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Using a new, free spectrograph program to critically investigate Acoustics

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Abstract
We have developed an online spectrogram program with a bank of over 30 audio clips to visualize a variety of sounds. Our audio library includes everyday sounds such as speech, singing, musical instruments, birds, a baby, cat, dog, sirens, a jet, thunder, and screaming. We provide a link to a video of the sound sources superimposed with their respective spectrograms in real time. Readers can use our spectrogram program to view our library, open their own desktop audio files, and use the program in real time with a computer microphone.

Introduction

The visualization of common sounds is an excellent teaching tool to illustrate their properties of acoustics. We have developed an HTML5 spectrogram program and prepared over 30 video clips of sources of sound: from a laughing baby to an opera singer, from the hit of a golf ball to the roar of a jet, from a flute solo to the blare of an orchestra. Our spectrograph program, Spectrograph, is free to use at our website academo.org [1]. You can also watch a 4-min video of the sources making the sounds with their spectrograms superimposed in real time [2]. Spectrograph can also open .mp3 and .wav files from your computer for viewing as the sound plays. Finally, our program allows you to make sounds using your microphone and the spectrogram is displayed as your students talk or sing. An advantage of our program is its design using the modern HTML5 audio application program interface (API) [3], which makes it accessible over the Internet with a browser supporting HTML5 audio such as Google Chrome. The computer code of our program is a software fork[3] from code of Boris Smus [3]. Readers may download the source code for Spectrograph and upload it to their school servers for educational non-commercial use. However, Spectrograph needs to run from a secure server with HTTPS. To run Spectrograph on your desktop you need a local server such as WAMP (PC) or MAMP (Mac), which you can download from the Internet.

Historical context

For many years spectrograms have been useful for the study of speech and speech therapy [4]. One of the best early desktop spectrogram programs for the personal computer was developed by Richard S. Horne [5]. Horne is the

[3] A software fork is a new independent program developed from earlier written source code.

founder of Visualization Software LLC, which has since closed. In 2008 Horne made his latest version Spectrogram 16 available as freeware, which can still be found on the Internet [6]. One can locate several software packages capable of producing spectrograms, including an HTML5 realtime spectrogram developed by Jan Schnupp (University of Oxford) that displays sounds entering your microphone in real time [7]. Physics teachers have employed spectrograms in a variety of settings such as demonstrating the Doppler effect [8], exploration of the electromagnetic environment [9], measuring the speed of sound [10], teaching mechanical waves [11], studying interference using a spectrogram app on the iPhone and the speed of sound [12], searching for exoplanets [13], and illustrating photoacoustics [14].

Our spectrograph

We now begin the tour of our program, Spectrograph, to show examples from our sound library and point out the main features of each spectrogram. Our program is designed with multiple choices of grid lines for easy measurements of sound features. Three basic characteristics of sound are loudness, pitch, and timbre. We will illustrate visualizations of these properties through our spectrogram examples. The spectrogram produced by a spectrograph is a plot of frequency spectrum against time. A sine wave is a single frequency represented by a horizontal line at an altitude determined by its frequency. Figure 1 illustrates a 500-Hz sine wave.

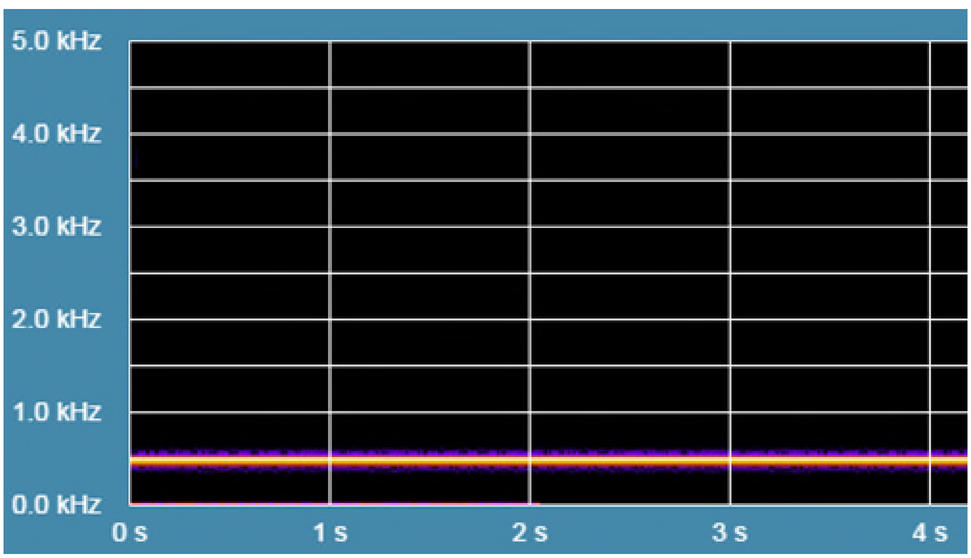

Figure 1. Spectrogram of a 500 Hz sine wave.

From Fourier's theorem [15] we know that any periodic wave with frequency f can be constructed from various contributions of its harmonic sine waves with frequencies f, $2f$, $3f$, and so on. Figure 2 illustrates a 500 Hz square wave pulsating in loudness. A variation in loudness is called amplitude modulation. The Fourier spectrum of harmonics gives the sound its timbre. The timbre allows us to tell the difference between the sine wave and square wave or between a flute and a violin. Note that the timbre of a 500 Hz square wave consists only of odd harmonics at frequencies 500 Hz, 1500 Hz, 2500 Hz, etc. Also note that louder sounds appear brighter on the screen. The amplitude modulation frequency is 1 Hz.

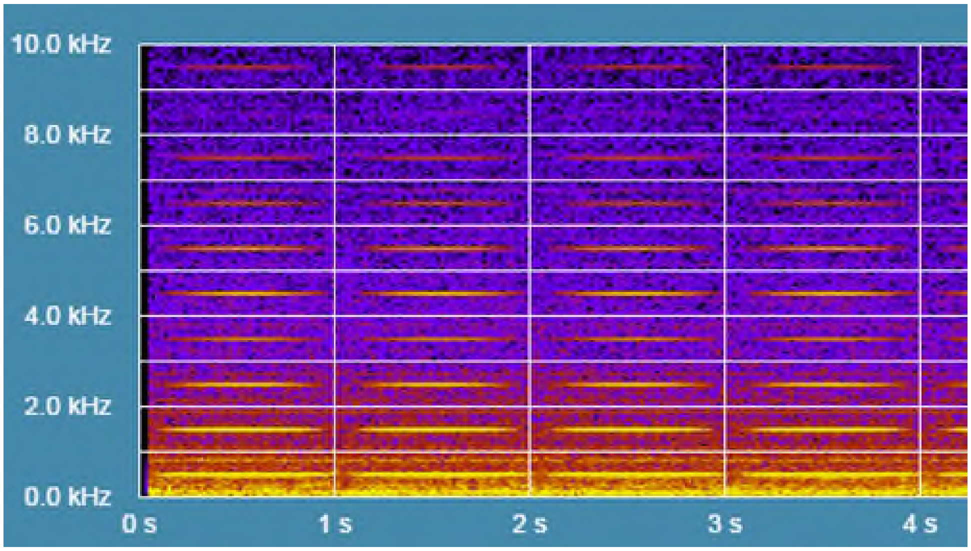

Figure 2. A 500 Hz square wave undergoing amplitude modulation.

A variation in frequency is called frequency modulation. Two examples of frequency modulation of a square wave appear in figure 3. For the first 2 s the variation is gentle and you can count six modulating periods in the span of 1 s. The original wave without the modulation, also called the carrier wave, in this case is a 500 Hz square wave. The modulation frequency is at 6 Hz with a small variation in the frequency of the carrier wave. Such a gentle frequency modulation at 6 Hz gives a vibrato effect.

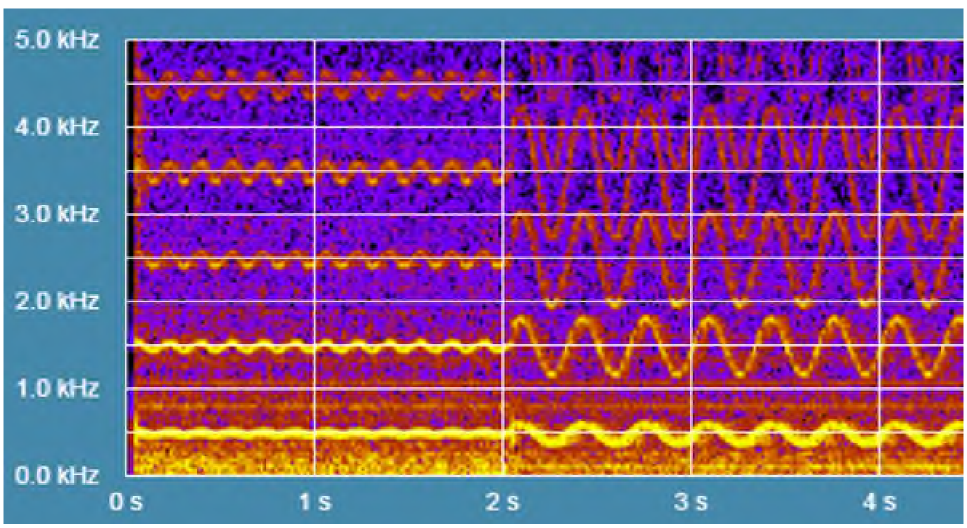

Figure 3. Frequency modulation.

The frequency modulation after 2 s has a considerable sweep with a modulation frequency of 3 Hz, i.e., 3 modulating periods in the span of 1 s. This type of modulation sounds like a siren. Note that the modulation appears to have greater sweeps for the higher harmonics. At first this might appear confusing to the student, but the explanation is very simple. If the first harmonic, which is also called the fundamental, varies from 500 Hz to 600 Hz, this variation is 20%. The next harmonic present for a 500 Hz square wave is the third harmonic at 1500 Hz. A 20% increase in 1500 Hz is a 300 Hz increase, three times the increase for the fundamental. The richness of the spectrogram visualization illustrates so much physics.

Harmonics are also called partials as each one represents a partial contribution to a periodic tone. The *n*th harmonic is sometimes referred to as the (n - 1)th overtone, where overtone means over the tone of the fundamental. Note that the waveforms for the modulators in figure 3 are sine waves since sine-wave patterns appear as the variations of the carrier wave.

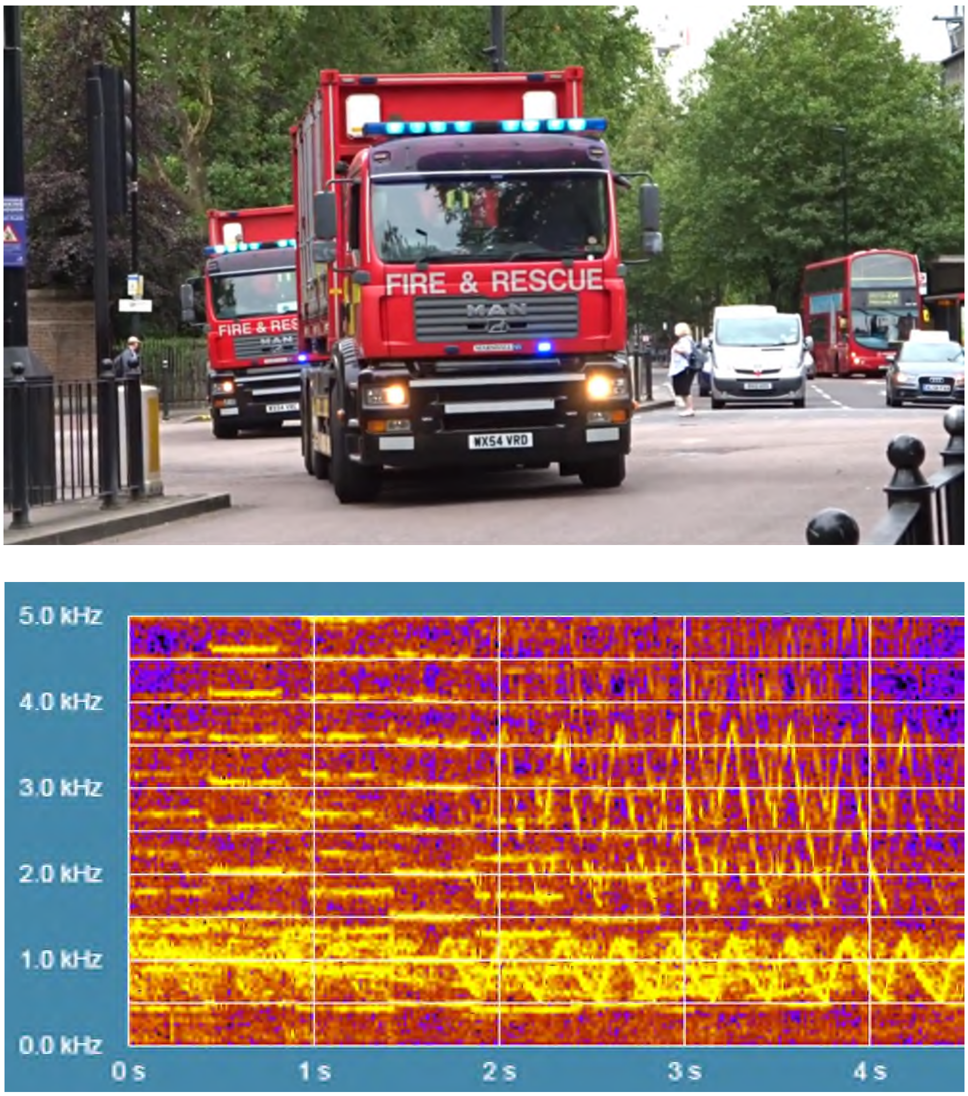

Figure 4. Sirens of British emergency vehicles. Photo courtesy of BluelightTV (YouTube), used with permission from https://www.youtube.com/watch?v=HDQyCmiloQQ.

A practical use of sirens is illustrated in figure 4. There you see two of several British emergency vehicles rushing to an accident scene. The entire convoy includes fire, police, and ambulance vehicles. For the first 2 s of the spectrogram you see Fourier spectra of alternating pitches. When the carrier frequency alternates between two pitches, the modulator is a square wave directing the carrier to abruptly alternate between the two tones. The two alternating pitches (flat lines) seen in figure 4 from 0 to 2 s form an interval very close to a major second in music, which is roughly a 9:8 frequency ratio. A singer in your class can identify this musical interval by listening to the sound. We can verify the musician's conclusion from the spectrogram. If you focus at 0.5 s on the harmonic at 2000 Hz, you see that this harmonic soon drops lower at 1 s. For dropping a major second, the lower pitch should be 2000 Hz (8/9) = 1800 Hz, which looks about right from the graph. At 1.7 s you can see harmonics with equal spacing of 500 Hz, indicating a rich 500 Hz complex tone. Brightening of higher harmonics are due to resonance enhancements caused by the specific siren mechanism.

At 2 s, a frequency-modulated siren appears where the modulating frequency is a triangle wave. In both cases, from 0 to 2 s and from 2 to 4 s, the modulator waveform is evident by the actual waveform pattern seen in the spectrogram. This fact can be confusing to students as they often erroneously think oscilloscope display, in which case the picture pattern is the carrier waveform. Reminding them that sine waves appear as flat lines on a spectrogram prevents them from being confused. The picture pattern on the spectrogram is actually the modulator waveform, while the carrier waveform is determined by its harmonic spectrum. The lowest pitch in the sweeps between 2 s and 4 s is about 500 Hz with the next harmonic at 1500 Hz. This data indicates a square wave for the carrier waveform. Note that the sweep of the third harmonic is three times the sweep of the fundamental.

An early electronic musical instrument, the theremin (1928), invented by the physicist Leon Theremin (1896-1993), is illustrated in figure 5. When the performer moves her right hand closer to the vertical metal rod, the pitch increases. Her left hand controls the volume, where moving her left hand closer to the metallic loop decreases the loudness. Casey is playing a modern theremin designed by Bob Moog (1934-2005), one of the inventors of the music synthesizer and founder of Moog Music, Inc., located in Asheville, North Carolina, USA.

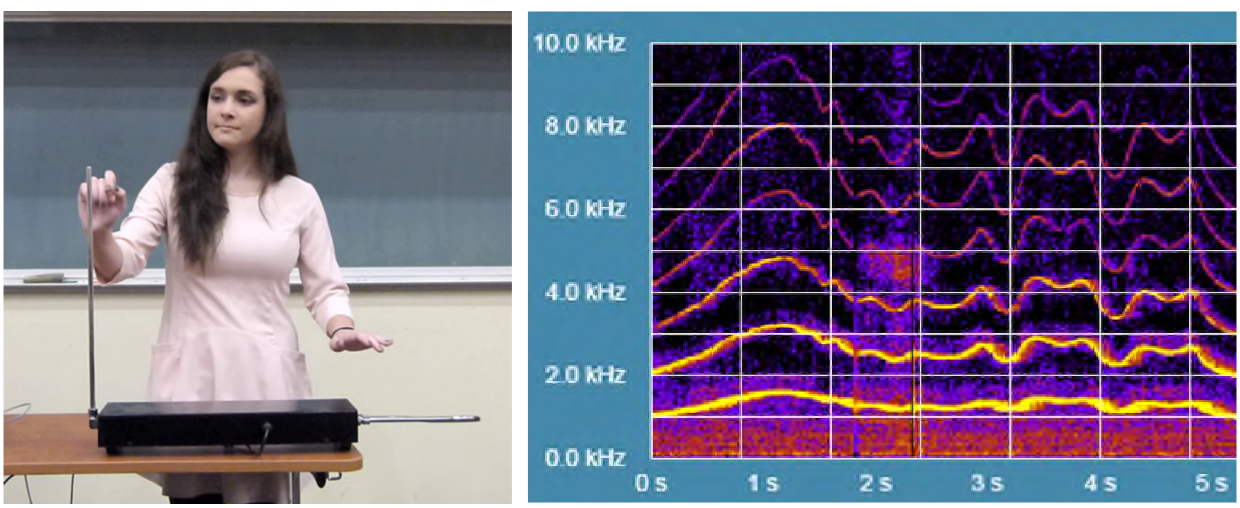

Figure 5. UNC Asheville physics student Casey Robinson playing the theremin.

The timbre of the theremin illustrated in figure 5 is very rich with all harmonics present. We have set our vertical frequency scale with 10 kHz as the maximum. The fundamental at 0 s is about 1000 Hz and you can see 7 harmonics. A fun game in class is to ask students how they would explain timbre to a relative over the phone, demonstrating different timbres. One solution is illustrated in figure 6, where one sings the vowel sounds, trying to keep loudness and pitch constant. Then, the third basic property of sound, timbre, is easily revealed.

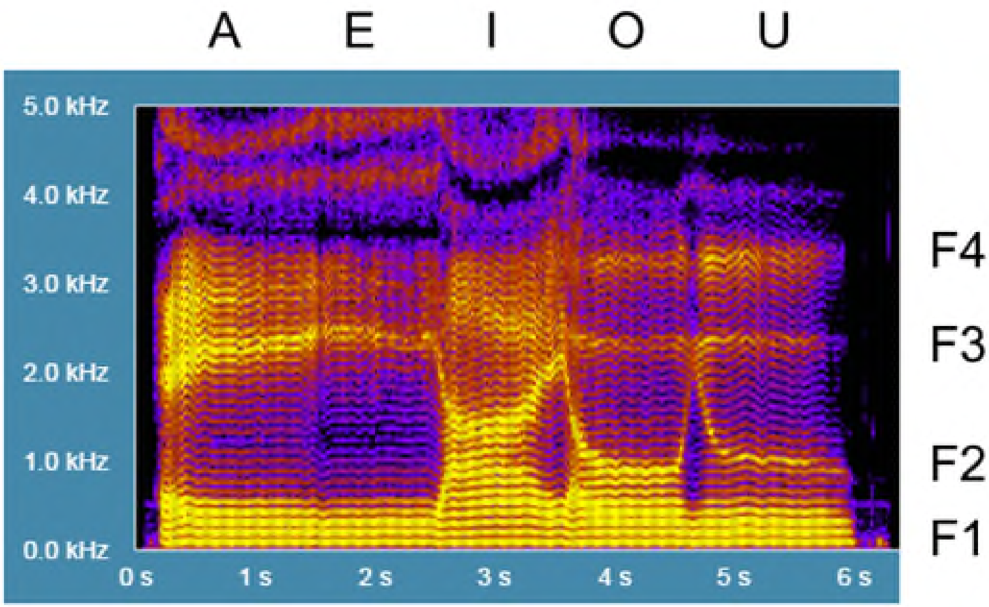

Figure 6. Vowel sounds illustrating harmonics (partials) and formant regions.

Figure 6 contains the singing of the five vowel sounds. The harmonics appear according to Fourier's theorem since the vowels are sung at a fixed pitch. Not the equal spacing of the harmonics. A musician can listen to the singing and determine that the pitch sung is close to a B-flat an octave lower than the B-flat near middle C on the piano. The sung pitch is therefore near 120 Hz. From the spectrogram, one finds about 8 harmonics between 0 Hz and 1000 Hz. Students can more readily count harmonics using our spectrogram grid lines, which we left off for the figure to better reveal the patterns of the vowel sounds. From the 8 equally-spaced harmonics spanning 1000 Hz, we estimate the fundamental pitch at 1000/8 = 125 Hz. This value is in close agreement with the musical pitch analysis.

Physics can be used to gain insight into the enhanced regions appearing brighter in figure 6. Such enhancements are due to resonances in the human vocal system. The simple physics model of the human vocal system is a closed pipe with the closed end at the vocal folds [16]. For an adult male like the one singing in figure 6, the distance from the vocal folds to the mouth is taken to be L = 17 cm (which one can estimate for oneself by using string to measure the distance from the laryngeal prominence, i.e. Adam's apple, to the mouth). The fundamental wavelength is given by $\lambda = 4L$ = 68 cm = 0.68 m for the closed pipe. The corresponding pitch is $f = v/\lambda$ = (340 m s^{-1})/(0.68 m) = 500 Hz, where v is the speed of sound. Resonances occur in a 17 cm closed pipe at 500 Hz, 1500 Hz, 2500 Hz, etc., the odd harmonics. Enhancements due to resonances appear as brighter regions on a spectrogram and are called formant regions. Note how the formant regions F1, F2, F3, and F4 fall near the above closed-pipe resonances, especially between 5 and 6 s for the ‘U’ sound.

Bird spectrograms are interesting to study and often appear in field guides to help hikers identify different species. We include several bird spectrograms in our video [2]. A spectrogram for a starling is illustrated in figure 7. Starlings were imported to the United States from England in 1890 as part of a project to introduce the United States to birds appearing in Shakespeare’s works. Note the rise and fall of the pitch between 0 and 1 s. The pitch sweeps from about 1 kHz to roughly 3 kHz, a musical interval of an octave and a fifth. Next in the spectrogram are rapidly descending, almost vertical lines, which are heard as short chirps.

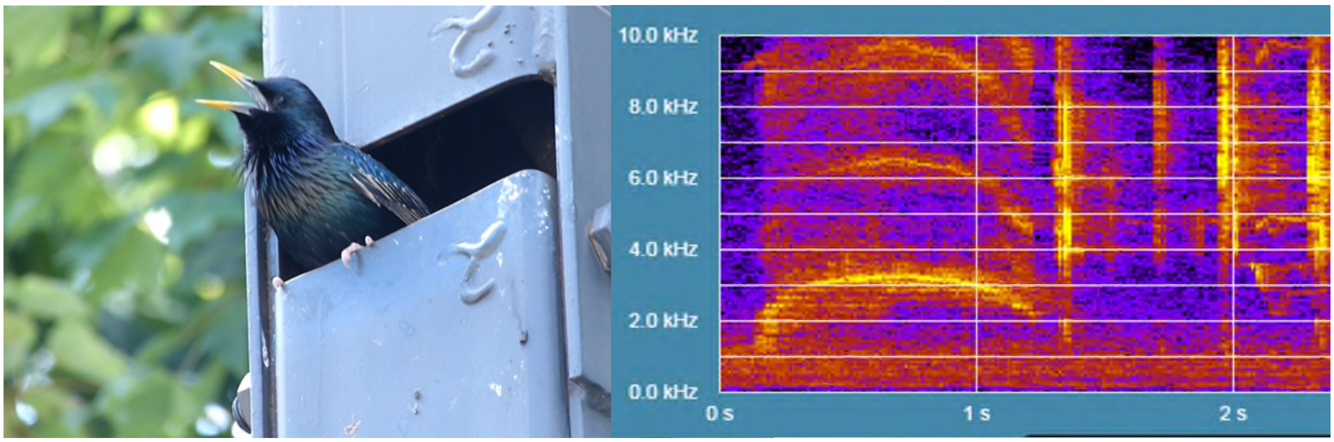

Figure 7. Starling

Compare the rise and fall of the starling sound to the rise and fall of the scream seen in figure 8. It is a little hard to see detail in the first harmonic. But the second harmonic shows a strong rise from 2 kHz to 3 kHz, which is consistent with the third harmonic rising from around 3 kHz to 4.5 kHz. This 3:2 ratio indicates a musical interval of a fifth, which corresponds to the musical jump at the beginning of ‘Twinkle, Twinkle, Little Star’. But the scream camouflages any semblance of singing. The acoustic effect of the many additional frequencies appearing in the scream is called noise, which we will investigate later.

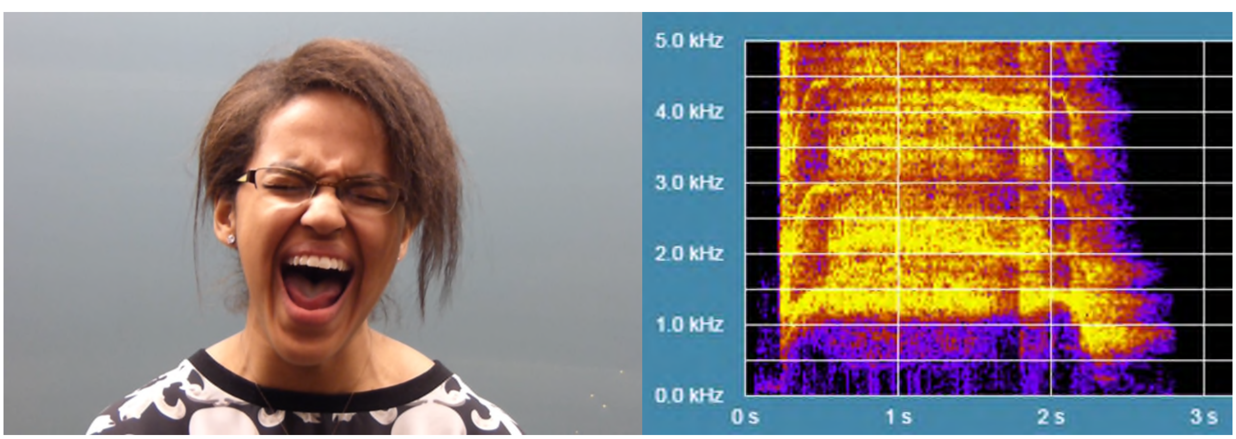

Figure 8. UNC Asheville student Madeleine Boone screams.

The spectrogram for a cat in figure 9 shows a gentle rise and fall of the fundamental over a time frame of 2 s. The spacing between each adjacent pair of harmonics is about 1 kHz. Fourier's theorem is again apparent for the cat's singing tone with a fundamental $f = 1$ kHz and the higher harmonics given by 2 kHz, 3 kHz, etc.

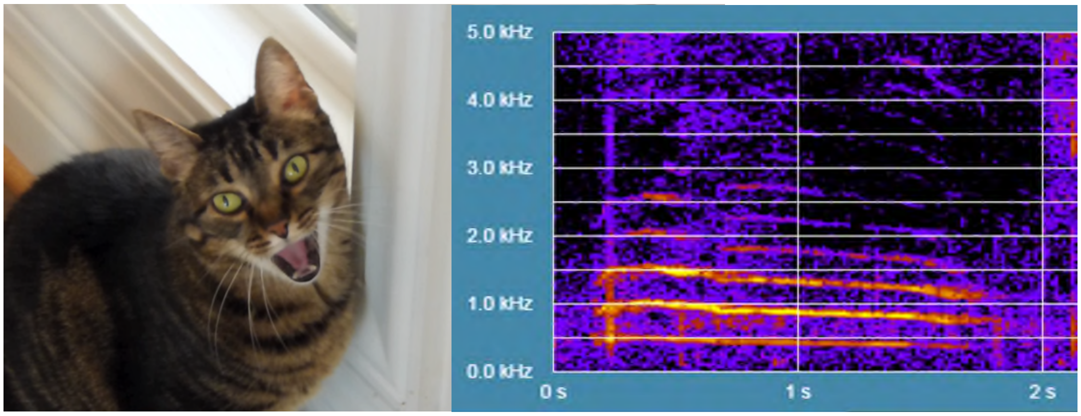

Figure 9. Phoebe making a soft sound.

In contrast to rising and falling pitches, percussive sounds appear as cliffs in a spectrogram. Refer to figure 10 for the spectrogram of a toddler banging a wooden toy on a can. Such cliffs indicate the abrupt production of all frequencies, which we perceive as noise.

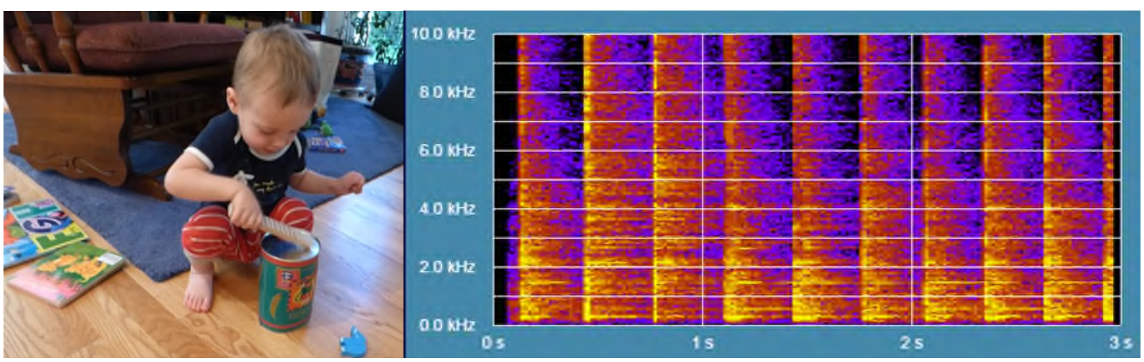

Figure 10. Toddler hitting a can with a wooden toy.

The frequency for the sound bursts is roughly 3 Hz as we count about three cliffs within each second. Note the lingering tin sound after each abrupt hit. A smooth presence of all frequencies is noise and if all the frequencies are well represented between 100 Hz and 10 000 Hz, the sound is referred to as white noise. The 'white' description comes from the analogy with light, where Isaac Newton (1642-1727) discovered that all the color frequencies mixed together produce white light. The waterfall in figure 11 is a good approximation of white noise.

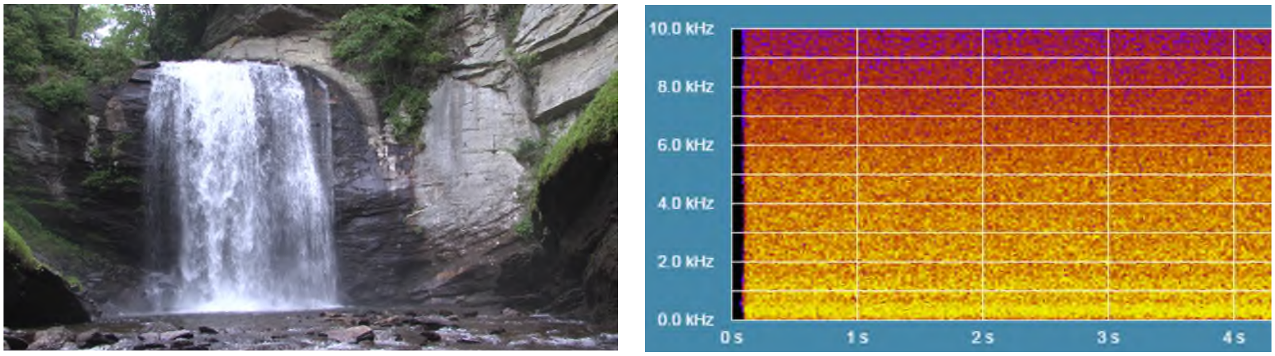

Figure 11. The soothing broadband noise of Looking Glass Falls, Western North Carolina, USA.

This waterfall is Looking Glass Falls located in Pisgah National Forest, Transylvania County, North Carolina, USA. The water descends from a height of 18 meters (60 feet). By way of contrast, the noise from the British Airways jet in figure 12 has a greater presence of lower-frequency noise due to the hum of its engines.

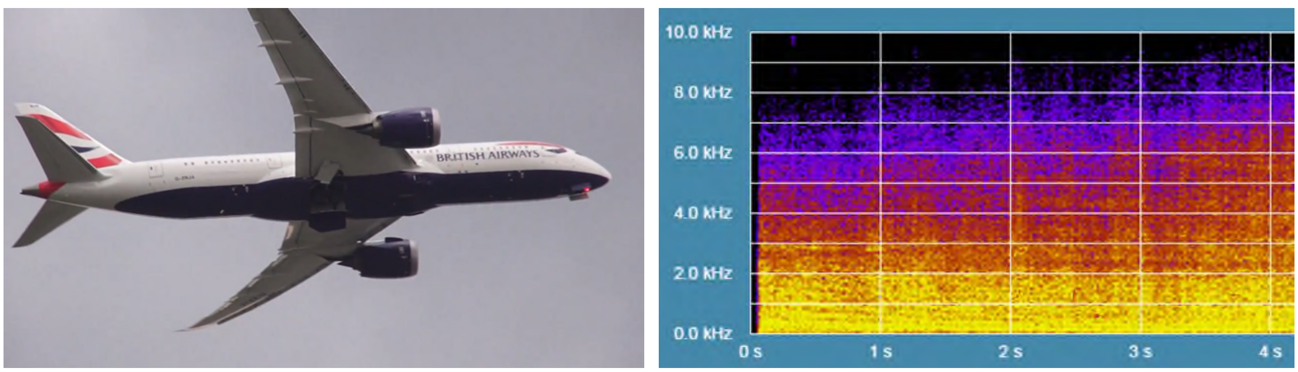

Figure 12. British Airways. Photo Courtesy Dave Isenor (YouTube). https://www.youtube.com/watch?v=vTKkZyD4KP4, under the Creative Commons Attribution license.

The loudest frequencies produced by the jet are those below 2 kHz as this region in the spectrogram appears the brightest. Continuing with our analogy of light, we might say that a higher presence of low-frequency noise is 'red noise'. Engineers actually use the term pink noise, where a measure of the strength of the signal is inversely proportional to frequency. Higher frequencies therefore contribute less to the sound. On the other hand, noise with a greater presence of high frequencies, which we can refer to as 'blue noise', is the hiss of a snake.

Various broadband 'noise' spectrograms occur for machinery. Figure 13 illustrates the noise of a miter saw and the tone of the rotating motor decreasing after the saw is turned off. The pitch of the miter saw, as its rotation decelerates, drops from 2500 Hz to 1000 Hz before it finally stops. Note how the harmonics approach each other as the fundamental frequency is lowered.

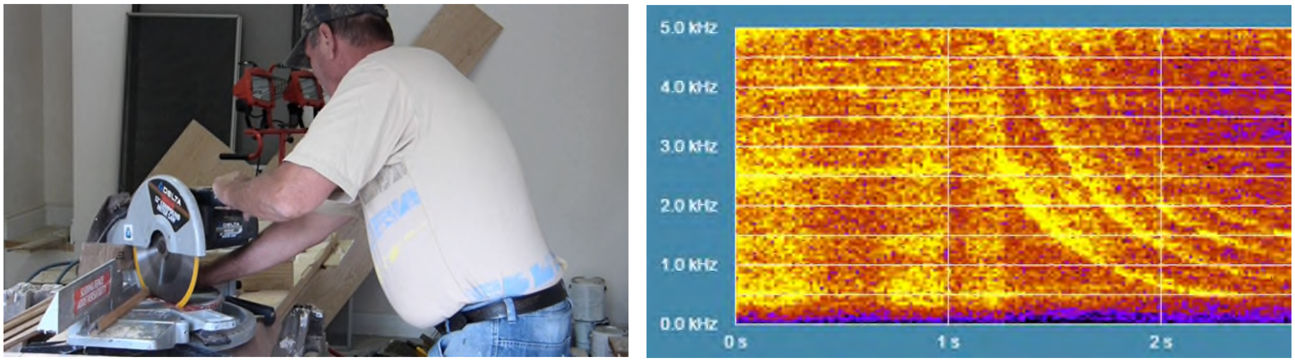

Figure 13. Joe Gosnell and the miter saw as the saw is powering down.

We finally give three examples from music. The spectrograms for a violin, soprano, and orchestra appear in figures 14-16. Eight harmonics are evident for the violin with fundamental frequencies near 1 kHz in figure 14 as the violinist plays Bach.

The spectrogram of the soprano in figure 15 reveals the beautiful vibrato of an opera singer. These vibrato regions are the rapid frequency modulations inherent in the singer's voice. Students can count the number of these ripples within a time frame and determine that the modulation frequency for a vibrato is about 6 Hz.

Note also the strong presence around 3500 Hz between 2.0 and 2.5 s. This value has significance from the point of view of physics. The ear canal of the average adult listener is a closed pipe about 2.5 cm in length with the closed end being the eardrum [17]. The ear canal will resonate to a wavelength $\lambda = 4L = 4(2.5\text{ cm}) = 10\text{ cm} = 0.1\text{ m}$. The corresponding resonance frequency is $f = v/\lambda = (340\text{ m s}^{-1}) / (0.1\text{ m}) = 3400\text{ Hz}$. We are especially sensitive to this frequency and our perceptual mechanism enhances this spectral component of the soprano's voice. The professional training of the opera singer allows her to produce a strong formant region around 3500 Hz, referred to as the singing formant [16].

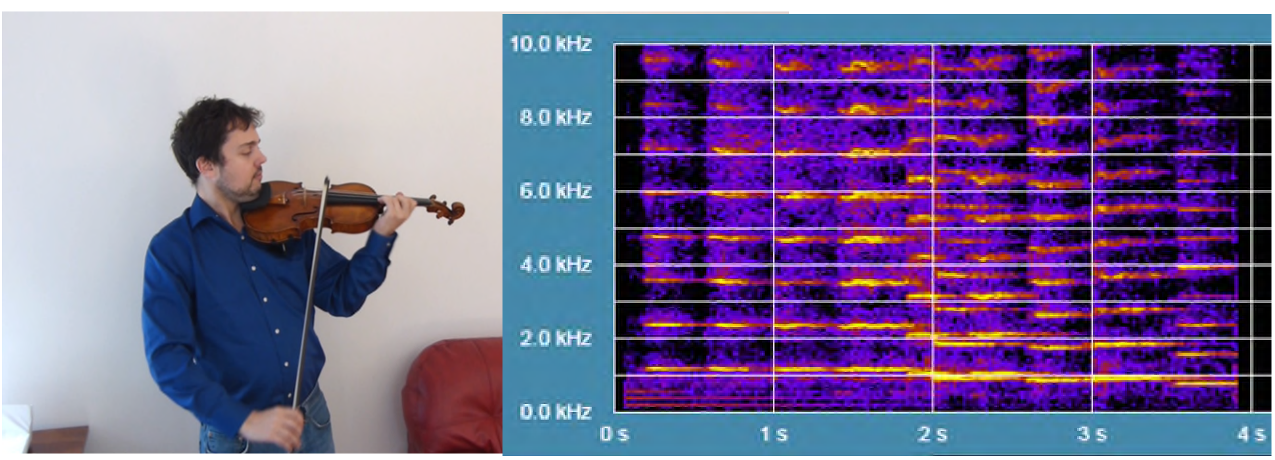

Figure 14. Violinist playing Bach.

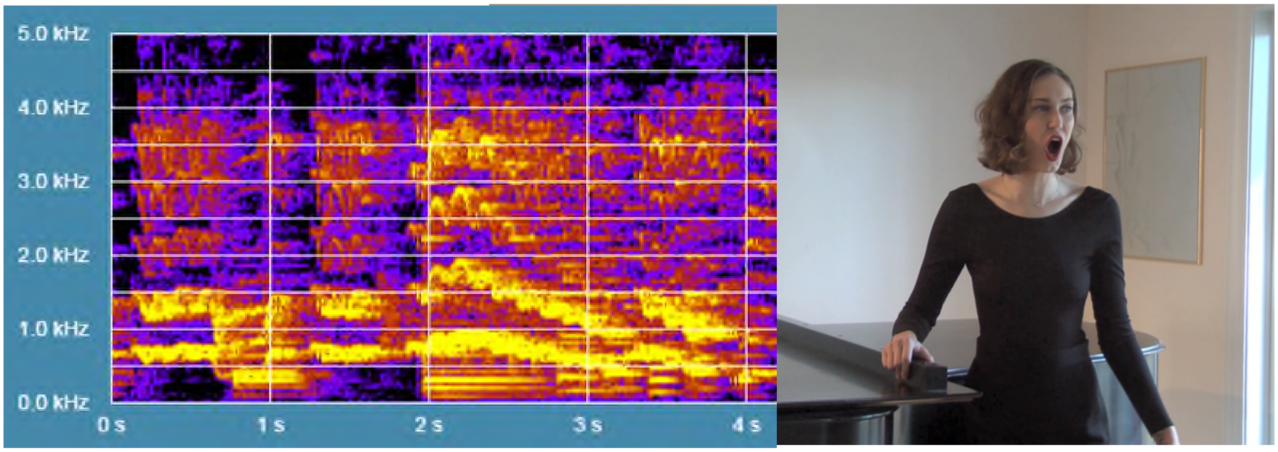

Figure 15. Soprano singing Mozart.

Finally we come to the orchestra in Fig. 16. The spectrogram shows the pulsating orchestral rhythm as the *Symphonie Fantastique* by Hector Berlioz (1803-1869) is coming to an end. The rapid orchestral sound bursts occur at about 6 Hz, a fast tempo for the exciting conclusion of this great symphony.

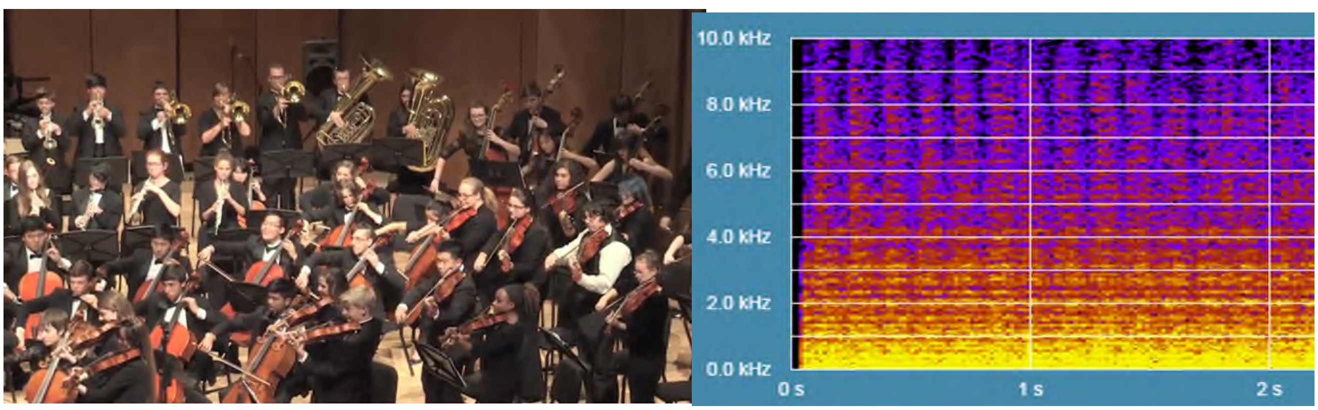

Figure 16. A Midwest Young Artists (MYA) Orchestra performing the end of Berlioz's *Symphonie Fantastique*. Photo Courtesy Dr. Allan Dennis, Conductor and Founder of MYA. https://www.youtube.com/watch?v=bIY9EyrmMYs, under the Creative Commons Attribution license.

Conclusion

We have introduced a new HTML5 spectrogram program, Spectrograph, which readers and their students can play with at Academo (academo.org). We include over 30 sampled sounds, many of which we have analyzed in this paper. With our spectrogram program, you can (1) run the sampled sounds from our library, (2) use our program to open .mp3 and .wav files on your computer, and (3) run Spectrograph in microphone mode where sounds entering your microphone are displayed in real time. You can also download the spectrogram source files for educational non-commercial use if you would like to upload Spectrograph to a school server. Note that a secure server (HTTPS) is needed to run the program. If you wish to run the program from your desktop you will need a local server such as WAMP (PC) or MAMP (Mac). An advantage to using our website is that you will be accessing the latest version, adapted to the latest changes in browsers. At this time, we recommend Google Chrome. Your students will love the variety of sounds in our library as well as exploring their own.

Acknowledgment

The authors would like to thank Boris Smus for allowing us to adapt his excellent HTML5 code for our application.

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Edward Ball received his Master of Physics from Durham University, UK. He currently works as a web developer and enjoys creating browser-based interactive demonstrations, particularly those featuring sound and waves. These demos can be accessed at his Academo website (academo.org).

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