


Scenario 3 'Scenario around the timbre of musical instruments and the tone colour'

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Title:	Lower Secondary Scenario 3: <b>Synthesize the timbre of your preferred instrument</b>		
Keywords:	timbre, harmonics, fundamental, natural tones		
Short Description:	iMuSciCA Scenario around the timbre of musical instruments and the tone colour		
Lesson Plans included:	Lesson Plan 1: Timbre of musical instruments and the tone colour	Date:	20/02/2018
Educational Objectives:	<p>The educational objectives of this scenario are:</p> <ol style="list-style-type: none"> <li>1. The students can show and explain how it comes that the same tone sounds differently on different instruments.</li> <li>2. The students can measure the frequencies and relative strength of the partials that determine the timbre of an instrument.</li> <li>3. The students can, to some approximation, synthesize the timbre of a particular instrument by adding partials in a proper relative strength. (using iMuSciCA's tone synthesizer)</li> </ol> <p>Extra: The students can show and explain how a resonance box influences the timbre of sound.</p>	Estimated Duration:	4-6 h
Author(s):	Renaat Frans, Erica Andreotti	Age Group:	Lower Secondary (approx. 12-15)
Contributor(s):	Mieke Schuermans, Jeroen Vanesser, Jeroen Op den Kelder, Marjan Van de Moer, Reinout Vaes, Tim Maes, Tom Jeunen	Language:	English
Status:		Difficulty Level:	Low
Dissemination level:		Special Needs Addressed:	


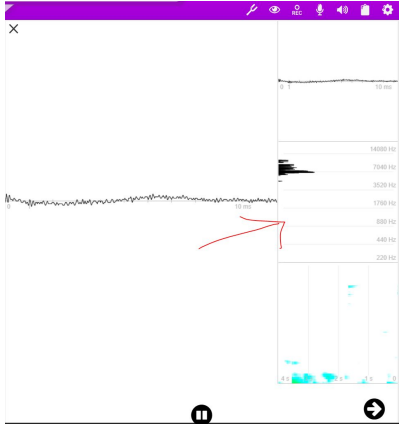
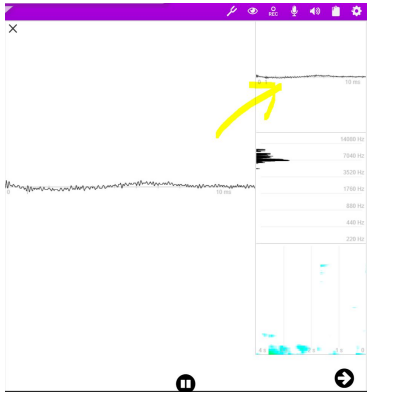
## Scenario (Synopsis)

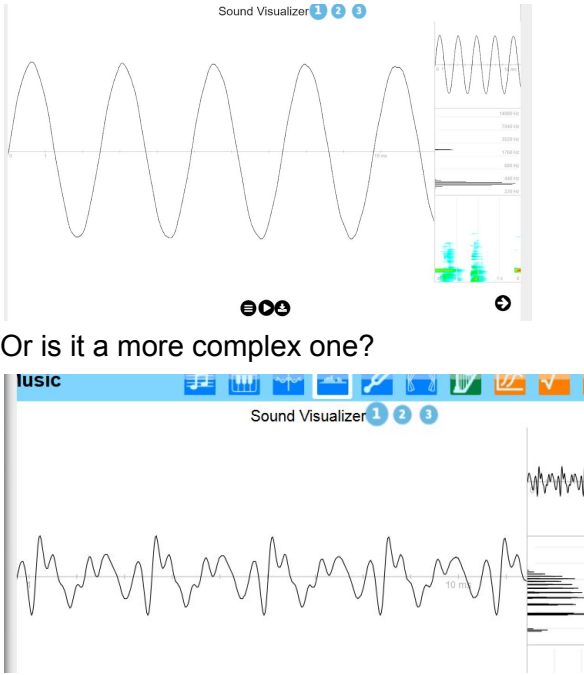
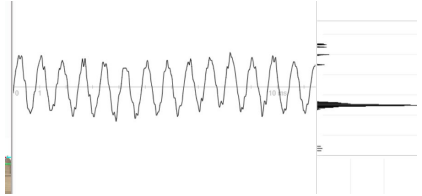
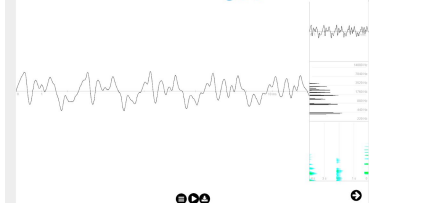
### Lesson 1: in development, first overview

Time	Phases	Field	Description	Activity	Remarks
	Engage/Imagine	E	Introduction	<p>In this scenario you are going to synthesize a sound similar to one produced by your favourite instrument.</p> <p>For instance: if the guitar is your favourite instrument, you are going to reproduce the timbre (tone colour) of a guitar by means of the iMuSciCA tone synthesizer on the workbench.</p>  <p>So your trying to make a simple synthesizer!</p> <p>We start by listening to two different instruments playing the same tone.</p>	<p>We start with an engineering question: the aim is to reproduce or synthesize, the sound of a musical instrument.</p> <p>After this lesson you should have learned that synthesizing a real musical instrument is quite a challenging task.</p> <p>However by means of the tone synthesizer on the iMuSciCA workbench it is possible to approximately reproduce the timbre of a real instrument (however not perfectly imitate it). This is due to different factors such as: i) the limited number of harmonics that can be measured (for a more accurate reproduction we should measure and reproduce more harmonics) ii) the relative strength and position can be measured only approximately.</p>

<p>1</p>	<p>Engage /Imagine</p>	<p>A</p>	<p>The same tone played on different instruments sounds differently. We will first experience this in the musical world.</p>	<p>Recognize different instruments. Exercise:</p> <ol style="list-style-type: none"> <li>1) Play the same tone on different instruments. Can you distinguish one instrument from another based on their quality of tone?  E.g. Play the same tone on a piano and on a flute : can you hear which tone is played on which instrument?</li> <li>2) Write down the names of <i>string instruments</i> that you know.</li> </ol> <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 10px auto;"> <p>Write here the names of the instruments</p> </div> <p>Listen and recognize the two string instruments which are playing together: CD1, Tracks <a href="#">9</a> [solution: <i>cello and piano</i>]</p> <p>Which <i>wind instruments</i> do you know?.</p> <p>Listen and recognize: which <i>wind instruments</i> do you hear: <a href="#">CD4. Track 46</a> [solution: <i>clarinet</i>] <a href="#">CD4. Track 54</a> [solution: <i>oboe</i>]</p> <p>Write down the <i>idiophones</i> you've heard of. <i>[examples: xylophone, carillon, table...]</i></p>	<p>Go to the following video in case you don't have a real instrument: <a href="https://www.youtube.com/watch?v=M6dA261tDRI&amp;feature=youtu.be">https://www.youtube.com/watch?v=M6dA261tDRI&amp;feature=youtu.be</a></p>
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				<p>Recognize which <i>idiophones</i> you hear:  <a href="#">CD1 track 59</a> [solution: xylophone]</p> <p>Write down the <i>membranophones</i> that you know:          [examples: djembe, drum, kettledrum...]</p> <p>Recognize which <i>membranophones</i> you hear:  <a href="#">CD1 track 60</a> [solution: kettledrum]</p> <p>Listen to the tracks. Write down which instruments you hear and to which group of instruments they belong:          CD1, Tracks 52 to 57          [solution: 1. <a href="#">concert flute</a>, aerophones; 2. <a href="#">alto saxophone</a>, aerophone; 3. <a href="#">guitar</a>, string instrument; 4. <a href="#">kettledrum</a>, membranophones; 5. <a href="#">harp</a>, string instrument; 6. <a href="#">Electric guitar</a>, <a href="#">String instruments</a>]</p>	
	Investigate /Analyze	S	Measurement and observation of the waveform of two instruments playing the same tone.	<p>Why does the same tone sound differently on different instruments?</p> <p>Take two different instruments on which you play the same tone. Or use a virtual keyboard like this:</p>	<p>You can use a Virtual Keyboard such as:  <a href="http://www.caseyrule.com/projects/piano/">http://www.caseyrule.com/projects/piano/</a></p> <p>You can also use a real instrument that you have in your class: a guitar, a flute...</p>

		<p><b>Observation:</b> we all play the same tone, but still it sounds differently on each instrument.</p> <p>When looking at the waveform it appears to be different on a different instrument.</p> <p><b>Conclusion:</b> the difference in waveform coincides with a difference in <b>'timbre'</b> or tone colour.</p>	<p><b>Online Virtual MIDI Keyboard</b></p>  <p>Verify if your two chosen instruments play the same tone e.g. a central A (la) of 220 Hz</p> <p>Now let's have a look at the <b>waveform</b> of the two tones. Compare the waveforms. What can you say about:</p> <ul style="list-style-type: none"> <li>- the number of times the pattern repeats itself within the same time period [<i>answ: the same</i>]</li> <li>- the shape of the pattern of both waves [<i>answ: different</i>]</li> </ul> <p>We assume that the difference in the shape of the waveform coincides with a difference in <b>'timbre'</b> or tone colour.</p> <p>But what is the origin of this difference in waveform if they have the same frequency?</p> <p>Observe the pattern of the chosen instruments: is it a 'simple' wave as the one below?</p>	<p>You could measure the frequency with the 2D <i>Sound visualization</i> (iMuSciCA workbench): click on the spectrometer at the center right on the screen:</p>  <p>To visualize the waveform use the 2D <i>Sound visualization</i> on the iMuSciCA workbench. Use the tool in the right upper corner:</p> 
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				 <p>Or is it a more complex one?</p> <p><b>Could it be that the more complex wave is the result of the sum (superposition) of a few simple waves?</b></p> <p>We will investigate whether it is indeed possible that waves can be added. You can learn more about how waves add up in Scenario 2.</p>	<p>See the example below for the waveform of the A on a trumpet:</p>  <p>On a violin:</p>  <p>In Sc2 it is demonstrated that standing waves originate in musical instruments precisely as the sum of back and forth going waves.</p>
Analyze	S	We try to reproduce a complex waveform by means of a	Let us investigate how <i>simple waves sum up to form more complex waves</i> using the <i>Tone Synthesizer</i> (on the iMuSciCA workbench). Reproduce a tone A (1a) of 220 Hz. This is called a 'pure tone' because it has no other frequency:	You can find more information on natural tones in scenario 2.  In the <b>Tone Synthesizer</b> you can change the frequencies by means of the slider at the right or by	

tone synthesizer.

**Observation:**

By adding up waves of different frequencies, where every new wave has a frequency that is a whole multiple of the first one, we end up with a more composite waveform.

The timbre of this resulting wave sounds differently depending on the strength of each of the composing frequencies.



Let's add another tone. We will not add a random tone. Let's try the next natural tone first: the 2nd harmonic. What will be the frequency of the 2nd harmonic? *[ans. 440 Hz]* Make with the tone synthesizer the resulting sum of the 1st and 2nd harmonic.




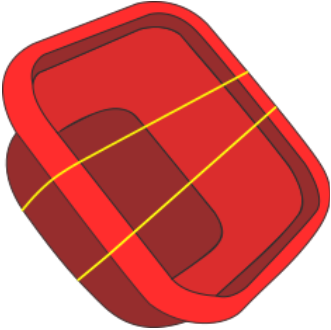
Try to change the strength of the 2nd harmonic, set the strength to a certain value and listen:

- to the pure tone of 220 Hz;
- to the sum of the 1st and 2nd harmonic.

writing the desired value between parenthesis:  $\sin(2 \times \pi \times \dots)$ . You can change the strength by writing a number between 0 and 1 in the first box (or by means of the slider at the left side).

				<p>Do you hear a difference? <i>[ans: yes!]</i></p> <p>Make the 2nd harmonic stronger than the first. Which difference do you hear? Make the 2nd harmonic weaker than the first one. Which difference do you hear? <i>[ans: by changing the strength of the harmonics the resulting tone sounds differently.]</i></p> <p>Do the same with a third and a fourth harmonic. Add one harmonic at a time and change the strength. Listen and describe which difference you hear. <i>[ans: by adding new harmonics and by changing their strength, the resulting tone sounds differently.]</i></p> <p>Observe the result of the sum of the different harmonics: which form has the resulting wave? Does it look like the form of a pure tone or is it the form of a more composite tone? <i>[ans: it is a complex form, therefore waves can sum up and form a more complex wave.]</i></p>	
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				 <p><b>Conclusions:</b></p> <ol style="list-style-type: none"> <li>1. By summing up different waves you can create a resulting wave with a more complex form. This resulting waveform determines the timbre of the sound.</li> <li>2. The strength of each component in the resulting wave has an influence on the tone colour (timbre) of the instrument.</li> </ol>	
	Investigate	S	We'll investigate the relation between the frequencies of	It looks like different waves can emerge from adding up a certain row of simple waves. But why did we choose to add the waves of the natural tones and not waves of random frequencies? We will investigate this.	Information about the natural tones can be found in scenario 2.

			<p>a row of harmonics (natural tones).</p>	<p>What was the mathematical relation between the frequency of the first natural tone (fundamental tone) and for instance the third natural tone?</p> <p><i>[ans: the mathematical relation between the frequency of the 1st natural tone (fundamental tone) and e.g. the 3rd natural tone is: <math>f_3 = f_1 * 3</math>].</i></p>	
	Create/Design	E	<p>Make a simple string instrument.</p>	<p>We will now measure the relation between the subsequent harmonics of a tone, as they originate if you play a musical instrument. Make a simple instrument as described below: take a plastic box and a rubber band. Stretch the rubber band around the box as shown in the figure below.</p> 	<p>Take care that the rubber band has sufficient tension, otherwise your instrument won't make a sound. Alternatively you can also use a monochord or a guitar or any other instrument that generates a clear tone.</p>
	Investigate/Analyze	S	<p>We investigate the relation between the frequencies of the subsequent</p>	<p>Measure the series of the frequencies generated when you 'play' on the rubber band. Use the <i>2D Sound visualization</i> on the iMuSciCA workbench.</p>	<p>Measure the frequency with <i>2D Sound visualization</i> (iMuSciCA workbench). Click on the spectrometer at the right side in the center:</p>



				<table border="1"> <thead> <tr> <th></th> <th>subsequent natural tone</th> <th>overtones</th> </tr> </thead> <tbody> <tr> <td>1</td> <td></td> <td></td> </tr> <tr> <td>2</td> <td></td> <td></td> </tr> <tr> <td>3</td> <td></td> <td></td> </tr> <tr> <td>4</td> <td></td> <td></td> </tr> <tr> <td>5</td> <td></td> <td></td> </tr> </tbody> </table>		subsequent natural tone	overtones	1			2			3			4			5			
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			<p>It could be that not all the predicted harmonics appear: in this case leave the corresponding box in the right column empty.</p> <p>Natural tones are the same as with the whirly tube (ref scenario 2): you can produce the natural tones one after the other. You can also play the natural tones on a string instrument, one natural tone after the other (ref video in scenario 2, harmonics on a monochord).</p> <p>Notice that if all the natural tones sound together at the same time, as is the case in many musical instruments, then we call them 'overtones'. <b>Overtones are natural tones which sound together with the fundamental.</b></p> <p>Is there a mathematical <b>relation</b> between the frequencies of the overtones and that of the natural tones?</p> <p><i>[Ans: Yes, there is a relation: the frequencies of the form entire multiples of the frequency of the fundamental. This</i></p>																				

*was also the case for the frequencies of the upper natural tones compared to the lowest.]*

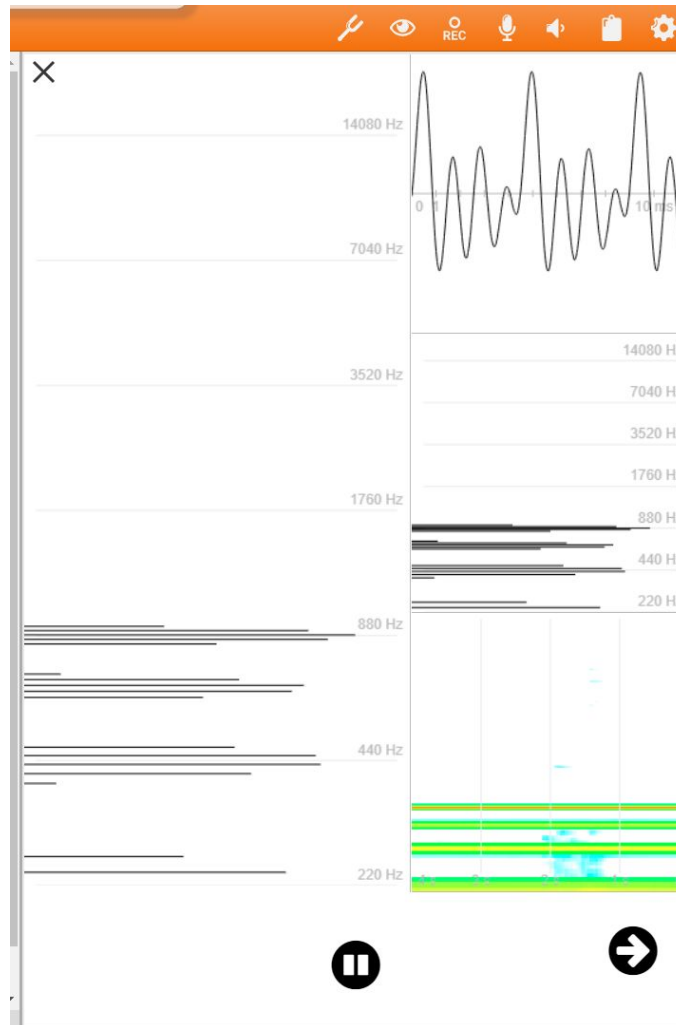
If the frequencies of the overtones are **entire multiples**, we call them **harmonics**.

**Investigate again that if you play for instance on a string instrument (monochord, guitar...) the overtones *sound together* and that their frequencies are entire multiples.**

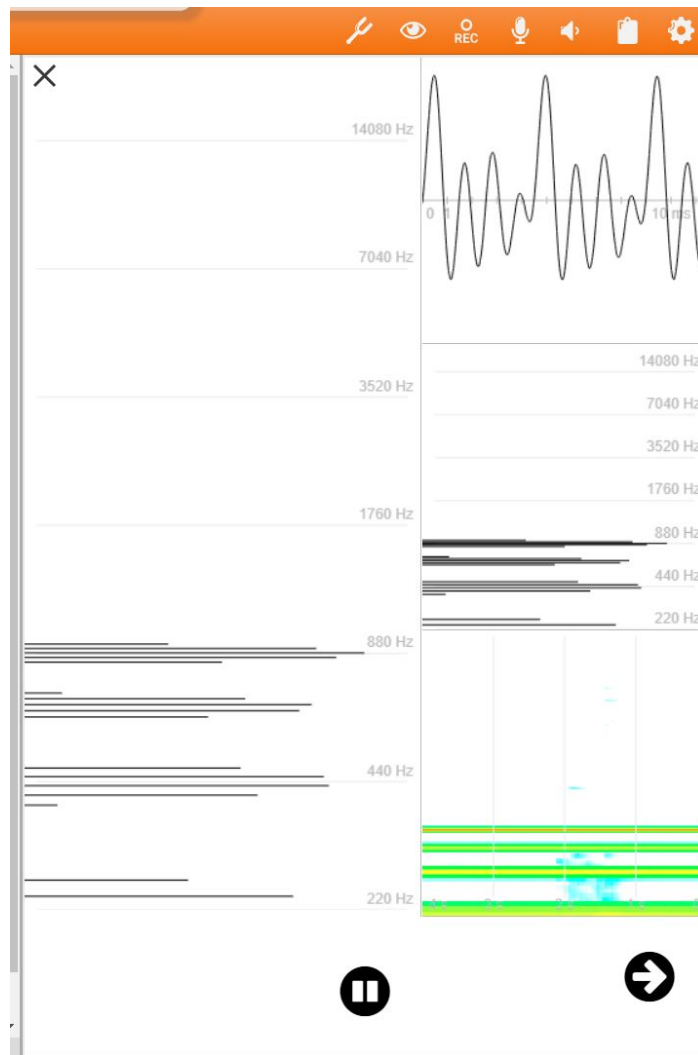
Observe the measured spectrum: do you see that the various harmonics sound together?



	Investigate	S	<p>We investigate which differences there are between the spectrums of the same tone played on different instruments.</p> <p>The same harmonics are measured, but with different relative strengths.</p>	<p>How can we explain that the same tone sounds differently on different instruments?</p> <p>Take the same two instruments as you did in the beginning.</p> <p>Play the same fundamental tone on both e.g. a low A (1a) of 220 Hz.</p> <p>Measure the spectrum and explain why the same A sounds different on both instruments. Explain why they have a different timbre! Use the 2D Sound Visualization tool.</p>	<p>If you want you can let the pupils reflect on a thesis like: "the sound of an instrument for a specific tone is determined by the fundamental frequency of that tone".</p>
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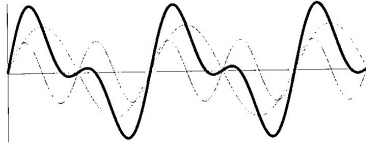
Spectrum of a low A (la) 220Hz on an organ



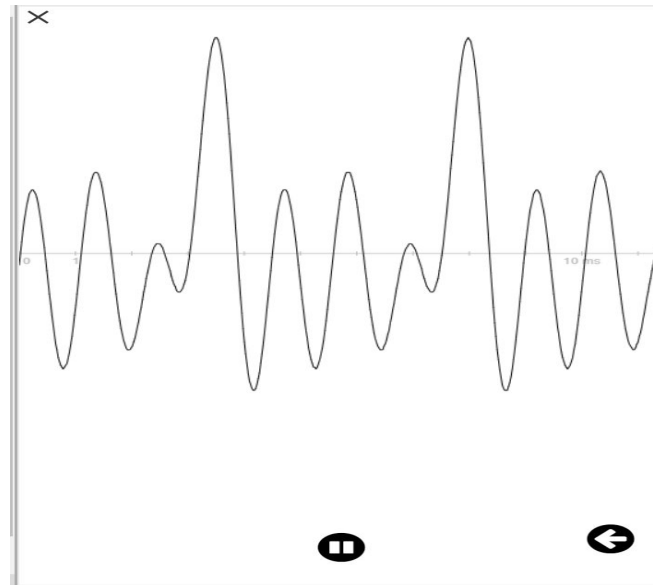
Spectrum of of a low A (la) 220Hz on a violin

What differences and similarities do you notice between the two frequency spectra? What do you notice concerning the strength of the various overtones?

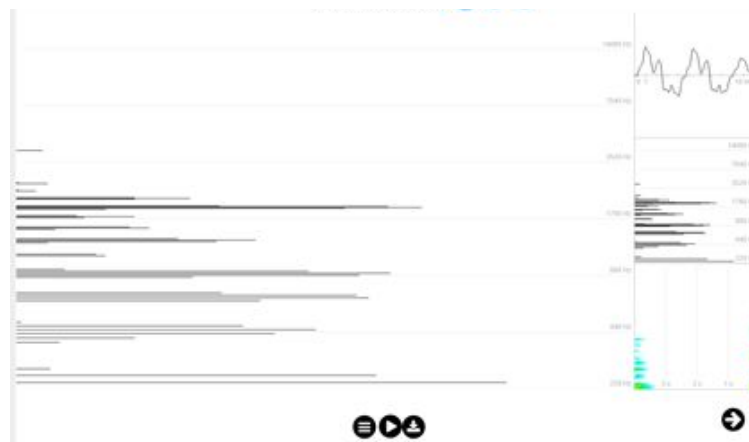
				<p><i>[Ans: the same frequencies are measured, but with different strengths]</i></p> <p>Conclusion: the timbre of an instrument is determined by the strength of the different overtones. The strength corresponds to the amplitude.</p>	
	Investigate	S	<p>We investigate why the waveforms of the instruments are different.</p>	<p>Explain also why the waveforms of the instruments are different, though both waves have the same frequency. Use again the <i>Tone Synthesizer</i>.</p> <p>Reproduce a tone A (1a) of 220 Hz. Change the strength of the tone: what does change in the waveform?  <i>[Ans: with the strength also the amplitude changes]</i></p> <p>Add the 2nd harmonic and change the strength of it: what does change in the waveform of the 2nd overtone?  <i>[Ans: the amplitude of the 2nd harmonics increases]</i></p> <p>What changes in the waveform of the sum?  <i>[Ans: the waveform of the sum changes as well if you change the strength of the different frequencies. The waveform of the tone you play on an instrument is generated as the sum of the different waves of the various overtones. Each of these different waves can contribute in a different way to the total amplitude of the sum].</i></p>	
				<p>Let us have another look at the wave pattern.                  What does a spectrum analyzer do, like the 2D sound visualization?</p>	<p>Spectrum Analysers decompose the composite wave in its components. The sum of the</p>

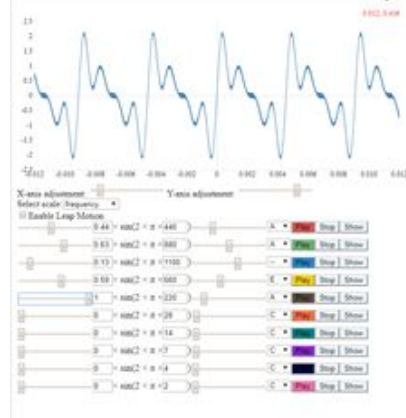
			 <p>How do you get the wave pattern of a composite wave?  <i>[Ans: by summing up different pure tones]</i></p> <p>So what does a spectrum analyzer do?  <i>[Ans: it decomposes a tone in its different components or harmonics.]</i></p> <p>What is the relationship between the fundamental and the overtones?  <i>[Ans: the frequencies are integer multiples of each other.]</i></p> <p>Background information:              It is the French mathematician and physicist Fourier (1768-1830) who discovered that you can write every periodic wave as a sum of pure sine waves. For this reason the process of decomposing a composite wave in its components is called Fourier analysis.</p>	<p>constituent overtones returns the composite wave again:</p>  <p>Note that the frequencies of harmonics of a chordophone and an aerophone are entire multiples of the fundamental. For membranophones and idiophones, however the overtones are not necessarily harmonics!</p>
	<p>Communicate &amp; Reflect</p>		<p>Explain how the 'tone colour' emerges.</p>	<p>Timbre is made to the extent of which every upper tone is more or less present in the sound spectrum. By adding up upper tones to a certain fundamental</p>

					tone, and changing their strength (or amplitude), we can create the timbre of a sound.
	Create	E	<p><b>'Application Synthesizer'</b>                  Make a composite sound as a sum of different sine waves. The aim is that the resulting waves sound like a certain instrument.</p>	<p><b>Imagine that you want to reproduce a tone as close as possible to the sound quality or timbre of a certain instrument.</b></p> <p>Imagine you want to reproduce a central A of 220 Hz on this instrument.</p> <p>What do you have to do with the relative strength of the first harmonic compared to the 2nd, 3rd and so on?                  [ans: the strength of the fundamental should be the strongest]</p> <p>Take your chosen instrument. Imitate the timbre, i.e. create a synthesizer that can play at least one tone with a timbre that looks as much as possible to the timbre of the instrument. Use the Tone Synthesizer.</p>	<p>Flute is perhaps a good choice because there are fewer overtones. The disadvantage might be that many recorders are sopranos and they start with high tones which can be harder to measure than lower ones..</p> <p>If you measure the timbre of an instrument via a keyboard, you may suffer from resonances from less qualitative speakers that add false 'harmonics'.</p> <p>In the 2D Sound Visualization it should be possible to measure the 'strength' of each frequency or at least the relative strength.</p>

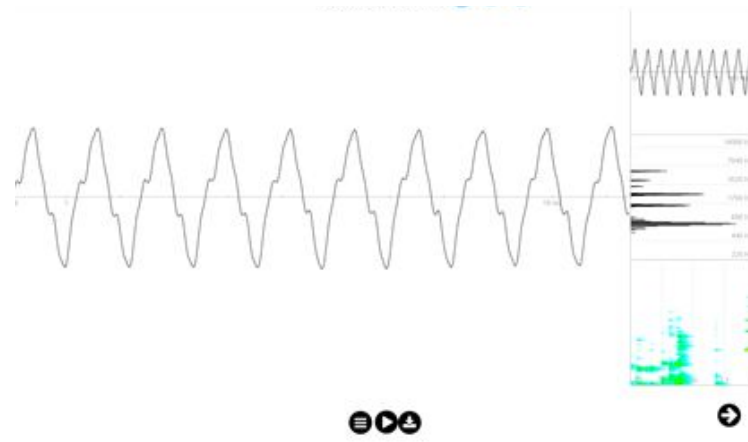


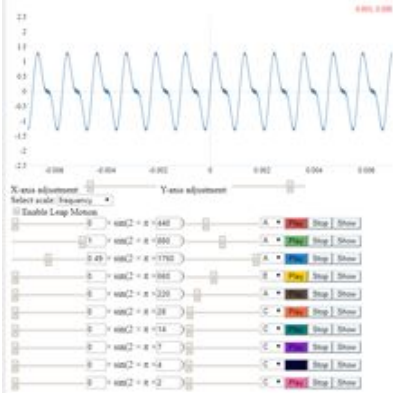
Guitar:



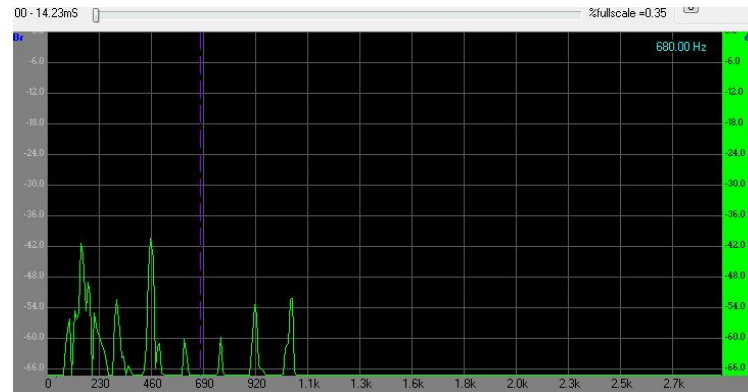


Recorder (type of flute):



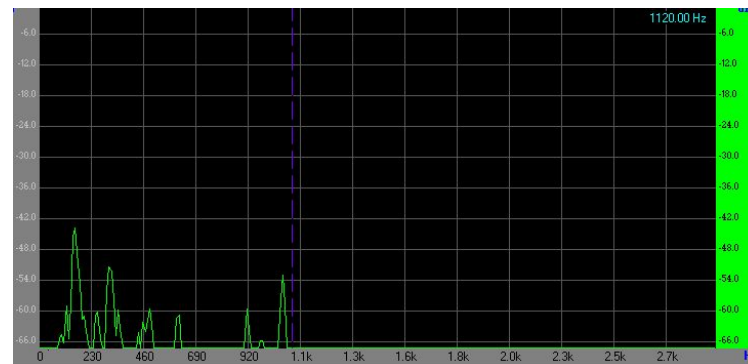
					
	<p>Reflect</p>	<p>S</p>	<p>Explain your experience while trying to synthesize your instrument</p>	<p><b>Reflects</b> Was it easy to reproduce the timbre of your chosen instrument? What do you think you could do better?</p>	<p>Synthesize a real musical instrument is quite a complex task. Indeed by means of the tone synthesizer on the iMuSciCA workbench it is possible to approximately reproduce the timbre of a real instrument, but not to perfectly imitate it. This is due to different factors such as: i) the limited number of harmonics that can be measured (for a more accurate reproduction we should measure and reproduce more harmonics) ii) the relative strength and position can be measured only approximately.</p>

	Create Design	A	Back to the musical world	<ol style="list-style-type: none"> <li>1) Recognise different choir types: boys choir, children's choir, mixed youth choir gospel group, oratorium choir boysband close harmony group etc...</li> <li>2) 5 different female students sing the same popsong (e.g. Galway Girl). We make a recording of that. Can you distinguish who is singing? Higher level of this exercise is when 2 voices sing together</li> <li>3) We will walk in a 'virtual environment' of performing musicians. Listen to the different timbres of the different voices.</li> </ol>	<p>Use for instance the accompaniment  <a href="https://www.youtube.com/watch?v=JJvYdF2RIYY">https://www.youtube.com/watch?v=JJvYdF2RIYY</a></p> <p>Example of Polyphonic Experience (Rudi Knoops)  <a href="https://vimeo.com/158234283">https://vimeo.com/158234283</a></p>
	Extra Investigation	S	<p>We investigate qualitatively the influence of the resonance box on the timbre.</p> <p>Try to change the resonance box so that you obtain a different timbre, e.g. softer or sharper.</p>	<p><b>Extra exercise:</b>  <b>Investigate the influence of the resonance box on the timbre.</b></p> <p>Let us now investigate whether the resonance box you see at many instruments (like a violin or a guitar) does influence the timbre.</p> <p>For this little experiment we can reuse the plastic box and the rubber band.</p> <p>Measure and observe now the row of the harmonics this simple instruments produces and look if altering the properties of the box alters the heard and measured timbre..</p>	<p>In this kind of investigation you have to pay attention that you only change the resonance box and not the tension of the rubber band. You also have to pay attention that the measurements are taken in the same conditions.</p>



**frequency spectrum of box with rubber band without sand**

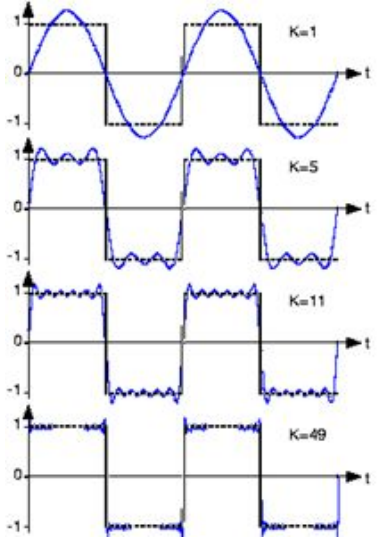
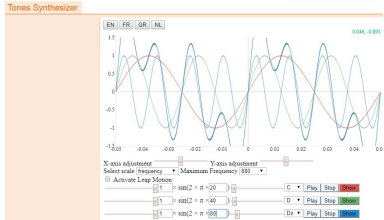
Place now sand inside the box and measure again the row of harmonics. Compare the frequency spectrum of the box with and without sand.



**frequency spectrum of box with rubber band with sand**

What can you conclude?

**Conclusion:** with sand the higher overtones are attenuated. The resonance box influences the timbre.

	Investigate	S	Extra Exercise	<p><b>Extra exercise:</b>          Try now to create a waveform by adding up overtones to a given fundamental tone. E.g. try to reproduce a 'square wave'.</p> <p>Use the Tone Synthesizer on the workbench.</p>	<p>Given: a waveform          Task: add harmonic sine waves which can approach the desired waveform</p> <p>Example: Fourier synthesis of a square wave.</p>  <p>Use the imuscula workbench tone synthesizer:</p> 
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