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INTRODUCTION

Over the last twenty-five years, computer technology has transformed the teaching environment. This is especially true for the field of music theory. Software programs designed for ear training, notation, and interval/chord spelling have been helpful in allowing students to improve their musicianship skills rapidly. There is another type of software program that can also be extremely beneficial for music theory students, which has direct applications in musical analysis—Fourier analysis and spectrographs. Fourier analysis and spectrographs can be used in a variety of ways to elucidate specific musical concepts and generate discussion in the theory classroom at both the undergraduate and graduate levels. Spectrographs are images of musical sound generated by Fourier analysis, which show not only the fundamental pitch, but also the overtones and complex noise-like sounds as well. These images are related to the way we hear and perceive sound, making them extremely relevant for all musicians.[1]

There are a number of recent published analyses that use Fourier analysis and spectrographs. Robert Cogan uses Fourier analysis and spectrographs as the basis for a theory of tone color based upon

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[1] Jean-Claude Risset and David L. Wessel, "Exploration of Timbre by Analysis and Synthesis," *The Psychology of Music*, ed. Diana Deutsch (San Diego: Academic Press, 1999), 113-169. As Risset and Wessel state (p. 153):

> The significance of Fourier analysis has a multiple basis. Clear evidence exists that the peripheral stages of hearing, through the mechanical filtering action of the basilar membrane, perform a crude frequency analysis . . . . The distribution of activity along the basilar membrane relates simply to the Fourier spectrum. Thus features salient in frequency analysis are of importance to perception.

See also Max Mathews, "The Ear and How it Works," *Music Cognition and Computerized Sound: An Introduction to Psychoacoustics*, ed. Perry R. Cook (Cambridge: MIT Press, 2001), 1-10; John Pierce, "Sound Waves and Sine Waves," *Music Cognition and Computerized Sound: An Introduction to Psychoacoustics*, ed. Perry R. Cook (Cambridge: MIT Press, 2001), 37-56.

thirteen sonic "oppositions" and specifically for the analysis of compositions.[2] I have used spectrographs to explore sonic differences in multiple performances of a Hildegard chant, a classical Chinese piece for the qin, and keyboard works by C.P.E. Bach and Beethoven.[3] Many of the essays in Thomas Licata's (ed.) *Electroacoustic Music: Analytical Perspectives* and Mary Simoni's (ed.) *Analytical Methods of Electroacoustic Music* make extensive use of Fourier analysis and spectrographs to analyze non-notated electroacoustic music.[4] None of these publications, however, specifically addresses ways in which a teacher might use this technology in the music theory classroom. How should one introduce the technology to students, and in what context? What musical concepts can be clarified, and how can this technology benefit music theory students? This essay addresses these questions by providing three specific pedagogic applications of Fourier analysis and spectrographs in the music theory classroom. Throughout, I draw upon my personal teaching experience of using this technology with students, focusing on the approaches I have found most successful.

Three specific pedagogic applications are discussed using three different pieces. First, two different performances of Chopin's *Prelude in C minor*, op. 28, no. 20, are discussed in relation to the spectrographic images. Fourier analysis can be extremely useful in highlighting performance differences for students. Second, a spectrographic image of *Hyojo Netori* from the Japanese *Gagaku* piece *Etenraku* is analyzed in relation to instrumental tone color. Fourier analysis can help illuminate the concept of timbre or tone color by providing students with acoustic images, enabling them to

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[2] Robert Cogan, *New Images of Musical Sound* (Cambridge: Harvard University Press, 1984); Robert Cogan, *Music Seen, Music Heard* (Cambridge: Publication Contact International, 1998); Robert Cogan, *The Sounds of Song* (Cambridge: Publication Contact International, 1999).

[3] John Latartara, "Multidimensional Musical Space in Hildegard's 'O rubor sanguinis':Tetrachord, Language Sound, and Meaning," *Indiana Theory Review* 25, nos. 1-2 (2004): 39-74; John Latartara, "Theoretical Approaches Towards Qin Analysis: 'Water and Clouds over Xiao Xiang'," *Ethnomusicology* 49, no. 2 (2005): 232-265; John Latartara and Michael Gardiner, "Analysis, Performance, and Images of Musical Sound: Surfaces, Cyclical Relationships, and the Musical Work," *Current Musicology* 84 (2007): 53-78.

[4] Thomas Licata, Ed., *Electroacoustic Music: Analytical Perspectives* (Westport, CT: Greenwood Press, 2002); Mary Simoni, ed., *Analytical Methods of Electroacoustic Music* (New York, New York: Routledge, 2006).

"see" the sounds of a particular musical passage or piece. Third, spectrographic images are used to explore the non-notated computer piece *Untitled #8* by Markus Popp, in relation to form.[5] Rather than relying solely upon aural perceptions, spectrographs can provide students with pictures of the non-notated computer piece, allowing them to examine, visually, the intensity of frequencies and the progression of the work over time. These three examples highlight what I have found to be the most useful pedagogic applications for this technology in the music theory classroom. I begin with an explanation of Fourier analysis and spectrographic images followed by a brief survey of Fourier analysis and spectrographs in relation to musical analysis.

Fourier Analysis and Spectrographs[6]

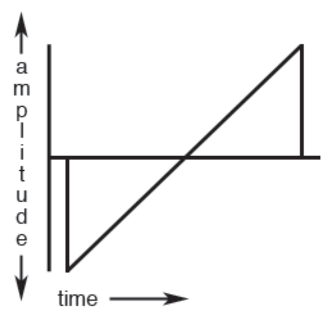
Fourier analysis (also called "spectral" or "spectrum analysis"), named after the mathematician and scientist Jean-Baptiste Joseph Fourier (1768-1830), is the separation of complex phenomena into simple units that, if added together, would re-create the original. Before discussing Fourier's theory in more detail, however, I will explain a few basic acoustic concepts and terms. Sounds can be categorized as simple, harmonic or complex. Simple sounds or sine tones have a single frequency or fundamental with no overtones. For example, a pitch played on a piccolo flute approximates a simple sine-tone sound. Harmonic sounds have two or more partials (fundamental plus one or more overtones) vibrating in whole number ratios. For example a string vibrating harmonically at a fundamental frequency of A 440 Hz (cycles per second) might have two overtones vibrating at 880 Hz (twice as fast) and 1320 Hz (three times as fast). This harmonic relationship is caused by regular or periodic wave motion. Complex or noise-like sounds have irregular or aperiodic wave motion and, therefore, do not

[5] Although my musical examples come from a variety of cultures, eras, and genres, I have purposely limited these analyses to instrumental music, as opposed to vocal music or instruments with voice. The unavoidable complexity of language meaning and language sounds require a special focus that would extend beyond the confines of this paper.

[6] I am indebted to Dr. Stephen V. Rice at The University of Mississippi and Dr. James P. Chambers at the National Center for Physical Acoustics for their valuable advice and suggestions regarding this section of the paper.

reinforce a single fundamental frequency. White noise is aperiodic and is characterized by all frequencies at equal intensities.

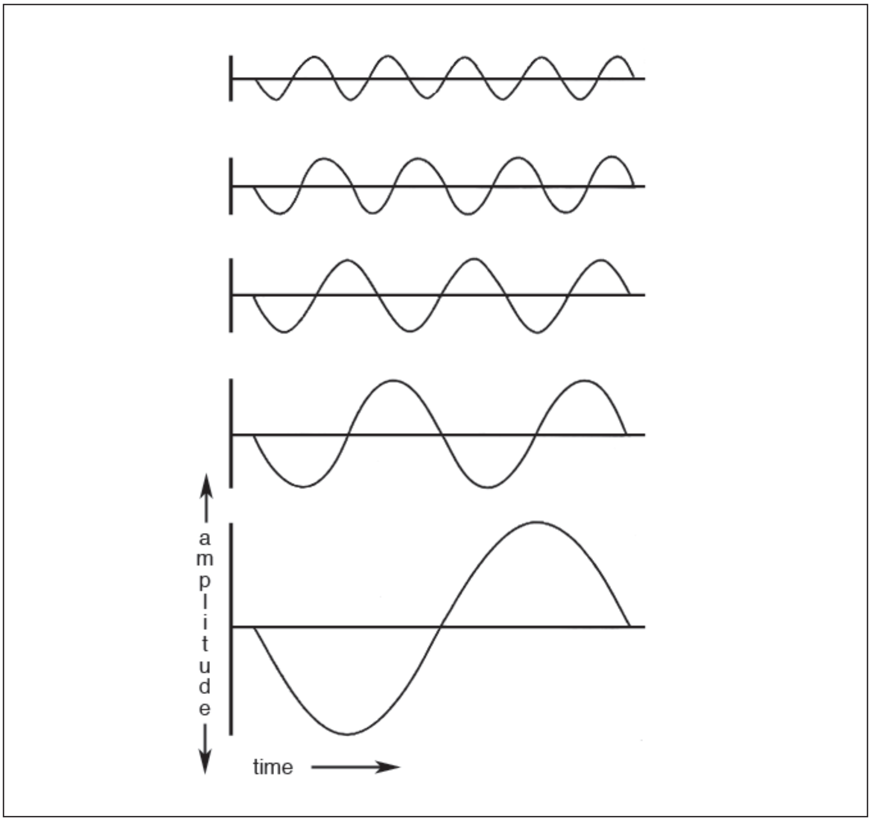
In relation to sound, Fourier's analytical theory states that any harmonic or periodic sound can be separated into simple sine-tone waves that, if added together, would re-form the original harmonic or periodic sound. For each simple sine tone, amplitude and phase are also calculated. Specifically, Fourier analysis is the separation of harmonic or complex sounds into constituent simple sine tones, and Fourier synthesis is the addition of simple sine tones re-creating the original harmonic or complex sound. Examples 1a,b and c show a waveform representation of Fourier analysis.



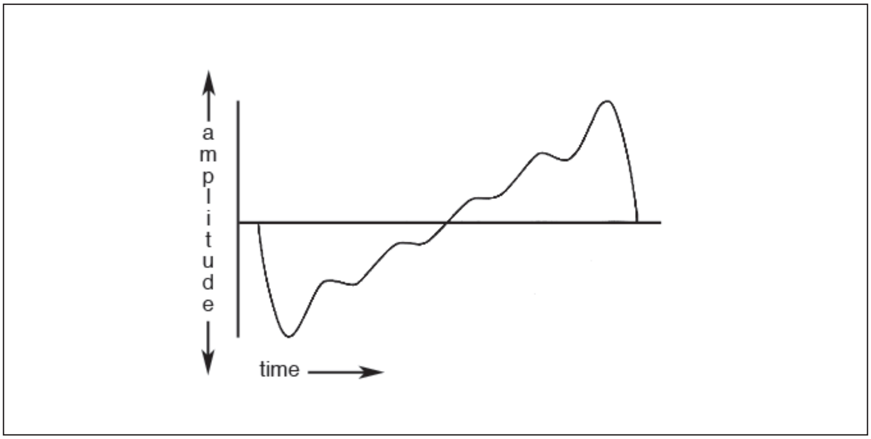
Example 1a - Original Sawtooth Wave

Example 1a shows the original saw-tooth wave and Example 1b separates the original saw-tooth wave into five simple sine tones. Example 1c shows the recombined five sine tones of Example 1b, which approximates the original saw-tooth wave (Example 1a). The concept of "approximation" is an important point. Fourier's theory actually describes the analysis of a wave into an infinite number of partials, but for practical calculation, this infinite number is changed to a finite number. Therefore, Fourier analysis is conceptually exact, but practically an approximation. The more sine tones used for the analysis of the original saw-tooth wave, the closer the approximation is to the original.

There are a variety of ways in which computers can image Fourier analyses of sound, including both static and time-varying images. Static images are like a snapshot of sound, showing the presence and

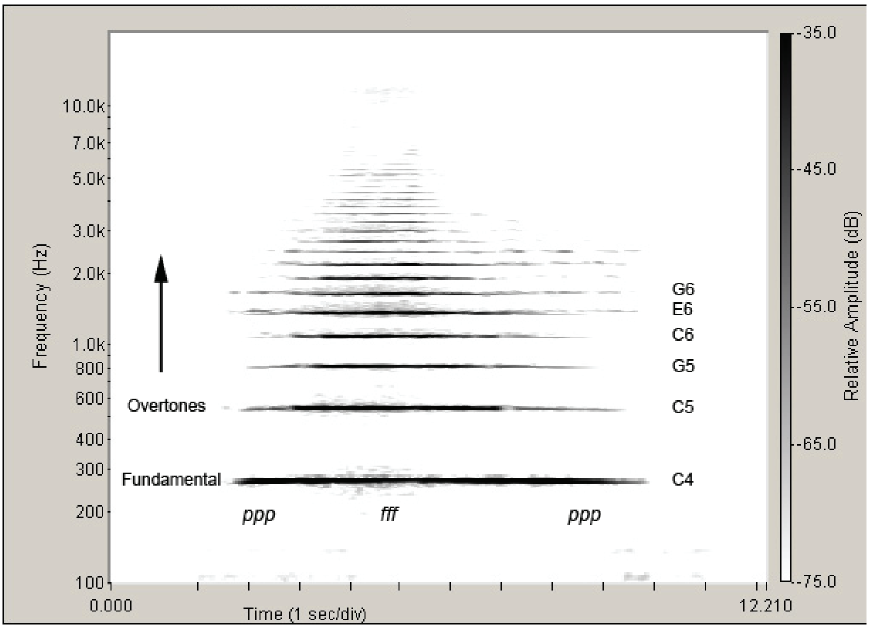


Example 1b - Five Simple Sine-Tones



Example 1c - Recombined Five Sine-Tones

strength of each partial, often displayed as a bar graph. These static analyses, however, are not so musically useful since the spectrum of even the briefest musical sound can change dramatically over time. Time-varying images display the changes of a sound's spectrum over time.[7] One of the most popular and useful time-varying images used today is the spectrograph (also called "sonogram" or "spectrogram"). Spectrographs are three-dimensional Fourier analyses of sound that show frequency and amplitude change over time. Example 2 displays a spectrograph of a flute playing the single pitch C^4, and is the first spectrograph I show when introducing Fourier analysis and spectrographs to students.



Example 2 - Flute playing single pitch C^4

The horizontal axis is time, read from left to right, and the vertical axis is frequency, moving from bottom (lower frequencies) to top (higher frequencies). Also, the relative amplitude or intensity scale is shown on the right side, with black representing the most intense sound, and light grey representing the least intense sound. As indicated in Example 2, the lowest horizontal line is the fundamental of the pitch, C^4, and the upper horizontal lines are the overtones or upper partials,

[7] This is achieved using the Short Time Fourier Transform (STFT). See Eduardo Miranda, *Computer Sound Design: Synthesis Techniques and Programming* (Oxford: Focal Press, 2002), 53.

C^5, G^5, C^6, E^6, G^6, etc. This pitch was played with a dynamic change from *ppp* to *fff* to *ppp*. Notice as the dynamic gets louder, the intensity and number of partials increases, and complex noise-like breath sound, seen as light grey, emerges near specific partials.

There is, however, a critical distinction that students need to understand in relation to the spectrographic image and musical hearing. Spectrographs provide a visual representation of a physical sound signal, while hearing is a human perception. Spectrographs, therefore, do not show us *what* we hear, but rather provide acoustic reasons *why* we hear the sounds we do. For example, a spectrograph may show (like Example 2) a fundamental pitch at 262 Hz with an accumulation of overtones above, as well as complex noise-like sound surrounding specific overtones. This would be perceived as the single pitch C^4 in a crescendo from soft to loud on a flute. The accumulation of many overtones above the fundamental 262Hz, with a strong intensity, and complex breath noise surrounding specific overtones, is the acoustic reason why this particular sound is perceived as the pitch C^4 played soft to loud on a flute. Having explained what Fourier analysis and spectrographs are, I will now present a brief history of Fourier analysis and spectrographs in relation to musical analysis. I usually do not cover these historical details with students, but I have found that understanding the origins of Fourier analysis and spectrographs, conceptually and practically, can help answer many questions students have regarding the technology.

Fourier Analysis, Spectrographs and Musical Analysis[8]

In 1822, Fourier published his landmark thesis entitled *Analytical Theory of Heat*. In this publication Fourier proposed a general theory for the propagation of heat in solid bodies, and extended the wave equation results derived in the eighteenth century to show that any arbitrary function or periodic sound can be represented as an infinite summation of sine and cosine terms.[9] Georg Ohm, in 1843, was the first to apply Fourier's theory to sound analysis. It was not, however, until the second half of the twentieth century that Fourier analysis and spectrographs became practically useful for musical analysis.[10]

In the second half of the twentieth century, Fourier analysis was greatly enhanced both theoretically and technologically by the rediscovery of Gauss's Fast Fourier Transform and the development

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[8] For in depth mathematical treatment of Fourier analysis see David W. Kammler, *A First Course in Fourier Analysis* (Upper Saddle River, New Jersey: Prentice Hall, 2000); Elias M. Stein and Rami Shakarchi, *Fourier Analysis: An Introduction* (Princeton: Princeton University Press, 2003); Loukas Grafakos, *Classical and Modern Fourier Analysis* (Upper Saddle River, New Jersey: Pearson Education Inc and Prentice Hall, 2004). For a more general overview of the mathematical formulas and concepts behind Fourier analysis see Philip Greenspun's Appendix in Curtis Roads, *The Computer Music Tutorial* (Cambridge MA: MIT Press, 1996), 1073-1112; Elena Prestini, *The Evolution of Applied Harmonic Analysis* (Boston: Birkhauser, 2004), 31-63. For biographical information on Joseph Fourier see I. Grattan-Guinness, *Joseph Fourier 1768-1830: A Survey of his Life and Work, Based on the Critical Edition of his Monograph on the Propagation of Heat, Presented to the Institut de France in 1807* (Cambridge MA: MIT Press, 1972), 1-25; John Herivel, *Joseph Fourier: The Man and the Physicist* (Oxford: Clarendon Press, 1975), 5-147; Prestini, *The Evolution of Applied Harmonic Analysis*, 1-29.

[9] Joseph Fourier, *The Analytical Theory of Heat* (New York: Dover, 1955). Fourier first developed his theory on heat in 1807 in a lecture presented to the French Academy of Sciences. The Members of the Academy, however, were not receptive and criticized his ideas. See Roads, *The Computer Music*, 1075 and E. Robinson, "A Historical Perspective of Spectrum Estimation," *Proceedings of the Institute of Electrical and Electronics Engineers* 70/9 (1982): 887.

[10] For early twentieth century developments see Dayton C. Miller, *The Science of Musical Sounds* (New York: MacMillan, 1916); Norbert Wiener, "Generalized Harmonic Analysis," *Acta Mathematica* 55 (1930): 117–258; Carl Seashore, *The Psychology of Music* (New York: Dover, 1938).

of the digital computer.[11] Fast Fourier Transform, or FFT, is an algorithm that calculates the frequency and intensity content of a sound. It is interesting to note that the use of computers specifically for musical analysis coincides with creation of the first computer applications for Fourier analysis in the 1940's.[12] Shortly before World War II, and continuing through the 1940's, groundbreaking results were achieved in the visual representation of Fourier analysis. These advances emerged from the field of phonologic research. Potter, Fletcher, and George and Harriet Kopp, all working at Bell Telephone Laboratories, utilized Fourier analysis technology to create spectrographs or spectrograms of human speech, as well as other sounds, including short musical excerpts.[13] These images are the immediate precursors to contemporary Fourier analysis of music.

In his 1960 attempt to "explain the physical, physiological and psychological portions of the musical happening," Winckel created a number of sonograms to analyze brief musical sounds and passages, including the beginning of Beethoven's Symphony no. 8.[14] In 1965 Cooley and Tukey, also working at Bell Telephone Laboratories, popularized one of the most important theoretical contributions to Fourier analysis (developed by Gauss in 1805), the Fast Fourier Transform or FFT.[15] It is in large part due to the work

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[11] Calculating the orbit of a comet in 1805, the mathematician Karl Gauss used Fourier techniques and employed a modern algorithm now known as the Fast Fourier Transform. This algorithm was revolutionary for Fourier calculation, but remained unpublished and ignored until its rediscovery in 1965 by Cooley and Tukey. See Roads, *The Computer Music Tutorial*, 1076; Elena Prestini, *The Evolution of Applied Harmonic Analysis*, xi.

[12] See Ian Bent, *Analysis* (New York: W.W. Norton and Company, 1987), 64. Bernard Bronson used a computer with punch cards in 1949 to analyze "range, metre, modality, phrase structure, refrain pattern, melodic outline, anacrusis, cadence and final of folksongs..."

[13] Ralph Potter,"Visible Patterns of Speech," *Science* (November 9, 1945); Harvey Fletcher, *Speech, Hearing and Communication* (New York: Van Nostrand, 1953); Ralph Potter, George Kopp and Harriet Kopp, *Visible Speech* (New York: Dover, 1966). See also W. Koenig, H.K. Dunn and L.Y. Lacy, "Sound Spectrograph," *Journal of the Acoustical Society of America* 18 (1946): 19-49.

[14] Fritz Winckel, *Music, Sound and Sensation: A Modern Exposition* (New York: Dover, 1960), 4.

[15] J. Cooley and J. Tukey, "An algorithm for the machine computation of complex Fourier series," *Mathematical Computation* 19 (1965): 297–301.

of Cooley and Tukey, coupled with the speed of digital computers, that Fourier analysis has become a useful and practical option for music analysts today.

With advancements in technology in the late twentieth and early twenty-first centuries, musical analyses using Fourier techniques have become increasingly prevalent. In 1978 Meyer used Fourier analysis to create sonagrams of more extended musical passages, such as mm. 51-71 from Bruckner's Ninth Symphony. Meyer also investigated instrumental spectra and the effect that seating location has on orchestral sound in concert halls.[16] Cogan (1984) became the first to publish a book based solely upon the analysis of complete musical works through Fourier analysis. Using technology developed by IBM's Watson Research Center, he created spectrographs of a variety of pieces from different eras and cultures.[17] By the end of the twentieth century, and beginning of the twenty-first, digital computers and software applications utilizing Fourier imaging techniques improved resolution, accuracy and even added color to the images.[18] Today anyone with access to a computer and the Internet can easily download a variety of software applications to create spectrographic images using Fourier analysis.

Pedagogic Applications of Fourier Analysis and Spectrographs

The following section describes three distinct pedagogic applications of Fourier analysis and spectrographs that I have found to be most useful in the music theory classroom. Analytically, my discussions of the pieces are similar; spectrographs show the entire frequency content for a sound and my analyses, therefore, detail specific frequency content of each performance and piece. In general, this is the important virtue of this technology for theory students – the images allow students to visualize the entire frequency content of any piece they are studying. Pedagogically, my focus is different for each piece. Chopin's *Prelude in C minor*, op. 28, no. 20, focuses on performance differences, the Japanese *Gagaku* piece *Hyojo Netori* from *Etenraku*, explores instrumental tone color, and the computer work *Untitled #8* by Markus Popp examines the form of a non-notated work.

[16] Jurgen Meyer, *Acoustics and the Performance of Music* (Frankfurt: Verlag Das Musikinstrument, 1978).

[17] Cogan, *New Images of Musical Sound.*

[18] Cogan, *Music Seen, Music Heard*; Cogan, *The Sounds of Song*; John Latartara, *Instrumental Tone Color: A Spectrographic Exploration* (D.M.A. Dissertation, New England Conservatory of Music, 2002).

Before showing students a spectrograph of a complete musical work, however, I have found it essential to stress another important concept. Fourier analyses and spectrographic images are best thought of as *models* of each performance or work. The approximations inherent in Fourier analysis calculation, as well as the variety of settings possible for most Fourier software programs (including dynamic sensitivity, frequency range, and micro or macro perspective), force us to concede that each spectrograph is a possible image of the given recording, but certainly not the only one. I try to create a balance between what the image displays and what the listener perceives, while highlighting the salient features of the work.

Score and Performance: *Prelude in C minor*, op. 28, no. 20 by Chopin

Traditionally, the study of form and analysis, especially at the undergraduate level, has been oriented toward the score. While this approach is certainly useful, and in many instances necessary, it can also have the detrimental effect of marginalizing other important elements such as the sound of the piece, and/or performance decisions. One effective way to engage students with these performance issues is to play and show them images of two different performances of the same piece.[19] The following discussion

[19] An increasingly rich body of literature within the analytic community has emerged that specifically attempts to draw connections between analysis and performance. These publications have included Janet Schmalfeldt, "On the Relation of Analysis to Performance: Beethoven's Bagatelles Op. 126, Nos. 2 and 5," *Journal of Music Theory* 29/1 (1985): 1-31; Wallace Berry, *Musical Structure and Performance* (New Haven: Yale University Press, 1989); Cynthia Folio, "Analysis and Performance of the Flute Sonatas of J. S. Bach: A Sample Lesson Plan," *Journal of Music Theory Pedagogy* 5/2 (1991): 133-59; Cynthia Folio, "Analysis and Performance: A Study in Contrasts," *Integral* 7 (1993): 1-37; Carl Schachter, "Chopin's Prelude in D Major, Opus 28, No. 5: Analysis and Performance," *Journal of Music Theory Pedagogy* 8 (1994): 27-45; Jonathan Dunsby, "Performance and Analysis of Music," *Music Analysis* 8/1-2 (1989): 5-20; Jonathan Dunsby, *Performing Music: Shared Concerns* (Oxford: Oxford University Press, 1995); Nicholas Cook, "Structure and Performance Timing in Bach's C major Prelude (WTC I): An Empirical Study," *Music Analysis* 6/3 (1987): 257-272; Nicholas Cook, "Analyzing Performance and Performing Analysis," *Rethinking Music*, ed. Nicholas Cook (Oxford: Oxford University Press, 1999), 239-261; John Rink ed., *The Practice of Performance: Studies in Musical*

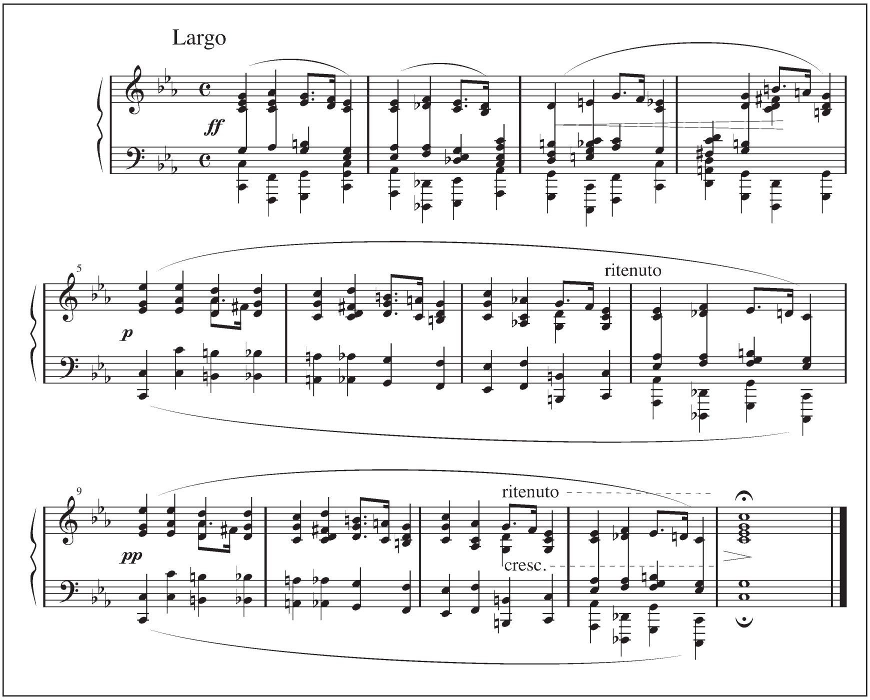
compares two performances of Chopin's *Prelude in C minor*, op. 28, no. 20 played by Cortot and Pollini. I have found these images extremely helpful for my undergraduate Form and Analysis class. The images help to reinforce not only what is aurally perceived by the student (dynamic and tempo differences), but also to reveal the acoustic reasons for their perceptions. Through the spectrographic images, parallels and discrepancies between each performance, and between performance and score are highlighted.[20] A useful distinction between score and spectrograph lies in their functional differences. In terms of performance, the score is *prescriptive*, but the spectrograph is *descriptive*.

Interpretation (Cambridge: Cambridge University Press, 1995); John Rink ed., *Musical Performance: A Guide to Understanding* (Cambridge: Cambridge University Press, 2002); John Latartara and Michael Gardiner, "Analysis, Performance and Images of Musical Sound."

[20] Over the past thirty-five years, Chopin studies have used an extraordinary variety of analytical methods. See Edward T. Cone, *Musical Form and Musical Performance* (New York: W.W. Norton and Co., 1968), 34-35; Robert Cogan and Pozzi Escot, *Sonic Design: The Nature of Sound and Music* (Englewood Cliffs NJ: Prentice Hall, 1976), 2-14; Lawrence Kramer, *Music and Poetry: The Nineteenth Century and After* (Berkeley: University of Berkeley Press, 1984), 91-117; Jim Samson, ed., *Chopin Studies* (Cambridge: Cambridge University Press, 1988); Harald Krebs, "Tonal and Formal Dualism in Chopin's Scherzo, Op. 31," *Music Theory Spectrum* 13/1 (1991): 48-60; Carl Schacter, "Chopin's Prelude in D Major, Opus 28, No. 5: Analysis and Performance," *Journal of Music Theory Pedagogy* 8 (1994): 27-45; John Rink and Jim Samson, eds., *Chopin Studies 2*, (Cambridge: Cambridge University Press, 1994); William Rothstein, "Ambiguity in the Themes of Chopin's First, Second, and Fourth Ballades," *Integral* 8 (1994): 1-50; John Rink, "Chopin's Ballades and the Dialectic: Analysis in Historical Perspective," *Music Analysis* 13 (1994): 99-115; Rose Rosengard Subotnik, *Deconstructive Variations: Music and Reason in Western Society* (Minneapolis: University of Minnesota Press, 1996); Laurie Suurpaa, "The Path from Tonic to Dominant in the Second Movement of Schubert's String Quintet and in Chopin's Fourth Ballade," *Journal of Music Theory* 44/2 (2000): 451-485; J.A. Sloboda and A.C. Lehmann, "Tracking performance Correlates of Changes in Perceived Intensity of Emotion During Different Interpretations of a Chopin Piano Prelude," *Music Perception* 19 (2001): 87-120. I am unaware of any attempt to approach the music of Chopin using Fourier analysis and spectrographs. For a critical score and historical context specifically regarding the preludes Op. 28 see Thomas Higgins ed., *Frederic Chopin Preludes, Opus 28: An Authoritative Score, Historical Background, Analysis, Views, and Comments* (New York: W.W. Norton & Company, 1973). For a general overview of Chopin and his music see Jim Samson, *Chopin* (New York: Schirmer Books, 1996).

Before analyzing the spectrographic images, I play both performances and ask students for their initial aural impressions. While one or two students usually point out the dynamic differences created by Cortot and Pollini, most seem unsure or hesitant about the performance differences. After analyzing the performance images, students immediately recognize the striking differences between each performance and appear more confident in their aural impressions. The images reinforce and help guide the student's listening.

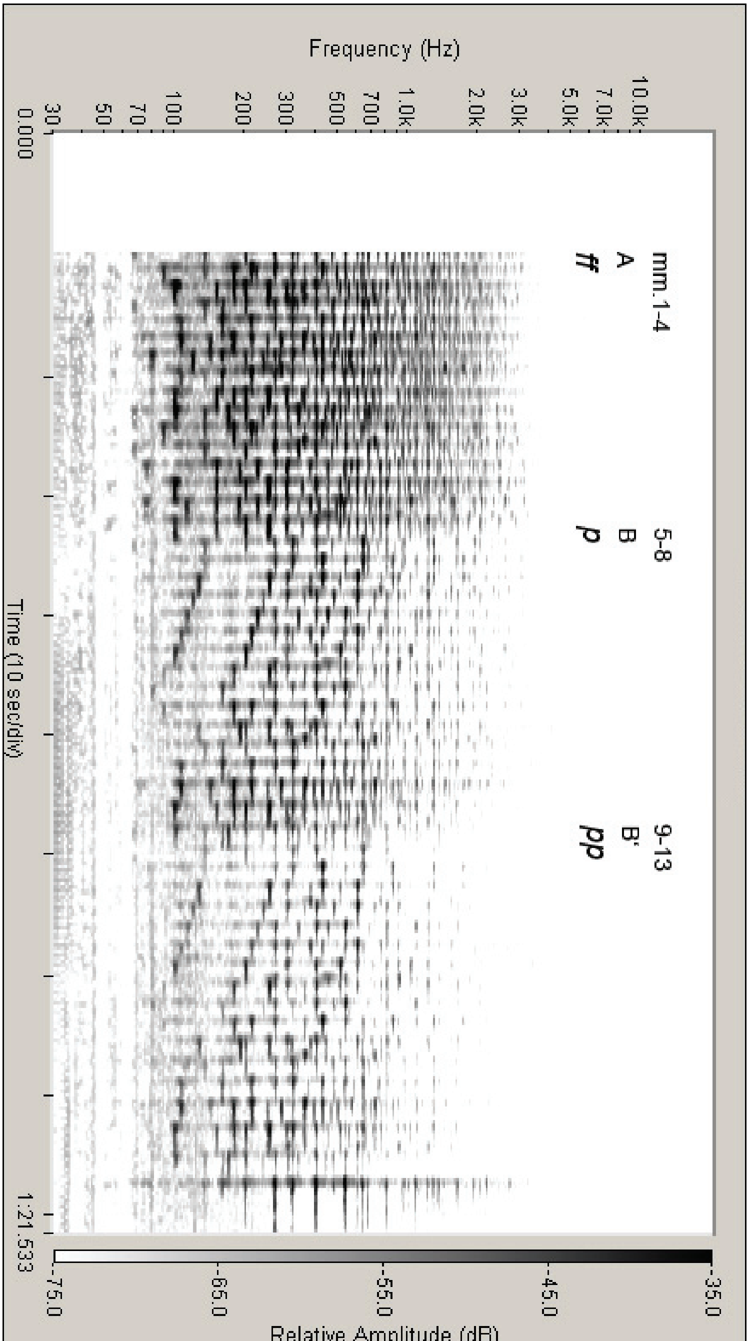
Example 3 shows the score of Chopin's *Prelude in C minor*, op. 28, no. 20 and Example 4 shows a spectrograph of a performance of that work by Cortot.[21]



Example 3 - Score of Chopin's *Prelude in C minor*, op. 28, no. 20

The prelude consists of two, four-measure phrases (A, bars 1-4, and B, bars 5-6) of different musical material, with the second

[21] Frederic Chopin, *Cortot plays Chopin: The Legendary 1925-1929 Recordings* (recorded 1926 for HMV), Alfred Cortot (Berkeley: Music and Arts Programs of America, Inc., 1987), 317. 0-17685-48712-5 (reissue of discontinued CD-317). I created all spectrographic images using Soundtechnology software.



Example 4 - Spectrograph of Cortot performing Chopin's *Prelude in C minor*, op. 28, no. 20

phrase B repeated (B′, bars 7-13).[22] Each of these three phrases is aligned with a different dynamic level, *ff*, *p*, *pp*, as shown in the score and revealed by the spectrograph.

Cortot's performance (Ex. 4) clearly projects three different dynamics, one for each phrase. Section A, mm. 1-4, is the loudest, as revealed by the intense spectra of black or dark grey, reaching as high as 2.5-3.0 kHz. Section B, mm. 5-8, is played softer with spectra becoming less intense (light grey) and predominating in the 2.0-2.5 kHz region. Finally, Section B′, mm. 9-13, is the softest section, shown by even less intense spectra (lighter grey) reaching only as high as 1.5-1.8 kHz. At each successive section Cortot decreases the intensity of the sound equally, resulting in a steady reduction in the number of upper partials by about 500 Hz (3.0kHz, to 2.5 kHz to 1.8 kHz). Notice also that the final chord in m. 13 is played much louder than Section B and B′, equal in intensity to Section A with spectra reaching just under 3.0 kHz.[23] Overall, Cortot creates an equal reduction of intensity for each section, ending with a suddenly louder final chord. How does Chopin's score indicate

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[22] Although the rhythmic motive of section A is also present throughout section B, the differences in outer melodic motion, dynamics, register, and density justifies the "section B" label. The repeat of mm. 5-8 at *pp* was added later at the suggestion of the French writer on music Francois-Henri-Joseph Blaze. Chopin in the autograph of this prelude wrote, "note for the publisher of the rue Rochechaurt: small concession made to Mr. XXX [Blaze] who is often right." See Higgins, *Frederic Chopin Preludes*, 68 and Frederic Chopin, *Complete Preludes and Etudes for Solo Piano: The Paderewski Edition*, eds. Paderewski, Bronarski, and Turczynski (New York: Dover, 1980), 190. In certain editions for students Chopin crossed out mm. 9-13. This would lend credence to the analysis of the C minor prelude as essentially binary in nature. Even with the addition of mm. 9-13, the exact repetition of material and subtle dynamic shift help to corroborate this binary viewpoint.

[23] Cortot's interpretation of this last chord is not surprising as we read from his own writing, "Two interpretations of the last chord are allowed – the first savagely definite, the second *piano* and indecisive." See Alfred Cortot, *Alfred Cortot's Studies in Musical Interpretation*, ed. Jeanne Thieffry (New York: Da Capo Press, 1989), 51. In Cortot's own edition of this Prelude he indicates a decrescendo in m.12 and what appears to be another short decrescendo, or accent, in m.13. Cortot apparently interprets this mark in m.13 as either a decrescendo or accent, thus providing two performance options. See Frederic Chopin, *24 Preludes Op. 28*, ed. Alfred Cortot (Paris: Editions Salabert, 1926). I wish to thank pianist Dr. Jon Sakata for his perceptive comments regarding not only this final chord, but also Chopin's C minor prelude in general.

the dynamic contrasts just described?[24]

Rather than an equal decrease in intensity, the score indicates an extreme dynamic drop from *ff* to *p* between Sections A and B, and then a subtle dynamic drop from *p* to *pp* moving from Section B to B′. As discussed above and shown by Example 4, Cortot chooses to create an alternate dynamic structure of equal contrasts. Furthermore, the score indicates a crescendo at mm. 3-4 and mm. 11-12. Cortot subtly projects a crescendo in mm. 3-4 as seen by the slight increase in upper partials towards the end of Section A, but ignores the crescendo in mm. 11-12. Finally, the last chord in m. 13 is marked with a decrescendo or, according to Cortot, an accent, as a whole note with fermata. Cortot plays this chord accented, but with a duration of one half note. Cortot's performance systematically alters what is indicated in the score, creating an interpretation defined by a gradual decrescendo, resulting in a gradual darkening of sound, followed by a suddenly loud accent on the final chord, which is quickly released.

Example 5 shows the same prelude performed by Pollini.[25] In Pollini's performance, Section A is played loudest, seen as black with intense spectra reaching as high as 6.0-6.5 kHz.[26] Section B, however, is played much more softly, seen as grey, with upper partials reaching only as high as 1.5-2.0 kHz. Section B′ is played slightly softer than Section B, seen as slightly lighter grey, decreasing the upper partials to a peak of 1.0-1.5 kHz. Unlike Cortot, Pollini

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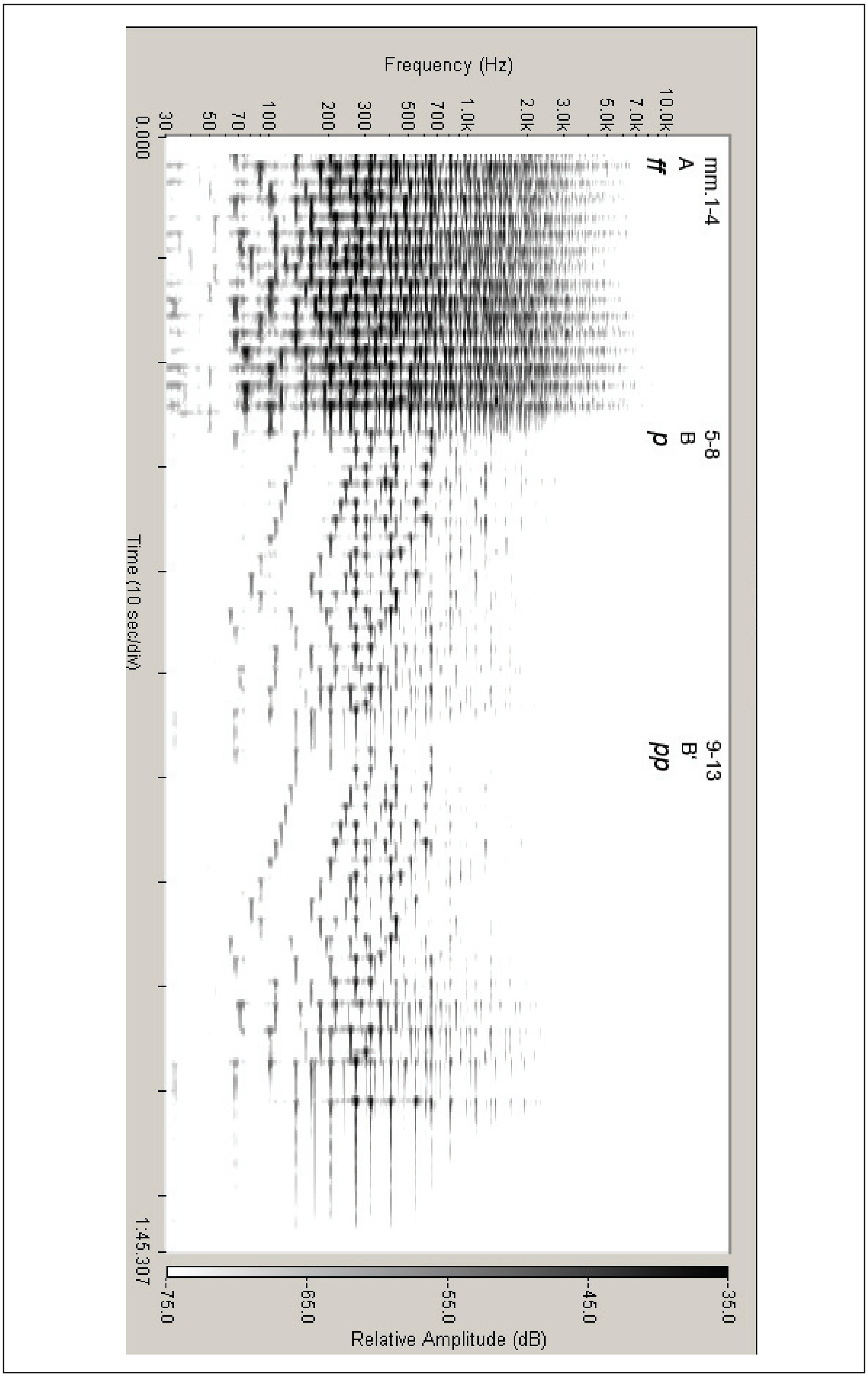
[24] It is important to make clear that I am not equating the "score" with the "work" and do not place any final authority with the score over a performer's interpretation. In relation to this analysis, I am comparing the indications of the score, specifically regarding dynamics, with each performance. Just as each spectrograph is a model of the performance, each performance and score is a model of "the work".

[25] Frederic Chopin, *Chopin Preludes*, Maurizio Pollini (Deutsche Grammophon, 1975), 413796-2.

[26] Differences in upper partial peaks between Cortot (3.0 kHz) recorded in 1926 and Pollini (6.5 kHz) recorded in 1975 are related to recording equipment used at the time, and not a measurement for absolute spectral/dynamic content between the two performances. As opposed to modern recording equipment, earlier equipment captured a narrower spectral/dynamic range with an upper partial peak at approximately 5.0 kHz. The relative spectral/dynamic relationships revealed within each performance, however, are still valid. See Peter Johnson, "The Legacy of Recordings," *Musical Performance*, ed. John Rink (Cambridge: Cambridge University Press, 2002), 197-212.



Example 5 - Spectrograph of Pollini performing Chopin's *Prelude in C minor*, op. 28, no. 20

creates a dramatic dynamic/spectral drop from section A to B, followed by a subtle dynamic/spectral drop from B to B′. In addition, Pollini projects a slight crescendo at mm. 3-4, shown by the increase in partials at the end of Section A from 5.0 to 7.0 kHz, and also at mm. 11-12, shown by the increase in intensity and partial peak at the end of Section B′ moving from 1.0 to 2.0 kHz. Like Cortot, Pollini plays the final chord louder and slightly accented. Rather than a sudden dynamic increase, he smoothly leads into it from the crescendo beginning at m. 11. Finally, as indicated by the score, Pollini holds the final chord for the entire whole-note duration. Overall, Pollini projects more literally what is indicated in the score. If an accurate translation from score to sound is the main criterion for a good performance, Pollini's interpretation might be preferred. This viewpoint, of course, places ultimate authority with the score. If sensitive and creative playing are the main criteria for a good performance, certainly both Cortot and Pollini are fine.

Spectrographic images provide a useful pedagogic application for performance analysis, allowing the visualization of detailed frequency and intensity content that help reinforce and guide aural perceptions. It is important for students to connect the sound with the image, and the image with the sound. Sometimes I will play the second recording and ask them to surmise what they think the image will look like, or show them the image and have them describe how it will sound. This helps to sensitize students to both the acoustic sound and their own musical perceptions, encouraging them to hear beyond the score into dramatic and subtle performance differences.

Tone Color and the Japanese *Gagaku* piece *Hyojo Netori*

Tone color is both ubiquitous and elusive. It is a constant element in all music, but has been historically and pedagogically difficult to discuss in any comprehensive way. Classroom discussions of tone color tend to rely only on aural perceptions and score analyses of instrumentation and texture. By examining the musical sound through Fourier analysis, students can see the acoustic reasons why a certain passage or piece may sound bright or dark, simple or complex. This helps to demystify the concept of tone color by making it more concrete, allowing the teacher and student to discuss tone color in terms of specific frequency strength and weakness. The following analysis, which I have used in graduate music theory seminars, explores the Japanese *Gagaku* piece *Hyojo Netori* from the perspective of tone color. I use a non-Western piece when introducing tone color for two reasons: in order to expose students to non-Western music, and to minimize cultural biases students may have regarding Western composers and music they feel they already know. In this way I create a more even playing field for musical discovery (as long as there are no ethnomusicology students in the seminar!). Following *Hyojo Netori* I move on to the more familiar Western repertoire. Using spectrographs, Cogan presents a theory of tone color based upon thirteen sonic oppositions.[27] While his theory is certainly useful, I do not teach it to my students because its detailed nature requires more time and explanation than a general graduate analysis seminar usually allows.

I begin our tone color discussion by asking students to describe in words the way the piece sounds. Responses like "bright, dark, mellow," and "sharp" are typical. While these descriptions are important, after examining the spectrographic images students begin connecting their descriptors with the acoustic bases for their perceptions. Later in the discussion I often encounter students discussing the "higher, stronger overtones" that relate to the "brighter" sound, or the simple "sine-tone like" sound relating to a "duller" sound. This is an important accomplishment because it gives students the technical language that they need to connect the percept of a sound with the physical sonic signal.

Gagaku or "elegant music" is a form of traditional Japanese court music, and stems from an aural tradition that emphasizes the transmission of music from teacher to student.[28] *Gagaku* can be

[27] Cogan, *New Images of Musical Sound*.

[28] Haruko Komoda and Mihoko Nogawa, "Theory and Notation in Japan," *The Garland Encyclopedia of World Music Volume 7: East Asia: China, Japan and Korea,* eds. Robert C. Provine, Yosihiko Tokumaru, and J. Lawrence Witzleben (New York: Routledge, 2002), 573; Naoko Terauchi, "Gagaku," *The Garland Encyclopedia of World Music Volume 7: East Asia: China, Japan and Korea*, eds. Robert C. Provine, Yosihiko Tokumaru, and J. Lawrence Witzleben (New York: Routledge, 2002). As Terauchi states, "In *gagaku*, as in Japanese music in general, oral transmission is of primary importance; written scores are secondary" (626). *Syoga* is a type of transmission system used by Japanese musicians that is unique for each instrument and is considered the first step towards learning a traditional instrument. Although some parallels to Western *solfege* can be drawn, *syoga* syllables do not necessarily correspond to absolute or relative pitch.

divided into three categories. The first is indigenous songs and dances such as *mikagura* and *azuma asobi*. The second is foreign music and dance such as *togaku* and *komagaku*. The third is vocal music of both indigenous and foreign origin such as *saibara* and *roei*. Dating back to the sixth century, *Togaku* pieces are from Chinese origin, and exist as instrumental music called *kangen*, or as accompaniment to dance called *bugaku*.[29] *Hyojo Netori* is an introductory piece from the famous *togaku* work, *Etenraku*. *Hyojo* indicates a specific mode, and *Netori* indicates a short composition in free rhythm played prior to a longer piece.[30] The title *Hyojo Netori*, therefore, describes the type, rhythm and mode of the work. Although the entire work reiterates the same pitch-class set of the *Hyojo* mode, three distinct sections are created, largely through instrumental combinations that result in three distinct tone-color profiles. What emerges is a fascinating variety of tone-color differences, achieved through instrumentation, which ultimately defines the form of the work.[31]

Example 6 shows a spectrograph of a performance of *Hyojo Netori*.[32]

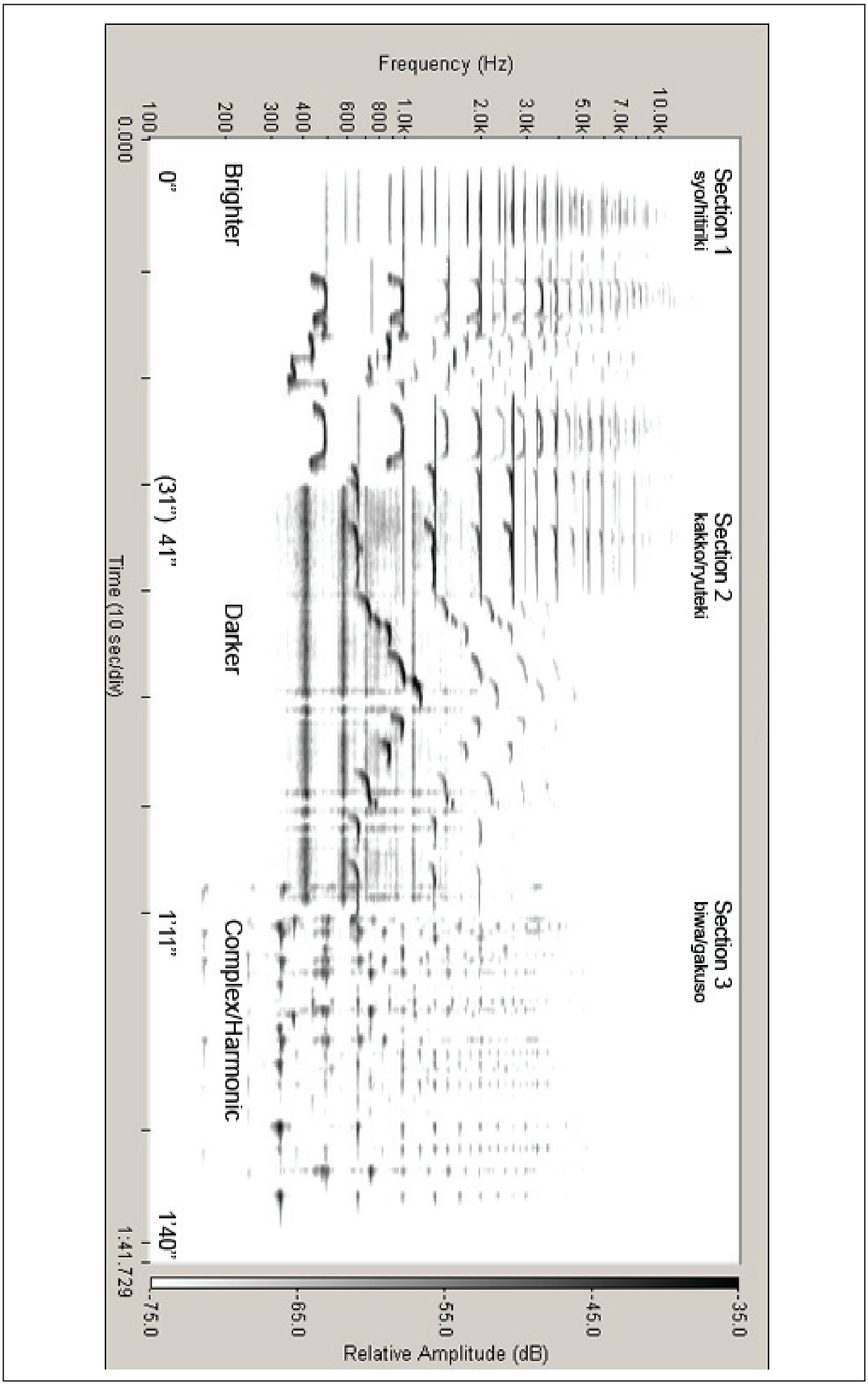
In addition, *syoga* syllables also indicate tonal range, tone color, melodic ornamentation, and playing technique. See Yuko Kamisango, "Oral and Literate Aspects of Tradition Transmission in Japanese Music: With Emphasis on Syoga and Hakase," *The Oral and the Literate in Music*, eds. Tokumaru Yosihiko and Yamaguti Osamu (Tokyo: Academia Music LTD, 1986), 288-299.

[29] Terauchi, "Gagaku", 619-620.

[30] *Hyojo* is one of the "six modes" from the *ritu* group of modes. The mode of *Hyojo*, as a pentatonic collection in the tuning for *gagaku* instruments, contains the pitches E, F#, A, B, and C#. This pentatonic collection, however, may also be expanded to include the pitches G and D creating a heptatonic collection. See Komoda and Nogawa, "Theory and Notation in Japan," 566-567.

[31] For detailed discussions of *gagaku* instruments see Terauchi, "Gagaku," 620-625 and Robert Garfias, *Music of a Thousand Autumns: The Togaku Style of Japanese Court Music* (Berkeley: University of California Press, 1975), 35-56.

[32] *Gagaku: Traditional Japanese Music*, King Records Kich (Tokyo, Japan, 2001, recorded 1990).



Example 6 - Spectrograph of a performance of *Hyojo Netori*

Section 1, lasting from 0″ to approximately 41″, is characterized by two distinct instrumental spectra. The *syo*, a mouth organ, begins by playing chords that result in rich harmonic spectra, seen as grey horizontal lines extending from 500 Hz up to 10.0 kHz. The *hitiriki*, a double reed instrument, enters next playing the main melodic part and is shown by thicker, black horizontal lines. This melody also uses glissandi (called *embai*) to slide into and out of notes, a typical technique for the instrument.[33] The *hitiriki* also has a rich spectral profile creating a large amount of partials stretching from the first fundamental at 500 Hz to the upper partials reaching 8.0 kHz. Section 1 overlaps into the next section with the introduction of the *kakko*, a double-headed cylindrical drum, and the *ryuteki*, a transverse flute. The *kakko*, which enters at 31″, creates two strong harmonic partials seen as straight horizontal lines between 400 and 600 Hz, but also as complex spectra between 600 Hz and 1.0 kHz. The *ryuteki* also enters at 31″, but on the same pitch as the *hitiriki* reinforcing the harmonic spectrum.

Section 2 lasts from approximately 41″ to 1′11″ and uses the *ryuteki* (transverse flute) and the *kakko* (drum). The *ryuteki*, like the *hitiriki*, plays the melody, and is shown by harmonic spectra with glissandi arching upwards and then down, creating a pyramid-like shape. The *ryuteki*, however, is much less spectrally rich than the *hitiriki*, displaying only 3-4 partials and dramatically reduces the upper partial peak, from 10.0 kHz (created by the *syo*) in Section 1, to 4.0 kHz in Section 2. This results in a shift from a brighter to darker sound. The *kakko*, as discussed previously, combines harmonic spectra in the lower region, from 400 to 600 Hz, with more complex spectra in the upper region, from 600 Hz to 1.5 kHz. From Section 1 to Section 2, therefore, a spectral shift occurs from rich, brighter harmonic spectra created by the *syo* and *hitiriki*, to less rich, darker harmonic/complex spectra created by the *ryuteki* and *kakko*.

Section 3, lasting from 1′11″ to 1′40″, is characterized by two plucked string instruments, the *biwa* and *gakuso*. Together these instruments create harmonic/complex spectra at the attack, and shorter harmonic spectra for the body and decay. Unlike the previous two sections, which use longer sustained pitches, Section 3 creates shorter pitches with more space between. It is interesting to note that the initial plucking or percussive attack of the *biwa* and *gakuso* is reminiscent of the attack of the *kakko* drum. The *kakko's*

[33] Terauchi, "Gagaku," 622.

spectral profile could be viewed as a foreshadowing of tone color, which leads into the *biwa* and *gakuso*. The spectrum for Section 3 encompasses a total range from 300 Hz to 3.0 kHz, but there are also resonating lower octaves that extend down to 150 Hz.

Overall, therefore, Section 1 begins with a brighter sound and predominance of harmonic spectra with many partials. Section 2 exhibits a darker sound, with a dramatic reduction of upper partials, and the introduction of harmonic/complex spectra. Finally Section 3 presents a mosaic of complex/harmonic attack sounds, followed by a brief harmonic body and decay with a sparser density. Each distinct instrumental pairing creates a unique tone color, which can be heard in performance and also seen in the spectrographic image.[34]

Tone color is, perhaps, the most difficult musical domain to discuss and teach. These images can be used to focus both the concept of tone color and classroom discussion, elevating the level of discourse from individual perceptions to concrete acoustic understandings. What at first seems to students a somewhat mystical musical element is clarified through the spectrograph into an acoustic representation of musical sound. By visually analyzing the frequency and intensity content of a musical work, students gradually move beyond mere descriptors of tone color to analyses of the physical signal. These physical analyses, made possible by

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[34] *Zyo ha kyu* is a three-section form concept found in Japanese books on art theory. *Zyo* acts as the introduction, *ha* the exposition, and *kyu* the conclusion. This three-section form also applies to music, and is a fundamental part of *gagaku* and Japanese musical structure in general. See Mari Shimosako, "Philosophy and Aesthetics," *The Garland Encyclopedia of World Music Volume 7: East Asia: China, Japan and Korea*, eds. Robert C. Provine, Yosihiko Tokumaru, and J. Lawrence Witzleben (New York: Routledge, 2002), 546-547 and 554; Komoda and Nogawa, "Theory and Notation in Japan," 571. As shown by the figure below, *Hyojo Netori* can be viewed in two ways; as the *Zyo*, or the beginning part in a much larger form, and as a projection of *zyo ha kyu* itself expressed through the systematic use of each instrumental combination.

Section	1	2	3
Instruments	syo/hitiriki	ryuteki/kakko	biwa/gakuso
Form	zyo______________		
	(zyo	ha	kyu)

Hyojo Netori projects this *zyo ha kyu* structure, revealing a direct link to Japanese art theory.

the spectrographic image, can then be used to formulate structural models of the musical work and performance. Both student and teacher can intelligibly explore the tone color design of any musical work.

Computer Music Without Score: *Untitled #8* by Markus Popp

Unlike traditionally-notated Western music realized by a performer, or music learned and sustained through aural traditions, music created using computers is often completely non-notated, rarely transcribed, and exists only in playback or as a digital file.[35]The computer and other digitized mediums have created a culture of composers whose works exist entirely in the digital realm. This type of music presents many challenges for the music theory teacher and student. How can these non-notated computer pieces be discussed and analyzed in the classroom without relying completely on aural impressions? One way would be to ask students to transcribe the piece using conventional or invented symbols that they feel best represents the sounds they hear. This can certainly be useful as a first step in the analytical process, but the results are still students' impressions, though now more formally organized. Fourier analysis and spectrographs can be of help by allowing us to make images of the work that provide acoustic evidence to explain our musical perceptions. Once imaged, the precise frequency content of the piece can be studied and both small and large-scale issues of form can be discussed through both aural and visual analyses. The computer generated piece *Untitled #8* by Markus Popp from his CD *Ovalprocess* is analyzed in relation to both small-scale content and the large-scale form.

Having used this piece in graduate music theory seminars, I have found the visualization of non-notated computer music to be one of the most useful pedagogic approaches for this technology. Before analyzing the spectrographic image, my students' first aural impressions of this piece are always extreme. They describe it as "just noise" or "chaos" or "sounds like a dentist drilling my teeth!" After examining the image the structure and even the harmonic elements of the piece are much more easily recognized. The images help to clarify the initial onslaught of frequencies and sounds that students hear, enabling both detailed classroom discussion and analytical projects.

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[35] Issues of performance practice for computer music are, however, still relevant, placing the emphasis on the quality of the source file (sample and bit rate) and quality of playback equipment.

(One student who chose the piece for her final project admitted that, after a while, she even "enjoyed" listening to it.)

Ever since the CD's *Diskont* and *Systemisch*, German composer Markus Popp, working under the name Oval, has been at the forefront of the laptop computer music revolution.[36] *Diskont* and *Systemisch* were created using, among other things, sampled sounds of skipping CD's. These skipping sounds were used to create pulses in the music. Popp intentionally scratches CD's in order to record these skips for his music. Journalists, therefore, label his music and the musical genre he created "glitch music". *Ovalprocess* is both a CD and software designed as, "…a model of how I work."[37] Popp views computer code and operating systems rather than artistic or musical concepts as more influential on the sonic outcome of his work.[38] As Popp has stated, "I'm less of a composer than I am a navigator, or a person who's working with a certain setup where it's more about coming up with a strategy in this setup, than creating innovative electronic music as part of an aesthetic."[39]

This strategy includes the editing and assembling of small audio files gathered from his collection of thousands on his Macintosh laptop to create longer files. These longer files are then arranged in standard audio sequencers (Logic Audio, Digital Performer, etc.), often as repeating loops, to create musical works. With *Ovalprocess*, Popp intentionally limited himself to certain parameters, including the use of guitar, organ, and feedback sounds. No score was created for *Untitled #8*, and it exists only on CD or as a digital file.

Example 7 shows a spectrographic detail from the beginning of *Untitled #8*. The work begins with complex spectra extending from 20 Hz to slightly above 2.0 kHz, seen as bands of black and grey,

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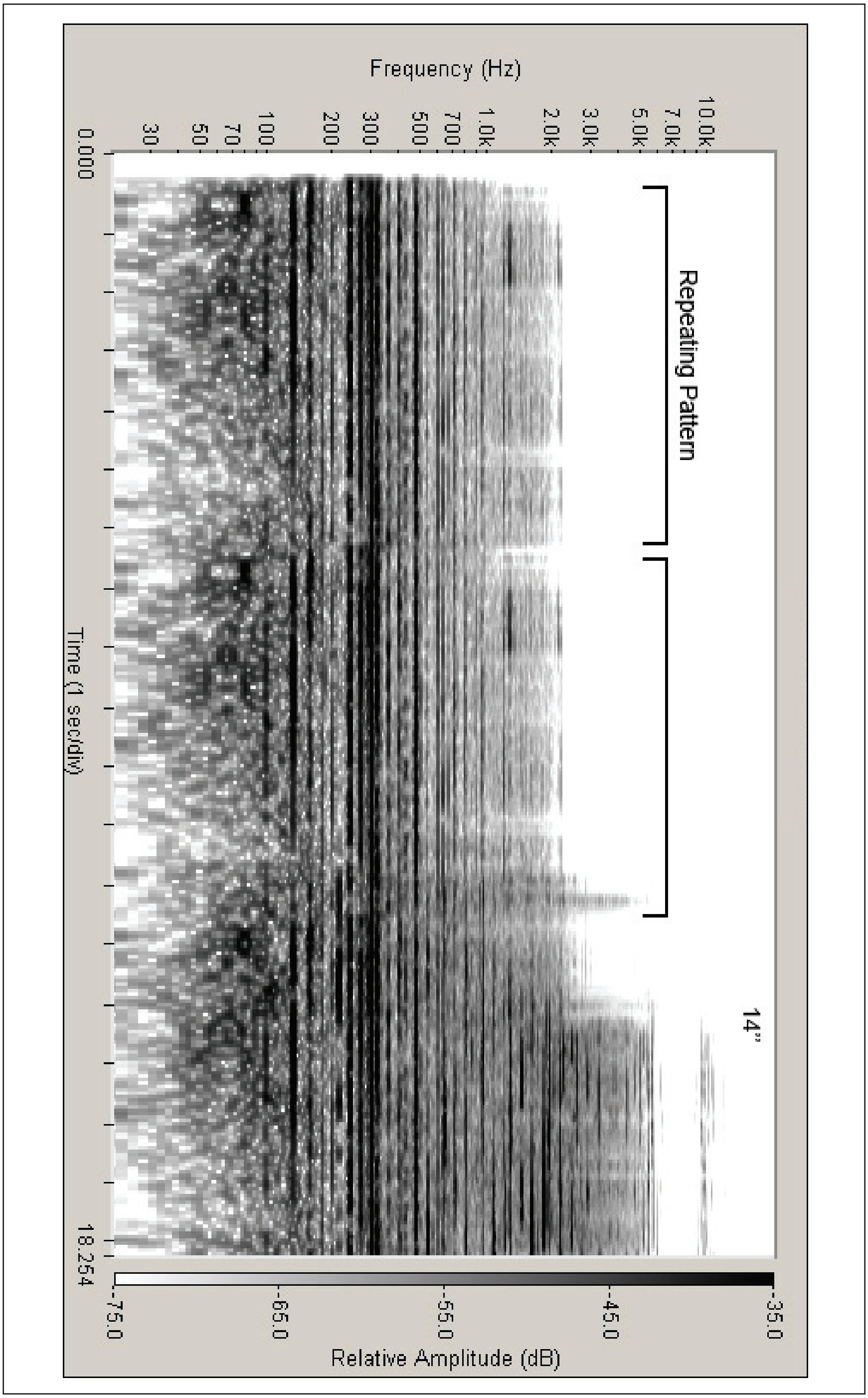
36 Oval, *Diskont*, Thrill Jockey, 28736, 1994 reissued 1996; Oval, *Systemisch*, Thrill Jockey, 28732, 1994 reissued 1996. Oval was originally comprised of three individuals, Markus Popp, Sebastian Oschatz, and Frank Metzger, but gradually Popp became the sole musician for Oval.

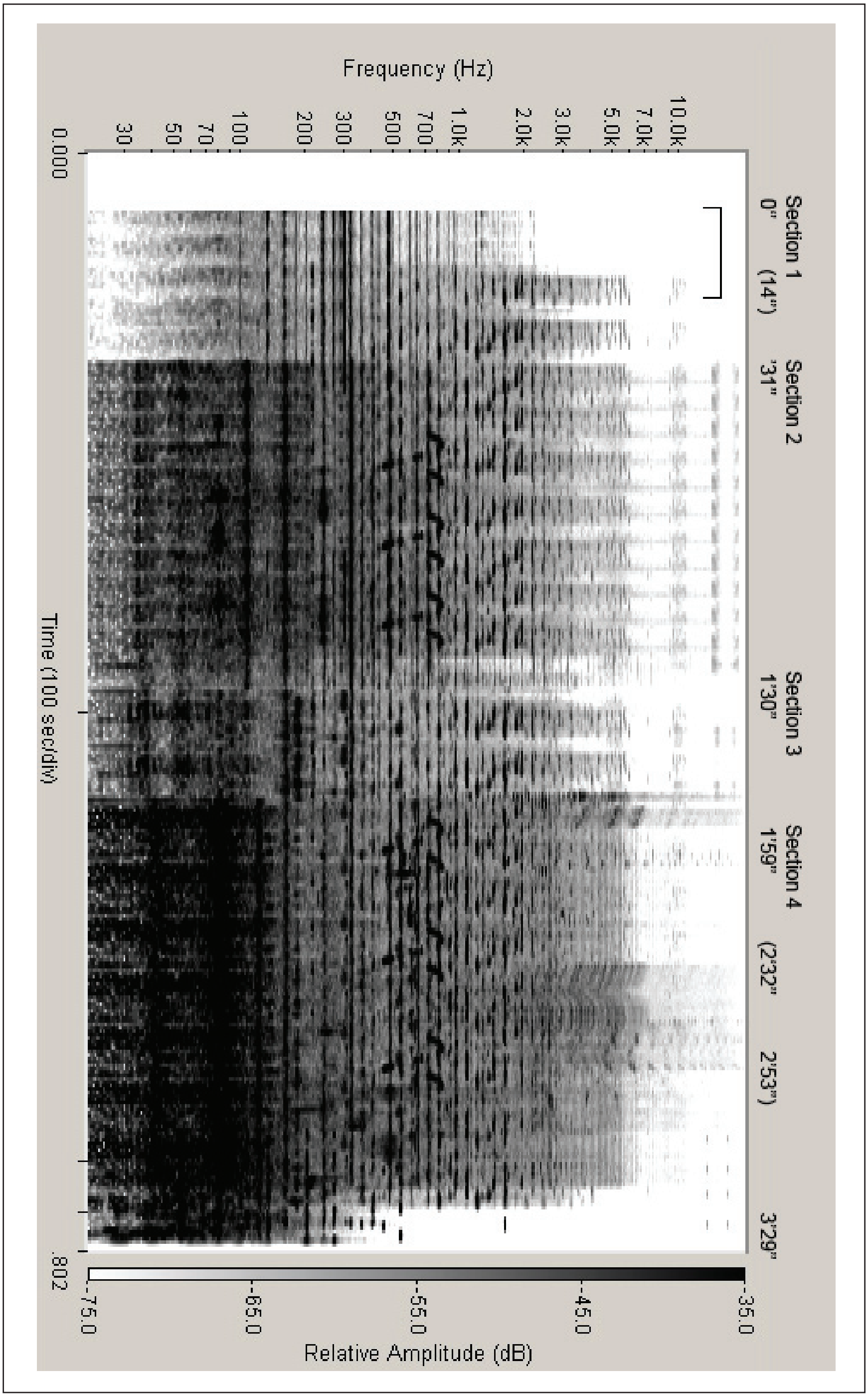
37 Oval, *Ovalprocess*, Thrill Jockey, 81, 2000. Sam Inglis, *Markus Popp: Music as Software*, 2002 (Accessed September 3, 2005). www.soundonsound.com/sos/oct02/articles/oval.asp.

38 Marc Weidenbaum, *A Conversation with Markus Popp, of Oval and Microstoria*, 1997 (Accessed September 5, 2005) www.disquiet.com/popp-script.html.

39 George Zahora, *Oval Processed*, 2002 (Accessed September 5, 2005) www.splendidezine.com/features/oval/. Although often emphasizing the process side of his work, Popp has also readily admitted that the music he created under the name Oval "…was completely musical." See Walt Miller, So: *The Power of Contentious Collaboration*, 2003 (Accessed September 15, 2005) www.splendidezine.com/features/so/.



Example 7 - Spectrographic detail from the beginning of *Untitled #8* by Popp



Example 8 - Complete *Untitled #8* by Popp with harmonic spectra emerging strongly between 150-500 Hz, seen as black horizontal lines. As indicated in the spectrograph, a repeating pattern can be seen, stated twice, and initiated by a louder frequency at about 1.3 kHz, seen as a black line. As part of this pattern, the lower frequencies create a V-shaped, wave-like arch. The second statement of this repeating pattern ends with a short spectral spike, which reaches up to 6.0 kHz, foreshadowing new material to come. At 14′′ an intense, complex, brighter sound enters, part of which was heard briefly at the end of the second statement of the initial repeating pattern. Dense bands of grey extend spectra upwards to 6.0 kHz, and upper partials appear between 9.0 and 10.0 kHz. This new material is also characterized by repetition, adding to the opening repetitive pattern. Popp's use of repeating loops is visible from the spectrographic image.

From this detailed view of the beginning, Example 8 zooms out revealing a spectrographic image of the complete *Untitled #8*. The opening detail of example 7 can now be seen as the beginning part of Section 1, in a larger four-section design. Example 9 summarizes this four-section design, along with durations and function labels for each section.

Section	1	2	3	4
Time	0-30′′	31′′-1′29′′	1′30′′-1′58′′	1′59′′-3′29′′
Function	Introduction	A	Transitional	B

Example 9 - Summary of four section design with functions of *Untitled #8* by Popp

Section 1, which I view as an Introduction, lasts from 0′′ to 30′′, and is characterized by a gradual buildup of spectral complexity through the addition of repetitive figures. As previously discussed, the work begins with two statements of a repeating pattern, seen by the arrangement of the upper and lower partials, and at 14′′ a brighter repetitive pattern appears, also sounding twice in Section 1. The bracket at the beginning of Example 8 represents the entire spectrograph in Example 7, now within the context of the complete piece.

Section 2 or A, lasting from 31′′ to 1′29′′, is immediately more intense, seen by the shift from grey to black. A brighter, repetitive CD skipping loop is added, extending the upper partial structure to 20.0 kHz (the upper limit of human hearing), and the lower region is also intensified down to 20 Hz (the lower limit of human hearing). In addition, nested in the middle of this band of dense spectra between 400-800 Hz, there appears a repeating sine-tone like glissando pattern, displayed as black curved lines. Notice, however, that Section 2 does not subtract anything from Section 1, but rather adds material that increases density. So far, the piece has exhibited a layering of different repeating patterns and an accumulation of density and complexity.

Section 3, which I view as transitional, lasts from 1′30′′ to 1′58′′. Section 3 reduces intensity and the upper partial peak, from 20.0 kHz to 3.0 kHz, and is characterized by two appearances of repetitive material from Section 2. The two appearances of repetitive material display two spectral peaks with the same spectral profile that extends up to 20.0 kHz. Section 3 ends with a loud, complex, bright sound that activates the entire human hearing range from 20-20.0 kHz. This powerful moment leading into Section 4 foreshadows material to come.

Section 4 or B, lasting from 1′59′′ to 3′29′′, is the most intense section of the piece, as seen by the dominance of black spectral bands in the lower region from 150 Hz and below, and the dense grey band in the upper region from 1.0-5.0 kHz. Unlike Section 2, however, the highest and brightest frequencies from 8.0-20.0 kHz are not consistently activated in Section 4. Between 2′32′′ and 2′53′′, there is a return to the same intense 20 Hz-20 kHz frequency activation heard at the end of Section 3. Also, the repeating sine-like glissando pattern between 400-800 Hz is consistently present throughout Section 4. Section 4 and the entire piece conclude with a quick subtraction of material, ending on sine tones in the highest register, and complex lower-frequency bands in the lowest register.

Untitled #8, therefore, reveals a cogent structure of increasing intensity and complexity. Moving from Sections 1 to 4, the work continuously intensifies and increases in complexity, with Section 3 acting as a temporary de-intensification. Within the seeming chaos of the sound and spectrographic images, *Untitled #8* creates a carefully constructed four-part design built upon patterns of repetition. The spectrographic images allow students to see the connections between their aural musical perceptions and the frequency content of the work. This can function at both the small-scale (opening repetitive material) and at the large-scale level (4 section design). Like a score, but different in function, these images provide an analytic constant to which both teacher and student can refer. The pedagogic advantage of Fourier analysis and spectrographs for non-notated computer works in the music theory classroom cannot be overstated. In this particular application, they allow students to analyze scoreless pieces using visual images to support and supplement their aural perceptions.

Concluding Thoughts

Music theory students are asked to do many things, from harmonic analysis and part writing, to Schenkerian graphs. Any tool that can aid in their musical education should be seriously considered. As a way of highlighting performance differences, elucidating the concept of tone color, and aiding in the analysis of non-notated computer works, I have found Fourier analysis and spectrographs to be tremendously beneficial. Spectrographs of Chopin's *Prelude in C minor*, op. 28, no. 20 highlight performance differences, revealing specific dynamic changes over the course of the work, and temporal durations for specific attacks. The spectrograph of *Hyojo Netori* reveals three specific tone colors created through instrumental pairings, allowing students to see the reasons for their "bright" and/or "dark" perceptions. Finally, the images of *Untitled #8* by Markus Popp provide students with a visual roadmap into both the small-scale repetitive structure and large-scale formal design of the non-notated work.

Paradoxically, the advantage of this technology lies in its simplicity and complexity. These images can be easily explained by the teacher and easily understood by the student. If well focused, classroom analysis and discussion can yield useful and comprehensible results. This technology, however, can also be used to raise more complex philosophical issues regarding the nature of music and the musical work. Does imaging musical sound destabilize the notion of the "Urtext" edition of the work? Where does the musical work reside—in the score, the performance, or the performance image? What should the music theorist analyze to derive plausible musical "theories"—the score or the performance? The answers to these questions are not as important as the questions themselves, and the questions themselves are not as important as getting our students to ask these questions.