Sonification in computational physics – QCD-audio

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Background. Sonification is a scientific method for the data-dependent generation of sound. The transformation is systematic, objective and reproducible (Hermann, 2008). It is an alternative and complement to visualisation, and particularly useful in the analysis of highly complex and multi-dimensional data sets. In recent years, it emerged in different fields, pushed by the development of real time audio synthesis software and the increased consciousness of human audition. It meets the needs of new approaches to display and analyse growing amounts of data in society and science. (Kramer 1994)

Our focus of interest lies in data stemming from computational methods in physics. In the project *QCD-audio,* a continuation of the SonEnvir project (http://sonenvir.at), we study models ranging from simple statistical systems to simulations of the most fundamental particles known today, the quarks and gluons. Their behaviour is described by quantum chromodynamics – thus the name of the project.

Aims. The aims of *QCD-Audio* are, on the one hand, new insights in the data and new perceptualization methods in the field that might fuel auditory display in many scientific disciplines. Also, listening examples for didactic purposes will be provided, and the sonifications evaluated on a pragmatic and aesthetic level. On the other hand, an outcome will be a multi-channel sound installation that allows amateurs to engage in data of lattice-QCD.

In this paper an introduction to sonification is given, illustrated with a first result from QCD-audio, a cluster occurrence sonification.

Main contribution – ***Methods.*** In general, any sonification has to take into account psychoacoustic considerations as auditory scene analysis (Bregman, 1990). Different sonification techniques can be distinguished: Audification, auditory icons and earcons, parameter mapping and model-based sonification. All these methods are utilized for our sonifications.

First Results. A first result presented in this paper is a new sonification of the Ising model, a simple numerical spin model. We apply a sonification based on principles of auditory scene analysis to this system. The emergence of a recognizable gestalt (e.g., a full, natural sound) represents the emergence of critical behaviour in the system.

Implications. Systematic Musicology is an interdisciplinary field that often starts its studies on the opposite side of sonification. The first one searches, e.g., for ways to describe elements of music and sound and their implication to the listener. Sonification tries to combine these elements and build up understandable sounds. Thus, an exchange might enhance new viewpoints for either side.

Sonification allows for new viewpoints in science. It is an inherently interdisciplinary method, requiring understanding of the data, acoustics, computation and, of course, auditory perception - many sonification scientists have a personal background in music.

In systematic musicology, methods of the sciences and humanities are used to extract information out of music (Parncutt, 2007). Sonification provides an opposite perspective. Information is encoded into sound in a meaningful way for the listener. It also uses methods of the humanities, as perceptual and aesthetic issues, and of science, as psycho-acoustics and audio engineering. The advantages of sonification lie in the accurateness of the human auditory system. While visualization is usually limited to a few dimensions, auditory display can represent higher dimensional systems.

This paper introduces sonification, its methods and research community. In this context, also gestalt perception in the auditory domain is discussed as a possible overlap to musicology. Finally, an example of a first result of the research project QCD-audio is given.

Sonification

Science usually focuses on vision: in both research and teaching, the data presentation via graphs and animated graphics plays a central role. These visualizations are used as analysis tools that are preceding or following mathematical or computational treatment.

A complementary approach to visualization is *auditory display*, which has emerged in the last 20 years for different reasons: Data amounts have been increasing both in science and society. Thus new techniques of perceptualization are being explored. Furthermore, audio synthesis has only reached sufficient quality and real-time efficiency in the last decades. Finally, the study of the sense of audition under various scientific aspects became popular.

The first International Conference on Auditory Display (ICAD, www.icad.org) took place in 1992. Since then, a community established, consisting of psychologists, computer scientists, sound engineers and scientists of various fields, many having also a background in music. A recent definition was given by Hermann (2008): Sonification is the data-dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as scientific method.

Selected examples

An interesting early example of a scientific sonification is an experiment by Galileo Galilei. In order to verify his law of falling bodies Galilei used auditory information of an inclined plane (Drake, 1980). He attached little bells in quadratically increasing distances on an inclined plane, which were hit by a ball rolling down; this resulted in a completely regular rhythm.

Modern devices using auditory information include the sonar or the Geiger counter. Also earthquakes have been studied by listening. As early as 1961, it was shown that subjects were able to distinguish bomb blasts from earthquakes in the audification of seismic data (Speeth, 1961).

There are also examples of the sonification of experimental data from physics (Pereverzev et al., 1997) to microbiology (Pelling et al., 2004).

Some applications of current scientific sonification research are: EEG data from neurology (Baier et al., 2007 and http://sonenvir.at), molecular structures in chemistry (Grond, 2008) or the exploration of musical and movement aesthetics (http://embodiedgenerativemusic.org). Also musicological data was displayed and analyzed by means of sonification. This application is straightforward, as musicologists already are open-minded to sound (Ferguson & Cabrera, 2008). Finally, sonification can also be used as a basis for electronic art, as algorithmic compositions. One example is a musical piece on Magellan's first world's circumnavigation (De Campo & Dayé, 2007). It is based on sociological data provided by the UN, and allows for critical comparisons of the world's resource distributions.

From 2005 - 2007 the interdisciplinary research project *SonEnvir* - Sonification Environment - took place at the Institute of Electronic Music and Acoustics (IEM) of the University of Music and Dramatic Arts Graz. The Institute of Physics of the University of Graz supplied data stemming from models of computational physics. Also three other disciplines took part: sociology (Dayé & de Campo, 2006), neurology (de Campo & Wallisch, 2007) and signal processing and speech communication (see SonEnvir homepage).

In the follow-up project QCD-Audio, funded by the FWF Translational Research Program, the collaboration with the Institute of Physics is continued.

Figure 1. QCD-audio logo.

Methodology

In a sonification, data features are mapped to sound features. Resulting (usually abstract) sound waves have to be distinguished from what we actually hear: *gestalt perception* is the theory of our brain processing perceptual input to meaningful entities. A. Bregman (1990) discussed gestalt perception in the acoustic domain as *auditory scene analysis*. According to his theory, the task of the auditory system is the fusion and segregation of frequency components in correspondence to real-world phenomena. This is achieved at two levels: as a bottom-up process, primitive stream segregation uses the acoustic cues (frequency, timbre, timing, etc.); and as a top-down process, schema-based segregation makes use of attention and learning.

He also regards music as a scene analysis problem. Composers, in this view, have tried on the one hand to segregate auditory streams to make many different voices discernible. On the other hand, they have fused sounds of different instruments to fictional entities that have no one-to-one real-world correspondence (*chimeric sounds)*.

Stream segregation is done on a sequential (horizontal) and a parallel (vertical) level. Some of the major influencing concepts in Bregman's theory, partly derived from gestalt theory, are:

- *Proximity and similarity*: If sounds are close to each other in, e.g., frequency or timbre, they tend to be grouped together. Also spatial location is used as a cue, but not necessarily the strongest one, as, e.g., reverberation may hide the true source.
- *Common fate*: If parts of a spectrum behave similarly, for instance in their temporal on- and off-set or their modulation, they are more likely to be grouped as a sound.
- *Context*: The interaction with other sensorial input, e.g., with what we see, can change our auditory perception.
- *Spectral relations*: Natural sounds often have harmonic relations in their partials and are thus known to belong together.
- *The old-plus-new heuristic*: If two sounds following each other in time have common attributes, it can be assumed that they stem from the same source.

All these concepts have to be taken into account in designing a sonification.

Different paradigms of sonification can be distinguished. In the practical application, they are freely combined and merged, as valid standards have not yet been set up - in contrary to strong conventions in visualization.

Audification is the most basic method. The data is directly transposed in the audible domain. This can be done with a wave-like signal, e.g., bats' orientation sounds. But the data can also be much more abstract. An example is shown in Fig. 2, the numerical Potts model with 4 possible states (the system is similar to the Ising model that is described below). Each state is interpreted as a certain signal level. This is read out as in a digital-to-analog converter. The resulting sound is a rough noise. An ordered state would lead to a periodic signal.

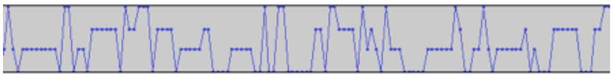

Figure 2. Audification of a 4-state Potts model.

Parameter Mapping Sonification can be used to map different data features to sound features, shown in Fig.3.

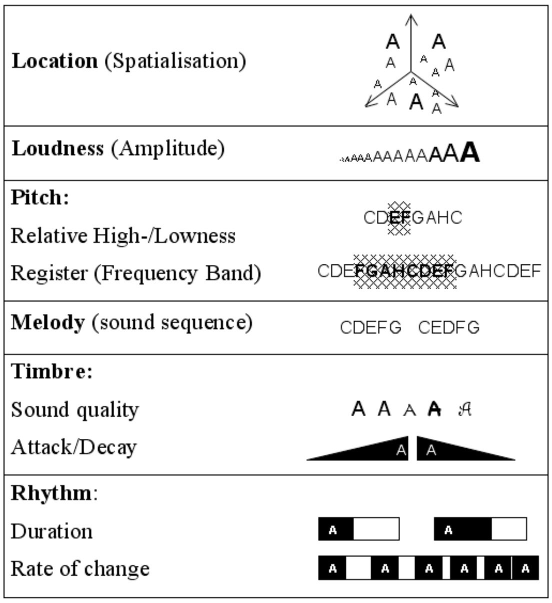

Figure 3. Parameters of sound (xSonify, 2007).

Contrary to what Fig. 3 schematically suggests parameter mapping can result in abstract sounds of different textures where the direct mapping cannot be easily traced back.

Auditory Icons and Earcons are sonifications of categorized events, often used in computer interfaces. An auditory icon is, e.g., the sound of a trashcan (see Fig. 4). Earcons are more abstract, often musical patterns. They are not as intuitive as auditory icons, thus their meaning has to be learnt by listeners in a training phase.

Figure 4. Trashcan icons. The according sounds are auditory icons.

Model-based sonification finally uses the parameters of the data to control a model generating a sound. This was developed in analogy to the real world, where objects usually do not produce sound by themselves, but can be "excited". E.g., we tap on a table to find out about its material (Hermann, 2002).

QCD-audio

In physics, sonification is relatively new, but has special advantages. The data is often high dimensional. It often treats wave phenomena, happening in time, thus any acoustic representation provides a very direct mapping. Modern methodology is often based on computational approaches, and their results have to be perceptualized to the human anyway.

Approaches to sonification in theoretical physics within SonEnvir project dealt with Constituent Quark Models (de Campo et al. 2005) and sonifications of the Dirac spectrum (e.g., de Campo et al., 2006). A smaller project dealt with the chaotic double pendulum (http://sonenvir.at).

It cannot be in the scope of this paper to go into detail with the physical interpretation of the QCD-Audio project. Very briefly, the project treats data of computational quantum chromo-dynamics. This branch of computational physics simulates quarks and gluons, the smallest particles of matter known today. The computational models are usually more than three-dimensional and data is huge. Vogt at al. (2008) give a detailed description of the project.

Spin models

In QCD-audio, we continue to work on simple numerical spin models. Sonification techniques tested on these simpler systems will then be used for highly complex data from computational physics. One first result that shall be presented here is the formation of a gestalt by taking into account principles of auditory scene analysis.

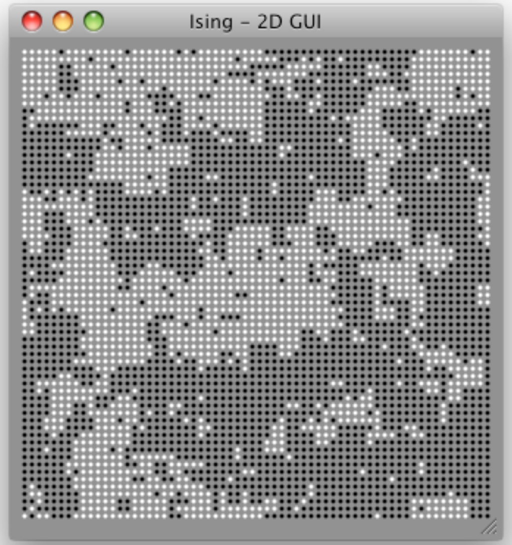

Figure 5. Visualization of Ising model at critical temperature.

Spin models describe macroscopic properties of materials (e.g., ferro-magnetism) by microscopic interactions between single elements of the material. The basic idea of spin models is to study the behavior of a complex system mirroring a real compound in a controlled way.

The Ising model is one of the oldest statistical spin models, modeling the behavior of a ferro-magnet. It is simple to implement but shows the same characteristic as more complex models. The physicist E. Ising assumed around 1925, that a ferro-magnet consists of simple atoms on a quadratic lattice. In the numeric model, at each lattice point an "atom" is located with a spin that can point in 2 possible directions (spin up or down). In the computation, on the one hand, neighboring spins try to align to each other, which is energetically more favorable. On the other hand, an overall temperature T causes random spin flips. At a critical T this process is undecided and there are clusters of spins on all orders of magnitude. A visualization of the Ising model is shown in Fig. 5.

- If the temperature is high, the spins form only small clusters and flip randomly, like Brownian noise. There is no overall magnetization.
- If the temperature is low, one spin will prevail and form a cluster of the whole lattice. The macroscopic system is now magnetic.
- The most interesting point is the critical temperature between these two states. There, the system shows suddenly a new, emergent, behavior. Clusters of all orders of magnitude appear, but no spin direction prevails over time.

During SonEnvir, the Ising model was sonified in different ways (Vogt et al., 2007). An audification allowed for a quick overview. A parameter mapping lead to granular sounds: a noisy texture for high temperatures could be distinguished from a rough sound at the phase transition and clear bleeps for low temperatures. Still, the critical temperature could not be clearly picked out. Therefore a new approach was taken.

In auditory scene analysis, everything is about emergent features, gestalts. They are fused together and are perceptually more than the sum of their parts (single frequencies). On the other side, the Ising model suddenly shows emergent behavior at the critical temperature. We wanted to link these analogies in a sonification.

We used information on the occurrence and sizes of clusters in the Ising model. This is calculated in every update. Then, a sound file is chosen that is sensitive to spectral and temporal changes – rhythmic instruments and voices, for instance. These sound files are decomposed into 24 spectral bands (see Fig. 6). Their limits are defined by the Bark scale, a psychoacoustic series of critical bands proposed by Zwicker (1961).

If there are clusters of all orders of magnitude, these bands will all play at the same time and with their original loudness – the original gestalt will appear. Any deviations are used to delay the trigger of the bands and their amplitude. They loose their common fate in

the temporal onset, and their spectral proportions, as the amplitudes of the partials are distorted. Thus the overall impression is blurred.
In the high temporal region, mostly small clusters appear, triggering only the higher parts of the spectrum of the sound file. In the other extreme, a large uniform cluster lets only the low parts through. Close to the critical region, most parts of the spectrum play, but they are staggered in their on-set times.

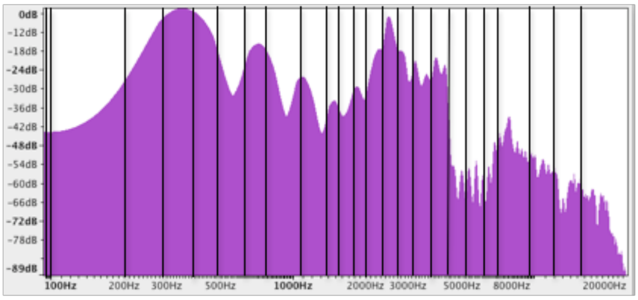

Figure 6. Spectrograph of a human singing voice on a logarithmic frequency scale. The signal is defragmented into 24 bands according to the Bark scale. Then the bands are manipulated in their on-set and their sound pressure level.

Discussion

The sonification described above has several advantages as being an illustrative example, but also shortcomings.

Firstly, the model is a statistical one that is only correct in the mean value over time. Thus a perfect configuration where all cluster sizes are equally present will not occur. Some deviations of the sound file's original gestalt will thus always be present. It was assumed in designing the sonification design that the human auditory system can learn to ignore small deviations. At the same temperature, similar configurations then lead to a similar impression.

Another problem is, that a lot of pre-processing is needed. When there is already data on the occurrence of clusters accumulated, a computational analysis can be done as well. But this is not the purpose of our work for two reasons. On the one hand, the

Ising model is one of the oldest and best-studied statistical models. No real new physical cognitions are to be discovered. A sonification can only enhance the imagination of the model and support didactics. On the other hand, the developed sonification techniques can be applied to different, more demanding models, and might lead to new insights there.

A benefit of the model is the direct mapping of the interesting characteristics to the auditory domain. The emergence of critical behavior is heard as the emergence of a clear gestalt.

Outlook

This paper gave an overview over different methods of sonification, interdisciplinary research in the field and the project QCD-audio. Auditory scene analysis was discussed, and an example for a sonification based on psychoacoustic considerations was presented.

Further research within QCD-audio is planned to examine more and more complex numerical models. Spin models can be extended in various ways: changing the possible degrees of freedom of the models and algorithms leads to new phenomena that we want to study. With this knowledge on multi-dimensional models we will start to sonify current research data of lattice quantum chromodynamics.

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For further information see www.qcd-audio.at.

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