Title:	**Scenario B: Timbre and power spectra**		
Keywords:	Timbre, Power spectrum		
Short Description:	Students will experiment and understand why different instruments sound differently. They will analyze different sounds and comprehend power spectra. It is a continuation of scenario A: "Investigating a monochord".		
Lesson Plans included:	Lesson Plan 1: Timbre and power spectra Lesson Plan 2: Investigating the harmonic content of a monochord	Date:	30/9/2017
Educational Objectives:	- Learn about timbre and why instruments sound differently - Learn what is a power spectrum and how it is manipulated	Estimated Duration:	12 hrs
Author(s):	E.Chaniotakis	Age Group:	14-16/16-18
Contributor(s):		Language:	English
Status:	Final	Difficulty Level:	Medium
Dissemination level:	Public	Special Needs Adressed:	No

LESSON PLANS

<table>
<tr><td colspan="6">Title: Lesson Plan B1: Timbre and power spectra</td></tr>
<tr><td colspan="6">Description: In this lesson plan, students will be introduced to the timbre of musical instruments and investigate the use of the waveform, the power spectrum and the spectrogram. The lesson plan is designed for High School students and has a duration of 4 hrs.</td></tr>
<tr><td colspan="6">E: Engineering/ Technology, S: Science/Mathematics, M: Music</td></tr>
<tr><th>Phases</th><th>Field</th><th>Time</th><th>Description</th><th>Activity</th><th>Rema</th></tr>
<tr><td>Engage

Wonder, Ask Questions, Explore, Observe – Identify Problems, questions and chances</td><td>M</td><td>0.5 hrs</td><td colspan="2">Have you ever wondered why different instruments sound differently? Why do humans' voices sound differently?
As we know, musical instruments can be categorised in three families: the stringed instruments, the percussive instruments and the wind instruments.
What do you think? Would the same note sound differently for different instruments?
Listen to the same note played by different instruments and try to identify differences. The sounds come from the McGill University Master Samples with each of the instruments presented being recorded in studio:
https://www.ee.columbia.edu/~dpwe/sounds/instruments
What do you believe? Do instruments belonging in the same family sound differently?
Let's find out! Watch the following videos of playing the same song with three different stringed instruments: cello, guitar and violin.
<table>
<tr><td>Cello:

https://www.youtube.com/watch?v=zdzYFHLHYAI</td><td>Classical Guitar:

https://www.youtube.com/watch?v=klKn2AmRnWU</td><td>Violin:

https://www.youtube.com/watch?v=KKVMxvFS5Qo</td></tr>
</table>
Try to listen to the three instruments in parallel. Can you tell them apart? (https://www.youtube.com/watch?v=sH0q7IWHMA0)
How would you describe the sounds that you hear? Which one seems to have a higher pitch? Which seems to have lower pitch? Discuss the differences you spot with respect to the components of the instruments, their size or the way they are triggered.</td><td></td></tr>
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Relate to Background Knowledge	S, M	0.5 hrs	Music is defined as vocal or instrumental sounds (or both) combined in such a way as to produce beauty of form, harmony, and expression of emotion. In music, *timbre* is the perceived sound quality of a musical note, sound or tone. The difference in the sound produced by a violin, a guitar and a cello can be identified as a difference in the timbre of the instruments. This difference derives from the different structure of the instruments and the different triggering mechanisms. In order to understand the timbre of musical instruments in a scientific basis, we need to remember that music derives from sound and sound is a wave. - Let us review the fundamental physics behind music: https://www.youtube.com/watch?v=XDsk6tZX55g *Discuss the following questions* -How do musical notes correspond to the frequencies of standing waves? -What is the fundamental frequency and what are the upper harmonics? - How do the frequency and the wavelength of a sound wave relate? -Compare the note G5 as it is produced by a tone generator and a violin: http://www.szynalski.com/tone-generator/ https://www.ee.columbia.edu/~dpwe/sounds/instruments/violin-G5.wav Can you spot any difference? The sound of the tone generator is “monochromatic”: it consists of a single frequency. Could you say the same for the sound produced by the violin: Is it monochromatic or it has overtones?	

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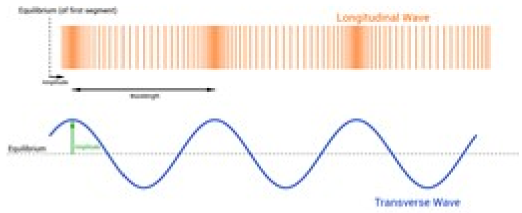
<tr>
<td>Imagine

Identify relevant variables to investigate – Identify Relevant Solutions to use</td>
<td>S</td>
<td>1 hr</td>
<td>In order to investigate the composition of the sound of a musical instrument and the correspondence of timbre to the harmonic structure of the sound waves produced, we need analysis tools which will facilitate our research.
The tools in question are:

- The waveform analyzer

See the picture below for the comparison of a transverse and a longitudinal wave with single frequency:



Picture 1</td>
<td></td>
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Sine waves of a single frequency, thus addressed as monochromatic, obey the equation:

$y = A\sin[2\pi(t/T - x/\lambda)]$ (1)

A: amplitude of the wave (measured in m)

T: period of the wave (measured in sec) is equal to 1/f

f: frequency of the wave (measured in Hz)

λ: wavelength of the wave (measured in m)

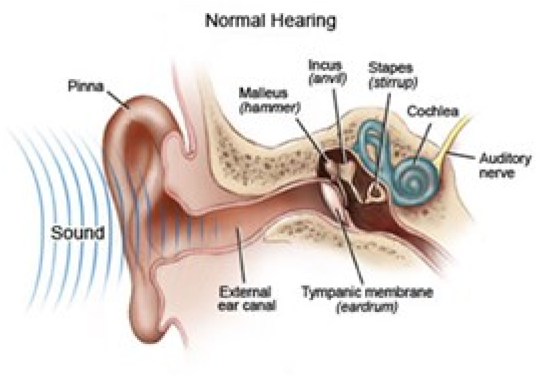
The detection of sound waves is done by devices located at fixed points in space, therefore the x variable is a constant. Imagine that we place our ear at a specific point in the path of the longitudinal wave of picture 1.

As a result, equation (1) can be written as:

$y = A\sin[2\pi(t/T) - \phi]$ (2)

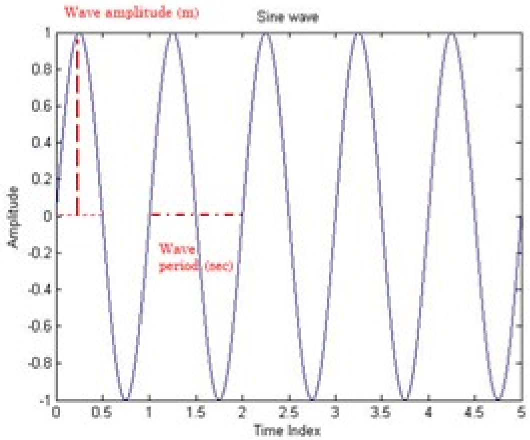
ϕ: the phase, measured in radians, is a constant

Equation (2) measures the displacement of our 'detector' with respect to time, resulting from a monochromatic wave reaching it. If the wave is a sound wave and the detector is the human ear, then displacement, y, is defined as the displacement of the tympanic membrane.



Picture 2

The plot of equation (2), measuring the displacement of a point in space (y-axis) due to a travelling wave versus time (x-axis), is called the waveform. Waveforms can be displayed through an oscilloscope.



Picture 3

Imagine that you place two sources of monochromatic sine waves with different frequencies at a distance from a microphone. The first source produces a sound of frequency f_1 and the second produces a sound of frequency $f_2 = 2f_1$, its first harmonic. The microphone utilizes a membrane which is forced to oscillate as the sound waves interact with it. This oscillation is transformed into an electric signal which can be sent to an oscilloscope for waveform visualization.

The equation displaying the displacement of the microphone with respect to time will be:

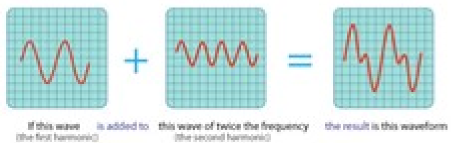
$$y = y_1 + y_2$$

$$y = A_1 \sin[2\pi(t/T_1) - \phi_1] + A_2 \sin[2\pi(t/T_2) - \phi_2]$$

y: total displacement

y1: displacement due to wave 1.

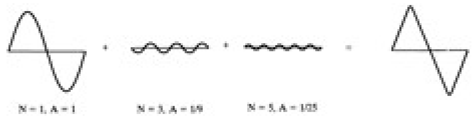
y2: displacement due to wave 2.



Picture 4

Let's assume that we want to produce a triangular waveform. How is this done?

We add a sine wave, with its third harmonic which has 1/9th of the initial amplitude and its fifth harmonic which has 1/25th of the initial amplitude and continue with odd numbered harmonics with decreasing amplitudes. In picture 5 you will see an approximate triangular waveform produced by the fundamental tone and its 3rd and 5th harmonic:



Picture 5

As a result, we understand that: *Any periodic wave with some frequency f can be synthesized from sine waves with the frequency f and its harmonics with amplitudes and phases determined by the shape of the complex wave. This statement is known as Fourier's theorem.*

- *The power spectrum*

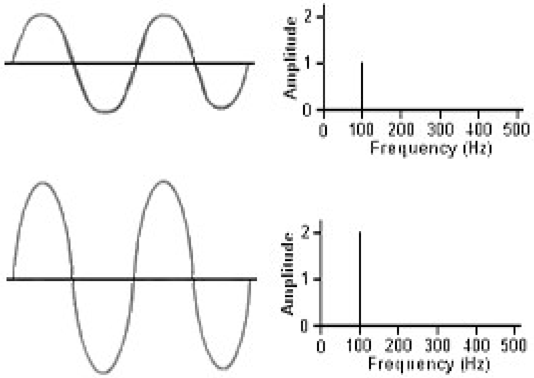
In picture 5 we saw that to approximate a triagonal waveform, we can add the fundamental tone with amplitude A_1, the third harmonic with $A_3=A_1/9$ and the fifth harmonic with amplitude $A_5=A_1/25$.

The total power (Power = Energy/Time) of the wave scales with energy, and energy scales with A^2. As a result, the fundamental tone contributes the most to the total power transferred by the wave, while the contribution of the 3rd harmonic is 81 times smaller and the contribution of the 5th harmonic to the total power is 625 times smaller.

A histogram called: "Frequency Spectrum", "Power Spectrum" or "Fourier Spectrum" is useful in order to display the harmonic component of a

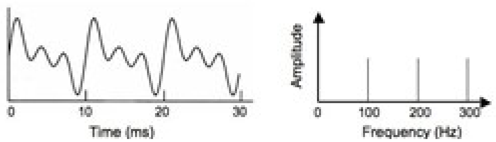
In the following picture, you can see the frequency spectra of two sine waves with frequencies equal to 100 Hz. The second wave has amplitude twice as high as the first.

The y-axis of the frequency spectrum can demonstrate the amplitude, the power, the pressure and other relevant variables whereas the x-axis displays the frequency.

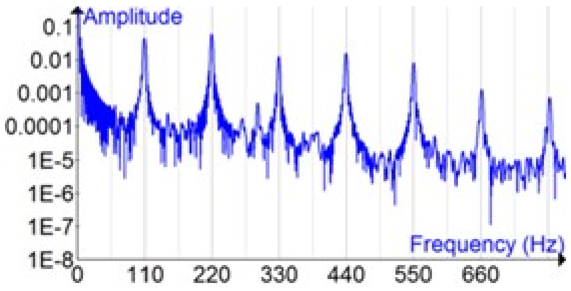


Picture 6

Observe picture 7 to see the power spectrum of a more complex waveform:



The spectra of real world everyday sounds can be analyzed in thousands of waves of different amplitudes, frequencies and phases. As a result, the power spectrum will be continuous with distinct peaks featuring the most prominent frequencies of the sound. You can see such a spectrum in picture 8.



Picture 8

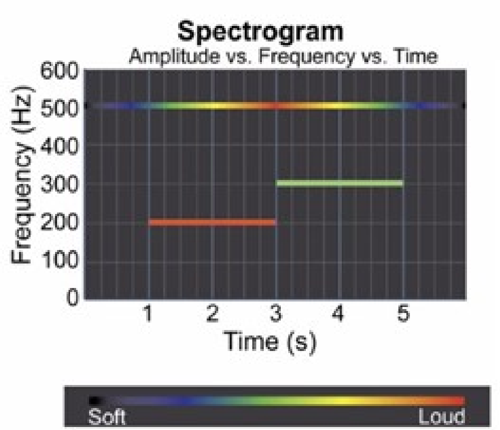
Compare the amplitude of the 110 Hz frequency and the 550 Hz frequency. What is their relationship?

- *The spectrogram*

Assume that you observe a complex waveform, such as the waveform of an earthquake.

The frequencies of which the waveform consists may contribute in different proportions over time. In order to visualize this attribute, we use the spectrogram. The spectrogram shows both frequency and amplitude with respect to time. A spectrogram is essentially a 3D plot:

It is a graph with x-axis representing time, y-axis representing frequency and the z-axis representing amplitude. Usually, the z-axis is replaced by a color code.

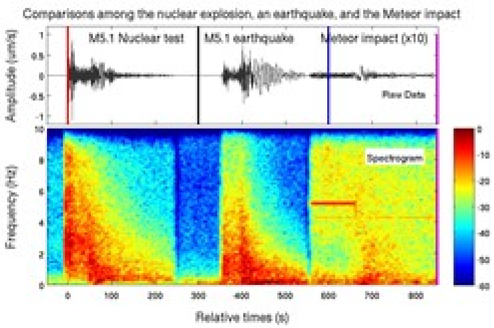


Picture 9

Picture 9 shows the spectrogram of a sound consisting of three frequencies. Can you say which frequency sounds the loudest at t=2s? At which time does frequency equal to 500 Hz sound louder than the others?

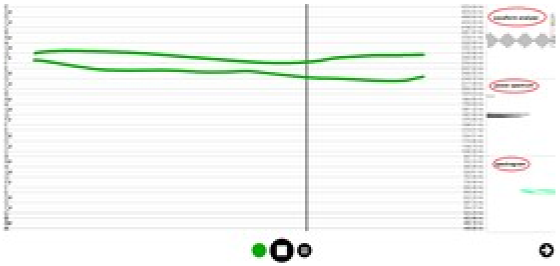
A spectrogram can be produced not only for sound waves, but by any kind of vibration. Such vibrations could be for example the oscillations of the ground resulting from an earthquake, a nuclear explosion or a meteor impact.

Observe picture 10 and see the waveforms and the spectrograms of these three events. What are your comments?



Picture 10

The color code shows the power in dB. The negative values are not to be confused with negative amplitudes. The topmost color (magenta) represents the highest amplitude of ground oscillation, whereas the bottom (cyan) represents the lowest amplitude.

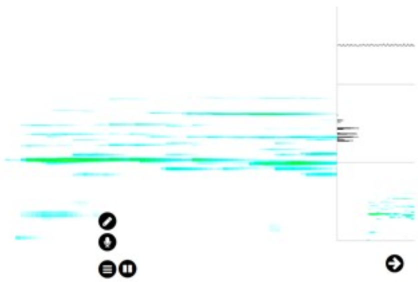
Use your imagination and make	E, S	0.5 hrs	Using the knowledge you obtained on the use of the: waveform, the power spectrum and the spectrogram, brainstorm on how you could use these tools to answer our initial question: Why do different instruments, even ones belonging in the same family, sound differently? Work in groups and propose your methods of investigation.	.
CREATE (Investigate / Design) Plan the Investigation / Design the Prototype	M, S	0.5 hrs	In this investigation you will use the iMuSciCA drawing canvas in order to investigate the use of the waveform, the spectrogram and the power spectrum.  Picture 11 Using the drawing canvas, you can left click and drag your mouse to draw a shape. The vertical axis represents frequency and the horizontal axis represents time. By choosing the option: “Play” you can hear the sound of the shape you drew. The three windows on the left display the: waveform analyzer, the power spectrum and the spectrogram of the sound you produce.	

Carry out Investigation / Build the Prototype	M, S	1 hr	- Use the iMuSciCA drawing canvas and investigate the sound produced by the different color options using the information from your ear, the waveform, the power spectrum and the spectrogram. How would you do it? Would you draw any shape, or would you follow a specific procedure? Experiment and write down your observations. - Use the magenta color and draw two parallel horizontal lines: You just produced a beat! - Draw parallel lines in various distances and observe the output in the various tabs. Write down your observations. - Try to "draw" this simple melody and let it sound:  **Mary had a Little Lamb** Ma-ry had a lit-tle lamb, E D C DE E E Lit-tle lamb, lit-tle lamb, D D D E E E Ma-ry had a lit-tle lamb, E D C DE E E Its fleece was white as snow. E D D E D C Picture 12 - Repeat the procedure with the different color options and listen to the sounds produced. Fix the playback speed at the lowest value. Do the sounds sound differently or similarly? How do you perceive each sound? What is the frequency content of each sound? Can you answer why, even though you play the same notes, the music you produce with each color has different timbre? - Use the drawing canvas to write your own melody or a melody you like and let it sound.	

Title: Lesson Plan B2: Investigating the frequency content of a monochord's sound

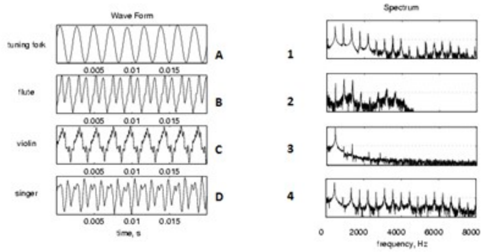
Description: In this lesson plan, students will analyze the sounds of everyday life as well as the sound of a virtual monochord and investigate its harmonic content. The lesson plan is addressed to upper high school students. The duration is 8 hours.

E: Engineering/Technology, S: Science/Mathematics, M: Music

Phase	**Field**	**Time**	**Description**	**Activity**	**Remarks**
CREATE (Investigate / Design) Plan the Investigation / Design the Prototype	S,E,M	1 hr	In part 1 you will use the iMuSciCA audio canvas analyzer in order to listen to different external sounds and observe their harmonic content, using the knowledge you obtained on the previous lesson concerning the waveform, the power spectrum and the spectrogram.  Picture 1 The iMuSciCA audio canvas analyzer imports the sound of your PC's microphone. The three windows on the right display the waveform, the power spectrum and the spectrogram of the sound. Part 2 In part 2 you will create a monochord playing note A and vary its parameters of interest as well as the way you interact with it in order to investigate which monochord attributes effect the timbre of the sound it produces. In order to create the monochord, follow the guidelines of scenario A, lesson plan A2: "Design a monochord playing note A". If you have already completed this lesson plan, open the saved instrument you have created and work with it.		

Carry out Investigation / Build the Prototype	S, E, M	3 hrs	Part 1: - Plug a microphone in your PC. - Choose the microphone option of the analyzer. - Use different sound sources to produce sound. Listen to the sound and using the iMuSciCA analyzer observe its frequency content. You can use a whistle, clap your hands, have two people speak the same word, sing the same note in different octaves, trigger a tuning fork etc. -Open a word document in which you will write the name of the source you used and place below the screenshot of the waveform, the power spectrum and the spectrogram. - Click on this link: https://www.ee.columbia.edu/~dpwe/sounds/instruments/ and listen to the same note played by different instruments. For each instrument, note its name to your word document and take a screenshot of the waveform, the power spectrum and the spectrogram. - Now, play a song using two or more different musical instruments. If you don't have access to musical instruments, search youtube in order to find a song that you prefer and listen to it being played by different instruments. As before, write the title of the song, the instrument you used and sample some screenshots. Part2: - Using the monochord playing note A you created, let it sound. - Use the iMuSciCA analyzer to listen to the sound and observe the frequency contents of it. Take a screenshot of the power spectrum. What do you observe? Does the monochord play only note A (440Hz) or do we have overtones? - Keeping the tension of the string constant, vary the length starting from 0,5m until 2m in steps of 0,25m. For each step, calculate the fundamental frequency. Let it sound and take a screenshot of the various power spectra. What do you observe? - Now, use the leap motion tool in order to change the way you interact with the monochord using the available options. Keep the fundamental tone constant at 440Hz. For different options, observe and take screenshots of the waveform and the power spectrum. - Alter the shape of the monochord keeping all other configurations constant and observe the power spectrum.	

Analyze Analyze Data from Investigations and Draw Conclusions/ Evaluate the Prototype.	S	1.5 hrs	Part 1 - Using the results you documented from Part 1, study the power spectra of the different sound sources you used. What are your observations concerning the frequency content of each sound? Write down your comments. - Using the results you documented on the same note being played by different instruments, note the differences between the different power spectra. Locate and estimate the frequencies occurring with highest intensity. Do different instruments have the same harmonic content? - Compare the power spectra you sampled from the same song with two different instruments. Note your observations. Part 2 - Observe the harmonic component of the sound produced by the monochord for each fundamental tone you have played. You will see that the overtones are different. - For each fundamental harmonic, find the frequencies which have the highest amplitude and divide them with the fundamental harmonic . Are the ratios constant? - Compare the waveforms and the power spectra of note A for different interaction configurations with the monochord. Does the harmonic content of the monochord's sound change with respect to the interaction method? With this comparison in mind, draw your conclusions. Why do different instruments of the same family sound differently?	

Explain by Relating to Background Knowledge/ Optimize the prototype	S,M	1 hr	- Match the following instrument waveforms with the correct power spectra  - Explain how you utilized the spectrogram, the power spectrum and the waveform in order to answer the question: “Why do different instruments sound differently”. - Which instrument of the three has a more “clean” power spectrum: The violin, the cello or the guitar? - Is the sound produced by a tuning fork strictly monochromatic? - When we use a monochord, what are the frequencies of the overtones we observe? Are they integer multiples of the fundamental frequency? - Make a short presentation with the instruments you employed and their power spectra.	
Describe and explain the results in the different STEAM-fields and the connections between them.	S, E , M	0.5 hrs	Discuss the design options of the monochord that contribute to the frequency content of the produced sound. Expand the discussion in other string instruments and discuss the design and the interaction parameters that may affect the sound output. You can use this link as reference: https://www.thoughtco.com/images-of-string-musical-instruments-4122917	

Communicate/Reflect Communicate Results and Conclusions/ Communicate the Product, perform	M, S, E	1 hr	- Present your results in a powerpoint format and explain the reason why different musical instruments sound differently. - You can work in groups and make a live demonstration of the waveform, power spectrum and spectrogram tools employing different sounds, the same notes or sounds played with different musical instruments or a music performance of your own. - Make sure that you highlight the interconnections between the design of the instrument (engineering component), the sound timbre (music component) and the harmonics content of the sound (physics component).	
Reflect on Feedback and incorporate in further process			- Discuss: What have you learned during this investigation. - Assume that you are an instrument maker. Would you take into account the harmonic content of your instrument while creating it? Would you listen to it and empirically try to figure out the best design parameters, or would you employ scientific reasoning and tools in order to produce the optimal output? In this context, you could get in touch with instrument makers and interview them on the design considerations they have in order to produce high quality string instruments. - Review the design of your monochord and evaluate which parameters were more important concerning the timbre of the instrument.	