise.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

This is a very interesting circuit to built and test. You may build one using $1\ \mu\text{F}$ capacitors, $2.7\ \text{k}\Omega$ resistors, and a $100\ \text{k}\Omega$ potentiometer that will successfully operate on 60 Hz power-line excitation. If you prefer to use audio frequency power, try $0.047\ \mu\text{F}$ capacitors, $1\ \text{k}\Omega$ resistors, a $100\ \text{k}\Omega$ potentiometer, and $3.386\ \text{kHz}$ for the source frequency. The circuit works best if each resistor value is equal in ohms to each capacitor's reactance in ohms.

An interesting thing to note about using line power is that any distortions in the excitation sine-wave will become obvious when the potentiometer wiper is turned toward the differentiating position (where θ is positive). If listened to with an audio detector, you may even hear the change in timbre while moving the wiper from one extreme to the other. If excited by a "clean" sine-wave, however, no change in timbre should be heard because there are no harmonics present.

General concepts and principles to emphasize

- The concept of *reactance*, and how it differs from *resistance*
- The concept of *impedance*, and how it relates to both *resistance* and *reactance*
- The relationship between capacitance, frequency, and capacitive reactance
- The concept of "balancing" a Wheatstone bridge circuit

Suggestions for Socratic discussion and experimentation

- A good problem-solving technique to apply in cases where we need to determine the direction of a change is to consider *limiting cases*. Instead of asking ourselves what would happen if the potentiometer's wiper position changed *slightly*, we ask ourselves what would happen if the wiper's position were moved *dramatically*. Explain how this problem-solving technique applies to this particular system. How, exactly, does the output voltage in this circuit become easier to analyze in these limiting cases?
- Explain why the circuit works better if the potentiometer's resistance is much greater than that of R_1 or R_2 . Hint: this is another good application of the "limiting cases" problem-solving technique.
- Explain what would happen to all voltages and currents in this circuit if resistor R_1 failed *open*.
- Explain what would happen to all voltages and currents in this circuit if resistor R_1 failed *shorted*.
- Explain what would happen to all voltages and currents in this circuit if resistor R_2 failed *open*.
- Explain what would happen to all voltages and currents in this circuit if resistor R_2 failed *shorted*.
- Explain what would happen to all voltages and currents in this circuit if capacitor C_1 failed *open*.
- Explain what would happen to all voltages and currents in this circuit if capacitor C_1 failed *shorted*.
- Explain what would happen to all voltages and currents in this circuit if capacitor C_2 failed *open*.
- Explain what would happen to all voltages and currents in this circuit if capacitor C_2 failed *shorted*.

The nature of the AC signal source is not crucial, so long as an accurate peak measurement may be obtained. I recommend specifying equal-value resistors to make the voltage drop calculation as easy as possible. The purpose of this exercise is not how to calculate voltage divider outputs, but rather how to utilize both inputs of a dual-trace oscilloscope to perform *differential* voltage measurements.

An important point to note in this exercise is that the “variable” adjustment on the vertical sensitivity for each channel must be turned fully so that the knob “clicks” into its calibrated position. If this fine-adjustment is not set in the calibrated position, your voltage measurements will be inaccurate!

General concepts and principles to emphasize

- The concept of differential voltage measurement on an oscilloscope
- Basic oscilloscope operation (vertical sensitivity, coupling, timebase, triggering)
- Location of “ground” connections on both the oscilloscope and signal generator

Suggestions for Socratic discussion and experimentation

- Explain why the oscilloscope must be configured to *subtract* one channel’s voltage from the other channel when performing a differential measurement.
- Is there a safe place to connect the oscilloscope’s “ground” clip in this circuit? Is this a necessary thing to do?
- Explain why it is critically important that the vertical sensitivity be set identically for both input channels when performing differential measurements.

You will need an AC signal source of variable voltage, so that the reference voltage at test point **A** (V_A) may be precisely adjusted to 1 volt RMS. The frequency of the signal source must be within the range of the voltmeter to measure, of course. You may use a sine-wave signal generator as the source, but a step-down transformer and series potentiometer works just as well! The purpose of this exercise is not how to calculate voltage divider outputs, but rather how to utilize a dB-reading meter to measure signal strength in decibels rather than volts AC.

Most high-quality digital multimeters will measure dBV in addition to AC volts RMS. Some have a “zero” or “relative” button which acts like the “tare” button on an electronic weigh scale. With such a meter, one may set 0 dB to reference at *any* measurable level of AC voltage. Of course, this means the meter will be measuring dB instead of dBV, since the reference point is made arbitrary with the press of the “relative” button. However, this is a very useful tool for electronic signal measurements, where source strength may be set to 0 dB and then losses measured directly in -dB (relative to the source) just as easily as normal voltage measurements.

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and capacitor values.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students’ results by asking them to predict the consequences of certain circuit faults.

Notes 23

Use a sine-wave function generator for the AC voltage source. I recommend against using line-power AC because of strong harmonic frequencies which may be present (due to nonlinear loads operating on the same power circuit). Specify standard resistor and capacitor values.

If students are to use a multimeter to make their current and voltage measurements, be sure it is capable of accurate measurement at the circuit frequency! Inexpensive digital multimeters often experience difficulty measuring AC voltage and current toward the high end of the audio-frequency range.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Notes 24

Use a sine-wave function generator for the AC voltage source. Specify standard resistor and capacitor values.

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of "cutoff". You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Notes 25

Use a sine-wave function generator for the AC voltage source. Specify standard resistor and capacitor values.

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of "cutoff". You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Filter circuits are tremendously useful in many different applications, because they allow us to screen out unwanted noise in signals and to isolate one signal from others mixed together. Filters built with a single capacitor and single resistor (“RC”) are simple yet effective circuits for this task, and it is important for students to thoroughly understand their functions.

Use a sine-wave function generator for the AC voltage source. Specify a cutoff frequency within the audio range.

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of “cutoff”. You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the “X-Y” mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

General concepts and principles to emphasize

- The concept of *reactance*, and how it differs from *resistance*
- The concept of *impedance*, and how it relates to both *resistance* and *reactance*
- The relationship between capacitance, frequency, and capacitive reactance

Suggestions for Socratic discussion and experimentation

- A good problem-solving technique to identify the function of an RC filter circuit is to perform a “thought experiment” whereby you consider how the circuit will respond to an input signal of low frequency versus an input signal of high frequency. By qualitatively analyzing the effects of frequency change on output voltage, you will be able to determine whether the filter circuit in question is high-pass or low-pass.
- A common tendency among students is to try to *memorize* various circuit topologies rather than to *analyze* their operation based on fundamental principles. Memorization is certainly the easier of the two tactics, but it suffers significant disadvantages. Identify some of these disadvantages and explain why it is better for your education to use *reason* rather than *rote* when learning the functions of new circuit forms.

Notes 27

Use a sine-wave function generator for the AC voltage source. Specify components giving a notch frequency within the audio range:

$$f_{notch} = \frac{1}{2\pi RC}$$

I have had good success using the following values:

- $R_1 = 10 \text{ k}\Omega$
- $R_2 = 10 \text{ k}\Omega$
- $R_3 = 5 \text{ k}\Omega$ (actually, two $10 \text{ k}\Omega$ resistors in parallel)
- $C_1 = 0.001 \text{ }\mu\text{F}$
- $C_2 = 0.001 \text{ }\mu\text{F}$
- $C_3 = 0.002 \text{ }\mu\text{F}$ (actually, two $0.001 \text{ }\mu\text{F}$ capacitors in parallel)

These component values yield a theoretical notch frequency of 16.13 kHz (the very high end of audio range), with the actual measured notch frequency for my circuit (without considering component tolerances) being 15.92 kHz.

I recommend setting the function generator output for 1 volt, to make it easier for students to measure the point of "cutoff". You may set it at some other value, though, if you so choose (or let students set the value themselves when they test the circuit!).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Notes 28

Use a sine-wave function generator for the AC voltage source. Specify standard resistor, capacitor, and inductor values. I have used a small 100 mH inductor, a $0.033 \text{ }\mu\text{F}$ capacitor, and $100 \text{ }\Omega$ resistor with good success. In any case I recommend keeping the resonant frequency within the mid-audio range (1 kHz to 10 kHz) to avoid problems with low inductor Q (frequency too low) and stray capacitance and inductance issues (frequency too high).

Notes 29

A digital oscilloscope capable of "capturing" the dampened oscillations will be necessary for this exercise. It will be very challenging to measuring the oscillation frequency using an analog (phosphor) oscilloscope!

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

This is perhaps the most reliable means of measuring inductance without an impedance bridge or an LCR meter. You may wish to ask your students to explain *why* this method of measurement is so good (hint: they must explain why the inductor's intrinsic resistance has no effect on the measurement).

I prefer this particular circuit design for L measurement because series resistance does not skew the resonant point, and because the series capacitor prevents any possible DC current from "biasing" or "saturating" the inductor's core.

If your students own high-quality multimeters capable of measuring audio-frequency AC current and frequency, then the best way to do this is to replace the resistor R_1 with their ammeters. Otherwise, use an oscilloscope to measure (maximum) voltage dropped across R_1 .

In order to obtain good measurements using this technique, I recommend following these guidelines:

- Choose a value of R_1 low enough to give a sharp bandwidth, but not so low that the voltage signal dropped across it is "fuzzy" with noise and difficult to accurately discern the period of.
- Choose a value for C_1 as low as possible to give sharp bandwidth (thereby maximizing the $\frac{L}{C}$ ratio), without pushing the circuit's resonant frequency too close to the inductor's self-resonant frequency.
- Avoid frequencies above the audio range, lest your students measure the inductor's self-resonant point!
- Use minimal output from the signal generator, to avoid voltage and current levels that will approach core saturation in the inductor.

I've had fair results using one of the windings of a small audio output transformer (center-tapped 1000 Ω primary winding, with 8 Ω secondary winding) as the inductor, connected in series with either a 0.1 μF or a 0.47 μF metal-film capacitor, all in series with a 100 ohm resistor. For best results, of course, pre-measure the value of the capacitor rather than go by its advertised value.

I have also used a 100 mH inductor (nominal), in series with a 0.033 μF capacitor and 100 Ω resistor, with good results.

General concepts and principles to emphasize

- The concept of *reactance*, and how it differs from *resistance*
- The relationship between inductance, frequency, and inductive reactance
- The relationship between capacitance, frequency, and capacitive reactance
- The concept of *impedance*, and how it relates to both *resistance* and *reactance*
- The concept of *resonance*, and how resonant frequency relates to both capacitance and inductance

Suggestions for Socratic discussion and experimentation

- Measure the voltages across the resistor, inductor, and capacitor. Compare these voltage measurements to the signal generator's output voltage. What do you notice about these component voltages in relation to the supply voltage? How does this differ from series voltage drops in a DC circuit? Is this a violation of Kirchhoff's Voltage Law?
- All real inductors contain wire *resistance* as well as *inductance*. Will the inevitable presence of wire resistance within the inductor skew your measurement of inductance in this resonant circuit? Why or why not?
- All real inductors contain inter-winding *capacitance* as well as *inductance*. Will the inevitable presence of some capacitance within the inductor skew your measurement of inductance in this resonant circuit? Why or why not?

Use a sine-wave function generator for the AC voltage source. Specify standard resistor, capacitor, and inductor values. I have used a small 100 mH inductor, a 0.033 μF capacitor, and 100 Ω resistor with good success. In any case I recommend keeping the resonant frequency within the mid-audio range (1 kHz to 10 kHz) to avoid problems with low inductor Q (frequency too low) and stray capacitance and inductance issues (frequency too high).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Use a sine-wave function generator for the AC voltage source. Specify standard resistor, capacitor, and inductor values. I have used a small 100 mH inductor, a 0.033 μF capacitor, and 100 Ω resistor with good success. In any case I recommend keeping the resonant frequency within the mid-audio range (1 kHz to 10 kHz) to avoid problems with low inductor Q (frequency too low) and stray capacitance and inductance issues (frequency too high).

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- The concept of *reactance*, and how it differs from *resistance*
- The relationship between inductance, frequency, and inductive reactance
- The relationship between capacitance, frequency, and capacitive reactance
- The concept of *impedance*, and how it relates to both *resistance* and *reactance*
- The concept of *resonance*, and how resonant frequency relates to both capacitance and inductance

Suggestions for Socratic discussion and experimentation

- A good problem-solving technique to identify the function of an RC filter circuit is to perform a "thought experiment" whereby you consider how the circuit will respond to an input signal of low frequency versus an input signal of high frequency. By qualitatively analyzing the effects of frequency change on output voltage, you will be able to determine whether the filter circuit in question is high-pass or low-pass.
- Modify this circuit so that it uses the same components but performs a different filtering function.
- A common tendency among students is to try to *memorize* various circuit topologies rather than to *analyze* their operation based on fundamental principles. Memorization is certainly the easier of the two tactics, but it suffers significant disadvantages. Identify some of these disadvantages and explain why it is better for your education to use *reason* rather than *rote* when learning the functions of new circuit forms.

Use a sine-wave function generator for the AC voltage source. Specify a resonant frequency within the audio range.

This exercise assumes access to a variety of capacitor and/or inductor sizes, so the student may make series-parallel networks to achieve the necessary values of L and/or C . It would be wise for you (the instructor) to check your students' component kits for L and C values prior to choosing resonant frequencies for them to try to achieve.

I also recommend having students use an oscilloscope to measure AC voltage in a circuit such as this, because some digital multimeters have difficulty accurately measuring AC voltage much beyond line frequency range. I find it particularly helpful to set the oscilloscope to the "X-Y" mode so that it draws a thin line on the screen rather than sweeps across the screen to show an actual waveform. This makes it easier to measure peak-to-peak voltage.

Here, students must calculate values for C_1 and R_1 that will produce the V_{out} waveshape specified in the “Given conditions” oscilloscope plot. The input signal, of course, is a square wave. Students must calculate the time constant of the circuit (τ) such that the pulse fully decays within the pulse width (half-period) of the square wave. With 5τ being the accepted standard for full charge/discharge of a time-constant circuit, this is an easy calculation.

There are many different combinations of values for C_1 and R_1 possible for any given square-wave signal frequencies. The purpose of this exercise is for students to be able to predict and select practical component values from their parts kits.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students’ results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- How to read resistor color codes
- How to interpret numerical capacitor value codes
- How to manipulate algebraic equations containing exponential terms
- The distinction between electrical *sources* and electrical *loads*

Suggestions for Socratic discussion and experimentation

- Sketch the direction of current in this circuit while the signal generator’s output is at its positive peak. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Identify whether each of the components in this circuit is an electrical *source* or an electrical *load* during this time period.
- Sketch the direction of current in this circuit while the signal generator’s output is zero. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Identify whether each of the components in this circuit is an electrical *source* or an electrical *load* during this time period.
- Sketch the direction of current in this circuit while the signal generator’s output is at its negative peak. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Identify whether each of the components in this circuit is an electrical *source* or an electrical *load* during this time period.

Here, students must calculate values for C_1 and R_1 that will produce the V_{out} waveshape specified in the “Given conditions” oscilloscope plot. The input signal, of course, is a square wave. Students should be able to show mathematically why the time constant of the integrator (τ) must be 1.443 times the waveform’s half-period ($e^{-\frac{t}{\tau}} = \frac{1}{2}$). Instructors, note: the calculations for this circuit, with $V_{out} = \frac{1}{3}V_{in}$, are exactly the same as for a 555 timer circuit, because 555 timers also cycle their capacitors’ voltages at peak-to-peak values equal to one-third of the supply voltage.

There are many different combinations of values for C_1 and R_1 possible for any given square-wave signal frequencies. The purpose of this exercise is for students to be able to predict and select practical component values from their parts kits.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students’ results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- How to read resistor color codes
- How to interpret numerical capacitor value codes
- How to manipulate algebraic equations containing exponential terms
- The distinction between electrical *sources* and electrical *loads*

Suggestions for Socratic discussion and experimentation

- Sketch the direction of current in this circuit while the signal generator’s output is at its positive peak. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Identify whether each of the components in this circuit is an electrical *source* or an electrical *load* during this time period.
- Sketch the direction of current in this circuit while the signal generator’s output is zero. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Identify whether each of the components in this circuit is an electrical *source* or an electrical *load* during this time period.
- Sketch the direction of current in this circuit while the signal generator’s output is at its negative peak. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Identify whether each of the components in this circuit is an electrical *source* or an electrical *load* during this time period.

Here, students must calculate values for C_1 and R_1 that will produce the V_{out} waveshape specified in the "Given conditions" oscilloscope plot. The input signal, of course, is a square wave.

If the chosen circuit is a differentiator, students must calculate the time constant of the circuit (τ) such that the pulse fully decays within the pulse width (half-period) of the square wave. With 5τ being the accepted standard for full charge/discharge of a time-constant circuit, this is an easy calculation.

If the chosen circuit is an integrator, students should be able to show mathematically why the time constant of the integrator (τ) must be 1.443 times the waveform's half-period ($e^{-\frac{t}{\tau}} = \frac{1}{2}$). Instructors, note: the calculations for this circuit, with $V_{out} = \frac{1}{3}V_{in}$, are exactly the same as for a 555 timer circuit, because 555 timers also cycle their capacitors' voltages at peak-to-peak values equal to one-third of the supply voltage.

There are many different combinations of values for C_1 and R_1 possible for any given square-wave signal frequencies. The purpose of this exercise is for students to be able to predict and select practical component values from their parts kits.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

A good source of audio signal is the headphone output jack of almost any radio, media player, or other portable audio device. Students like being able to do a lab exercise that directly relates to technology they're already familiar with.

The higher-impedance the headphones are, the better this circuit works, since the combination of potentiometers and mixing resistors tends to result in a relatively high output impedance. I have used cheap headphones (32 ohm) with some success, given the following component values:

- $C_1 = 0.1 \mu\text{F}$
- $L_1 = 200 \text{ mH}$ (actually two 100 mH inductors in series)
- $R_1 = R_2 = 1 \text{ k}\Omega$
- $R_{pot1} = R_{pot2} = 10 \text{ k}\Omega$

Some students with limited hearing range have difficulty detecting the changes in tone using 10 k Ω potentiometers. You may wish to use 100 k Ω potentiometers instead for added attenuation. Operating such a circuit is akin to operating a water faucet with "hot" and "cold" water valves: the two settings together determine temperature *and* flow (tone and volume, respectively, for the metaphorically challenged).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

If you plan to use this exercise as a troubleshooting assessment, I recommend *against* inducing the following component failures, as they are difficult to detect when the signal source is music rather than a constant tone of known frequency and amplitude:

- Shorted capacitor (C_1)
- Shorted inductor (L_1)
- Shorted fixed-value resistors (R_1 or R_2)

Notes 38

A good source of audio signal is the headphone output jack of almost any radio, media player, or other portable audio device. Students like being able to do a lab exercise that directly relates to technology they're already familiar with.

I have experienced good success with the following component values:

- $C_1 = 0.1 \mu\text{F}$
- $L_1 = 200 \text{ mH}$ (actually two 100 mH inductors in series)
- $R_1 = R_2 = 1 \text{ k}\Omega$
- $T_1 = 1000:8 \text{ ohm}$ audio output transformer
- $R_{pot} = R_{pot2} = 10 \text{ k}\Omega$
- Speaker = small 8Ω unit (salvaged from an old clock radio or other inexpensive audio device)

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Notes 39

The longer the cable, the better the coupling between the motor conductors and the other conductors. I have found that this exercise is practical with just a few feet of four-wire telephone cable.

It is very important to use a battery for this exercise, and not an AC-DC power supply. The filter capacitors in an AC-DC power supply naturally decouple the motor's noise voltage, making it difficult to measure any at all!

Noise voltage should be measured with an oscilloscope set to AC input coupling, and recorded as peak-to-peak volts.

Notes 40

You may use an audio frequency impedance matching (1000:8 ohms) transformer or a step-down power transformer for this exercise. In either case, students need to know or figure out the turns ratio before proceeding with the experiment. If you are using an audio transformer, use a sine-wave signal generator for the voltage source, but avoid frequencies below 1kHz. If you are using a power transformer, use a Variac to provide adjustable primary voltage.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Use line-frequency power transformers for this exercise, with load resistor values low enough to “swamp” the primary winding’s excitation current, so that the primary/secondary current ratio is realistic. Choosing a resistor value low enough to load the transformer near 100 % rated secondary current is a good start. Be careful that your load resistor can handle the power dissipation!

It might be a good idea for students to take careful measurements of primary and secondary voltage in an *unloaded* condition in order to calculate the actual winding turns ratio of their transformer. Knowing this precise ratio will be helpful to them later on when they use their transformers in other performance assessment activities, so their predictions will more closely match their actual measurements.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students’ results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- Electrical safety (e.g. the “one-hand rule” when working with energized circuits harboring shock potential)
- Making sound electrical connections using a *terminal block* rather than a *solderless breadboard*
- Mutual inductance and basic transformer operation
- The relationship between transformer turns ratio and voltage ratio
- The relationship between transformer turns ratio and current ratio

Suggestions for Socratic discussion and experimentation

- If you were to test an unpowered transformer using an ohmmeter, which winding would exhibit the greatest amount of resistance? Explain why.
- Explain why transformers only work with AC (or pulsed DC), not with continuous DC.
- Can a step-down transformer be used as a step-up transformer? If so, what limitations must be respected in order to ensure safe operation?

Use an audio frequency impedance matching (1000:8 ohms) transformer for this exercise, using a load resistance great enough not to overload the signal generator powering it. I recommend using a 100 k Ω resistor for the load. With the audio transformer’s impedance ratio, this should appear as an 800 Ω load to the signal generator. Avoid frequencies below 1 kHz – power line frequency is much too low for this type of transformer.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students’ results by asking them to predict the consequences of certain circuit faults.

The *real* challenge in this assessment is for students to determine their transformers' "polarities" before connecting them to the AC voltage source! For this, they should have access to a small battery and a DC voltmeter (at their desks).

You may use a Variac at the test bench to provide variable-voltage AC power for the students' transformer circuits. I recommend specifying load resistance values low enough that the load current completely "swamps" the transformer's magnetization current. This may mean using wire-wound power resistors instead of $\frac{1}{4}$ watt carbon composition resistors.

Note that there may very well be a shock hazard associated with this circuit, as the output voltage is not far below the line voltage! Be sure to take this into consideration when specifying load resistor values. You may also want to use low supply voltage levels (turn the Variac *way* down).

In lieu of using a line-powered transformer, you may also do this exercise with a signal generator and an audio-frequency transformer. The principles are the same, and the safety hazard will be vastly reduced. If using a 1000:8 ohm transformer, the winding turns ratio is approximately 11.18 to 1.

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- Electrical safety (e.g. the "one-hand rule" when working with energized circuits harboring shock potential)
- Making sound electrical connections using a *terminal block* rather than a *solderless breadboard*
- Mutual inductance and basic transformer operation
- The relationship between transformer turns ratio and voltage ratio
- The relationship between transformer turns ratio and current ratio

Suggestions for Socratic discussion and experimentation

- Explain why anyone would want to use an autotransformer, instead of just using a regular (isolated) transformer to perform the same task.
- Explain why transformers only work with AC (or pulsed DC), not with continuous DC.
- Can a step-down transformer be used as a step-up transformer? If so, what limitations must be respected in order to ensure safe operation?

The *real* challenge in this assessment is for students to determine their transformers' "polarities" before connecting them to the AC voltage source! For this, they should have access to a small battery and a DC voltmeter (at their desks).

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Note that there may very well be a shock hazard associated with this circuit, as you are "boosting" the supply voltage! Be sure to take this into consideration when specifying load resistor values. You may also want to use low supply voltage levels (turn the Variac *way* down).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

General concepts and principles to emphasize

- Electrical safety (e.g. the "one-hand rule" when working with energized circuits harboring shock potential)
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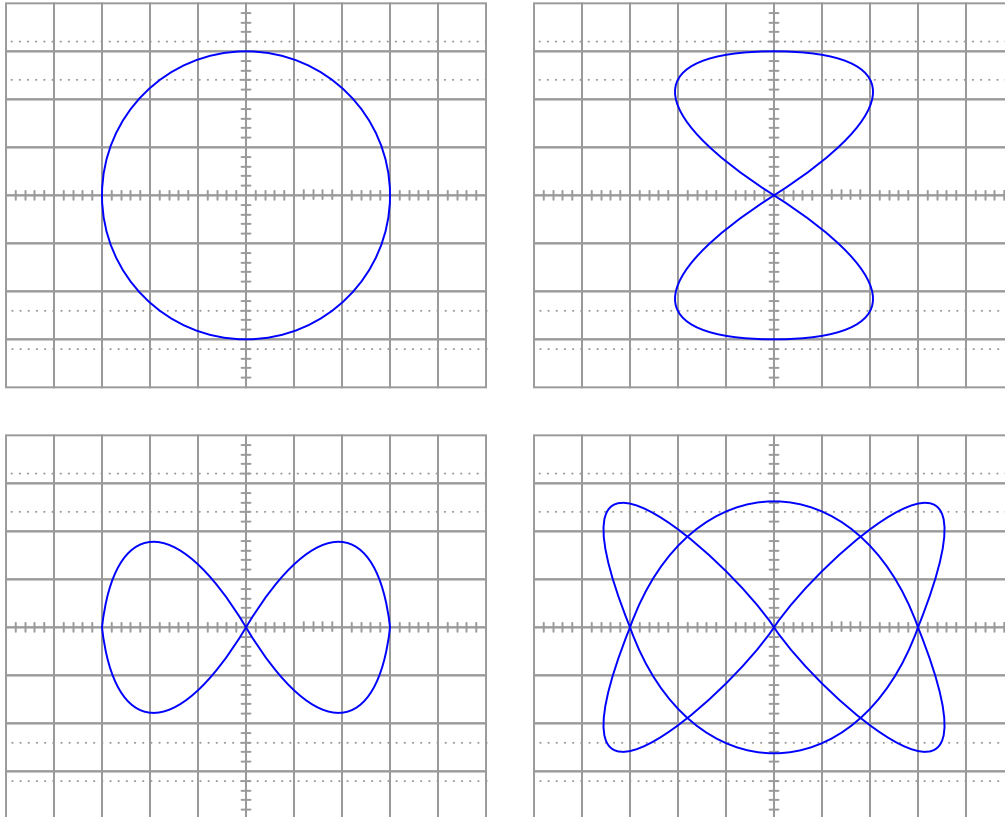
Note that there may very well be a shock hazard associated with this circuit! Be sure to take this into consideration when specifying load resistor values. You may also want to use low supply voltage levels (turn the Variac *way* down).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

Lissajous figures are very informative if one understands how to interpret them. The purpose of this exercise is for students to learn exactly how to do that, in the context of measuring frequency (ratios). Please use sinusoidal AC sources (variable-frequency signal generators) for this exercise.

The instructor will determine the voltage of the two sources (set the same), and also will graphically specify the Lissajous figure by drawing the desired figure on the oscilloscope screen illustration. The student's task is to figure out what frequency ratio will generate this pattern on the oscilloscope screen, and set the signal generators to that ratio (one set to 1 kHz, the other to the appropriate frequency). This works best if the student can only see the signal generator controls and frequency counter displays, and only the instructor can see the oscilloscope display.

Here are some sample Lissajous figures to draw for your students to duplicate:



By the word *overtone*, I imply the musical concept: the successive harmonics appearing in this particular non-sinusoidal waveform. If I were to say "1st harmonic," "2nd harmonic," and "3rd harmonic," this would specifically refer to $f_{\text{fundamental}}$, $2f_{\text{fundamental}}$, and $3f_{\text{fundamental}}$, respectively. The first of these would be given, the second nonexistent in a square wave with 50% duty cycle, leaving only the third as something to actually predict and measure. By "overtones," I mean the first, second, and third frequencies greater than the fundamental frequency found in a square wave, that happen to be harmonics of the fundamental.

If you lack a spectrum analyzer in your lab, fear not! There are free software packages in existence allowing you to use the audio input of a personal computer's sound card as a (limited) spectrum analyzer and oscilloscope! You may find some of these packages by searching on the Internet. One that I've used (2002) successfully in my own class is called WinScope.

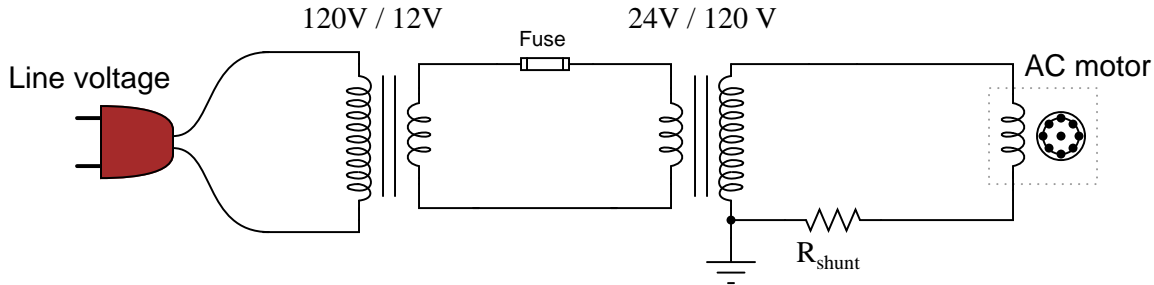
Use a square-wave function generator for the AC voltage source. I have built this circuit using resistances of approximately 4.7 k Ω and capacitances of approximately 0.1 μ F, and achieved good results with a square-wave (fundamental) frequency of about 300 Hz. Of course, the R_1 resistance calculation is more challenging if the two capacitor values are unequal!

Incidentally, this circuit may be used to comparatively measure reactive components such as capacitors and inductors, since the square wave signal will be faithfully reproduced only when the $\frac{R_1}{R_2}$ ratio equals the $\frac{X_{C1}}{X_{C2}}$ or $\frac{X_{L1}}{X_{L2}}$ ratio. To be honest, the idea was not mine. I found it in an old book, the *Electronics Manual for Radio Engineers*, by Vin Zeluff and John Markus, first edition (1949), page 427. Apparently, the inventor of this ingenious impedance measurement technique was an employee of Allen B. DuMont Lab., Inc. named Peter S. Christaldi, who obtained a patent for the technique on October 15, 1946 (patent number 2,409,419 for those who are interested).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

When presenting this as a performance assessment for a group of students, you will need to show the voltage/current waveforms as part of the “given” conditions. A good way to do this is to use a PC-based oscilloscope to measure the waveforms, and then display the image using a video projector.

I have found that small synchronous AC motors such as those used in clock mechanisms and in some appliances (microwave oven carousels, for example) will run satisfactorily at 24 volts AC. Small shaded-pole motors such as those used in household bathroom fans and household appliances (microwave oven cooling fans, for example) may be operated in a relatively safe manner from low-voltage AC power by stepping the voltage up through a power transformer connected directly to the motor. Use a “step down” power transformer operating in reverse (as a step-up unit), with the higher voltage wires connected and taped to the motor so that the only “loose” wire connections are on the low-voltage side. Here is a power supply circuit I recommend for the task:



This circuit ensures the motor only receives about 60 volts, reducing shock hazard somewhat and allowing the use of capacitors rated for 100 volts (a common mylar capacitor rating). The smaller the motor, the less capacitance will be required to correct for power factor. Remind your students that the capacitors used in this exercise must be *non-polarized*, since they must operate on AC and not DC!

A shunt resistor value of 1 ohm is recommended, but not absolutely required. You just need a low-value resistor that will provide a ready point of measurement for current (with the oscilloscope) without imposing too much series resistance in the motor circuit.

General concepts and principles to emphasize

- The concept of *power factor* and why it is important in AC power systems
- The concept of *reactance*, and how it differs from *resistance*
- The concept of *impedance*, and how it relates to both *resistance* and *reactance*
- Making sound electrical connections using a *terminal block* rather than a *solderless breadboard*

Suggestions for Socratic discussion and experimentation

- What will happen if the capacitor is moved closer to the power source (i.e. to the left of the shunt resistor)? Will this still alter the circuit’s power factor? Will the oscilloscope still be able to “see” any difference?
- Will the power factor for an AC motor change depending on mechanical load? For example, will the power factor be the same while the motor is spinning freely versus powering a machine?

This is a very simple yet effective exercise in demonstrating the effects of reflections in cables where the termination resistance (R_{pot}) is unequal to the cable's characteristic impedance (Z_0). It is also an easy way to measure Z_0 , by adjusting R_{pot} until a match is shown by an undistorted square-wave between points **A** and **B**.

I've used ordinary "zip cord" type speaker wire for this experiment. You can also use household extension cords or lengths of coaxial cable if you prefer. Coax has the benefit of already being rated for a specified impedance, unlike the other cable types listed. A length of 100 feet works well to produce time delays easily measurable with inexpensive oscilloscopes.

The purpose of resistor R_1 is to "swamp" the square-wave signal generator's own Thévenin impedance, so it does not become a significant factor in the system. The maximum resistance of rheostat R_{pot} is really not that critical. I've easily achieved a match on speaker cable with $Z_0 \approx 136\Omega$ using a 10 k Ω potentiometer for R_{pot} . A 1 k Ω potentiometer would probably be best.

If you wish your students to be able to accurately predict the length of their cable from the waveshapes displayed by the oscilloscope, you need to determine the cable's velocity factor beforehand, and write that value in the "Given conditions" section. Otherwise, you could have students infer velocity factor from cable length and oscilloscope measurements.

Any relevant notes for the assessment activity go here.