

## Performance-based assessments for analog integrated 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.

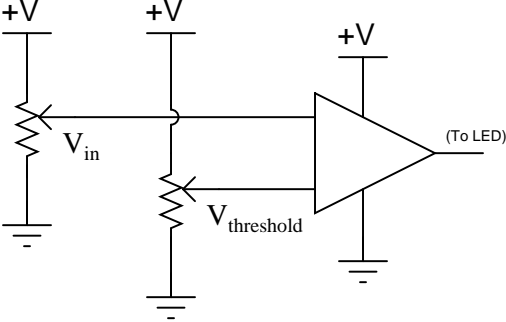
These assessments more closely mimic real-world work conditions than traditional written exams:

- 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).

Competency: <b>Voltage comparator</b>	Version:																									
<b>Schematic</b>																										
<b>Given conditions</b>																										
$+V =$	$R_{pot1} = R_{pot2} =$																									
<b>Parameters</b>																										
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 10%;"></th> <th style="width: 15%; text-align: center;">Predicted</th> <th style="width: 15%; text-align: center;">Measured</th> <th style="width: 15%;"></th> <th style="width: 15%;"></th> </tr> </thead> <tbody> <tr> <td><math>V_{out}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td><math>V_{in(+)} =</math> _____</td> <td><math>V_{in(-)} =</math> _____</td> </tr> <tr> <td><math>V_{out}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td><math>V_{in(+)} =</math> _____</td> <td><math>V_{in(-)} =</math> _____</td> </tr> <tr> <td><math>V_{out}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td><math>V_{in(+)} =</math> _____</td> <td><math>V_{in(-)} =</math> _____</td> </tr> <tr> <td><math>V_{out}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td><math>V_{in(+)} =</math> _____</td> <td><math>V_{in(-)} =</math> _____</td> </tr> </tbody> </table>		Predicted	Measured			$V_{out}$			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____	$V_{out}$			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____	$V_{out}$			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____	$V_{out}$			$V_{in(+)} =$ _____	$V_{in(-)} =$ _____	
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<b>Fault analysis</b>																										
Suppose component <span style="border: 1px solid black; display: inline-block; width: 40px; height: 15px; vertical-align: middle;"></span> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted <i>What will happen in the circuit?</i>																										

Competency: <b>Voltage comparator with LED</b>	Version:
<b>Description</b> <p>Design and build a comparator circuit that turns on an LED when the specified condition is met.</p>	
<b>Given conditions</b> <p>The LED will turn on when (instructor checks one)</p> <p>+V = <input type="checkbox"/> <math>V_{in}</math> exceeds <math>V_{threshold}</math></p> <p><input type="checkbox"/> <math>V_{in}</math> falls below <math>V_{threshold}</math></p>	
<b>Schematic</b> <i>Label each comparator input terminal (+ and -) and show how the LED connects to the comparator output!</i> 	
<b>Parameters</b> <p>LED energizes when it should <input type="checkbox"/> (Yes/No)</p>	

file 02765

Competency: <b>Voltage comparator with hysteresis</b> Version:					
<b>Schematic</b>					
<b>Given conditions</b>					
$+V =$	$R_{pot1} = R_{pot2} =$				
$V_{ref} (VR_1 \text{ setting}) =$	$R_1 =$ $R_2 =$				
<b>Parameters</b>					
$V_{UT}$	<table 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="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> </tbody> </table> <span style="margin-left: 10px;">(upper threshold voltage)</span>	Predicted	Measured		
Predicted	Measured				
$V_{LT}$	<table 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="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> </tbody> </table> <span style="margin-left: 10px;">(lower threshold voltage)</span>	Predicted	Measured		
Predicted	Measured				
<b>Fault analysis</b>					
Suppose component <span style="border: 1px solid black; display: inline-block; width: 40px; height: 20px; vertical-align: middle;"></span> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted <i>What will happen in the circuit?</i>					

Competency: <b>Opamp voltage follower</b>		Version:				
<b>Schematic</b>						
<b>Given conditions</b>						
$+V =$	$R_{pot} =$	$V_{TP1} =$				
$-V =$						
<b>Parameters</b>						
$V_{out}$	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 2px;">Predicted</th> <th style="padding: 2px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="height: 20px;"></td> <td style="height: 20px;"></td> </tr> </tbody> </table>	Predicted	Measured			Inverting . . . <input type="checkbox"/> or noninverting? <input type="checkbox"/>
Predicted	Measured					
$A_V$ (ratio)	<table border="1" style="display: inline-table; border-collapse: collapse;"> <tbody> <tr> <td style="height: 20px;"></td> <td style="height: 20px;"></td> </tr> </tbody> </table>					
$A_V$ (dB)	<table border="1" style="display: inline-table; border-collapse: collapse;"> <tbody> <tr> <td style="height: 20px;"></td> <td style="height: 20px;"></td> </tr> </tbody> </table>					
$V_{TP1}$ resulting in <i>latch-up</i>	<table border="1" style="display: inline-table; border-collapse: collapse;"> <tbody> <tr> <td style="height: 20px;"></td> </tr> </tbody> </table>					
Rail-to-rail output swing?	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 2px;">Measured</th> </tr> </thead> <tbody> <tr> <td style="height: 20px;"></td> </tr> </tbody> </table> (Yes/No)	Measured				
Measured						

Competency: <b>Linear voltage regulator circuit</b>		Version:	
<b>Schematic</b>			
<b>Given conditions</b>			
$V_{\text{supply (min)}} =$	$R_1 =$	Load =	
$V_{\text{supply (max)}} =$	$V_{\text{zener}} =$	$C_1 =$	
<b>Parameters</b>			
	Predicted	Measured	
$V_{\text{in}(+)}$	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	Calculated
$V_{\text{load}}$	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	$P_{Q1}$ <input style="width: 80px; height: 25px;" type="text"/>
$V_B(Q_1)$	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	
<b>Fault analysis</b>			
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?			

Competency: <b>Opamp noninverting amplifier</b>		Version:
<b>Schematic</b>		
<b>Given conditions</b>		
$+V =$	$R_{pot} =$	$V_{TP1} =$
$-V =$	$R_1 =$	$R_2 =$
<b>Parameters</b>		
	Predicted	Measured
$V_{out}$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
$A_V$ (ratio)	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
$A_V$ (dB)	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
<b>Fault analysis</b>		
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?		

Competency: <b>Opamp inverting amplifier</b>	Version:	
<b>Schematic</b>		
<b>Given conditions</b>		
$+V =$	$R_{pot} =$	$V_{TP1} =$
$-V =$	$R_1 =$	$R_2 =$
<b>Parameters</b>		
	<b>Predicted</b>	<b>Measured</b>
$V_{out}$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
$A_V$ (ratio)	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
$A_V$ (dB)	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
<b>Fault analysis</b>		
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 01970

Competency: <b>Op-amp amplifier circuit w/specified gain</b> Version:															
<b>Description</b>	Design and build an op-amp amplifier circuit with a voltage gain ( $A_V$ ) that is within tolerance of the gain specified.														
<b>Given conditions</b>	$V_{in} =$ <span style="margin-left: 150px;">Inverting</span> <input type="checkbox"/> $A_V$ (ratio) = <span style="margin-left: 150px;">Non-inverting</span> <input type="checkbox"/> Tolerance $_{A_V} =$														
<b>Schematic</b>	<i>Show all component values!</i>														
<b>Parameters</b>	<table style="width: 100%; border: none;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 20%; text-align: center;">Measured</th> <th style="width: 15%;"></th> <th style="width: 20%; text-align: center;">Calculated</th> <th style="width: 30%;"></th> </tr> </thead> <tbody> <tr> <td><math>V_{in}</math></td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> <td><math>A_V</math> (ratio)</td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> <td rowspan="2" style="text-align: center; vertical-align: middle;"> <math>\frac{A_{V(\text{actual})} - A_{V(\text{ideal})}}{A_{V(\text{ideal})}} \times 100\%</math> </td> </tr> <tr> <td><math>V_{out}</math></td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> <td><b>Error</b><math>_{A_V}</math></td> <td style="border: 1px solid black; width: 80px; height: 20px;"></td> </tr> </tbody> </table>		Measured		Calculated		$V_{in}$		$A_V$ (ratio)		$\frac{A_{V(\text{actual})} - A_{V(\text{ideal})}}{A_{V(\text{ideal})}} \times 100\%$	$V_{out}$		<b>Error</b> $_{A_V}$	
	Measured		Calculated												
$V_{in}$		$A_V$ (ratio)		$\frac{A_{V(\text{actual})} - A_{V(\text{ideal})}}{A_{V(\text{ideal})}} \times 100\%$											
$V_{out}$		<b>Error</b> $_{A_V}$													

file 02132

Competency: <b>Opamp difference amplifier</b>		Version:	
<b>Schematic</b>			
<b>Given conditions</b>			
$+V =$	$R_{pot1} = R_{pot2} =$	$R_1 =$	
$-V =$		$R_2 =$	
		$R_3 =$	
		$R_4 =$	
<b>Parameters</b>			
	Predicted	Measured	
$V_{out}$			$V_{TP1} = \text{---} V$ $V_{TP2} = \text{---} V$
$V_{out}$			$V_{TP1} = \text{---} V$ $V_{TP2} = \text{---} V$
$V_{out}$			$V_{TP1} = \text{---} V$ $V_{TP2} = \text{---} V$
$V_{out}$			$V_{TP1} = V_{TP2} = \text{---} V$
$V_{out}$			$V_{TP1} = V_{TP2} = \text{---} V$
			} <i>Common mode voltage</i>
$A_V$ (ratio)	Predicted	Calculated	Differential $\frac{V_{out}}{V_{TP1} - V_{TP2}}$
$A_V$ (ratio)	Predicted	Calculated	Common-mode $\frac{\Delta V_{out}}{\Delta V_{in}}$

file 02466

Competency: <b>Precision rectifier, half wave</b>		Version:	
<b>Schematic</b>			
<b>Given conditions</b>			
$+V =$	$-V =$	$R_1 = R_2 =$	
		$R_{pot} =$	
<b>Parameters</b>			
	Predicted	Measured	
$V_{out}$			$V_{TP1} =$ ____
$V_{out}$			$V_{TP1} =$ ____
$V_{out}$			$V_{TP1} =$ ____
<b>Fault analysis</b>			
Suppose component <span style="border: 1px solid black; display: inline-block; width: 40px; height: 15px; vertical-align: middle;"></span> fails			
<input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted			
<i>What will happen in the circuit?</i>			

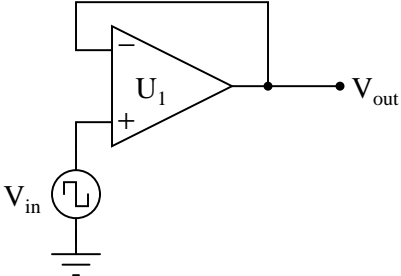
file 02540

Competency: <b>Precision rectifier, full wave</b>		Version:	
<b>Schematic</b>			
<b>Given conditions</b>			
		$R_{pot} =$	
$+V =$	$-V =$	$R_1 = R_2 = R_3 = R_4 = R_5 =$	
<b>Parameters</b>			
	Predicted	Measured	
$V_{out}$			$V_{TP1} =$ _____
$V_{out}$			$V_{TP1} =$ _____
$V_{out}$			$V_{TP1} =$ _____
<b>Fault analysis</b>			
Suppose component <span style="border: 1px solid black; display: inline-block; width: 40px; height: 15px; vertical-align: middle;"></span> fails <span style="margin-left: 20px;"><input type="checkbox"/> open</span> <span style="margin-left: 20px;"><input type="checkbox"/> other _____</span>			
<span style="margin-left: 40px;"><input type="checkbox"/> shorted</span>			
<i>What will happen in the circuit?</i>			

file 02560

Competency: <b>Positive peak follower-and-hold circuit</b>		Version:	
<b>Schematic</b>			
<b>Given conditions</b>			
$+V =$	$R_{pot} =$	$R_3 =$	$D_1 = D_2 =$
$-V =$	$R_1 = R_2 =$	$C_1 =$	$U_1 = U_2 =$
<b>Parameters</b>			
(Set $V_{in}$ to $-V$ , push reset) Step 1			
$V_{out}$	Predicted	Measured	$V_{TP1} = \underline{\hspace{1cm}}$ Step 2
$V_{out}$	<input style="width: 50px; height: 20px;" type="text"/>	<input style="width: 50px; height: 20px;" type="text"/>	$V_{TP1} = \underline{\hspace{1cm}}$ Step 3
$V_{out}$	<input style="width: 50px; height: 20px;" type="text"/>	<input style="width: 50px; height: 20px;" type="text"/>	(Push reset) Step 4
$V_{out}$	<input style="width: 50px; height: 20px;" type="text"/>	<input style="width: 50px; height: 20px;" type="text"/>	$V_{TP1} = \underline{\hspace{1cm}}$ Step 5
$V_{out}$	<input style="width: 50px; height: 20px;" type="text"/>	<input style="width: 50px; height: 20px;" type="text"/>	$V_{TP1} = \underline{\hspace{1cm}}$ Step 6
$V_{out}$	<input style="width: 50px; height: 20px;" type="text"/>	<input style="width: 50px; height: 20px;" type="text"/>	$V_{TP1} = \underline{\hspace{1cm}}$ Step 7

file 02640

Competency: <b>Opamp slew rate</b>	Version:				
<b>Schematic</b>					
					
<b>Given conditions</b>					
+V =	$V_{in} =$				
-V =	f =				
<b>Instructions</b>					
<p>Adjust input signal amplitude and frequency until the opamp is no longer able to follow it, and the output resembles a triangle waveform. The slope of the triangle wave will be the slew rate.</p>					
<b>Parameters</b>					
$+\frac{dv}{dt}$ (max.)	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Measured</th> <th style="padding: 5px;">Advertised</th> </tr> </thead> <tbody> <tr> <td style="width: 100px; height: 25px;"></td> <td style="width: 100px; height: 25px;"></td> </tr> </tbody> </table>	Measured	Advertised		
Measured	Advertised				
$-\frac{dv}{dt}$ (max.)	<table border="1" style="display: inline-table; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">Measured</th> <th style="padding: 5px;">Advertised</th> </tr> </thead> <tbody> <tr> <td style="width: 100px; height: 25px;"></td> <td style="width: 100px; height: 25px;"></td> </tr> </tbody> </table>	Measured	Advertised		
Measured	Advertised				

file 02567

Competency: <b>Opamp gain-bandwidth product</b>		Version:		
<b>Schematic</b>				
<b>Given conditions</b>				
+V =	Unity-gain frequency of opamp =			
-V =				
<b>Instructions</b>				
<div style="border: 1px solid black; padding: 5px; display: inline-block;"> <math>f = f_{-3dB} \text{ when } V_{out} = \frac{V_{out(max)}}{\sqrt{2}}</math> </div>				
<p>Keep <math>V_{in}</math> low enough that <math>V_{out}</math> remains sinusoidal (undistorted)</p> <p>Predict and measure <math>f_{-3dB}</math> at three different gains (<math>A_{CL}</math>)</p> <p>Calculate gain-bandwidth product (GBW) at those gains, and then average.</p>				
<b>Parameters</b>				
	Predicted	Measured	$(R_2 / R_1) + 1$	Calculated
$f_{-3dB}$	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	@ $A_{CL} =$ <input style="width: 60px; height: 25px;" type="text"/>	GBW <input style="width: 80px; height: 25px;" type="text"/>
$f_{-3dB}$	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	@ $A_{CL} =$ <input style="width: 60px; height: 25px;" type="text"/>	GBW <input style="width: 80px; height: 25px;" type="text"/>
$f_{-3dB}$	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>	@ $A_{CL} =$ <input style="width: 60px; height: 25px;" type="text"/>	GBW <input style="width: 80px; height: 25px;" type="text"/>
			GBW <sub>average</sub>	<input style="width: 100px; height: 25px; border: 2px solid black;" type="text"/>

file 02360

Competency: <b>Opamp active integrator</b>	Version:		
<b>Schematic</b>			
<b>Given conditions</b>			
$+V =$	$V_{in} =$	$R_1 =$	$C_1 =$
$-V =$	$f =$	$R_2 =$	
<b>Parameters</b>			
$V_{out}$	Predicted	Measured	} <i>With sinusoidal input</i>
$\theta$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>	
$V_{out}$	Predicted weshape	Measured weshape	<i>Sine wave input</i>
$V_{out}$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>	<i>Triangle wave input</i>
$V_{out}$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>	<i>Square wave input</i>

file 02565

Competency: <b>Opamp active differentiator</b>	Version:		
<b>Schematic</b>			
<b>Given conditions</b>			
$+V =$	$V_{in} =$	$R_1 =$	$C_1 =$
$-V =$	$f =$	$R_2 =$	
<b>Parameters</b>			
	Predicted	Measured	
$V_{out}$			} <i>With sinusoidal input</i>
$\theta$			
	Predicted waveshape	Measured waveshape	
$V_{out}$			<i>Sine wave input</i>
$V_{out}$			<i>Triangle wave input</i>
$V_{out}$			<i>Square wave input</i>

Competency: <b>First order active lowpass filter</b>	Version:					
<b>Schematic</b>						
<b>Given conditions</b>						
+V =	R <sub>1</sub> =	C <sub>1</sub> =				
-V =	R <sub>comp</sub> =					
<b>Parameters</b>						
f <sub>-3dB</sub>	<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: 20px;"></td> <td style="width: 60px; height: 20px;"></td> </tr> </tbody> </table>	Predicted	Measured			
Predicted	Measured					
<b>Fault analysis</b>						
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>						

file 02766

Competency: <b>First order active highpass filter</b>	Version:					
<b>Schematic</b>						
<b>Given conditions</b>						
$+V =$	$R_1 =$	$C_1 =$				
$-V =$	$R_{comp} =$					
<b>Parameters</b>						
$f_{-3dB}$	<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: 20px;"></td> <td style="width: 60px; height: 20px;"></td> </tr> </tbody> </table>	Predicted	Measured			
Predicted	Measured					
<b>Fault analysis</b>						
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>						

file 02767

Competency: <b>Sallen-Key active lowpass filter</b>	Version:	
<b>Schematic</b>		
<b>Given conditions</b>		
$+V =$	$R_1 =$	$C_1 =$
$-V =$	$R_2 =$	$C_2 =$
	$R_{comp} =$	
<b>Parameters</b>		
$f_{-3dB}$	Predicted	Measured
	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>
<b>Fault analysis</b>		
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 02577

Competency: <b>Sallen-Key active highpass filter</b>		Version:
<b>Schematic</b>		
<b>Given conditions</b>		
$+V =$	$R_1 =$	$C_1 =$
$-V =$	$R_2 =$	$C_2 =$
	$R_{comp} =$	
<b>Parameters</b>		
	Predicted	Measured
$f_{-3dB}$	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>
<b>Fault analysis</b>		
Suppose component <input style="width: 50px; height: 25px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted What will happen in the circuit?		

file 02578

Competency: <b>Active RC filter circuit design</b>		Version:
<b>Description</b>		
Design and build an active RC filter circuit with a cutoff frequency specified by the instructor.		
<b>Given conditions</b>		
$f_{-3dB} =$	High-pass <input type="checkbox"/>	Low-pass <input type="checkbox"/>
<i>(instructor checks one)</i>		
<b>Schematic</b> <i>Show all component values!</i>		
<b>Parameters</b>		
$f_{-3dB}$	Predicted <input type="text"/>	Measured <input type="text"/>

file 02133

Competency: <b>Twin-T active bandpass filter</b>	Version:			
<b>Schematic</b>				
<b>Given conditions</b>				
$+V =$	$R_1 =$	$R_3 =$	$C_1 =$	$C_3 =$
$-V =$	$R_2 =$	$R_4 =$	$C_2 =$	
<b>Parameters</b>				
$f_{\text{center}}$	Predicted	Measured		
	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>		

file 02588

Competency: <b>Twin-T active bandstop filter</b>	Version:			
<b>Schematic</b>				
<b>Given conditions</b>				
$+V =$	$R_1 =$	$R_3 =$	$C_1 =$	$C_3 =$
$-V =$	$R_2 =$	$R_4 =$	$C_2 =$	
<b>Parameters</b>				
$f_{\text{notch}}$	Predicted	Measured		
	<input style="width: 80px; height: 20px;" type="text"/>	<input style="width: 80px; height: 20px;" type="text"/>		

file 02589

Competency: <b>Opamp relaxation oscillator</b>	Version:	
<b>Schematic</b>		
<b>Given conditions</b>		
$+V =$	$R_1 =$	$R_3 =$
$-V =$	$R_2 =$	$C_1 =$
<b>Parameters</b>		
	Predicted	Measured
$V_{out}$ (pk-pk)	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>
$f_{out}$	<input style="width: 80px; height: 25px;" type="text"/>	<input style="width: 80px; height: 25px;" type="text"/>
<b>Fault analysis</b>		
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 02568

Competency: <b>Opamp triangle wave generator</b>	Version:			
<b>Schematic</b>				
<b>Given conditions</b>				
$+V =$	$R_1 =$	$R_3 =$	$R_5 =$	$C_2 =$
$-V =$	$R_2 =$	$R_4 =$	$C_1 =$	
<b>Parameters</b>				
	Predicted	Measured		
$V_{out}$ (pk-pk)	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>		
$f_{out}$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>		
<b>Fault analysis</b>				
Suppose component <input style="width: 50px;" type="text"/> fails		<input type="checkbox"/> open	<input type="checkbox"/> other _____	
<i>What will happen in the circuit?</i>		<input type="checkbox"/> shorted		

file 02569

Competency: <b>Opamp Wien bridge oscillator</b>	Version:					
<b>Schematic</b>						
<b>Given conditions</b>						
$+V =$	$R_1 = R_2 =$	$R_{pot} =$				
$-V =$	$C_1 = C_2 =$					
<b>Parameters</b>						
$f_{out}$	<table border="1" style="margin: auto; 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: 30px;"></td> <td style="width: 60px; height: 30px;"></td> </tr> </tbody> </table>	Predicted	Measured			
Predicted	Measured					
<b>Fault analysis</b>						
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: **Opamp Wien bridge oscillator w/limiting** Version:

**Schematic**

**Given conditions**

+V =                       $R_1 = R_2 =$                        $R_{pot} =$

-V =                       $C_1 = C_2 =$                        $R_3 = R_4 =$

**Parameters**

	Predicted	Measured
$f_{out}$	<input type="text"/>	<input type="text"/>

**Fault analysis**

Suppose component  fails  open  other \_\_\_\_\_  
 shorted

*What will happen in the circuit?*

Competency: <b>Opamp LC resonant oscillator</b>	Version:				
<b>Schematic</b>					
<b>Given conditions</b>					
$+V =$	$R_1 =$	$L_1 =$			
$-V =$	$C_1 =$	$R_{pot} =$			
<b>Parameters</b>					
$f_{out}$	<table border="1" style="margin: auto;"> <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> </tbody> </table>	Predicted	Measured		
Predicted	Measured				
<b>Calculations</b>					

file 02637

Competency: <b>Opamp LC resonant oscillator</b>	Version:				
<b>Schematic</b>					
<b>Given conditions</b>					
$+V =$	$R_1 =$	$L_1 =$			
$-V =$	$C_1 =$	$R_{pot} =$			
<b>Parameters</b>					
$f_{out}$	<table border="1" style="margin: auto;"> <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> </tbody> </table>	Predicted	Measured		
Predicted	Measured				
<b>Calculations</b>					

file 02638

<b>Competency: Opamp LC resonant oscillator w/limiting</b> Version:					
<b>Schematic</b>					
<b>Given conditions</b>					
$+V =$	$R_1 =$	$L_1 =$	$R_2 = R_3 =$		
$-V =$	$C_1 =$	$R_{pot} =$			
<b>Parameters</b>					
$f_{out}$	<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> </tbody> </table>	Predicted	Measured		
Predicted	Measured				
<b>Calculations</b>					

file 02699

Competency: <b>Opamp oscillator w/specified frequency</b> Version:	
<b>Description</b>	
Design and build an opamp oscillator circuit to output a <i>sine-wave</i> AC voltage at a frequency within the specified tolerance.	
<b>Given conditions</b>	
+V =	f =                      Tolerance <sub>f</sub> =
<b>Schematic</b> <i>Show all component values!</i>	
<b>Parameters</b>	
Measured f <input style="width: 80px; height: 25px;" type="text"/>	Calculated Error <sub>f</sub> <input style="width: 80px; height: 25px;" type="text"/>
$\frac{f_{(\text{actual})} - f_{(\text{ideal})}}{f_{(\text{ideal})}} \times 100\%$	

file 02764

Competency: <b>Astable 555 timer</b>	Version:	
<b>Schematic</b>		
<b>Given conditions</b>		
$+V =$	$R_1 =$	$R_2 =$
$-V =$	$C_1 =$	$C_2 =$
<b>Parameters</b>		
	Predicted	Measured
$t_{high}$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
$t_{low}$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
$f_{out}$	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
<b>Fault analysis</b>		
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>		

Competency: <b>555 oscillator w/specified frequency</b>		Version:
Description		
Design and build a 555 oscillator (astable multivibrator) circuit to output a frequency within the specified tolerance.		
Given conditions		
+V =	f =	Tolerance <sub>f</sub> =
Schematic <i>Show all component values!</i>		
<div style="border: 1px solid black; height: 200px; width: 100%;"></div>		
Parameters		
Measured	Calculated	
f <input style="width: 80px; height: 25px;" type="text"/>	Error <sub>f</sub> <input style="width: 80px; height: 25px;" type="text"/>	$\frac{f_{(\text{actual})} - f_{(\text{ideal})}}{f_{(\text{ideal})}} \times 100\%$

file 02862

## Answers

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Answer 1

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

---

Answer 2

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

---

Answer 3

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

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Answer 4

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

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Answer 5

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

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Answer 6

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

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Answer 7

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

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Answer 8

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

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Answer 9

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

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Answer 10

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

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Answer 11

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

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Answer 12

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

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Answer 13

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

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Answer 14

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

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Answer 15

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

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Answer 16

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

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Answer 17

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

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Answer 18

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

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Answer 19

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

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Answer 20

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

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Answer 21

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

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Answer 22

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

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Answer 23

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

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Answer 24

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

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Answer 25

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

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Answer 26

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

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Answer 27

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

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Answer 28

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

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Answer 29

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

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Answer 30

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

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Answer 31

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

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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.

---

Notes 1

You may wish to use either an operational amplifier or a true comparator for this exercise. Whether or not the specific device has rail-to-rail output swing capability is your choice as well.

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 2

Students are free to connect the LED to the comparator in any way they choose (current-sourcing or current-sinking).

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 3

You may wish to use either an operational amplifier or a true comparator for this exercise. Whether or not the specific device has rail-to-rail output swing capability is your choice as well.

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 4

Use a dual-voltage, regulated power supply to supply power to the opamp.

I have had good success using the following values:

- $+V = +12$  volts
- $-V = -12$  volts
- $V_{TP1} =$  Any voltage well between  $+V$  and  $-V$
- $R_{pot} = 10$  k $\Omega$  linear potentiometer
- $U_1 =$  TL081 BiFET operational amplifier (or one-half of a TL082)

In order to demonstrate latch-up, you must have an op-amp capable of latching up. Thus, you should avoid op-amps such as the LM741 and LM1458. I recommend using an op-amp such as the TL082 for this exercise because it not only latches up, but also does not swing its output voltage rail-to-rail. Students need to see both these common limitations when they first learn how to use op-amps.

In case your students ask, test point **TP1** is for measuring the output of the potentiometer rather than as a place to inject external signals into. All you need to connect to **TP1** is a voltmeter!

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 5

Use a power transistor for this circuit, as general-purpose signal transistors may not have sufficient power dissipation ratings to survive the loading students may put them through! I recommend a small DC motor as a load. An electric motor offers an easy way to increase electrical loading by placing a mechanical load on the shaft. By doing this, students can see for themselves how well the circuit maintains load voltage (resisting voltage "sag" under increasing load current).

I have found that this circuit is excellent for getting students to understand how negative feedback really works. Here, the opamp adjusts the power transistor's base voltage to *whatever it needs to be* in order to maintain the load voltage at the same level as the reference set by the zener diode. Any sort of loss incurred by the transistor (most notably  $V_{BE}$ ) is automatically compensated for by the opamp.

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 6

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $V_{TP1}$  = Any voltage well between +V and -V not resulting in output saturation
- $R_1$  = 10 k $\Omega$
- $R_2$  = 27 k $\Omega$
- $R_{pot}$  = 10 k $\Omega$  linear potentiometer
- $U_1$  = TL081 BiFET operational amplifier (or one-half of a TL082)

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 7

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $V_{TP1}$  = Any voltage well between +V and -V not resulting in output saturation
- $R_1$  = 10 k $\Omega$
- $R_2$  = 27 k $\Omega$
- $R_{pot}$  = 10 k $\Omega$  linear potentiometer
- $U_1$  = TL081 BiFET operational amplifier (or one-half of a TL082)

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.

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## Notes 8

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 9

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify all four resistors as equal value, between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k, 47k, 68k, etc.). This will ensure a differential voltage gain of unity. If you *want* to have a different voltage gain, then by all means specify these resistor values however you see fit!

Differential gain is calculated by averaging the quotients of each measured  $V_{out}$  value with its respective  $V_{in(+)} - V_{in(-)}$  differential input voltage. Common-mode gain is calculated by dividing the difference in output voltages ( $\Delta V_{out}$ ) by the difference in common-mode input voltages ( $\Delta V_{in}$ ).

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.

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## Notes 10

Choose both positive input voltage values and negative input voltage values, so that students may predict and measure the output of this circuit under both types of conditions. The choice of diodes is not critical, as any rectifier diodes will work. The two resistor values should be equal, and at least as high as the potentiometer value. I recommend a 10 k $\Omega$  potentiometer and 15 k $\Omega$  resistors.

A good follow-up question to ask is what would be required to change the polarity of this half-wave precision rectifier circuit.

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 11

Choose both positive input voltage values and negative input voltage values, so that students may predict and measure the output of this circuit under both types of conditions. The choice of diodes is not critical, as any rectifier diodes will work. All resistor values need to be equal, and at least as high as the potentiometer value. I recommend a 10 k $\Omega$  potentiometer and 15 k $\Omega$  resistors.

A good follow-up question to ask is what would be required to change the polarity of this full-wave precision rectifier circuit.

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 12

Choose values for  $V_{in}$  that show the circuit's ability to "hold" the last highest (most positive) input voltage.

I have found these values to work well:

- $+V = +12$  volts
- $-V = -12$  volts
- $R_1 = R_2 = 10$  k $\Omega$
- $R_3 = 10$  k $\Omega$
- $R_{pot} = 10$  k $\Omega$
- $C_1 = 1$   $\mu$ F (non-electrolytic, low leakage polyester or ceramic)
- $D_1 = D_2 = 1N4148$  switching diode
- $U_1 = U_2 = TL082$  dual BiFET opamp

The TL082 opamp works well in this circuit for three reasons: first, it is a dual opamp, providing both necessary opamps in a single 8-pin package. Second, its JFET input stage provides the low input bias currents necessary to avoid draining the capacitor too rapidly. Third, it is free from latch-up, which makes it possible to reset the capacitor voltage to the full (negative) rail voltage and still have a valid output.

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 13

Use a dual-voltage, regulated power supply to supply power to the opamp. I recommend using a "slow" op-amp to make the slewing more easily noticeable. If a student chooses a relatively fast-slew op-amp such as the TL082, their signal frequency may have to go up into the megahertz range before the slewing becomes evident. At these speeds, parasitic inductance and capacitance in their breadboards and test leads will cause bad "ringing" and other artifacts muddling the interpretation of the circuit's performance.

I have had good success using the following values:

- $+V = +12$  volts
- $-V = -12$  volts
- $V_{in} = 4$  V peak-to-peak, at 300 kHz
- $U_1 =$  one-half of LM1458 dual operational amplifier

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 purpose of this exercise is to empirically determine the gain-bandwidth product (GBW) of a closed-loop opamp amplifier circuit by setting it up for three different closed-loop gains ( $A_{CL}$ ), measuring the cutoff frequency ( $f_{-3dB}$ ) at those gains, and calculating the product of the two ( $A_{CL}f_{-3dB}$ ) at each gain. Since this amplifier is DC-coupled, there is no need to measure a lower cutoff frequency in order to calculate *bandwidth*, just the high cutoff frequency.

What GBW tells us is that any opamp has the tendency to act as a low-pass filter, its cutoff frequency being dependent on how much gain we are trying to get out of the opamp. We can have large gain at modest frequencies, or a high bandwidth at modest gain, but not both! This lab exercise is designed to let students see this limitation. As they set up their opamp circuits with greater and greater gains ( $\frac{R_2}{R_1} + 1$ ), they will notice the opamp "cut off" like a low-pass filter at lower and lower frequencies.

For the "given" value of unity-gain frequency, you must consult the datasheet for the opamp you choose. I like to use the popular TL082 BiFET opamp for a lot of AC circuits, because it delivers good performance at a modest price and excellent availability. However, the GBW for the TL082 is so high (3 MHz typical) that breadboard and wiring layout become issues when testing at low gains, due to the resulting high frequencies necessary to show cutoff. The venerable 741 is a better option because its gain-bandwidth product is significantly lower (1 to 1.5 MHz typical).

It is very important in this exercise to maintain an undistorted opamp output, even when the closed-loop gain is very high. Failure to do so will result in the  $f_{-3dB}$  points being skewed by slew-rate limiting. What we're looking for here are the cutoff frequencies resulting from loss of small-signal open-loop gain ( $A_{OL}$ ) inside the opamp. To maintain small-signal status, we must ensure the signal is not being distorted!

Some typical values I was able to calculate for GBW product are  $3.8 \times 10^6$  for the BiFET TL082,  $1.5 \times 10^6$  for the LM1458, and around  $800 \times 10^3$  for the LM741C.

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 dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k, 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $V_{in}$  = 1 V peak-to-peak, at 10 kHz
- $R_1$  = 10 k $\Omega$
- $R_2$  = 100 k $\Omega$
- $C_1$  = 0.001  $\mu$ F
- $U_1$  = one-half of LM1458 dual operational amplifier

A good follow-up activity for this circuit is to change the input frequency, and predict/measure the phase shift ( $\Theta$ ) between input and output for sinusoidal waveforms. The results may be surprising, especially if you are accustomed to the behavior of a *passive* integrator circuit.

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.

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## Notes 16

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between  $1\text{ k}\Omega$  and  $100\text{ k}\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k, 47k, 68k, etc.).

I have had good success using the following values:

- $+V = +12\text{ volts}$
- $-V = -12\text{ volts}$
- $V_{in} = 1\text{ V}$  peak-to-peak, at  $1\text{ kHz}$
- $R_1 = 1\text{ k}\Omega$
- $C_1 = 0.1\text{ }\mu\text{F}$
- $U_1 =$  one-half of LM1458 dual operational amplifier

A good follow-up activity for this circuit is to change the input frequency, and predict/measure the phase shift ( $\Theta$ ) between input and output for sinusoidal waveforms. The results may be surprising, especially if you are accustomed to the behavior of a *passive* differentiator circuit.

Students may become dismayed if they see a "noisy" output waveform, especially if they have just completed the active integrator circuit exercise. Explain to them that noise on the output of a differentiator circuit is quite normal due to the proper function of a differentiator: to provide voltage amplification proportional to the frequency of the signal. This means that even a little high-frequency noise on the input will show up on the output in magnified form. Remind them that this is what differentiators are supposed to do, and it is not some idiosyncrasy of the circuit.

Active differentiator circuits are great for displaying distortions in the input waveform. While pure sine waves in should produce pure sine waves out, and pure triangle waves in should produce pure square waves out, deviations from these "pure" waveform types will produce output waveforms that obviously deviate from their ideal forms. Usually, a "distorted" output does not indicate a fault in the circuit, but rather a subtle distortion in the input signal that would otherwise go unseen due to its miniscule magnitude.

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.

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## Notes 17

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.

Be sure to choose component values that will yield a frequency well within the range that the specified opamp can handle! It would be foolish, for example, to specify a cutoff frequency in the megahertz range if the particular opamp being used was an LM741.

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## Notes 18

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.

Be sure to choose component values that will yield a frequency well within the range that the specified opamp can handle! It would be foolish, for example, to specify a cutoff frequency in the megahertz range if the particular opamp being used was an LM741.

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## Notes 19

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!).

For capacitors, I recommend students choose three (3) capacitors of equal value if they wish to build the Sallen-Key circuit with a Butterworth response (where  $C_2 = 2C_1$ ). Capacitor  $C_1$  will be a single capacitor, while capacitor  $C_2$  will be two capacitors connected in parallel. This generally ensures a more precise 1:2 ratio than choosing individual components.

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.

Values that have proven to work well for this exercise are given here, although of course many other values are possible:

- $+V = +12$  volts
- $-V = -12$  volts
- $R_1 = 10$  k $\Omega$
- $R_2 = 10$  k $\Omega$
- $R_{comp} = 20$  k $\Omega$  (actually, two 10 k $\Omega$  resistors in series)
- $C_1 = 0.001$   $\mu$ F
- $C_2 = 0.002$   $\mu$ F (actually, two 0.001  $\mu$ F capacitors in parallel)
- $U_1 =$  one-half of LM1458 dual operational amplifier

This combination of components gave a predicted cutoff frequency of 11.25 kHz, with an actual cutoff frequency (not factoring in component tolerances) of 11.36 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!).

For resistors, I recommend students choose three (3) resistors of equal value if they wish to build the Sallen-Key circuit with a Butterworth response (where  $R_2 = \frac{1}{2}R_1$ ). Resistor  $R_1$  will be a single resistor, while resistor  $R_2$  will be two resistors connected in parallel. This generally ensures a more precise 1:2 ratio than choosing individual components.

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.

Values that have proven to work well for this exercise are given here, although of course many other values are possible:

- $+V = +12$  volts
- $-V = -12$  volts
- $R_1 = 10$  k $\Omega$
- $R_2 = 5$  k $\Omega$  (actually, two 10 k $\Omega$  resistors in parallel)
- $R_{comp} = 10$  k $\Omega$
- $C_1 = 0.002$   $\mu$ F (actually, two 0.001  $\mu$ F capacitors in parallel)
- $C_2 = 0.002$   $\mu$ F (actually, two 0.001  $\mu$ F capacitors in parallel)
- $U_1 =$  one-half of LM1458 dual operational amplifier

This combination of components gave a predicted cutoff frequency of 11.25 kHz, with an actual cutoff frequency (not factoring in component tolerances) of 11.11 kHz.

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.

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## Notes 22

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.

Values that have proven to work well for this exercise are given here, although of course many other values are possible:

- $+V = +12$  volts
- $-V = -12$  volts
- $R_1 = 10$  k $\Omega$
- $R_2 = 10$  k $\Omega$
- $R_3 = 5$  k $\Omega$  (actually, two 10 k $\Omega$  resistors in parallel)
- $R_4 = 100$  k $\Omega$
- $C_1 = 0.001$   $\mu$ F
- $C_2 = 0.001$   $\mu$ F
- $C_3 = 0.002$   $\mu$ F (actually, two 0.001  $\mu$ F capacitors in parallel)
- $U_1 =$  one-half of LM1458 dual operational amplifier

This combination of components gave a predicted center frequency of 15.92 kHz, with an actual cutoff frequency (not factoring in component tolerances) of 15.63 kHz.

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## Notes 23

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.

Values that have proven to work well for this exercise are given here, although of course many other values are possible:

- $+V = +12$  volts
- $-V = -12$  volts
- $R_1 = 10$  k $\Omega$
- $R_2 = 10$  k $\Omega$
- $R_3 = 5$  k $\Omega$  (actually, two 10 k $\Omega$  resistors in parallel)
- $R_4 = 20$  k $\Omega$  (actually, two 10 k $\Omega$  resistors in series)
- $C_1 = 0.001$   $\mu$ F
- $C_2 = 0.001$   $\mu$ F
- $C_3 = 0.002$   $\mu$ F (actually, two 0.001  $\mu$ F capacitors in parallel)
- $U_1 =$  one-half of LM1458 dual operational amplifier

This combination of components gave a predicted notch frequency of 15.92 kHz, with an actual cutoff frequency (not factoring in component tolerances) of 15.87 kHz.

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## Notes 24

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k, 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = 10 \text{ k}\Omega$
- $R_2 = 10 \text{ k}\Omega$
- $R_3 = 10 \text{ k}\Omega$
- $C_1 = 0.1 \mu\text{F}$
- $U_1 =$  one-half of LM1458 dual operational amplifier

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.

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## Notes 25

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k, 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = 10 \text{ k}\Omega$
- $R_2 = 10 \text{ k}\Omega$
- $R_3 = 10 \text{ k}\Omega$
- $R_4 = 10 \text{ k}\Omega$
- $R_5 = 100 \text{ k}\Omega$
- $C_1 = 0.1 \mu\text{F}$
- $C_2 = 0.47 \mu\text{F}$
- $U_1 =$  one-half of LM1458 dual operational amplifier
- $U_2 =$  other half of LM1458 dual operational amplifier

It is a good idea to choose capacitor  $C_2$  as a larger value than capacitor  $C_1$ , so that the second opamp does not saturate.

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.

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## Notes 26

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = R_2 = 10 \text{ k}\Omega$
- $R_{pot} = 10 \text{ k}\Omega$  multi-turn
- $C_1 = C_2 = 0.001 \mu\text{F}$
- $U_1 =$  one-half of LM1458 dual operational amplifier

Note that due to the lack of automatic gain control in this circuit, the potentiometer adjustment is *very* sensitive! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion).

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.

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## Notes 27

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = R_2 = 10 \text{ k}\Omega$
- $R_3 = R_4 = 10 \text{ k}\Omega$
- $R_{pot} = 10 \text{ k}\Omega$  multi-turn
- $C_1 = C_2 = 0.001 \mu\text{F}$
- $D_1 = 1\text{N}4148$
- $D_2 = 1\text{N}4148$
- $U_1 =$  one-half of LM1458 dual operational amplifier

With the presence of the amplitude-limiting diodes  $D_1$  and  $D_2$ , the potentiometer adjustment is not nearly as sensitive as without. Try removing both diodes to see what happens when there is no amplitude limiting at all! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion). With the diodes in place, however, you may adjust the potentiometer for a loop gain just above unity with the only consequence being slight distortion of the waveform rather than severe distortion.

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.

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## Notes 28

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = 10 \text{ k}\Omega$
- $R_{pot} = 10 \text{ k}\Omega$  multi-turn
- $C_1 = 0.001 \mu\text{F}$  or  $0.47 \mu\text{F}$
- $L_1 = 100 \text{ mH}$
- $U_1 =$  one-half of LM1458 dual operational amplifier

Note that due to the lack of automatic gain control in this circuit, the potentiometer adjustment is *very* sensitive! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion).

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.

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## Notes 29

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = 10 \text{ k}\Omega$
- $R_{pot} = 10 \text{ k}\Omega$  multi-turn
- $C_1 = 0.001 \mu\text{F}$  or  $0.47 \mu\text{F}$
- $L_1 = 100 \text{ mH}$
- $U_1 =$  one-half of LM1458 dual operational amplifier

Note that due to the lack of automatic gain control in this circuit, the potentiometer adjustment is *very* sensitive! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion).

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.

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### Notes 30

Use a dual-voltage, regulated power supply to supply power to the opamp. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k, 47k, 68k, etc.).

I have had good success using the following values:

- +V = +12 volts
- -V = -12 volts
- $R_1 = 10 \text{ k}\Omega$
- $R_2 = R_3 = 1 \text{ k}\Omega$
- $R_{pot} = 10 \text{ k}\Omega$  multi-turn
- $C_1 = 0.001 \mu\text{F}$  or  $0.47 \mu\text{F}$
- $L_1 = 100 \text{ mH}$
- $D_1 = D_2 = 1\text{N}4148$
- $U_1 =$  one-half of LM1458 dual operational amplifier

With the presence of the amplitude-limiting diodes  $D_1$  and  $D_2$ , the potentiometer adjustment is not nearly as sensitive as without. Try removing both diodes to see what happens when there is no amplitude limiting at all! Students will have to finely adjust the multi-turn potentiometer to achieve a good sine wave (meeting the Barkhausen criterion). With the diodes in place, however, you may adjust the potentiometer for a loop gain just above unity with the only consequence being slight distortion of the waveform rather than severe distortion.

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.

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### Notes 31

Students are free to choose any oscillator design that meets the criteria: sinusoidal output at a specified frequency.

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.

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### Notes 32

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.

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### Notes 33

Students are free to choose any duty cycle they wish. The only performance criterion is output frequency.

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.