

Music and Operations Research - The Perfect Match?

By Elaine Chew

Operations research (OR) is a field that prides itself in its versatility in the mathematical modeling of complex problems to find optimal or feasible solutions. It should come as no surprise that OR has much to offer in terms of solving problems in music composition, analysis, and performance. Operations researchers have tackled problems in areas ranging from airline yield management and computational finance, to computational biology and radiation oncology, to computational linguistics, and in eclectic applications such as diet formulation, sports strategies and chicken dominance behavior, so why not music?

I am an operations researcher and a musician. Over the past ten years, I have devoted much time to exploring, and building a career at, the interface between music and operations research. At the University of Southern California, I founded the Music Computation and Cognition (MuCoaCo) Laboratory¹, and direct research in music and computing. To bring music applications to the attention of the OR community, I have organized invited clusters at INFORMS meetings: 'OR in the Arts: Applications in Music'² at the 2003 INFORMS meeting in Atlanta; and, 'Music, Computation and Artificial Intelligence'³ at the 2005 INFORMS Computing Society (ICS) meeting in Annapolis. The summer 2006 issue (volume 18, issue 3⁴) of the INFORMS Journal on Computing (JoC) featured a special cluster of papers on Computation in Music that I edited with Roger Dannenberg, Joel Sokol, and Mark Steedman.

The goal of the present article is to provide a broader perspectives on the growth and maturation of music and computing as a discipline, resources to learn more about the field, and some ways in which operations research impacts, and can influence, this rapidly expanding field. My objective is to show that music – its analysis, composition, and performance – presents rich application areas for OR techniques. Any attempt to give a comprehensive overview of the field in a few pages must necessarily be doomed to failure, due to the vastness of the domain. I shall give selected examples, focusing on a few research projects at the MuCoaCo Laboratory and some related work, of musical problems that can be framed and solved mathematically and computationally. Many of the techniques will be familiar to the OR community, and some will borrow from other computing fields. These examples will feature the modeling of music itself, the analysis and description of its structures, and the manipulation of these structures in composition and performance.

Why Model Music Mathematically or Computationally?

The widespread access to digitally encoded music, from desktop browsers to handheld devices, has given rise to the need for mathematical and computational techniques for generating, manipulating, processing, storing, and retrieving digital music. For example, Shazam⁵ provides a service for users to dial a number, hold their cell phones to a music source, and receive a text message with the name of the song and recording for future purchase. Pandora⁶ recommends songs with music qualities similar to the user's current favorite; much of the technology still depends on human annotation of existing soundtracks. A possible future application could

be a musical Google, whereby one could retrieve music files by humming a melody or by providing an audio sample.

Beyond such industrial interests in mathematical and computational modeling of music, such approaches to solving problems in music analysis and in music making have their own scientific and intellectual merit as a natural progression in the evolution of the disciplines of musicology, music theory, performance, composition, and improvisation. Formal models of human capabilities in creating, analyzing, and reproducing music serve to further knowledge in human perception and cognition, and advance the state of the art in psychology and neuroscience. By modeling music making and analysis, we gain a deeper understanding of the levels and kinds of human creativity engaged by these activities.

The rich array of problems in music analysis, generation (composition/improvisation), and rendering (expressive performance) present new and familiar challenges to mathematical and computational modeling and analytical techniques, the bread and butter of operations researchers, in a creative and vast domain.

Publication Venues

While the use of computers in music can be traced back to the beginnings of computers themselves, the use of mathematics and computing to mimic human intelligence and decision-making when appreciating or making music has gathered momentum only in recent years. The escalating activity in mathematical and computational research in music has led to the birth of new societies, conferences and journals. For example, I am a founding member and secretary of the Society for Mathematics and Computation in Music⁷, formed in 2006 by an international group of researchers. The society unveiled the inaugural issue of its flagship publication, the Journal of Mathematics and Music⁸ at its first meeting in May of 2007. A special issue on Computation will appear in summer 2008, edited by Alfred Cramer, Christopher Raphael, and myself. More traditional archival publication venues include the Journal of New Music Research⁹, the Computer Music Journal¹⁰, and Computing in Musicology¹¹.



(left) Journal of the Society of Mathematics and Computation in Music. (right) Editors-in-chief, Peck and Noll, and society members amongst speakers of the Mathematical Techniques in Musical Analysis sessions at the Joint Mathematics Meeting, New Orleans, January 6, 2007. Left-to-right: Franck Jedrzejewski, William Sethares, Godfried Toussaint, Robert Peck, Thomas Noll, Elaine Chew, Rachel Hall, Julian Hook, Ching-Hua Chuan, Kathryn Elder.

¹ MuCoaCo Laboratory: www-ref.usc.edu/~mucoaco

² INFORMS OR in the Arts: www-ref.usc.edu/~echew/INFORMS/cluster.html

³ ICS Music, Computation, AI: www-ref.usc.edu/~echew/INFORMS/ics2005.html

⁴ INFORMS JoC vol. 18 no. 3: joc.journal.informs.org/content/vol18/issue3

⁵ Shazam: www.shazam.com

⁶ Pandora: www.pandora.com

⁷ Society for Mathematics and Computation in Music: www.smc-net.info

⁸ Journal of Mathematics and Music: www.tandf.co.uk/journals/titles/17459737.asp

⁹ Journal of New Music Research: www.tandf.co.uk/journals/titles/09298215.asp

¹⁰ Computer Music Journal: 204.151.38.11/cmj

¹¹ Computing in Musicology: www.ccarb.org/publications/books/cm

Music and Computing Conferences founded since 2000	
founded	conference (organization or earliest available website)
2000	International Conference on Music Information Retrieval www.ismir.net
2001	International Conference on New Interfaces for Musical Expression www.nime.org
2002*	2nd International Conference on Music and Artificial Intelligence www.music.ed.ac.uk/iomai (*the first meeting took place in 1995)
2003	International Symposium on Computer Music Modeling & Retrieval www.lma.cnrs-mrs.fr/~cmmr2005
2004	International Conference on Sound and Music Computing recherche.ircam.fr/equipes/repmus/SMC04
2006	ACM Workshop on Audio and Music Computing for Multimedia www.create.uscb.edu/amcmm06 ; portal.acm.org/toc/fm?id=1178723
2007	International Workshop in Artificial Intelligence and Music www.iaa.upf.es/mig/MusAI
2007	International Conference on Mathematics and Computation in Music www.mcm2007.info

The intensifying activities in mathematics/computation and music are best reflected in the proliferations of conferences founded in only the past few years. A partial listing of some of the main conferences, together with the years they were founded and url of their earliest available websites, is given in the table above. As in other fast moving fields in computing applications, publications in this new field most frequently occur in the peer-reviewed proceedings of the conferences, which are archived in online libraries for ready access.

Open Courseware

One cannot begin research in any field without appropriate contextual knowledge. It can take years to familiarize oneself with the state of the art, even in a relatively new field. To give graduate science and engineering students opportunities to acquaint themselves with mathematical and computational modeling of music, and to try their hand at small-scale projects that could potentially grow into larger-scale or into thesis research projects, I have designed a three-semester course on topics in engineering approaches to music cognition¹². Each course

in the sequence focuses on a topic in one of three areas: music analysis, performance, and composition/improvisation.

The course allows students to learn by example, by surveying and presenting literature on current research in the field, and to learn by doing, by creating (designing and implementing) their own research projects in the topic addressed in class. Since the inception of the class in 2003, all course material – week-by-week syllabi, better paper reports, presentations, and student project descriptions, and demonstration software – have been posted online as open courseware, and serve as a resource to the community. In the picture below is an example of a week-by-week syllabus from the 2006 class, which focused on computational modeling of expressive performance.

While the courses provide a broad and structured introduction to topics in music and computing, and the reader is urged to check it out for an overview of research in the field, the next sections provide some concrete examples of mathematical and computational modeling of problems in music.

Mathematical Representation of Music

Music representation and analysis underlie many of the techniques for composition and performance. The mathematical nature of music makes it particularly amenable to effective representation in numerical and digital forms. The mathematical representation of music is a centuries-old puzzle, tackled by luminaries such as mathematician Leonhard Euler, physicist Hermann von Helmholtz, and cognitive scientist Christopher Longuet-Higgins. It remains an important area of research today. Choosing an appropriate music representation can mean the difference between convexity and non-convexity, and make the problem at hand an intractable one, or one that is solvable in reasonable time.

Perhaps more than most time-based or sequential data, music information possesses a high degree of structure, symmetry, and invariance (Shepard, 1982). Tonal music, which refers to almost all of the music that we hear, consists of collections of sequences, or sequences of collections, of tones, also called pitches. The most common way to represent the fundamental frequencies of these tones is on a logarithmic scale – like on a piano keyboard. However, two pitches next to each other on this logarithmic scale can sound jarring when sounded simultaneously, while pitches farther apart can sound more pleasing. A number of representations have been proposed in which proximity mirrors perceived closeness.

An example of such a model is the spiral array (Chew, 2000). Like Euler's (Cohn, 1997) tonnetz and Longuet-Higgins' (1962ab) harmonic network, the spiral array arranges pitch classes, classes of pitches whose frequencies are related by a factor of a power of two, in a lattice so that neighbors along one axis are related by 2:3 frequency ratios, and neighbors along a

Home	Syllabus	Week-by-week	Homework FAQ	Archives	Final Projects
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ISE575b Topics in Engineering Approaches to Music Cognition
 CSC575b **Computational Modeling of Expressive Performance**
 EE675b

Spring 2006 Daniel J. Epstein Department of Industrial and Systems Engineering
 University of Southern California Andrew and Erna Viterbi School of Engineering

Introduction Course syllabus [PDF] Class list [HTML] [PDF] Signup information sheet [HTML] Reading plan [PDF]

Week 1 (Jan 11) Overview

Palmer, C. (1997). Music Performance. *Annual Review of Psychology*, 48:115-38. [PDF] presentation: [chew]

Gabrielsson, A. (1999). Music Performance. In D. Deutsch (Ed.): *The Psychology of Music*, Vol.2, pp.501-602. San Diego, CA: Academic Press.

Read and write a report on one of the following: set A (= pp.501-523) OR set B (= pp.523-557, 577-579). presentation (A): [unal] reports (A): [jer, lin, wang, vaziri] report (AB): [liu] presentation (B): [miles] reports (B): [cheng, miles]

Tempo, Dynamics, Articulation

Week 3 (Jan 25) Todd, N. P. M. (1992). The dynamics of dynamics: A model of musical expression. *Journal of the Acoustical Society of America*, June 1992, Vol. 91, Issue 6, pp.3540-3550. [PDF] presentation: [liu] reports: [cheng, chuan, liu]

Repp, B. H. (1998). A microcosm of musical expression. I. Quantitative analysis of pianists' timing in the initial measures of Chopin's Etude in E major. *Journal of the Acoustical Society of America*, Aug 1998, Vol.104, Issue 2, pp.1085-1100. [PDF] presentation: [mossi] reports: [cheng, chuan, lin]

Repp, B. H. (1999). A microcosm of musical expression. II. Quantitative analysis of pianists' dynamics in the initial measures of Chopin's Etude in E major. *Journal of the Acoustical Society of America*, Mar 1999, Vol. 105, Issue 3, pp.1972-1988. [PDF] presentation: [vaziri] report: [wang]

Playing Vivaldi's Son

Week 4 (Feb 1) Music and Motion

Todd, N. P. M. (1998). [PDF] presentation: [cheng]

Friberg, A., Sundberg Research, 29 (2000).

Week 5 (Feb 8) Articulation and

Bresin, R. & Battel, C. pp.211-224. [PDF]

Lindstrom, E. (2003). *Research*, Vol.32, No.

Palmer, C., & Hutchins [er] reports: [cheng,]

Week 6 (Feb 15) Interpretation

Palmer, C. (1998). O [mattiasian]

Mazzola, G., & Golle presentation: [cheng]

De Poli, G. (2004). M pp.189-202. [PDF]

Analytical and Generative Tools

Week 7 (Feb 22) Visualization

Langner, J. & Goebel W. (2002). Visualizing Expressive Performance in Tempo-Loudness Space. *Computer Music Journal*, Vol.27 No.4, Winter 2003, pp.69-83. [PDF] presentation: [cheng] report: [cheng, chuan, liu, unal, vaziri]



Excerpt from week-by-week syllabus (left) and final project presentation (right) for the Spring 2006 course on Topics in Engineering Approaches to Music Cognition.

second axis are related by 4:5 frequency ratios. Unlike planar and network models of musical entities, the spiral array wraps the plane into its three dimensional

¹² Topics in Engineering Approaches to Music Cognition: www.scf.usc.edu/~ise575

configuration to exploit its continuous interior space, and uses the convexity of tonal structures, such as chords and keys, to define spatial representations of these objects in the interior.

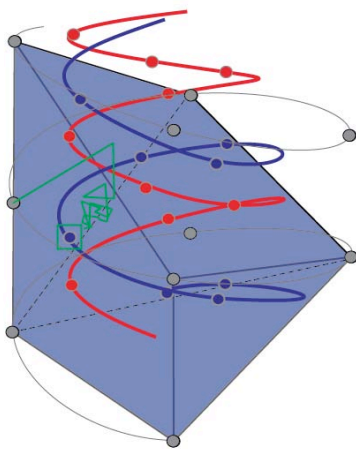
Automating Music Analysis

A discussion of music representation naturally leads mathematical formulations of problems in music analysis. At a crude level, tonal compositions can be organized into sections, each section consists of regions in particular keys that determine the predominant tones that are sounded in that region, each key region consists of segments of chord sequences, and chord comprises of tone clustered in or over time. Music and computing researchers have sought ways to automatically abstract these structures from music data, using both discrete and probabilistic methods.

In tonal music, the key refers to the predominant pitch set used in the music, and is identified by what is perceived to be the most stable tone. An early key finding algorithm by Longuet-Higgins and Steedman (1971) used shape matching on the harmonic network to determine the key. Inspired by Longuet-Higgins and Steedman's method and by interior point approaches to linear optimization, the center of effect generator (CEG) algorithm by Chew (2000) uses the three-dimensional configuration of the harmonic network, and the interior space to track the evolving tonal context. In the CEG method, a piece of music or its melody generates a sequence of centers of effect that traces a path in the interior of the array of pitches. The key at any given point in time is computed by a nearest neighbor search for the closest major or minor key representation on the respective major/minor key helices. By moving from the lattice to the interior space, the model becomes more robust to noise, and finds the key in fewer note events.

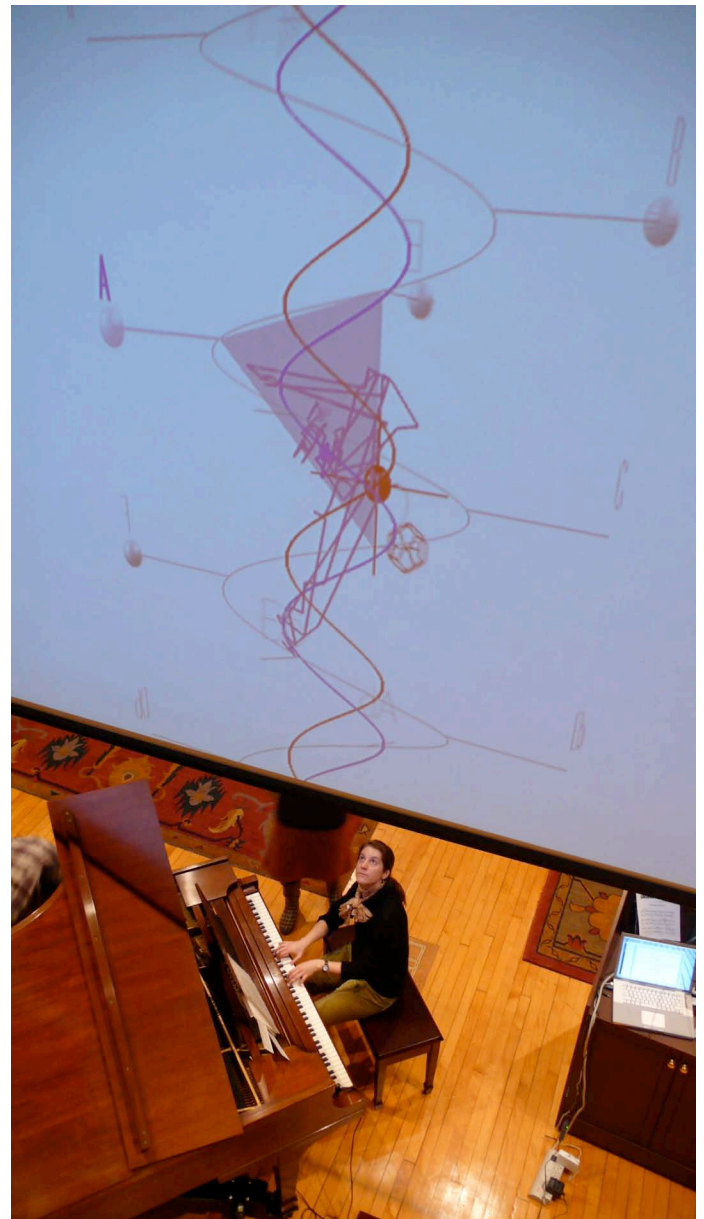
E	B	F#	C#	G#	D#	A#	E#	B#
C	G	D	A	E	B	F#	C#	G#
Ab	Eb	Bb	F	C	G	D	A	E
Fb	Cb	Gb	Db	Ab	Eb	Bb	F	C
Dbb	Abb	Ebb	Bbb	Fb	Cb	Gb	Db	Ab

The Harmonic network and Longuet-Higgins and Steedman's major (red) and minor (blue) key templates for their key finding algorithm.



Pitch class (silver), major key (red), and minor key (blue) helices in the spiral array model. The squiggly green line shows a center of effect path produced by a hypothetical segment of music, and the green box indicates the closest key. The translucent blue shape covers the convex hull of the pitches in the closest key, which happens to be a minor key.

The spiral array model and its associated tonal analysis algorithms have been implemented in the MuSA.RT (Music on the Spiral Array . Real-Time) system for interactive tonal analysis and visualization (Chew & François, 2005). Any operations researcher who has implemented a mathematical algorithm for computational use can attest that it is one



Composer Lisa Bielawa tries out the MuSA.RT music analysis and visualization system following Chew and François' presentation at the Radcliffe Gymnasium, January 16, 2008. Photo by E. Chew.

thing to design an algorithm of low computational complexity, and another to implement it so that it runs in real time. MuSA.RT is built using François' Software Architecture for Immersipresence framework (2004), which allows for the efficient processing of multiple concurrent data streams. MuSA.RT has been featured in numerous presentations, including *The Mathematics in Music* concert-conversation, which made its debut in Los Angeles, in Victoria, B.C., and in Singapore in 2007. Venues in 2008 include North Carolina State University and the Massachusetts Institute of Technology in the Eastern United States.

Apart from the pitch structures described in the previous paragraphs, music also possesses time structures. When listening to music, humans are quickly able to pick out the beat, and to tap along with it. The patterns of long and short durations along the grid of the beat produce rhythm. Periodicity in the accent patterns lead to the establishing of meter. Using the mathematical model for metrical analysis, developed at the Multimedia Laboratory headed by Guerino Mazzola (now at the University of Minnesota), and described and advanced by Anja Volk (2002), Chew, Volk, and Lee (2005) proposed a method for classifying dance music by analyzing their metrical patterns, providing an alternative to the inter-onset-interval distribution and



MIMI's international debut at the Musical Instrument Museum, Berlin, with the Seiler piano – the first MIDI grand piano, built in the 50s for TV production, May 2007. Photo by E. Chew.

autocorrelation methods proposed by Dixon, Pampalk, and Widmer (2003).

Apart from the issues of determining tonal and rhythmic contexts, which can be thought of as finding vertical structures, there are equally interesting and challenging questions with regard to the determining of horizontal structures, such as melody and voice. A number of models have been proposed for finding motivic patterns, an example of a motive is the opening four notes of Beethoven's Fifth, and for separating voices, independent melodic threads superimposed in time. Their sequential nature means that techniques inspired by DNA sequence analysis and tree structure approaches lend themselves readily to solving problems of motivic pattern discovery – see, for example, Conklin & Anagnostopoulou (2006) and Lartillot (2005). In the same strain of computational biology-inspired approaches, we proposed a contig mapping approach to voice separation by first fragmenting, then assembling, the voices that make up a polyphonic (multi-voice) composition (Chew & Wu, 2004).

Music Composition and Improvisation

One of the first applications of music and computing that comes to mind is the use of mathematical and computational models for generating music. Music composition and improvisation can often be conceived of, and modeled as, the exploration of a solution space bounded by constraints imposed by the composer or improviser. Truchet & Codognot (2004) modeled a number of problems in computer-assisted composition as constraint satisfaction problems. A few composers have also discovered operations research techniques: Tom Johnson (2004) poses composition problems to mathematicians / operations researchers, for example tracing a Hamiltonian circuit through a network of n -note chords connected to other n -note chords that share k pitches, and Daniel Schell (2002) explores the ideas of optimality in harmonic progressions.

Taking advantage of the fact that music bears similarities with language, Steedman (1996) proposed a formal grammar for generating jazz chord sequences. Computational linguistics approaches typically require large corpora of annotated data for learning, which poses numerous challenges for music data. In efforts spearheaded by Ching-Hua Chuan and Reid Swanson, we are seeking ways to generate style-specific accompaniment given only a few examples (Chuan & Chew, 2007), and to segment melodies using unsupervised techniques so as to assist in computational creativity projects in music (Swanson, Chew & Gordon, 2008).

Most systems for generating music originate in some Markov model, as exemplified by Pachet's *Continuator* (2003), which builds a variable order Markov model from an input sequence for generating

new sequences. An alternate approach, using Factor Oracles, is proposed by Assayag & Dubnov (2004) for their OMax human-machine improvisation system.

Inspired by OMax, Alexandre François led the development of MIMI – Multimodal Interaction in Musical Improvisation, which centers on a performer-centric interaction environment. MIMI's visual interface (François, Chew, and Thurmond, 2007), achieved through collaborative design, gives the user information about the current state of the system,

including the region from which musical material was being sampled for recombination, ten seconds' lead time before the sounding of the new material, and an equal amount of time to review the improvisation, and to plan future strategies during the performance. MIMI received its international debut at the Musical Instrument Museum in Berlin in May, 2007, at the International Conference on Mathematics and Computation in Music.

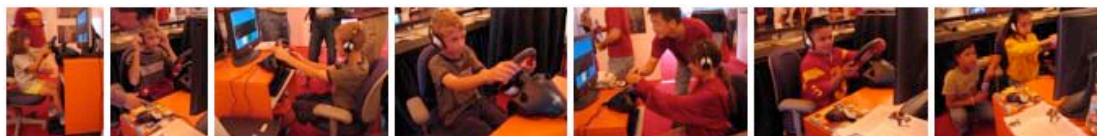
Expressive Music Performance

While the music score specifies the notes to be played, and to some degree how they should be played, it contains ambiguities the resolution for which can be influenced by a performer. Interpretation in music performance has numerous analogies in speech, where the expression with which a text is spoken, the grouping of words in a sentence, and strategic pauses can affect the meaning of, and add nuance to, the words. The devices by which a performer injects expression into a score include timing deviations, loudness modulations, and articulation (the shortening and lengthening of note durations). A performance can be viewed as a set of decisions regarding the employment of these expressive strategies, constrained by the structure of the notes in the score. Researchers have worked to understand and model the principles of expressive strategies, for example, using machine-learning tools (Widmer, 2001), or through direct observation of empirical data (Palmer, 1996, and Repp, 1998, 1999).

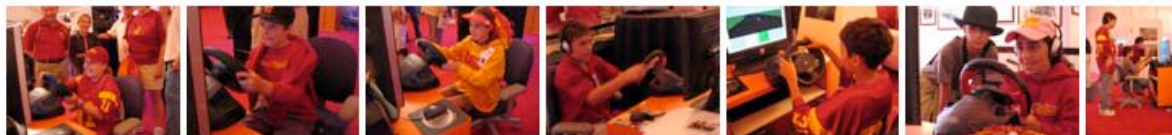
In the Expression Synthesis Project (Chew et. al., 2005, 2006) we employ an analysis-by-synthesis approach to study expressive performance. Taking the cue from motion capture for the generation of realistic animation, ESP uses the metaphor of driving for expressive performance, and a driving (wheel and pedals) interface to map car motion to tempo (speed) and amplitude in the rendering of an expressionless piece. The road is designed to guide expression: bends in the road encourage slowdowns, while straight sections promote speedups. Buttons on the wheel allow the user to change the articulation, by shortening or lengthening the notes. A virtual radius mapping strategy (Liu et. al.) ensures tempo smoothness.

A goal of ESP is to make high level decision making in expressive performance widely accessible to both experts and novices alike. The system was exhibited at the University of Southern California Festival 125 Pavilion over three days in October, 2005. It was showcased again at the National University of Singapore Techno-Arts Festival in March 2007.

One cannot discuss expression without considering its effect on the emotion perceived or experienced by the listener. In Parke, Chew, and Kyriakakis (2007ab), we present quantitative modeling, visualization, and regression analyses of the emotion perceived in film



ESP at the Festival 125 Pavilion at USC. The pavilion housed exhibits, and was visited by 10,000 visitors over three days, October 6-8, 2005. Photos by E. Chew.



E. Chew and X. Wu, 2004. "Separating Voices in Polyphonic Music: A Contig Mapping Approach," in Uffe K. Wiil (ed.): *Computer Music Modeling and Retrieval: Second Intl. Symposium, CMMR 2004, Esbjerg, Denmark, May 26-29, 2004*. Revised Papers Lecture Notes in Computer Science



with and without music, showing that perceived emotion in film with music can be reliably predicted by perceived emotion in film alone and in music alone. In Mosst's Masters thesis (2006), he models and visualizes individuals' emotion responses to music using features extracted from the music's audio. An interesting finding is that humans' responses to music differ widely, and require individualized models for accurate prediction.

Conclusion

While many examples have been given in the areas of music representation, analysis, composition/improvisation, and expressive performance, we have only begun to scratch the surface with regard to furthering knowledge about these areas of creative human activity through mathematical and computational modeling. I hope I have succeeded in demonstrating the breadth of opportunities that abound for operations researchers to make significant contributions in this fledgling field.

EC. February 6, 2008.

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