SONIFICATION OF SIMULATIONS IN COMPUTATIONAL PHYSICS

Dissertation by

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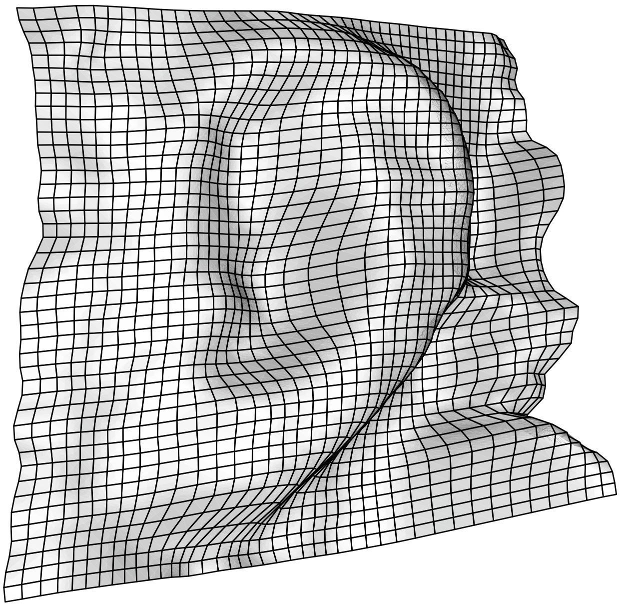

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In the order of appearance.

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The graphic on the title page stems from [Kli98].

ABSTRACT

Sonification is the *translation of information for auditory perception, excluding speech itself*. The cognitive performance of pattern recognition is striking for sound, and has too long been disregarded by the scientific mainstream. Examples of *'spontaneous sonification'* and systematic research for about 20 years have proven that sonification provides a valuable tool for the exploration of scientific data.

The data in this thesis stem from computational physics, where numerical simulations are applied to problems in physics. Prominent examples are spin models and lattice quantum field theories. The corresponding data lend themselves very well to innovative display methods: they are structured on discrete lattices, often stochastic, high-dimensional and abstract, and they provide huge amounts of data. Furthermore, they have no inherently perceptual dimension.

When designing the sonification of simulation data, one has to make decisions on three levels, both for the data and the sound model: the level of *meaning* (phenomenological; metaphoric); of *structure* (in time and space), and of *elements* (*'display units'* vs. *'gestalt units'*). The design usually proceeds as a *bottom-up* or *top-down* process.

This thesis provides a *'toolbox'* for helping in these decisions. It describes tools that have proven particularly useful in the context of simulation data. An explicit method of top-down sonification design is the *metaphoric sonification method*, which is based on expert interviews. Furthermore, qualitative and quantitative evaluation methods are presented, on the basis of which a set of *evaluation criteria* is proposed. The translation between a scientific and the sound synthesis domain is elucidated by a sonification operator. For this formalization, a *collection of notation modules* is provided.

Showcases are discussed in detail that have been developed in the interdisciplinary research projects SonEnvir and QCD-audio, during the second Science By Ear workshop and during a short-term research visit at CERN. They show diverse applications of sonification for data exploration.

ZUSAMMENFASSUNG

Sonifikation ist jedwedes *Übersetzen von Information für das Hören, mit Ausnahme der Sprache*. Das menschliche Gehör verfügt über außerordentliche kognitive Leistungen, Muster in Klängern zu erkennen; diese Fähigkeiten werden in der Wissenschaft großteils ignoriert. Beispiele von *"spontaner Sonifikation"* und die systematische Forschung der letzten 20 Jahre zeigen aber, dass Sonifikation eine Bereicherung für die Datenexploration darstellt.

Die Daten in dieser Dissertation stammen aus der Computerphysik, einer Disziplin, die numerische Lösungsstrategien auf Probleme der Physik anwendet. Prominente Beispiele sind Spinmodelle und Gitter-Quantenfeldtheorien. Die Daten eignen sich aus verschiedenen Gründen sehr für neue Darstellungsformen; sie sind auf Gittern strukturiert, oft stochastisch, hoch-dimensional und abstrakt, und die Datenmengen immens. Simulationsdaten weisen keine inherent perzeptive Dimension auf.

Bei der Entwicklung von Sonifikationen für diese Daten müssen Entscheidungen auf drei Ebenen getroffen werden, und das sowohl für das Klang- als auch für das Datenmodell: auf der *Bedeutungsebene* (phänomenologisch; metaphorisch), der *Strukturebene* (in Zeit und Raum), und der *Ebene der Elemente* (*"Darstellungs"*- vs. *"Gestalteinheiten"*). Die Entscheidungen verlaufen entweder "*bottom-up*" oder "*top-down*". Eine expliziter Ansatz für ein top-down-Design ist die *metaphoric sonification method*, die auf ExpertInneninterviews basiert. Für alle Entscheidungsebenen werden in der vorliegenden Arbeit *Werkzeuge* vorgestellt, die sich im Umgang mit Simulationsdaten als nützlich erwiesen haben. Darüber hinaus werden quantitative und qualitative Evaluierungsmethoden diskutiert, aus denen ein *Kriterienset zur Evaluierung* abgeleitet wurde. Um die Übersetzung zwischen der Wisenschaftsdomäne und der Klangsynthese zu formalisieren, wird eine Sammlung an *Notationsmodulen* eines Sonifikationsoperators zusammengestellt.

Beispiele aus den interdisziplinären Forschungsprojekten SonEnvir und QCD-audio, des 2. *Science By Ear* Workshops und eines Forschungsaufenthalts am CERN zeigen Anwendungen von Sonifikation in der Exploration von Simulationsdaten.

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Part I

BACKGROUND

1

MOTIVATION

Sonification is a rather young method of data display, and can be defined as the translation of information to auditory perception, excluding speech itself. It has emerged in the last 20 years in different domain sciences as an alternative to and complement of visualization. Its rapid growth has been driven by the development of real-time audio synthesis software and the increased awareness of the capabilities of human auditory perception. At the same time, the amounts of data in society and science have grown constantly, calling for new and better adapted approaches in data analysis and display. One prospering field is computational physics, where especially the Monte Carlo simulation approach has created categorically new data in large amounts.

Science usually focuses on vision: in both research and teaching, data presentation via graphs and animated graphics plays a central role. We accept such visual interpretation in many scientific fields as an analysis tool, which is often superior to mathematical treatment or at least concluding it. Two simple examples can illuminate the dominant role of visual perception in scientific exploration, even in the 'hard' sciences: Marsaglia [Mar95] has described tests for the quality of random number generators that are still generally valid. One of these is the parking lot test, where mappings of randomly filled arrays in a plane are plotted and visually searched for regularities. Marsaglia argues that visual tests are striking – an all-encompassing mathematical or numerical test of this task cannot be provided, as one does not know beforehand which kinds of patterns to expect. The second example is taken from CERN, the European Organization for Nuclear Research. During the 50-year history of particle detection, measurement has become highly automatized. The measurement procedure has been objectified as much as possible, but ultimately the results of this extensive process are plotted as simple histograms and interpreted by the physicists.

Generic pattern recognition is a feature requiring intelligence and is not within reach of computer algorithms today. In order to cope with the growing amounts of data, our perceptualization techniques have to be extended.

In physics and related disciplines, sonification has general benefits: State-of-the-art theories, e.g. for particle physics, are described in multi-dimensional spaces, where full visualization is not possible in any case. Due to the 'transparency' of sound, information can be displayed as superposition of many different parameters. Even if sound usually does not provide absolute values, data relations can be discerned at very high accuracy and allow for a qualitative analysis. Furthermore, many phenomena in nature are wave phenomena that evolve dynamically in time. While scientific graphs often depict physical phenomena statically, 'physical time' can persist in a sonification as listening time.

The research landscape

The first International Conference on Auditory Display (ICAD[1]) took place in 1992. Since then, a community of psychologists, computer scientists, sound engineers and scientists of various fields has been established, many having also a background in music. In the 18 years of systematic research since then, many basics of sonification have been worked out. Different methods have been defined and tested in various applications, psychoacoustical principles have been examined, a common terminology has been created and institutional resources have been built up. Nevertheless, Auditory Display (AD) is at an early stage compared to visualization, and widely used role model applications for sonification are missing. This was the starting point for two interdisciplinary projects[2], and for this thesis. The logos are depicted in Fig. 1.

The project *SonEnvir* (Sonification Environment) [son] was run at the Institute of Electronic Music and Acoustics (IEM) of the University of Music and Performing Arts Graz, in cooperation with other local universities, from 2005 to 2007. It attempted to create a generalized framework for sonification by bringing together scientists from different domains with sonification re-

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[1] www.icad.org

[2] The SonEnvir projekt was funded by Zukunftsfond Steiermark. The QCD-audio project was funded by the Austrian Science Fund, FWF, in the Translational Research Program.

Figure 1: Project logos of SonEnvir [son] and QCD-audio [qcd]

searchers. The sonified data sets were as diverse as stemming from computational physics (Baryon spectra of Constituent Quark Models [CFH^{+}05, dCDF^{+}06], sonifications of the Dirac spectrum [dCHM^{+}06]), a prototype supportive toilet for elderly or disabled people, EEG recordings of epilepsy patients [dCWHE07], data of regional election's results, or a tracked juggling performance [BGdCE07].

The follow-up project *QCD-audio* [qcd] also took place at the IEM, from 2008 to 2010, in cooperation with the Institute for Physics of the University of Graz, especially with its doctoral program in Hadron physics[3]. It was thus focussed solely on sonification of data from computational physics, mainly spin models and lattice quantum field theories. The sonification examples developed during QCD-audio are summarized in Sec. 6.

During both projects, two international workshops were organized as well. *Science By Ear* I and II followed an innovative workshop design. Interdisciplinary groups worked in parallel sessions on one data set, which allowed direct comparison of the chosen sonification strategies in the end of the workshop. Results can be found at [qcd, son] and in the Appendix, and conclusions on evaluation are drawn in this thesis (Sec. 4.4).

Overview of the thesis

The thesis is structured in 3 main parts, Background, Theory, and Showcases and Conclusion:

In Part I, (*Background*), Section 2, I briefly summarize the basics of auditory perception and give an overview of the history, aims and methods of sonification (Sec. 2.1). In addition, examples of spontaneous sonification are cited (Sec. 2.2), that give some in-

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[3] http://physik.uni-graz.at/itp/doktoratskolleg

sights into why and when sonifications are ‘intuitively’ useful (Sec. 2.3). A general discussion of sonification and physics concludes the section and links the display method (sonification) to the subject matter (computational physics) (Sec. 2.4).

Background, Section 3 starts with the Standard Model of elementary particle physics (Sec. 3.1). As a method that helps in solving parts of the Standard Model, computer simulations are discussed in Sec. 3.2, showing that mainly the Monte Carlo algorithm has introduced a new approach to physics. As concrete examples that also serve as data sets for sonification, spin models (Sec. 3.3), lattices quantum field theories (Sec. 3.4) and simulations of CERN experiments (Sec. 3.5) are introduced. In the last section (Sec. 3.6) I conclude with general remarks on the data.

In Part II, *Theory*, Section 4, I discuss steps of sonification design (Sec. 4). Meaning, structure, and elements are the 3 levels of design making. They have to be taken into account in the sound model and the data model, which both evolve during the sonification design process. This section also presents a ‘toolbox’ with tools for data organization, sound synthesis and interface designs (depicted in boxes), that have proved especially useful for each of these decisions. The design process has often been seen as a bottom-up approach starting with the basic elements in the data and the sound; but I argue that a top-down process, that shapes the metaphoric content of the sound from the beginning, can be the appropriate approach to many design problems (Sec. 4.3). Finally, quantitative and qualitative evaluation methods are discussed, and a set of criteria for the evaluation of sonifications in general is proposed (Sec. 4.4).

Theory, Section 5 deals with a general challenge in the interdisciplinary work with sonification – the communication between domain scientists and sonification experts. While this problem cannot be solved completely, because domain scientists have to get involved in sonification, e.g. by understanding auditory parameters, the recently suggested sonification operator [Roh10] opens the door to a concise formulation, linking domain science and sound synthesis (Sec. 5.2). A collection of notation modules for this task is given there as well. These notation conventions will be used for the description of the examples.

Part III of this thesis, *Showcases and Conclusion* presents examples in Sec. 6. In brief, the methodology of the implementation of the examples is explained. Then, the examples themselves are discussed: the Ising and the Potts model (Sec. 6.1.2), the XY model (Sec. 6.2), the *data listening space* – an interactive virtual listening space of quantum electrodynamics (Sec. 6.3), a sonification of topological excitations in quantum chromodynamics (Sec. 6.4), simulation data of the Time Projection Chamber at CERN (Sec. 6.5), and the clustering of center symmetry domains in SU(3) (Sec. 6.4.2).

The conclusion in Section 7 completes the thesis.

2

AUDITORY PERCEPTION AND SONIFICATION

In this chapter I introduce sonification, a method of translating information for auditory perception, excluding speech itself. While this definition as well as alternative ones will be discussed in Sec. 2.3.2, I will start with a condensed description of the impressive capabilities of human auditory perception (Sec. 2.1). Sonification owes its methodological value to these capabilites, but they make sonification design a highly non-trivial task. Then I will discuss 'spontaneous sonification' (Sec. 2.2) – examples from different scientific domains that have used sonification as an improvised tool rather than during the systematic research on the method. In Sec. 2.3, an overview of the definitions, the research community, and the methods of sonification will be given. Finally, Sec. 2.4 links sonification to computational physics, and I discuss general benefits and drawbacks of applying it to the field of physics.

2.1 AUDITORY PERCEPTION

Human auditory perception, like any cognitive process, is much more complex than at first assumed. *"This perceptual accomplishment, often taken for granted since it is such a common experience, may not be truly appreciated until one undertakes the effort to construct a machine system that matches human performance"* [WB06, p.xvii]. This citation stems from the context of attempting to model these processes numerically, at least in part. How big this effort is, can be seen in the as yet unconvincing automatized speech recognition. Also the Cocktail-Party effect reveals that perception allows to focus on something, and filters out all peripheral information accordingly (see e.g. [Aro92]).

In the following, I will briefly explain different physiological levels, with the major focus on the cognitive level of auditory perception.

The first level is the peripheral auditory system. The mechanical excitation of the eardrum due to sound waves is transmitted by the middle ear to the cochlea in the inner ear. The cochlea is a spiral organ equipped with the Basilar membrane. In the traditional view, the oscillation activates hair cells according to the specific frequency content of the sound and converts the mechanical signal into nerve impulses. For details see [ZF90].

The next level of hearing is treated by psycho-acoustics, which studies the relationship between physical stimuli and human percepts. This study involves mechanical, neurological and even cognitive factors, and is done with hearing tests. Independent perceptual features are extracted and tested. Some parameters are straightforward, even if the mapping is not linear: e.g., frequency is perceived as pitch and amplitude is perceived as loudness. The hearing area spanned by these dimensions is well-known (e.g., [ZF90]).

Other percepts are much harder to grasp, the most prominent being *timbre*. Due to its complexity, until the 1990s it was usually *"defined by what it wasn't: that which distinguishes two sounds presented in a similar manner and being equal in pitch, subjective duration, and loudness"* ([MWD+95] referring to the American Standards Association in 1960). In more recent experiments, at least three abstract perceptual dimensions have been found to span timbre space [MWD+95].

Another important phenomenon studied by psycho-acoustics is *spatial hearing*. Auditory perception uses the amplitude and phase differences between the two ears, the timbrel characteristics caused by the sound propagation in the pinna, and the interplay with other perceptual modalities to discern the location of a sound source. Because of the symmetrical position of the ears, see Fig. 2, sound sources still might be ambiguous. There are *cones of confusion* to the left and right hand side of the head. Small head movements often clarify an ambiguous localization.

The highest level of perception is the cognitive level. A. Bregman [Bre90] has described *auditory scene analysis* (ASA) as the process of the listener's cognition that segregates and groups waveforms into auditory streams that are portrayals of properties of objects in the environment. He argues that the auditory system (like all our perceptual systems) is heuristic and deduced the principles on which it possibly works. A similar approach for visual perception was followed by the *gestalt* psychologists in the early 20th century.

Bregman explains the basic problem by a metaphor. At a lakeside, two tunnels are dug to connect the lake water to small

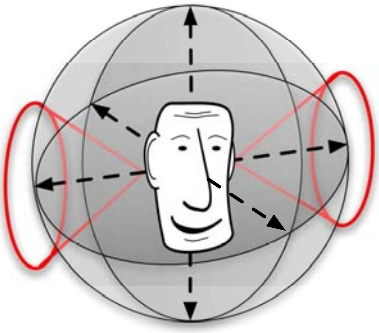

Figure 2: Symmetry axis and listening planes for listening. The cones of confusion are sketched in red.

wells. All waves in the lake that reach the wells are superimposed there. Suppose you are interested in what happens on and in the lake, but you can only observe the surface of the two wells. This sounds like a stupid idea – the oscillations seem to provide far too little information for the task. But it is an analogy to how our hearing system works, accessing only the vibration at the eardrums and still providing detailed information on the kind and location of sound sources in our environment. Thus the task of the auditory system is the segregation and fusion of frequency components in correspondence to real-world phenomena. Streams are segregated sequentially, taking into account successive parts of sound, but also in parallel, processing simultaneous information. Segregation is a pre-condition for grouping: as a bottom-up process, *primitive stream segregation* uses the acoustic cues, e.g., frequency or timing. According to Bregman, this ability is innate. As a top-down process, *schema-based segregation* makes use of attention and learning. Major cues for primitive grouping are:

- proximity in frequency and time,
- periodicity,
- continuous or smooth transition,
- on- and offset,
- amplitude and frequency modulation,
- rhythm, and
- spatial location

Most of these cues have also been found analogously in vision by *gestalt* psychologists. Some of these general principles are discussed in the following.

Figure 3: *Gestalt* principle of context. The same sign, as shown in the middle, can mean two very different things, as can be seen in the numerical or alphabetical context on the left-hand and right-hand side respectively.

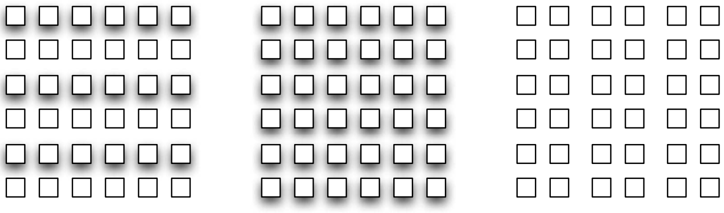

Figure 4: *Gestalt* principle of similarity and proximity. The central group shows equal squares. On the left-hand side, we perceive rows – the *similar* squares (with/without shadowing) tend to be grouped. On the right-hand side, three columns emerge, as squares that are *closer* to each other are grouped.

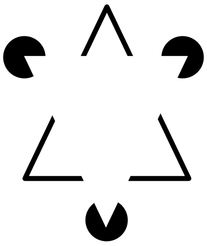

Figure 5: Kanisza triangle, showing the *gestalt* principle of good continuation and completion. An inverted white triangle is perceived, even if only lines and circle segments are plotted.

CONTEXT: A sound is interpreted depending on what was heard a moment before and even on what is heard in the moment afterwards (!). This is the *concept of context*, see Fig. 3. In addition, the interaction with other sensorial input can change our auditory perception as well. What we see, for instance, influences what we hear, as can be realized in the McGurk effect [MM76]. Context is also related to 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.

PROXIMITY AND SIMILARITY: If sounds are close to each other, e.g., in frequency or timbre, they tend to be grouped together. This is the *gestalt* principle of *proximity and similarity*, as outlined in Fig. 4.

COMMON FATE: If parts of a frequency 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. This is the principle of *common fate*, a dynamic feature of grouping.

GOOD CONTINUATION AND COMPLETION: Single, similar sounds that are interrupted by bursts of noise tend to be heard as if they continued throughout the noise. This is the principle of *good continuation and completion* and is shown in Fig. 5.

An important example of good completion in sound are the harmonic relations of the partials of natural sounds, which are known by experience to belong together.

Figure 6: Emergence in visual display. Even if there are only few cues of black and white spots, we complete the picture of a Dalmatian dog under a tree. When the object has been recognized, it is very hard *not* to see it any more. (Source: http://en.wikipedia.org/wiki/File:Emergence.jpg.)

These (and additional) principles allow the listener to retrieve information about the environment. The auditory system is constantly and sub-consciously analyzing information.

In the foreword to [WB06], Bregman poses the question: *"Can the use of sound in data displays (sonification) profit from knowledge about human's ASA?"*. The answer is clearly yes: sonification benefits from ASA knowledge. As AD has no established conventions, the perceived content of the display depends more on what we automatically hear than what we have learned (as it is the case for usual visualizations). Therefore, the emergence of *gestalts*, as illustrated in Fig. 6, has to be taken into account when designing sonifications.

2.2 EXAMPLES IN SCIENCE: 'SPONTANEOUS SONIFICATION'

There are many applications of sonifications, which were originally *not* developed in the context of sonification research. I refer to them as *'spontaneous sonifications'*. Their creators were (as far as I can see) not conscious that they were developing prototypes of a new methodology. Sound has been used in scientific exploration and monitoring precisely because it was a useful way to do so. Therefore these examples are illuminating in what type of data and which tasks make sense for AD. (Additional examples of spontaneous sonification can be found e.g. in [Kra94].)

An early but historically interesting example of spontaneous sonification is Galileo Galilei's experiment with an inclined plane. Following Drake [Dra80], it is plausible that Galilei used auditory information to verify the quadratic law of falling bodies (see Fig. 7 and [Dom02b]). When rolling down an inclined plane, a ball excites some sound making objects (in the reconstruction in Fig. 7 these are bells, in the original setting they were probably cat-gut strings). The sounding objects are attached at a quadratically increasing distance from each other. They can be adjusted until the resulting rhythm of the ball rolling down is regular. In reconstructing the experiment, Riess et al. [RHN05] found that 17th-century time measuring devices were less precise than auditory time perception. Galilei used his exact rhythmic perception for physical time measurement because he had no other way to do so.

We take a big step towards contemporary science. In 1961, Speeth [Spe61] showed that subjects were able to classify bomb

Figure 7: Device of Galileo Galilei for experiments on the law of falling bodies. This device was rebuilt at the Istituto e Museo di Storia della Scienza in Florence. ©Photo Franca Principe, IMSS, Florence.

blasts and earthquakes in the audification of seismic data. Frantti and Leverault [FL65] conducted a second test, resulting in a two-thirds chance that a trained listener would be able to identify seismic sounds correctly. The appearance of spontaneous sonification in this field came as a result of common physical principles (wave propagation in earth and in sound) and possibly via their technical matches – in the early 1960s, seismometer recordings were stored on regular audio tapes [Dom02a]. Since the early ICAD conferences, audification of seismic data has been a recurring research topic.

A similar development is known from astronomy, where data of radio and plasma wave science (RPWS) from space missions were analyzed initially as audio signals. The audification of radio-astronomy data of Jupiter led to now common scientific terms stemming from auditory descriptions, see [CSM06]. For instance, a *'whistler'* refers to a very low frequency electromagnetic radio wave which can be generated by lightning, and according to its name it is easy to imagine what it sounds like. Another example is a *'hiss'* that sounds like white noise when played through an audio system, describing an extremely low frequency wave in the plasma which is generated in the Earth's higher atmosphere. Candey et al. [CSM06] also cite that micrometeoroids impacting Voyager 2 when traversing Saturn's rings were detected using audification. These impacts were obscured in the plotted data but clearly evident acoustically as 'hailstorm' sounds. The radio waves, that are transmitted by spacecrafts exploring outer space are mostly within human hearing range. It seems that established traditions of listening to the data persists even today, as can be heard in [cas].

A compilation of spontaneous sonification in physics, using sound in detecting some new phenomenon or monitoring some data feature, cannot be complete due to the vast field. Two examples illustrate completely different phenomena but used audification because it was possible, and technically even simple, to hear them.

The first example is given in a paper by Pereverzev et al. [PLB+97], where quantum oscillations between two weakly coupled reservoirs of superfluid helium 3 (predicted decades earlier) were found by listening to the amplified raw signal: *"Owing to vibration noise in the displacement transducer, an oscilloscope trace [...] exhibits no remarkable structure suggestive of the predicted quantum oscillations. But if the electrical output of the displacement transducer is amplified and connected to audio headphones, the listener makes a most remarkable observation. As the pressure across the array relaxes to zero there is a clearly distinguishable tone smoothly drifting from high to low frequency during the transient, which lasts for several seconds. This simple observation marks the discovery of coherent quantum oscillations between weakly coupled superfluids."* [PLB+97, p. 450f].

The second example comes from CERN, where scientists listened to the beam spectra *"because there was nothing else to do and you just had to plug in headphones"* (personal interview). Parameters of accelerated particle beams, such as horizontal and vertical position in the vacuum chamber, are measured at many places. The particles are grouped in bunches that have transversal and longitudinal oscillation modes. These oscillations can be described in phase space and should not coincide with resonating areas, otherwise beam oscillations grow and the beams might get lost. The oscillation modes are measured accurately, as they are very important for keeping the beam in a stable orbit for the 27 kilometer circumference. Because the resulting transversal (β-tron) and longitudinal (synchrotron) oscillation frequencies range from a few tens of Hz to a few kHz, they are audible without any further processing. With sonification, many details of beam dynamics can be monitored by listening, in parallel to standard observations usually done in the frequency domain by performing real-time Fourier analysis of the beam signals. Sonification of beam oscillation signals from the Super Proton Synchrotron at CERN has been tried out, but no regular studies have been done. Information and soundfiles can be found at [CER05, Gas, VHP+10].

Particle detection is an important branch of experimental physics. During the long development of detectors, sound was occasionally used implicitly or explicitly in the field. Very early versions of the Geiger-Mueller counter had such a large voltage supply that a sparkover caused a bang as well. Even today, the typical Geiger counter display is auditory. Eyes-free conditions in radio-active environments have obviously huge advantages for physicists and engineers. While working on the machinery, they get otherwise unperceivable sensory information. The logic of the Geiger counter was pursued in spark chambers, where an energetic report is produced between two plates. If a spark crackles through air, a loud *bang* is produced, which is recorded by microphones and thus can be counted. These detectors were called sonic chambers, and sound was mainly an intermediate step of measurement. The sonic chamber was used in the 1960s at CERN, and one example is still shown in the main exhibition there (*Microcosm* [mic]).

Coming to life sciences, an example of spontaneous sonification can be found in microbiology. Oscillations of living (healthy or ill) and dead yeast cells can be detected with the help of an atomic force microscope (AFM) [PSG+04]. This approach combines the standard visualization practice of microbiology (even if, in this case, it is an AFM) with an auditory one, as dynamic information is better resolved by the ear. Neurology has also made some early sonification attempts, mainly conceived of as artistic performances. Already in 1965, the composer Alvin Lucier began to listen to alpha brain waves and performed the *'Music for Solo Performer'* [DBF+08]. EEG data has since also been listened to in a scientific context (e.g., [BHS07]). This example shows the difficulty of differentiating between sonification and music. Following the above argumentation, this is not an instance of spontaneous sonification, for Lucier did his work in a musical context. Facing new complex and vast amounts of data, as EEG data surely were in the 70s and still are, may be an impulse for spontaneous sonification.

What can be learned from these examples of spontaneous sonification? They have surely proved useful, as many of the examples cited above were involved in the detection of new phenomena. They have also been intuitive for the scientists involved. A detailed analysis of their various rationales would be interesting, but is impossible here due to scarce sources and the variety of scientific fields and measurement methods involved. Nevertheless, the following hints for the appearance of spontaneous sonification can be deduced from the above examples:

No other measurement device is available: this was true in the 17th century for time measurement but probably not today [Galilei]

The sound is a by-product of measurement: e.g., particle detection encountered sounds when searching for traces of sub-atomic particles [Galilei, Particle detection]

There exists a conceptual similarity between sound and the studied phenomenon, as it is a wave phenomenon anyway, or simply its dynamics are the most interesting part [astronomy, AFM]

Domain science and sound use the same technological aids, which can be used for measurement or data storage and for sound as well (this was true for tape recordings of seismographs, and it is becoming increasingly true again in the computer age) [seismology, astronomy, CERN]

An ongoing process has to be monitored, and/or the sound is used as a pastime, as there is nothing else to do when an experiment is running, and, for instance, if the state of the process cannot be directly perceived as running by any human sense [Particle detection]

In the field, there is a tradition of listening to the data [seismology, astronomy, EEG]

'Let's see' - approach, in the view of the vast amounts of new and complex data, and the absence of conventions and/or strategies [EEG]

This list may give an indication of the situations in which sonification can be useful. When implementing sonifications today in a more systematic way, these factors can be kept in mind, as they might lead to a better acceptance of sonification(s) in the domain community.

2.3 INTRODUCTION TO SONIFICATION

2.3.1 *History and definition*

Since 1992, when the first International Conference on Auditory Display (ICAD) took place and the term *sonification* was coined, AD research is being done systematically.

In a review of the first ten conferences, Kramer and Walker [KW05] found the main foci of research to be *application areas*, e.g., for blind users, general user interfaces, or sonifications as seismic audifications, *disciplinary issues*, e.g., human factors, pedagogy, sound synthesis, or perceptual psychology, *technological factors*, mainly tool building and *associations* with music, aesthetics or general design principles. A detailed overview, with a main focus on ICAD research from 1992 to 2002, can be found in [Her02]. For all conferences from 1992 - 2009, I did a simple quantitative analysis of research topics, which is visualized as a wordle in Fig. 8. It provides an overview and shows the diversity of disciplines while obviously confirming that sonification is the central research topic of the community.

Different definitions for sonification or auditory display (AD) have been suggested. One of the first and still the most widespread was given by Kramer et al.: *"Sonification is the use of non-speech audio to convey information"* [Kra99]. This explanation is very open in terms of the information that can be conveyed, including practically any sound that is nonspeech. Sometimes the definition is extended by adding *"or perceptualize data"* [wikf]. This extension lays the focus on the perceptual side and points to scientific *data* instead of to general *information* that can be used. The definition of Kramer et al. has been criticized for its imprecision on the one hand and for the exclusion of speech on the other [Her02] – human perception of speech is so refined that it would be unreasonable not to use it for AD, therefore elements of speech are used in sonifications as well.

Building on the work of Scaletti [Kra94], Barrass [Bar97] defines *auditory information design* as *"the design of sounds to support an information processing activity"*. This phrasing makes the

Figure 8: Wordle of ICAD research topics (1992 to 2009). Titles, abstracts and keywords of all ICAD papers were analyzed (data source: www.icad.org/biblio). The most frequent words were extracted for the visualization, as for instance *'sound(s)'* or *'audio'*. Font size reflects the number of the occurrence of the word proportionally. Grey-scaling has no implications for the interpretation of the data but allows for better readability. (Compiled with the help of http://manyeyes.alphaworks.ibm.com)

design component central, and subsumes the conveying and perception of information. Without explicitly referring to it, this definition also encompasses sonification.

Hermann [Her08] recently suggested a stricter definition: *"A technique that uses data as input, and generates sound signals (eventually in response to optional additional excitation or triggering) may be called sonification, if and only if: C1 –The sound reflects objective properties or relations in the input data. C2 – The transformation is systematic. C3 – The sonification is reproducible. and C4 – The system can intentionally be used with different data, and also be used in repetition with the same data."*

In this definition, criterion C4 is problematic. Most sonifications are developed for a very special use, as general conventions have yet to be developed. These sonifications have a strong focus on a special data set and cannot easily be used with different data structures or types. As for C1 to C3, the principles of objectivity, systematics and reproducibility can be implicitly assumed wherever sonification is used as a scientific method. Furthermore, the notion of reproducibility has changed from an exact repetition of experiment to the case where results can only be formulated in a probability statement.

A map of organized sound, subdivided into functional sounds, music and media arts, and sonification based on Hermann [Her08, p. 2] is depicted in Fig. 9. *Organized sounds* are shaped by intention in their occurrence or structure, excluding, e.g., environmental sounds. *Functional sounds* serve a certain function or purpose. Many functional sounds, as a telephone bell or an alarm are sonifications – some are not. Hermann refers to a mosquito device, which is intended to drive teenagers away from public spaces by emitting irritating high frequency signals. This is certainly a functional sound but neither music nor sonification. *Sonification* also overlaps with music and media arts. Hermann demands that the composer provides precise definitions of the data and the transformation (criterion C2) and that the sonification is intended to be used with different data (C4). Thus he tries to distinguish most sonifications from music and media arts. In Fig. 9, I have slightly modified his map of sounds in terms of proportions, showing sonification with equal backgrounds of functional sounds and music and media arts because clear discrimination between these categories is not always possible. Many music pieces are based on sonification.[1] The appropriateness of the term *'music'* as opposed to sonification can often only be determined from the *context and goal* rather than from the definition. Vickers and Hogg argue that *"whether we hear a sonification or a piece of music is simply a matter of perspective."*[VH06, p. 214]

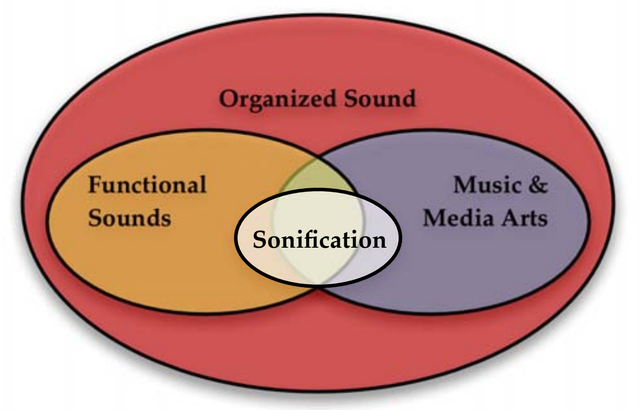

Figure 9: Map of organized sound (slightly modified following [Her08]).

Within the context of this thesis, sonification is regarded as a *method of translating information for auditory perception, excluding speech itself*[2]. It is applied in technical devices and machines, mostly for monitoring tasks and human-computer interaction, and in research for monitoring and exploration tasks. Sonification research and domain research are intertwined, as the first assists the latter, and domain research is inspired by sonification.

2.3.2 *Aims*

Different applications of sonification aim at different users and tasks. As for any perceptualisation method, the following aims can be stated:

Sonification is an alternative or complementary approach to (mainly) visualization in *data representation*. It can be used for scientific data exploration, didactic purposes, to sup-

---

[1] A collection of art pieces that can be regarded as sonifications is given by [DBF+08]. The International Conference on Auditory Display (ICAD) also hosts a concert where the winning pieces of a competition of sonification-based compositions are presented.

[2] I am grateful to Julian Rohrhuber for his suggestions regarding this definition!

port visually impaired people or to form multi-modal displays.

Sonification is used as an information channel in *monitoring processes*. Often the ear leads the eye after sudden changes in the soundscape, e.g., an alarm. Changes in constant noises are easily detected, as for instance the starting and stopping of the computer fan. At the same time, one may gradually become unaware of uniform noises.

Used as a non-expert application, due to the affective nature of sound, sonification is highly apt for *knowledge transfer to a general public*. Outreach becomes more and more important not only for scientific projects. Sonification provides an unconventional tool for addressing a society already overwhelmed by visual information. Media arts in general and electronic music in particular use sonification.

2.3.3 *Benefits and limitations*

Understanding auditory perception is the basis for sonification, as discussed in Sec. 2.1. Despite its general advantages, it also has drawbacks in comparison to other perceptualization modalities. The following listing mainly follows Hermann [Her02] and Kramer [Kra94].

+ Hearing is an additional sensory input channel that *does not physically interfere* with seeing. It makes AD perfectly suited for distance-monitoring, while the eyes are free for other tasks. Also, AD enhances generally the realism of a multi-modal display, e.g. in virtual environments.
+ The ear is very *sensitive to rhythm and pitch*. The high temporal resolution can be seen when comparing the sampling rate of films (24 frames per second) to audio (44100 samples per second) in order to create the illusion of continuity. The perceived frequency bandwidth in audio encompasses around 10 octaves (~20 Hz to 20 kHz), while in vision we see approximately one 'octave' (~380 to 780 nm).
+ Due to auditory scene analysis, we are able to listen to *more than one auditory stream in parallel*. This is made possible by the inherently transparent nature of sound and by the for-

mation of holistic listening that allows perceiving complex sound patterns as a whole.

+ *Attention* can either be drawn to acoustic signals, or they are assigned low priority while one remains aware of the sound. This is called *backgrounding* and is very useful in monitoring tasks.
+ *The identification of sounds*, such as voices or melodies, is a basic human skill. Auditory memory allows us to recognize sonic structures that have been heard before.

On the other hand, AD also has its militations:

– Some auditory variables exhibit *low resolution*, e.g., timbre and spatial localization.

– There are *no absolute values* in AD. Absolute pitch, the ability to assign names of notes to the perceived pitch, is rare. Auditory legends are largely missing as they overlap the data display and might confuse the listener more than they help.

– Many auditory *parameters are perceptually not orthogonal* to each other. One well-known psychophysical relationship is that between perceived amplitude and pitch changes. Many other dependences of percepts are much harder to assess as they cannot be directly linked to a single dimension of physical stimuli (as, e.g., timbre).

– Potentially, sounds tend to be *annoying*, as we cannot 'close' our ears and we are aesthetically demanding in our listening, perhaps due to our adaption to music. Sound interferes with verbal communication, which poses a problem whenever several people use an AD together.

– There is *no persistence* and thus no print-out in AD. Time is an inherent property of sound. This can be an advantage when a display is explored intensively, but a disadvantage for classical publication and demonstration facilities. There is no 'instantaneous' overview, as is suggested in vision (nota bene: visual perception is actually sequential).

– *Cultural biases* are probably the biggest challenge to AD. Event though abilities of humans to interpret sound can be trained, visualization is much better positioned in (early) education and society and for all methodologies in science. Seeing is valued more by our society than hearing, as suggested by the rich supply of visual metaphors in language. In English, *'I see'* is used to express comprehension or believe: *'I believe it when I see it'*. *Hearsay* evidence can be rejected, while *eyewitness* testimony is accepted. (These and more examples are discussed in [Dun04]; some German examples can be found in [Dom02b]).

– Finally, *working premises* also have to be changed in practical terms. For instance, high fidelity audio equipment is missing in most workplaces, and open-plan offices are not suitable for people working with sound.

The listing of benefits and limitations of AD leads to the conclusion that some information is better suited to AD while other information is better suited to visual display (or some other perception channel). It is one of the goals of this thesis to show which aspects of numerical physics are suitable for sonification. But even if such suitability is found, the cultural bias against AD must be overcome.

2.3.4 *Sonification methods*

A few now 'classical' sonification methods have been developed. These can be categorized as event-based and continuous methods, see Fig. 10.

AUDITORY ICONS, EARCONS, SPEARCONS: Auditory icons, earcons and spearcons are event-based approaches, short sounds that are used lexically, e.g. to denote specific items in the computer. Their meaning can be intuitive, as they are deduced from real world sounds, as is the case with auditory icons. The trashcan sound in different computer platforms is an example of an auditory icon. (For Apple, e.g., it sounds like rumpling a sheet of paper.) By contrast, earcons consist of short melodic and rhythmic patterns which have to be learned (for an application with tool palettes see [BC05, Bre05]). Finally, spearcons are based on spoken words that are shortened [WNL06].

AUDIFICATION: Audification is the mapping of any data to a one-dimensional data stream that can be listened to. A very simple example of audification is the shifting of the ultrasound communication of bats to the (human) auditory

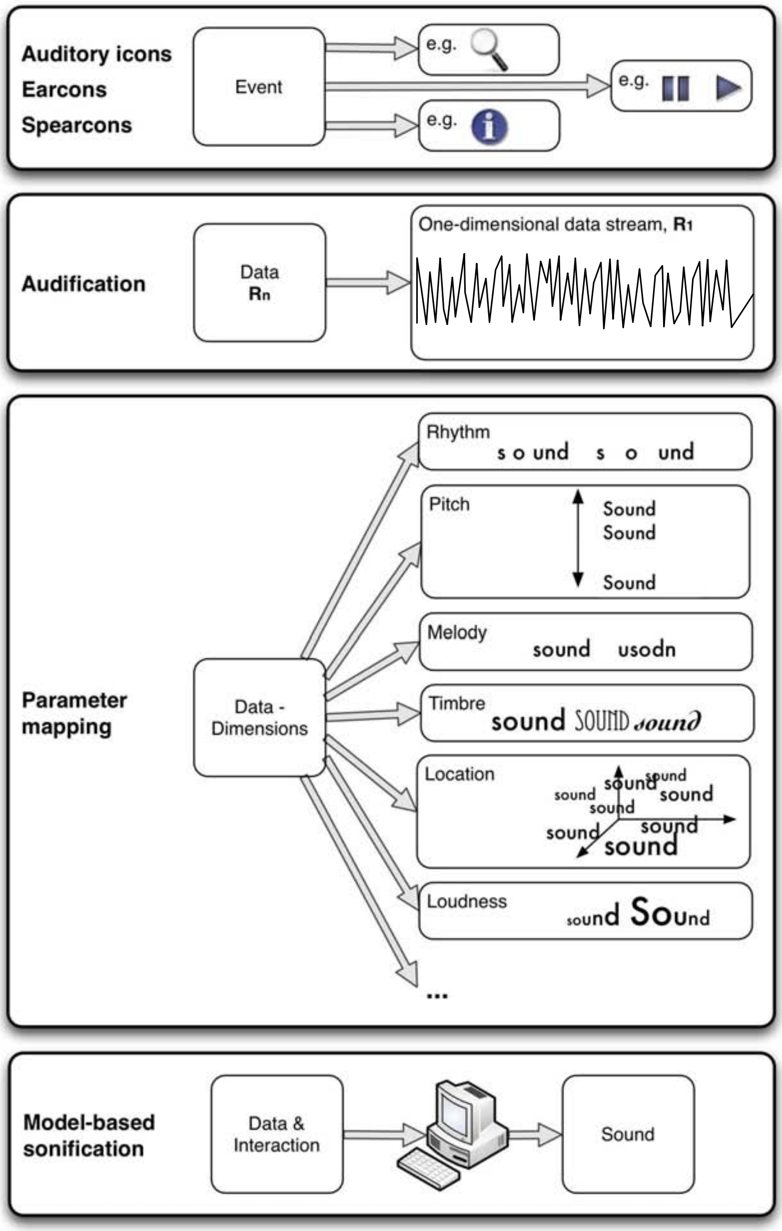

Figure 10: Schematic plot of methods of continuous sonification. Audification, Parameter mapping and model-based sonifications are shown. The figure does not include event-based methods, such as earcons, auditory icons and spearcons. (Partly based on: http://spdf.gsfc.nasa.gov/research/sonification.)

domain. Data that is far more abstract and is not a priori in a one-dimensional stream can also be audified. Reading the 0 or 1 values of the Ising model line-by-line gives an audification. Periodicities or outliners from a trend are easily detected with this method, or else a specific noise sound is created. Audification is very efficient AD due to the high frequency bandwidth of the ear and thus the high time compression that can be achieved.

PARAMETER MAPPING: Parameter mapping links different dimensions of the data to parameters of sound. It has been probably the most widely used sonification method in the context of data exploration. The amount of available parameters is a clear benefit of AD, as rhythm, pitch, loudness, location, timbre and other parameters can be used as sound dimensions. Still, it has to be taken into account that most parameters are not completely independent of each other on a perceptual level (e.g., loudness and pitch affect each other in our perception). This and other limitations of parameter mapping have been discussed in [Her02].

MODEL-BASED SONIFICATION: Hermann [Her02] developed the concept of model-based sonification. This approach is inherently interactive, because a user explores the data. The main idea follows the real-world analogy where objects are, e.g., struck or shaken to get information about their composition or content. The sound provides information about the object, as its parameters depend on the data. The process of ‘knocking’ or ‘shaking’ is the interaction with an implemented model.

Many sonifications are hard to classify as rigorously as the categories above suggest. Usually, the methods are mixed and adjusted according to the data and task in question.

2.4 SONIFICATION AND PHYSICS

Some general remarks on the application of sonification to physics conclude this introduction.

As we have seen from spontaneous sonification (Sec. 2.2), it is intuitive to use sonification for the display of wave phenomena due to their conceptual equivalence. Many if not most data of physics are dynamic, and sonification provides very direct mapping. Time in the data is used as play-back time in the sonification. While standard scientific graphs plot time on one axis, this is not necessary in a sonification, where physical time persists as *sonification time*.

Modern particle physics is usually described in a *4d framework*. This makes it hard to visualize completely. (Even if we are dealing with a 3d space evolving in time, a computer animation can only show the surface of the data.) In sonification, many dimensions can be displayed in parallel, e.g. with parameter mapping. Multi-modal and interactive displays provide obvious benefits for the handling of dimensions.

In this thesis, the focus is placed on data from numerical simulations. As discussed in Sec. 3.2.1, results from computer simulations are unperceivable if not displayed by an interface. They 'live' in the computer on abstract lattices. Often, only the results, aggregated observables, are displayed for interpretation. Sonification can give direct insights into the simulations.

Many projects can be found at the border between science and the arts that use sonification of physical data for exploratory and artistic purposes. For instance, algorithmic composition tools are based on physical event generation as for example the fission model [Bok04] or when scientific experiments become music (e.g. the composition *50 Particles*, [Stu01]). In the AlloSphere, a 3-story high sphere for virtual environments, theoretical physics data can be explored [HKMA09]. An example of a scientific rather than an artistic project is the sonification of the cooling of quark-gluon plasma by A. Móscy et al. [MSD].

Sonification aims to be a complementary tool to classical analytical methods in computational physics. A new 'view'point always opens up the possibilities for new hypotheses.

3

COMPUTATIONAL PHYSICS

The examples in this thesis are sonifications of data from computational physics. This field, for a physics discipline rather young, profits from the growing capabilities of computers. Especially models give us insights into systems that are otherwise more, or even too complex to solve, such as spin models (Sec. 3.3), lattice quantum field theories (Sec. 3.4), and even simulations of detector data at CERN (Sec. 3.5). These models are Monte Carlo simulations, based on stochastic algorithms; according to the 'stochasticists', they are even said to reflect the true face of nature (Sec. 3.3).

What is known of the most basic building blocks of Nature is summarized in the Standard Model of particle physics, a success story of modern science, despite many unanswered fundamental questions (Sec. 3.1).

3.1 THE STANDARD MODEL OF PARTICLE PHYSICS

The basic subject and motivation behind all examples in this thesis is the Standard Model of particle physics. It describes successfully three of the four known interaction types (the strong, the weak, and the electromagnetic force), and the elementary particles that interact with each other by exchanging force-mediating particles. All visible matter in the universe is constituted of particles as described by the Standard Model.

A schematic plot of the Standard Model is shown in Fig. 3.1. In mathematical terms, the Standard Model is a gauge theory of strong interaction (SU(3)) and electroweak (SU(2)xU(1)) interaction, thus of SU(3)xSU(2)xU(1) (Sec. 3.4). Elementary matter particles are *fermions*, spin $1/2$ particles: there are six different quarks and six leptons, both for matter and (anti-quarks and anti-leptons) for anti-matter, in three 'generations' which group together particles at different mass scales. Everyday matter consists of *up* and *down* quarks (forming protons and neutrons) and the electrons.

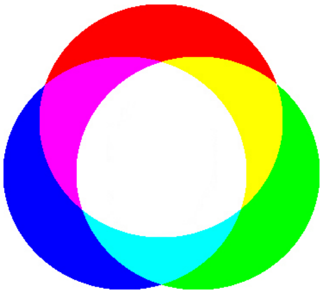

Figure 11: QCD color neutrality – the overlap of the three primary colors gives white light.

Force-mediating particles are *bosons*, particles with integer spin. Photons mediate electro-magnetic force, and are described by quantum electrodynamics (QED). Gluons 'glue' the quarks together, mediating the strong interaction force. Gluons also interact among themselves, which due to non-linearities makes the underlying theory, quantum chromodynamics (QCD), much harder to solve than QED. Both QED and QCD are quantum field theories, QFTs. *Gauge bosons* (W^-, its antiparticle W^+, and Z) are responsible for the electroweak interaction between quarks and leptons. The famous Higgs boson has been theoretically predicted but not yet observed. It is needed to explain the masses of the electroweak gauge bosons. The Large Hadron Collider at CERN, launched in 2009, is constructed such that it would be able to detect the Higgs particle.

Quarks interact via the strong force, and have a so-called *color charge*. However, they cannot be observed freely – only color neutral objects can be observed. (Color here is defined in analogy to additive colors, where the combination of the primary colors gives white light, see Fig. 3.1). The color-neutral particles are firstly baryons, consisting of three quarks carrying the primary colors, secondly – respectively – anti-baryons, and thirdly mesons, consisting of a colored quark and an anti-colored antiquark. Baryons and mesons are both *hadrons*, held together by the strong force, as opposed to elementary *leptons* and *bosons*. There are hundreds of particles which are constituted by different quarks, therefore often referred to as a *'particle zoo'*.

The Standard Model is not the 'Theory of Everything', as some basic questions remain to be answered. Because quantum field theory cannot be reconciled with general relativity, *gravitation is not included* in the Standard Model. Furthermore, it does not explain *why so many constants* are needed, particle masses and coupling constants. Theoretical physicists are searching for a more 'beautiful' theory that can be reduced to a few constants and equations (Dirac exaggerated this attitude in the 1930s by saying that *"it is more important to have beauty in one's equations than to have them fit [the] experiment."* [Dir]). Also the *hierarchy problem*, the fact that the Standard Model exhibits (mass/ energy-) constants at completely different scales, is thus seen as a drawback of the theory [wikg]. Still, the Standard Model is a very powerful theory that predicted many particles and their properties correctly before they were measured.

QFTs are highly complicated theories that can be simulated, as is discussed in the following sections.

3.2 NUMERICAL SIMULATIONS IN PHYSICS

3.2.1 *The 'tertium quid'*

"[W]ithout the computer-based simulation, the material culture of late-twentieth-century microphysics is not merely inconvenienced - it does not exist." [Gal97, p. 689] This harsh statement by Peter Galison, Professor in History of Science and Physics at Harvard University, emphasizes the importance of computers and simulations for today's physics. As this thesis deals with simulation data, I want to discuss the novelty of the computational approach in physics.

Computers, and the Monte Carlo (MC) simulation method that will be discussed in Sec. 3.2.2, had major break-throughs during and after World War II. The basics of the MC method were developed by Stanislaw Ulam and John von Neumann in the context of the development of the H-bomb. The method was first published in detail by Nicholas Metropolis and Ulam in 1949 [MU49]. It is a class of algorithms which rely on repeated random sampling to compute their results. They are usually applied if a deterministic algorithm or an analytic solution is not feasible [wikd]. From the beginning, practicability was a major influence in the rapid spreading of the simulation techniques, and, evidently, computers in general. Already von Neumann made a rough estimate of time-saving capability of the computer in 1949 [Gal97]. Hand calculations of one of the first large MC simulations would have taken a human computer 211 *"woman*

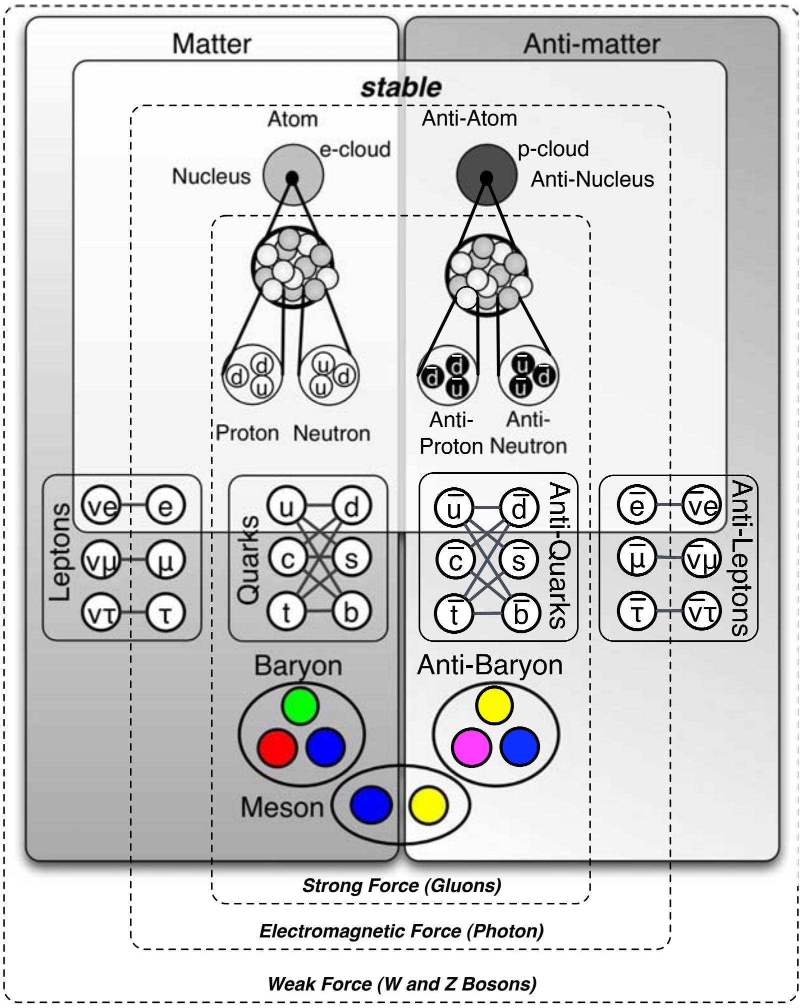

Figure 12: Overview of the particles in the Standard Model. They are sorted in three generations. Color neutral observables are baryons, consisting of three quarks, respectively anti-baryons and mesons consisting of a quark and an anti-quark. The three basic interactions of the Standard Model act on different particles. The following abbreviations are used:
leptons: ν_e - electron neutrino, ν_μ - muon neutrino, ν_τ - taon neutrino, e - electron, μ - muon, τ - taon;
quarks: u - up, d - down, c - charm, s - strange, t - top, b - bottom. Based on [Wal].

years"[1], while the ENIAC, the Electronic Numerical Integrator and Computer, at the time required the same number of hours.

Simulations became what Galison calls a *trading zone* – scientists and co-workers from different domains are united by a common 'dialect' (he calls it *pidgin*, or, if wider spread, *creole*). Their activities are locally, but not globally, coordinated. The *lingua franca* of the MC technique was soon shared by extremely diverse disciplines, that have little in common except the computational solution approach: thermonuclear weapons, weather prediction, particle interactions, number & probability theory, industrial chemistry, and quantum mechanics; and many more recent disciplines.

Elements of the 'Monte Carlo trading zone' were *(pseudo) randomness*, *model*, and *generation of data*, and these key features are briefly discussed as follows:

The simulations are based on *pseudo random numbers*, often called just random numbers, expanding the original meaning of the term because real random numbers could not be numerically generated. They were a major cause of misgivings vis-à-vis the new method, but *"to workers in these various domains, the most astonishing feature of these simulations was that they worked as well as they did."* [Gal97, p. 690] This attitude can still be found today: *"However dubious [the Monte Carlo method] may seem at first sight, in actual calculations the method works amazingly well"* [GL10, p. 74].

Other key terms are *model*, referring to a theoretical entity, and *generation of data*, which rather points to an experimental practice – a duality often found in simulation descriptions. The open question of whether simulation is a theoretical or an experimental approach is evident already in the very first MC paper, and reads ironically: *"These experiments will of course be performed not with any physical apparatus, but theoretically"* [MU49, p. 337]. MC simulation is still often regarded as 'just' a technique, but this is too short-sighted according to Galison. The 'technique' launched a metaphysical discussion about whether it reflects the true face of nature or is a stupid trial and error procedure. Gallison calls the idea that MC models actually correspond to nature *stochasticism*, as opposed to the *platonic* view. *"To the platonist, the stochasticist has merely developed another approximation method, useful per-*

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[1] Before the term was used for the machine, 'computers' were humans, usually females, employed for repetitive calculation tasks.

haps but not more. To the stochasticist, the platonist has interposed an unnecessary conceptual entity (the analytic continuum equation) between our understanding and nature – [in the stochastic view] the Monte Carlo [...] offers a direct gaze into the face of nature" [Gal97, p. 743]. The dispute shows that simulations have introduced something new to physics. On the one hand, they are scale-free and operate in phase space as well as in real space, like theoretical physics does. All parameters can be completely controlled. On the other hand, the physicist uses simulations to draw data samples, search for a signal against a noise background, and calculate error estimations, as experimental physicists do. Galison argues that the MC method is best seen as a *tertium quid*, a new counterpart to the traditional classification in theory and experimentation, see Fig. 13.

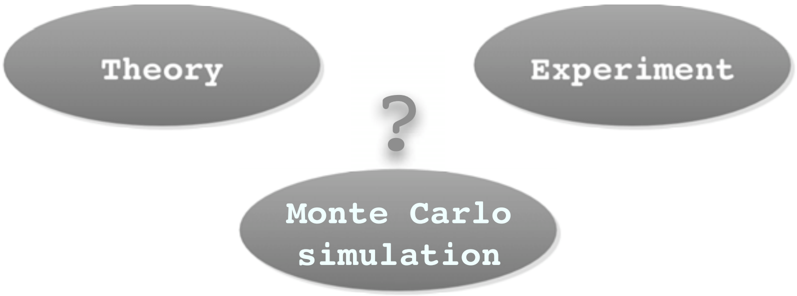


Figure 13: While the classical two-fold of physics in theory and experiment is clear, the Monte Carlo simulation can hardly be classified as one of the two, and is more than a simple 'technique'. [Gal97]

Harvey Gould and Jan Tobochnik argue along the same line in a now standard book of computational simulation methods [GTC02]. They view simulations as laboratory experiments, the physical apparatus is replaced by the computer program, the calibration by program testing, and measurement by computation. The success of simulations in physics can partly be explained by the non-linearity of natural phenomena; while analytic tools (such as differential calculus) are best suited to linear problems, simulations can handle non-linear problems as well. Moreover, systems with many degrees of freedom can easily be simulated. The authors clearly adhere to the stochastic view and argue that the ways of thinking about physical systems have changed due to computers: *"Asking the question, 'How can I formulate the problem on a computer?' has led to new formulations of physical laws and* *to the realization that it is both practical and natural to express scientific laws as rules for a computer rather than in terms of differential equations"* [GTC02, p.4].

The results of computer simulations are unperceivable if not displayed by an interface. They are 'born' in the computer from raw data 'living' on abstract lattices. These raw data are often complex and numerous. Therefore, only the results, aggregated observables, are displayed for interpretation. (Of course, attempts to visualize high dimensional data have been made, e.g. in quantum mechanics [Tha00].)

Gould & Tobochnik point to the importance of graphics: *"[...] as the computer plays an increasing role in our understanding of physical phenomena, the visual representation of complex numerical results will become even more important. [...] For example, what does a sine function mean to you? We suspect that your answer is not the series,* $\sin x = x - x^3/3! + x^5/5! + ...$*, but rather a periodic, constant amplitude graph [...]. What is important is the visualization of the form of the function"* [GTC02, p.5]. Another example is random number generators. Their quality strongly influenced the quality of the results of an MC simulation, and was not guaranteed in particular in the early simulation tests. *"The lesson many people drew was that tests alone had their limits: better plot and look than pile arbitrary tests one on the other"* [Gal97, p. 704].

Any simulation results are ultimately presented as visualizations. This can be a direct plot of data with often numerous 2d slices of the data, or the graphics of an aggregated outcome, as for example the histograms of particle detection in CERN. Physicists are very experienced in generating and manipulating graphics for finding evidence to confirm of refute hypotheses, or to gain an idea of the data. In visualization, many conventions exist that help to objectify the perceptualization process. Still, *no* visualization is *objective*, but implies human pattern recognition with psychological factors involved. In efforts towards an objective physics, the virtue of pattern recognition is also seen as problem. At CERN in the 1960s, measurement data consisting of 'bumps', indicating new particles, were compared to MC-generated graphics in a blind test. Only when the physicists rated the real measurement data as 'bumpier' than any of the random data, the results were published [Gal97]. Current experimentation cycles at CERN are trying to objectify their results by ruling out the human factor of seeing 'what one wants to see'.

After extensive simulation of the whole detector with random data, the real machine is calibrated on the basis of this knowledge. When then real data from a collision is measured, the procedure of data taking and plot production is *not* changed any more, thus any human manipulation towards a more 'bumpier' picture is suppressed.[2] Still – even in this case the final result of the measurement is a visualization, e.g. a histogram, and it depends on human pattern recognition abilities.

I argued in Sec. 2.3.3 that visualization is not the only, and in some cases also not the best way to display. A sine can easily be recognized when heard (assuming that the listener has learned what a sine sounds like). Sonfication is a logical continuation of the necessity of human-computer interface in physical simulation. The abstractness and multi-dimensionality of the data, as well as all of the factors cited in Sec. 2.4, make simulations of physical systems especially suitable for sonification.

3.2.2 *The Monte Carlo simulation*

The historical appearance of MC simulation was briefly discussed above. In this section, I focus on essential parts of the simulation as applied in lattice quantum field theories and spin models, following [GL10] and [GTC02].

Spin models stem from statistical mechanics, but are often considered as simple test cases for lattice quantum models, as their algorithmic structure corresponds to those of the latter (Sec. 3.4). In a spin system, a given lattice of dimensionality d is filled with data values – the spins s_n. The simplest case is the Ising model with only two possible spin states (Sec. 3.3.1). For such a model in $d=4$ dimensions and with rather few sites $N^4 = 16^4$, there are $2^{N^4} = 2^{65,536} \approx 10^{19,728}$ (!) different spin configurations possible. The probability, that the system is found in one of these configurations is the Boltzmann factor, $P[s]$, depending on the energy of the system, $H[s]$, the inverse temperature, $\beta = 1/k_B T$ with the Boltzmann constant, k_B, and temperature, T:

$$P[s] = \frac{1}{Z} e^{-\beta H[s]} \tag{3.1}$$

---

[2] Werner Riegler, technical coordinator of the Time Projection Chamber, CERN, in a personal interview in Nov. 2009.

Z, the partition function, is a sum over all possible spin configurations {s}:

$$Z = \sum_{\{s\}} e^{-\beta H[s]} \tag{3.2}$$

In addition, the calculation of the expectation value of an *observable* O sums the whole set of configurations:

$$\langle O \rangle = \frac{1}{Z} \sum_{\{s\}} e^{-\beta H[s]} O[s] \tag{3.3}$$

Because the expectation value is what can be measured in experiments, it is necessary to get macroscopic information from a microscopic system. But such a sum is incalculable – as we have seen above for a simple and small system, the number of possible configurations is incredibly huge. A method is needed that operates with only a few configurations on a statistical basis, like an opinion poll that draws only a sample of the whole society. An MC simulation is a trading zone linking social science to computer physics.

Derived from probability theory, the sum, Eq. (3.3), can be approximated by choosing random configurations. This is *simple sampling*. As the configurations have a weight factor (the Boltzmann factor, P[S]), they do not have all the same probability, and completely randomly chosen configurations typically have an extremely small weight. Therefore, *importance sampling* is needed, where those configurations are considered that have a larger weight.

In most applications of the MC method, the s_n are chosen according to the probability distribution density in Eq. (3.4), the *Gibbs measure*,

$$dp[s] = \frac{e^{-\beta H[s]}}{Z}. \tag{3.4}$$

The expectation of the observable now becomes a manageable sum over N observables of the sampled configurations s_n, Eq. (3.5).

$$< O >= \lim_{N \to \infty} \sum_{n=1}^{N} O[s_n] \tag{3.5}$$

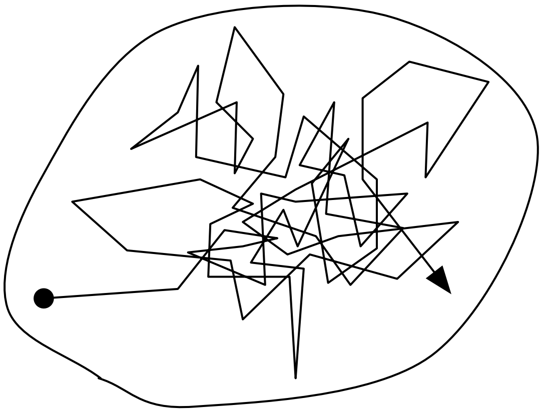


Figure 14: A Markov chain in a configuration space. In the space of all possible configurations of a given system, the Markov chain moves randomly. It is able to visit any of the configurations, but visits configurations with higher weights more often. In this schematic plot these are in the center. [GL10]

To find the configurations s_n with the probability distribution of Eq. (3.4), *Markov chains* are used, as schematically shown in Fig. 14.

The s_n are subsequently generated from each other, and the chain is able to access all configurations in a finite number of steps (condition of *strong ergodicity*), but visits configurations with greater probabilities more often. It is started at an arbitrary chosen configuration s. The probability that it goes to the configuration s' is given by the transition matrix $T(s'|s)$. The *balance equation*, Eq. (3.6), guarantees that it is equally probable to go from any $s \to s'$ as it is to go from $s' \to s$, such that there are no sources or sinks of probability.

$$\sum_s T(s'|s)P(s) \overset{!}{=} \sum_s T(s|s')P(s') \tag{3.6}$$

A sufficient condition for solving Eq. (3.6) is the *detailed balance condition*, which demands that the equality holds term-wise:

$$T(s'|s)P(s) = T(s|s')P(s'). \tag{3.7}$$

The first MC algorithm building on this condition is the *Metropolis algorithm*, the prototype for many MC simulations. Therefore, the terms MC and Metropolis algorithm are often used synonymously. A Metropolis MC consists of the following steps:

0. Establish a random configuration.
1. Choose a random candidate configuration (ideally rather close to the original one, $\tilde{s} = s + \delta s$).
2. Compute the energy difference ΔE of the proposed and the original configuration.
3. If $\Delta E \leqq 0$, accept the candidate configuration, $s' = \tilde{s}$. Else compute the ratio $\rho = \frac{P(\tilde{s})}{P(s)} = e^{-\Delta E}$.
4. Generate a random number $r \in [0.0, 1.0]$.
5. If $r \leqq \rho$, accept the candidate configuration, $s' = \tilde{s}$. Else keep the old one, $s' = s$.
6. Repeat steps 1 to 5 until the configuration is statistically independent from the last (or, just after starting the simulation, until the system is equilibrated).
7. Calculate observable(s) O.
8. Repeat steps 6 (steps 1 to 5) and 7, until sufficient measurements of the observable(s) are calculated.
9. Compute averages of the observable(s) $\langle O \rangle$ and its (their) statistical error(s), Eq. (3.5).

Table 1: Metropolis algorithm, following [GL10].

Before discussing applications, I conclude with some general remarks on the Metropolis-Monte Carlo algorithm.

The Markov chain introduces a *'computer time'* that does not reflect 'physical time'. This is especially important in the context of sonification, where a time mapping always has to be chosen. Another important factor is the boundary conditions of the lattice. Often, periodic boundary conditions are used that leave the translational invariance intact and minimize *finite size effects*. They lead to a toroidal structure, as shown in Fig. 15. It is a drawback of periodic boundary conditions that the maximal distance between two sites is only half the lattice size.

In starting the Markov chain from an initial configuration, sufficient *equilibration* steps are very important. Only then will the algorithm produce configurations with the desired distribution, and the observables can be taken into account in Eq. (3.5). Statistical measures can be used to determine what 'sufficient' means.

A final important technique in simulation is *cooling*. All models described below exhibit strong random fluctuations that either reflect the quantum nature of the physical system they describe or are statistical heat fluctuations. Often, interesting structures are hidden under these incoherent, short ranged fluctu-

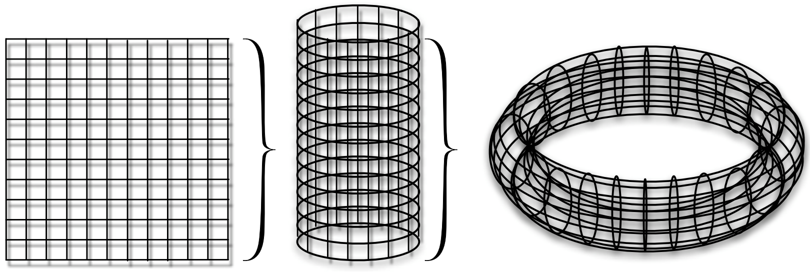


Figure 15: Schematic lattice structure in 2d. The boundary conditions are periodic, thus the structure is toroidal – after a roll-up along the first dimension, the cylinder shown in the middle is formed; after a second role-up, a toroidal (doughnut-shaped) structure.

ations. Therefore a method is useful that suppresses the fluctuations. If a configuration is cooled, a Metropolis update is applied where the overall energy is always decreased. A new spin thus is only accepted if the energy depending on its neighbors is lowered. (In a proper Metropolis step, there would still be a random decision allowing also a configuration leading to a higher energy.) In many cases, cooling exhibits hidden structures which are worth studying. The problem is that cooling ultimately drives the system into a trivial configuration of minimum energy. Thus it depends on the experience of the programmer to know when to stop the cooling process.

3.3 SPIN MODELS

Spin models contain simple microscopic interactions between elementary spins. Macroscopic properties (e.g., ferro-magnetism) emerge as a collective phenomenon of these spins. One of the central characteristics of a spin model is the symmetry group under which the microscopic interactions are invariant. Besides the dimensionality and the structure of the lattice, this symmetry entirely determines the macroscopic behavior at a phase transition. Already in 1945, E. A. Guggenheim found that the phase diagram of eight *different* fluids he studied shows the very *same* coexistence curve. (This is true when plotted in so-called reduced variables, the reduced temperature being T/T_{crit}, the actual temperature T in relation to the critical one, likewise the pressure; cited in [Yeo92]). The theoretical explanation is the classification in symmetry groups – all of these different fluids belonged to the same mathematical group. Likewise, the study of a simple spin system can lead to conclusions about real compounds or different, more complex computational models.

Spin models are discrete, thus the data 'live' on lattice sites that are characterized by their geometry and lattice spacing a. When applying QFT to the lattice, the theory has to be discretized, which involves a frequency cut-off: only wavelengths larger than the lattice spacing a and smaller than one lattice side (na) are representable on the lattice. This is called the infrared and ultraviolet cut-off of lattice QFT.

The data on the lattice are the degrees of freedom of the model, the *spins* s_i. In the Ising model, only two values are possible, spin up or spin down. The Potts model has $q > 2$ possible discrete spin states. A straight-forward extension is the XY model, where the spins are continuous in two dimensions. (These models are explained in some detail below.) There is a global symmetry in the spins, thus, in the absence of an external magnetic field, no spin orientation is preferred. All spins could be rotated by the same angle without influencing the observables. Thus in the case of the XY model the symmetry group is a continuous one, while it is discrete for the Ising and the Potts model.

In general, two factors drive spin models: random fluctuations, on the one hand, and neighbor-interaction aligning one spin to its neighbor, on the other. An overall factor controls the influence of these two: the coupling constant, inverse to the temperature. The models in this thesis are based on nearest neighbor interactions, but also next-to-nearest neighbor interactions or higher orders have been studied.

Many spin models exhibit a *phase transition*. Depending on the coupling constant, the observables change suddenly, indicating a shift from one phase to another. The models typically exhibit fluctuations at all scales at these special values of the coupling. The order of the phase transition is defined by the behavior of an order parameter (see Fig. 16). If there is a discontinuity, the transition is called *first-order*. If the function changes continuously, the phase transition is called *continuous*. For the two-dimensional case, the Ising model (Sec. 3.3.1) exhibits a continuous phase transition, as the mean magnetization rises continuously with the coupling constant up to a final value (+1 or -1). Equally, the 2d Potts model for $q \leqq 4$ states exhibits a continuous phase tran-

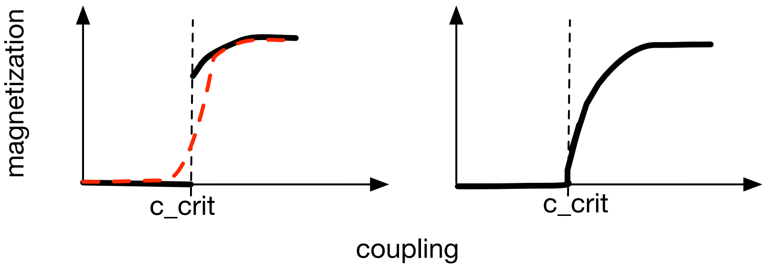


Figure 16: Scheme of the order of the phase transition. An observable, the mean magnetization, is plotted vs. the coupling constant. The left plot shows a discontinuous phase transition (of *'first-order'*) and the right one a *continuous* phase transition. In the first, the function is discontinuous at the critical temperature for an infinite system. The red dotted line gives an approximation on a finite system, as one is always limited to a numerical simulation.

sition, but a first-order transition for $q \geqq 5$ states. Infinite-order phase transitions also exist that are continuous but break no symmetry, e.g. the Kosterlitz-Thouless phase transition of the 2d XY model (Sec. 3.3.2).

A first-order phase transition cannot be measured on a finite system, as no discontinuities are possible for this case. The discontinuity is approximated by a smooth curve (see Fig. 16), however this curve becomes more edgy as the volume is increased. A systematic study to find the critical properties of a system is *finite-size scaling*. The same observables are calculated at lattices of different size. With bigger and bigger lattices, the observables converge to the real infinite-volume value, which can be deduced from such an analysis.

3.3.1 *The Ising and the Potts model*

Gould & Tobochnik write in their introduction to the Ising model that *"[o]ne of the more interesting natural phenomena in nature is ferromagnetism"* [GTC02, p. 537]. Even if this statement is rather harsh, studying ferromagnetic systems is surely very interesting. Ernst Ising and his thesis advisor Wilhelm Lenz started doing that in the 1920s. They modeled a ferromagnet as an array of simple 'atoms' on a lattice each atom carrying a spin *up* or *down*. If the majority of spins points in one way, the system on the whole is in the magnetic phase, otherwise not. An example of

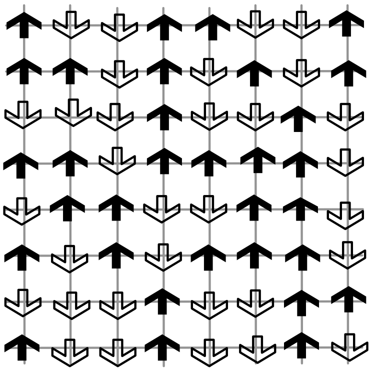
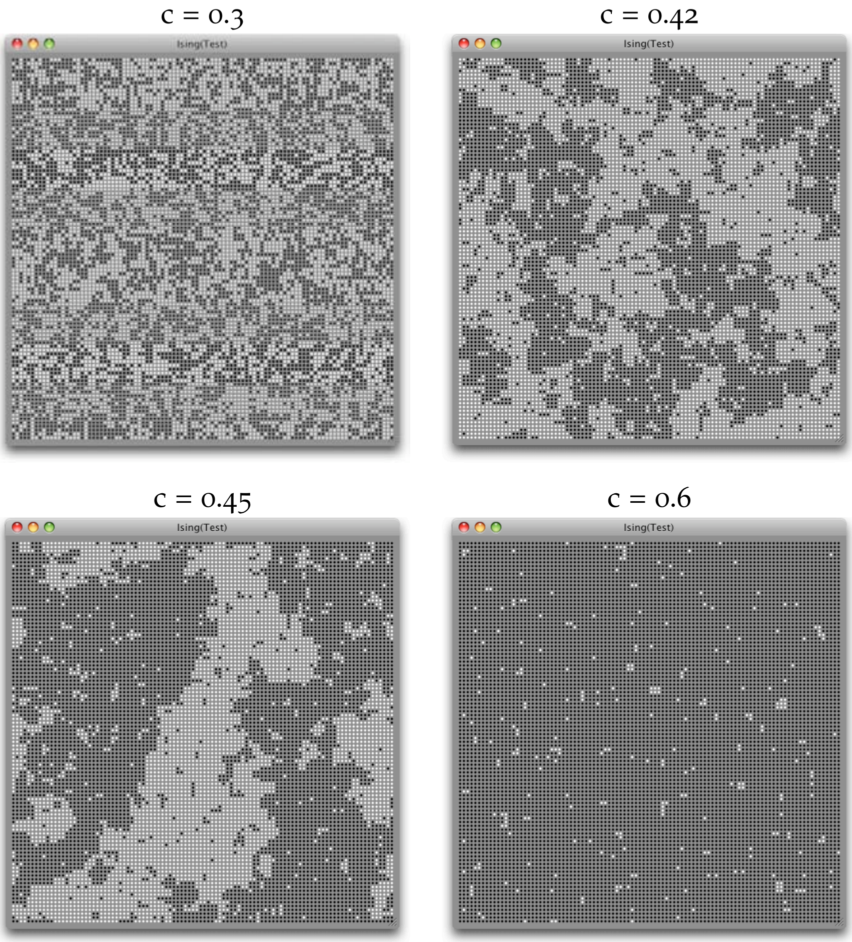


Figure 17: The Ising model with a lattice size of 8 times 8. At each lattice site, a spin can take two possible values (up or down).

a 2d case is shown in Fig. 17. The model is a classical simplification for the quantum mechanical effect. In Ising's and Lenz's model, the dimensionality of the lattice was only $d = 1$, and did not show much interesting behavior. However, the model does exhibit a phase transition for $d \geqq 2$ dimensions, and started its triumph in a variety of application domains with the development of computational soft- and hardware. The Ising model has become one of the best studied models in statistical physics, and it remains interesting as a simplified test case for more complex models. It has been extended in various ways, even e.g. describing social systems as in [FFH06].

A straightforward generalization of the Ising model is the admission of additional spin states besides just up and down. This was realized by Renfrey B. Potts in 1952, and was accordingly called the Potts model.

The visualization of the Ising model, as in Fig. 18, shows different structures depending on the temperature. At $T > T_{\mathrm{crit}}$, the random fluctuations are strong, thus there is mainly noise – small clusters of spins, and no macroscopic magnetization. At a critical temperature T_{crit} (also called the Curie temperature), the process is undecided and there are clusters of spins on all scales. If the temperature is lowered below T_{crit}, one spin orientation will prevail, which one being decided randomly in a process called 'spontaneous symmetry breaking'. Macroscopically, this is the magnetic phase. Watching a simulation of the Ising model remains fascinating, for a simple interaction algorithm, as described below, leads to evolving, complex structures.



$c = 0.3$

$c = 0.42$

$c = 0.45$

$c = 0.6$

Figure 18: Examples of configurations of the Ising model at different temperatures: below the phase transition, there are many small clusters ($c = 0.3$). At the phase transition, there are clusters on all magnitudes of scale ($c = 0.42 \equiv c_{\mathrm{crit}}$). Above the transition, the clusters grow ($c = 0.45$) until one cluster prevails after some equilibration steps (in this case, by chance, the 'black' spin 'won', $c = 0.6$).

Like any physical system, the Ising model tries to minimize its energy. The energy function is given by the *Hamiltonian* H, Eq. (3.8):

$$H = -J \sum_{<i,j>} s_i s_j - \mathcal{M} \sum_i s_i. \tag{3.8}$$

J is the coupling parameter between spin s_i and its neighboring spin s_j. The first sum contains all nearest neighbors and describes the coupling term. It is responsible for the phase transition. If $J = 0$, only the second term remains, and the Hamiltonian describes a paramagnet, being magnetized only in the presence of an exterior magnetic field. $\mathcal{M}$ is the field strength of this exterior field acting on each spin s_i. The second term is ignored in the following discussion. In this case the Hamiltonian is invariant under the discrete symmetry group $\mathbb{Z}^2$, which transforms all spins as $s_i \to \pm s_i$.

The partition function, Eq. (3.2), sums up all possible spin configurations and weights them with the Boltzmann factor, Eq. (3.1), which inversely depends on the temperature, T. Thus, energetically unfavorable states are less probable than energetically favorable ones.

Only few spin models have been solved exactly, and in 3d not even the simple Ising model has been analytically solved. Therefore classical treatment relies mainly on approximation methods, which allow partial estimates of the critical exponents[3].

As discussed above, spin models can be simulated with MC algorithms. To calculate the energy difference ΔE, the function in Eq. (3.8) is used.

The simplest observable in the Ising and the Potts model is mean magnetization, $< M >$, the sum over all spins, see Fig. 16:

$$< M > = < \sum_i s_i > \tag{3.9}$$

For an observable in the Potts model, each spin state's magenization can be measured separately. A plot of a configuration of the 4-state Potts model is shown in Fig. 19. The development of the magnetization for each state is shown in the bottom, giving the last 50 computer time steps in 'simulation time'.

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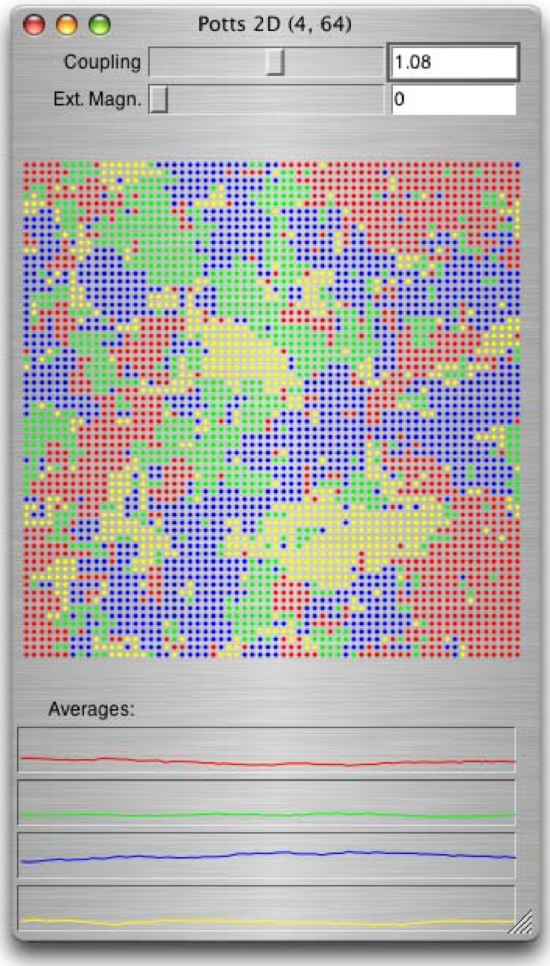
[3] Van der Waals theory of fluids and Weiss theory of magnetism; the renormalization group approach by K. G. Wilson [WK74] explains why critical exponents are universal for different systems. For a detailed review of phase transition theories see [Yeo92].



Potts 2D (4, 64)

Coupling 1.08

Ext. Magn. 0

Figure 19: Graphical user interface of the 4-state Potts model showing a configuration slightly above the critical temperature. The lattice size is 64x64. The averages below the spin frame show the development of the mean magnetisation for the 4 spin states over the last 50 configurations. The system was previously equilibrated.

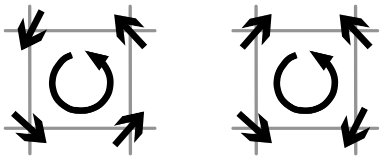


Figure 20: Scheme of an ideal vortex (left) and an anti-vortex (right). If one follows the spins in counterclockwise direction and adds up the angle differences, the vortex turns by $+2\pi$ and the anti-vortex by -2π.

3.3.2 *Topological objects in the XY model*

An interesting spin model is the 2d XY model of continuous U(1) symmetry. The spins may assume values on the unit circle. The XY model is richer in structure than either the Ising or the Potts model: topological structures emerge, so-called *vortices* and *anti-vortices*[4]. The energy functional of the XY model is given by Eq. (3.10). J is the coupling constant, and the interaction is over nearest-neighboring values given by their angles θ_i, $\theta_j \in [-\pi, \pi]$.

$$E[\{\theta_i\}] = -J \sum_{<i,j>} \cos(\theta_i - \theta_j) \tag{3.10}$$

Anti/vortices are defined as special configurations of the four spins located at the corners of an elementary square of the lattice (a plaquette), in Sec. 6.2 referred to as a *spin quartet*. If the differences of the angles θ_i at the corners sum up to 2π when visiting them in the counterclockwise direction, we speak of a vortex. If the sum is -2π, an anti-vortex sits at the plaquette (see Fig. 20). In case the sum is 0, no topological object is present at the plaquette.

The behavior of anti/vortex pairs changes depending on the temperature and at the critical temperature gives rise to the Kosterlitz-Thouless phase transition [KT73]. While the anti/vortex pairs are bound close together at low temperatures, they become unbound at higher temperatures, see Fig. 22.

This mechanism is topological in nature and is very different from the long-range ordering of spins which causes the transition in the discrete models. There is no such long-range order

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[4] 'Anti/vortices' is shorthand here for for vortices and anti-vortices, or, accordingly, 'anti/vortex'.

in the 2d XY model. The Kosterlitz Thouless phase transition can be calculated with the help of nonlocal observables, taking the whole configuration into account. Such an observable is the vorticity, the number of anti/vortices in the configuration (see Fig. 23), but the exact point of the phase transition cannot be deduced by this analysis, as it shows no scaling behavior.

In developing the sonification of the XY model (Sec. 6.2) it turned out that the plaquette is not necessarily the most basic geometry carrying topological objects. 'Micro-vortices' can also describe the system. Four micro-vortices can be found in each plaquette, as depicted in Fig. 21. The 'micro-vorticity' shows exactly the same behavior as the vorticity in Fig. 23.

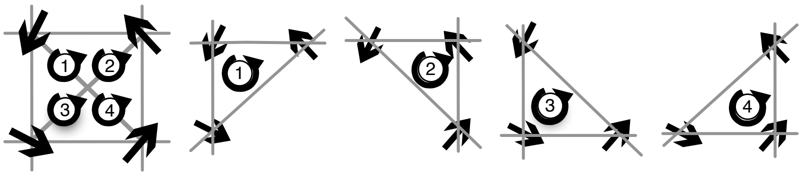

Figure 21: 'Micro-vortices' in a vortex. In taking a triangular part of the plaquette into account rather than the whole plaquette, anti/micro-vortices can be studied that show the same behavior as anti/vortices.

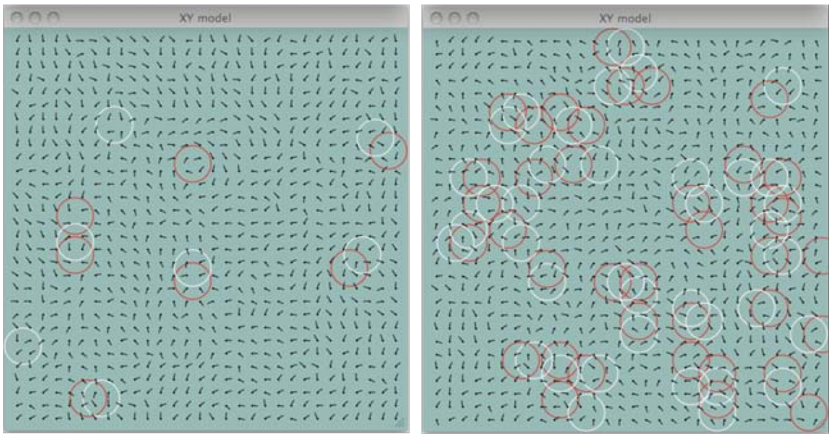

Figure 22: Visualization of typical configurations of the XY model below (left) and above the phase transition (right). The higher the temperature, the more vortices (red) and anti-vortices (white) can be found (see Fig. 23). Anti/vortices usually form pairs that appear more tightly bound above the phase transition.

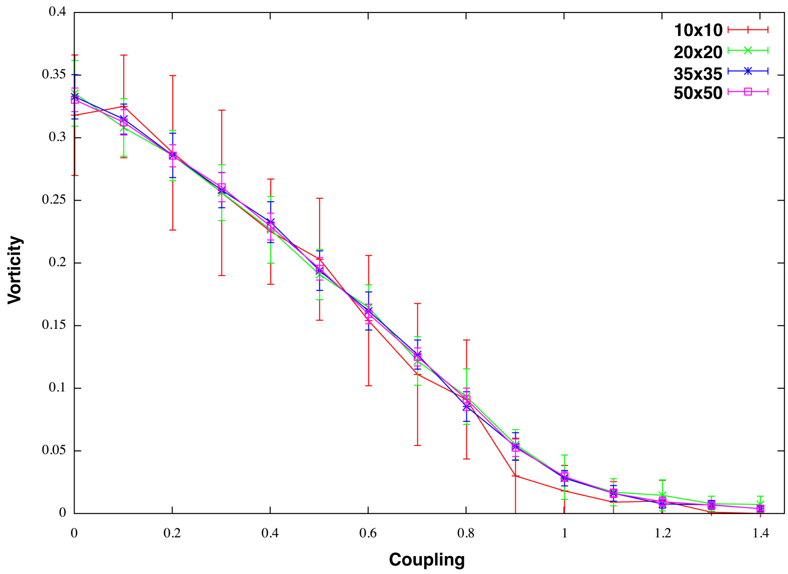

Figure 23: Average vorticity in the XY model of different lattice sizes, the number of anti/vortices, with mean deviation for different couplings. Four simulations for different lattice sizes were done (10x10, 20x20, 35x35 and 50x50 sites). For each lattice site and each coupling, 20 random configurations were chosen and equilibrated. The vorticity was normalized to 1, a vorticity of 1 meaning that there is a vortex or anti-vortex starting at each lattice site. No scaling behavior is observed, only the error bars of the standard deviations of the different runs become smaller for bigger lattice sizes.

3.4 LATTICE QUANTUM FIELD THEORIES

Lattice QFTs are structurally equivalent to spin models. In the following, I give only a very short summary on the subject, for details refer to [GL10].

The central equation of lattice QFT is the Euclidean correlator expressed as a path integral.

$$\langle O_2(t)O_1(0)\rangle_T = \frac{1}{Z_T}\int \mathcal{D}[\Phi]e^{-S_E[\Phi]}O_2[\Phi(.,n_t)]O_1[\Phi(.,0)] \quad (3.11)$$

O_2 is an interpolator for an observable (i.e. the functional of the field variables $\Phi(.,n_t)$ with $t = a \cdot n_t$.) at time t, correlated with an interpolator O_1 at time 0; they are the lattice transcriptions of operators $\hat{O}_1$ and $\hat{O}_2$ in the underlying QFT. For instance, a particle travels in space-time and is generated by O_1 at time 0, and annihilated by O_2 at time t. Z_T is a normalization factor, $Z_T = \mathrm{tr}[e^{-T\hat{H}}]$, where $\hat{H}$ is the Hamiltonian of the system. (The notation of Z is not arbitrary – in the context of statistical mechanics it is interpreted as the partition function.)

The Euclidean action $S_E[\Phi]$, on a 4d discretized system is given by Eq. (3.12). The continuum integral over space-time is approximated by the sum $a^4\sum_x$, where a is the lattice spacing. The terms in the sum are the discretized versions of the kinetic terms and the potential V.

$$S_E[\Phi] = a^4 \sum_{n\in\Lambda}\left(\frac{1}{2}\sum_{\mu=1}^{4}\left(\frac{\Phi_{n+\hat{\mu}} - \Phi_{n-\hat{\mu}}}{2a}\right)^2 + \frac{m^2\Phi_n^2}{2} + V(\Phi_n)\right) \quad (3.12)$$

The action of a physical system is a functional of the field configuration, Φ_n, and describes the dynamics of the system.

$$S[\Phi] = \int \mathcal{L}[\Phi(x)]d^4x \quad (3.13)$$

Classical systems are characterized by the configuration of minimal action. In the quantum mechanical case, the path integral samples all configurations (see Fig. 24 for a schematic representation).

Eq. (3.11) thus gives a prescription for calculating the correlation describing two observables. The structure of the equation equals Eq. (3.3), the expectation value of the spin models dis-

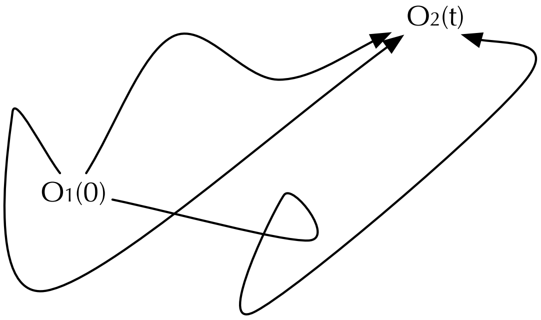

Figure 24: Scheme of the path integral. Three of infinitely many possible paths of connecting a generator O_1 at time 0 to an annihilator O_2 at time t, that are summed with amplitudes depending on the action.

cussed above. Therefore, MC simulations of statistical physics can be used as algorithm in this case as well. A comparison of equivalent entities of statistical mechanics and Euclidean field theory is shown in Tab. 2.

Statistical mechanics	Euclidean Field Theory
canonical ensemble average $\langle O \rangle$: $= \frac{1}{Z}\sum_{\{s\}} e^{-\beta H[s]} O[s]$	vacuum expectation value $\langle 0 \vert O \vert 0 \rangle$: $= \frac{1}{Z_T}\int \mathcal{D}[\Phi] e^{-S_E[\Phi]} O[\Phi]$
Hamiltonian H	Action S_E
(in units $\beta = 1/k_B T$)	(in units $\hbar = 1$)
correlation functions: correlation length $1/M$	Green's functions: mass m

Table 2: Equivalences between classical statistical mechanics and Euclidean QFT. [Dre03]

For an MC simulation of QFT, the theory obviously has to be discretized. For the 4d framework, a hyper-cubical lattice is introduced, $\Lambda = a\mathbb{Z}^4$. Matter fields (scalars, fermions) 'live' on the lattice points n. The gauge field is described by *link variables* U_μ, that are placed on the links which connect a point n and its neighbor $n + \hat{\mu}$, where $\hat{\mu}$ is the unit vector in direction μ. The gluon field A_μ is discretized with the U_μ (for QED it is invariant under U(1) symmetry, for QCD under SU(N) symmetry):

$$U_\mu(n) = e^{ieaA_\mu(n)}. \tag{3.14}$$

From the link variables, one needs to construct gauge-invariant entities that can be used to discretize the action and as observables. Every closed loop of link variables on the lattice is gauge-invariant. The simplest closed loop 'sits' on an elementary square and is referred to as plaquette $U_{\mu,\nu}(n)$, where the trace of the corresponding product of link variables is taken (for gauge group U(1), no trace appears):

$$U_{\mu,\nu}(n) \equiv \mathrm{Tr}\left[U_{\mu}(n)U_{\nu}(n+\hat{\mu})U_{\mu}(n+\hat{\nu})U_{\nu}(n)\right]. \qquad (3.15)$$

where μ and ν are the axes of the plaquette and n is the lattice site from which the plaquette is started, see Fig. 25.

The first and simplest example of an observable is the Wilson loop $W_{n,m}$, which is the traced product of link variables on a $n x m$ rectangle. The plaquette action or *Wilson gauge action* is defined as:

$$S_W = \frac{2}{g^2}\sum_{n,\in\Lambda}\sum_{\mu<\nu}\mathrm{ReTr}\left(\mathbb{1} - U_{\mu,\nu}(n)\right). \qquad (3.16)$$

After inserting Eq. (3.14), the limit $a \to 0$ reprodices the usual continuum action. The expectation value of the Wilson loop is related to $V(r)$, the static quark potential, at distance $r = ma$ via $\langle W_{n,m}\rangle = c \cdot e^{-naV(ma)}$. If one computes the expectation value for several loop sizes n, m, the static quark potential $V(r)$ can be determined.

The second important loop-type variable is the Polyakov loop:

$$P(\mathbf{m}) = \mathrm{tr}\left[\prod_{j=0}^{N_T-1} U_4(\mathbf{m}, j)\right]. \qquad (3.17)$$

It is a loop that closes around the compact time direction and is interpreted as the 'worldline' of a static quark potential. After suitable renormalization it can be related to the free energy F_g of a static quark via $\langle P\rangle = c \cdot e^{-F_g/(N_t a)}$.

A simpler lattice field theory to start with is lattice QED.

3.4.1 *Lattice QED*

The first quantum field theory was quantum electrodynamics (QED). It was fully developed in the 1940s by Richard P. Feyn-

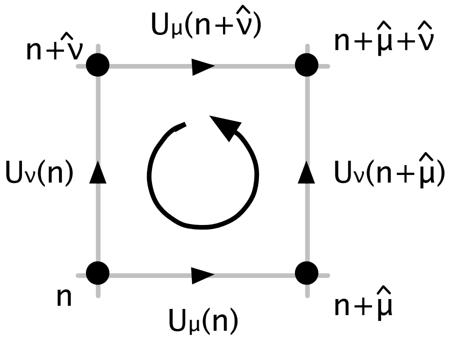

Figure 25: The plaquette as most basic gauge-invariant entity of a lattice gauge theory, carrying matrices U on the bonds between the lattice sites. The two shown lattice directions are μ and ν, the starting site of the plaquette is n. The $U_{\mu,\nu}(n)$ are directed quantities, with, e.g., $U_\mu(n+\hat{\nu})^\dagger \equiv U_{-\mu}(n+\hat{\mu}+\hat{\nu})^\dagger$.

man, Julian Schwinger, and, independently by Shinichiro Tomonaga, all three of whom received the Nobel Prize in 1965. QED describes the electromagnetic force as a QFT, where one of the key features is particle creation and annihilation out of/ into electromagnetic energy. It is one of the most successful theories in that it was experimentally verified with an accuracy of 10^{-8} as compared to the theoretical prediction.

The Euclidean action for QED is derived from the Lagrangian of a spin $\frac{1}{2}$-field, and consists of a pure gauge part, S_G, and a fermionic part, S_F:

$$\begin{aligned} S_{QED} &= -S_G + S_F \qquad (3.18) \\ &= -\frac{1}{4e^2}\int d^4x F_{\mu\nu}F^{\mu\nu} + \int d^4x \bar{\phi}(x)(i\gamma^\mu \mathcal{D} - M)\phi(x) \end{aligned}$$

It uses the electromagnetic field tensor $F_{\mu\nu} = \delta_\mu A_\nu - \delta_\nu A_\mu$ (A_μ being the vector potential), the covariant derivative $\mathcal{D}$, the Dirac matrices $\gamma^\mu = \{\gamma^0, \gamma^1, \gamma^2, \gamma^3\}$, and the spinor field of spin $\frac{1}{2}$-particles Φ.

QED has a U(1) gauge symmetry and is invariant under local Abelian gauge transformation (3.20). This means that the field at every lattice site can be multiplied with an arbitrary phase, leaving the resulting action the same.

$$\begin{aligned} \phi'(x) &= U(x)\phi(x) \qquad (3.19) \\ U(x) &= e^{-i\theta(x)} \in U(1), \qquad \theta(x) \in [-\pi, \pi] \end{aligned}$$

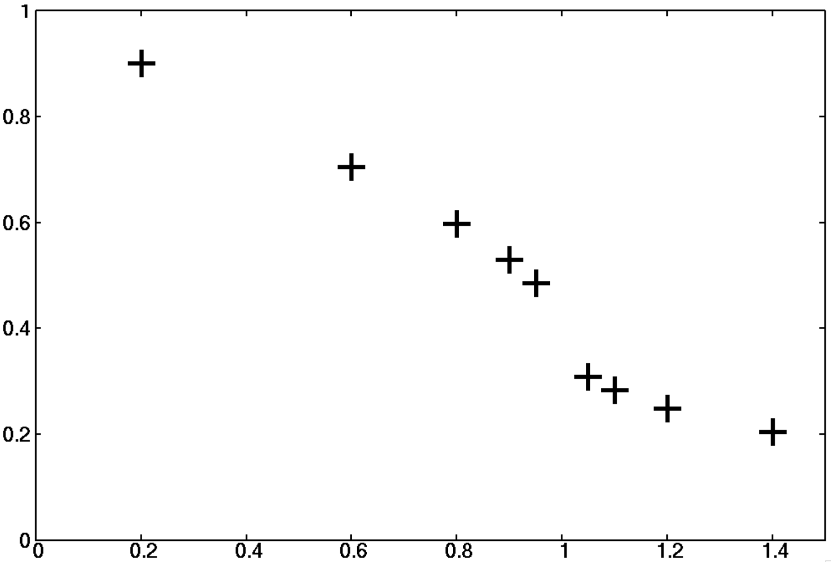

Figure 26: Phase transition in QED. At each of the 9 temperatures (inversely plotted at the x-axis) 100 measures of the Wilson gauge action, Eq. (3.16), y-axis, were taken, with 10,000 equilibration steps in between them. The phase transition is approximately at 1.

The compact lattice formulation of pure $U(1)$ gauge theory has two phases, a cooling phase at strong coupling and a Coulomb phase at weak coupling. The phases are separated by a phase transition which is believed to be first-order. QED is obtained only in the Coulomb phase, but the transition is an interesting toy model for studying deconfinement. The two phases may also be distinguished by the behavior of certain topological structures, so-called local monopole loops.

The monopoles are constructed as follows (rf. to [GJJ$^+$85]). The plaquette $U_{\mu,\nu}(n)$ is written as $e^{i\Theta_{\mu,\nu}(n)}$. The plaquette *flux variables* $\theta_{\rho\sigma}(x)$ are calculated as sums over the original link variables:

$$\theta_{\rho\sigma}(n) = \theta_{\mu}(n) + \theta_{\nu}(n+\hat{\mu}) - \theta_{\mu}(n+\hat{\nu}) - \theta_{\nu}(n). \tag{3.20}$$

The physical flux is defined as:

$$\bar{\theta}_{\mu\nu}(n) = \theta_{\mu\nu}(n) + 2\pi n_P, \qquad \Theta_{\mu\nu}(n) \in [-\pi, \pi] \quad n_p \in [-2; -1; 0; 1; 2]. \tag{3.21}$$

The monopole content of a cube is given by the net number of Dirac strings n_P through its surface. On the dual lattice, the cube corresponds to a link, and the monopoles form closed loops on the dual lattice. (A dual lattice is an equivalent representation to the link variables, see Fig. 27.)

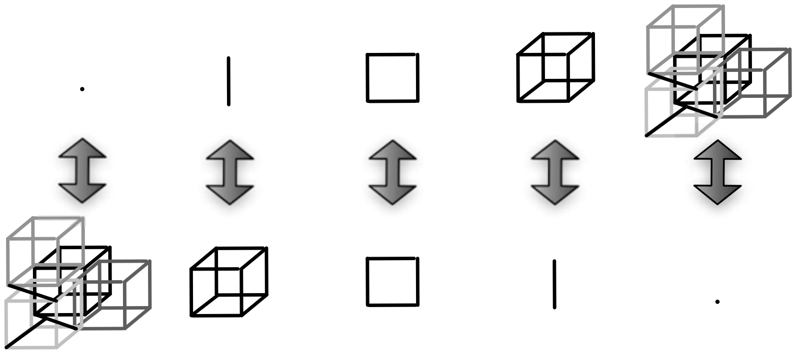

Figure 27: A dual lattice is constructed from corresponding elements of different dimensionality: the hypercube is described by a point (0-dimensional structure); correspondingly a cube becomes a link, but a plaquette is also described by a plaquette on the dual lattice.

In the confining phase, the loops are small, whereas in the deconfined phase they wind over large areas of the lattice.

3.4.2 *Lattice QCD*

Quantum Chromodynamics (QCD) is a field theory describing the strong force in the Standard Model. Quarks and gluons carry so-called color-charge (thus *chromo*dynamics), which can assume three values. In this case, the link variables $U_{\mu\nu}$ are complex 3x3 matrices in the gauge group SU(3), and the traces of Eq.s (3.15)-(3.17) are needed for gauge invariance. As stated above, observable states are color-neutral, which means that no single quark can be observed.

Lattice QCD has proven to be an important analysis tool for the theory. While for a long time computation resources admitted only calculations at unphysical energy scales, lattice QCD has recently advanced to the point where it can provide precision data for the measured observables [DFF08]. It also allows for studying non-physical systems in order to gain better insight into the physical mechanisms that nature actually 'realizes'.

The symmetry of QCD is SU(3), the *special unitary group* for 3 x 3 matrices. The three color indices of the quarks can be rotated at every space-time x without changing the action. The rotations are given as the 3 x 3 matrices $\Omega(x)$ and act on the field via

$$\phi'(x) = \Omega(x)\phi(x), \quad \bar{\phi}' = \bar{\phi}(x)\Omega^{\dagger}(x) \qquad \Omega(x) \in SU(3). \quad (3.22)$$

Contrary to QED, the SU(3) symmetry of QCD is *non-abelian*, thus non-commutative.

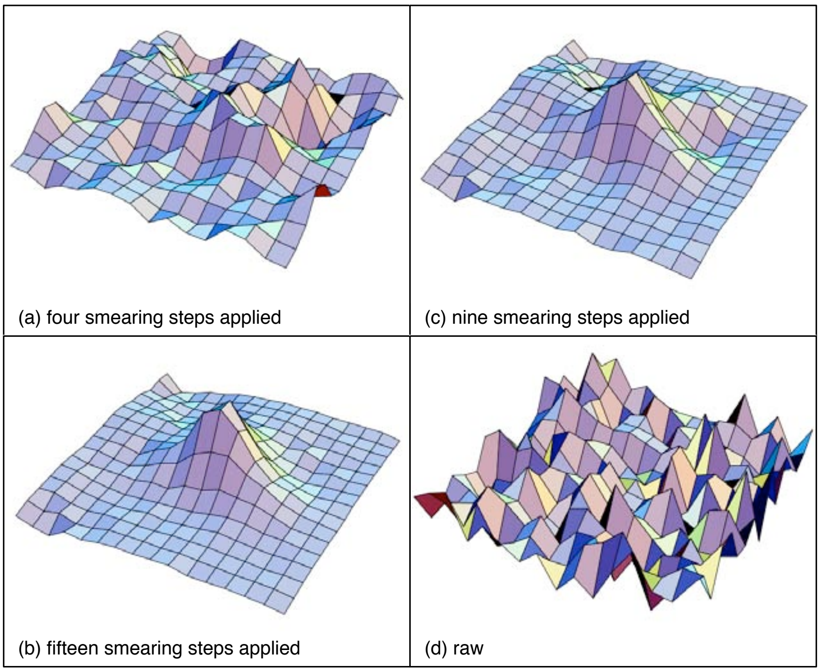

Figure 28: 2d slices of the 4d lattice showing the topological charge density of one configuration. (d) depicts the raw data, while (a)-(c) show different steps of smearing. A stable topological structure becomes visible after 4 - 9 smearing steps. Eventually, after sufficient steps, the smearing will also average out the topological structures. Again the expertise of the programmer is needed to stop the smearing process after an optimal number of steps.

Of interest in QCD research are *topological excitations* (e.g., instantons, calorons, or monopoles). These are localized bumps of action and of topological charge (see below), and represent effective infrared degrees of freedom in the QCD vacuum. They are believed to play an important role in several key mechanisms of QCD, in particular chiral symmetry breaking and confinement. In a gauge field configuration taken from an MC simulation, they are masked by quantum fluctuations with large amplitude. Therefore, the data needs to be filtered, one method being *smearing*, see Fig. 28. A Fourier analysis of the raw data does not exhibit the structures due to non-linear effects. It may be questioned whether the filtering generates unphysical artifacts, but different methods lead to similar results [BGI+07].

The topological charge density is defined as

$$q(x) = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}, \tag{3.23}$$

where $F_{\mu\nu}$ is the field-strength tensor and ϵ the totally antisymmetric tensor of rank 4. Analyzing the charge density $q(x)$ of suitably filtered lattice gauge configurations allows one to identify and study topological excitations.

Another interesting set of properties concern QCD at finite temperature. At very high temperatures, QCD undergoes the so-called deconfinement transition where the hadronic bound states are broken up and quarks can move freely. Understanding the mechanisms that drive the deconfinement transition is one of the great challenges in lattice QCD.

For the case of pure gauge theory, the deconfinement transition can be linked to the breaking of center symmetry: The center elements of SU(3) are $z \in [\mathbb{1}, \mathbb{1}e^{2\pi i/3}, \mathbb{1}e^{-2\pi i/3}]$. The center transformation is a multiplication of all temporal links at time $n_4 = t_0$ with the same center element.

$$U_4(\mathbf{n}, t_0) \rightarrow zU_4(\mathbf{n}, t_0) \tag{3.24}$$

The action S and the path integral measure D[U] are invariant under the transformation: $S \rightarrow S' = S$, $D[U]\ \mathrm{to} D[U'] = d[U]$. The Polyakov loop, on the other hand, transforms non-trivially as $P \rightarrow zP$ and thus is an order parameter for the spontaneous breaking of the center symmetry. Its expectation value vanishes, i.e. $\langle P \rangle = 0$, if the system is in the confinement phase, where the center symmetry is intact, but $\langle P \rangle \neq 0$ for the deconfined phase, where the symmetry is broken spontaneously.

It has been demonstrated [Gat10] that the breaking of the center symmetry is not uniform but organizes itself into spatial clusters whereby locally the Polyakov loop has coherent phases near the center elements (see Fig. 29). These clusters might in turn be related to topological excitations. Understanding and establishing such a relation is again a problem of analyzing massive amounts of highly complex data.

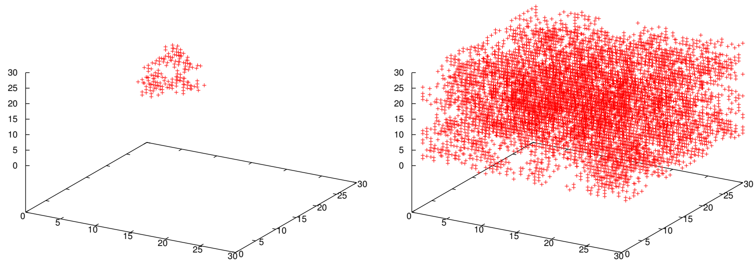

Figure 29: Clusters derived from the local Polyakov loop. Always the largest cluster (of any state) is depicted. Below the phase transition (*left figure*), clusters are small. Above the transition (*right figure*), clusters percolate, thus 'connect' opposing lattice sides. (Source: C. Gattringer)

3.5 SIMULATION OF CERN EXPERIMENTS

The MC technique also plays an indispensable role today, as can be seen in the work being done at CERN. The latest running experiment of CERN, the Large Hadron Collider (LHC), started in 2009. The dimensions of the LHC are impressive in every respect. Particle beams are accelerated in a tunnel 27 kilometers in length to nearly the speed of light. Two counterrotating beams collide at four possible sites, where different detectors are mounted. They detect traces of the particles they are specialized at that have been produced in the collisions. (One of the collision points is ALICE, A Large Ion Collider Experiment, see Fig.30). The LHC experiment has been planned for two decades and will run for 10 to 20 years. In the planning of the beam acceleration and the various detector facilities, simulations were done for experiments that have been conducted much later.

During a three-month period at the end of 2009, I did research at CERN, where I received data from the ALICE experiment. The heart of ALICE is a time projection chamber (TPC, see Fig. 31) – the most exact and, with a diameter of five meters, the largest ever built. It is a detector consisting of a cylindrical gaseous volume mounted around the collision spot. If particles are produced in the collision, they pass through the gas and ionize it by hitting the gas molecules. The freed electrons are led into an electric field parallel to the beam direction, to the left or right. At both sides, read-out chambers are situated. They consist of different layers of wires at high potential, producing an electrical field and accelerating the electrons towards them. In an avalanche process electrons are multiplied, thus inducing an electric current which can be read out by 'pads' behind the wires. The measurement is thus discrete in space, determined by the dimension of the pads, and in time, determined by their reaction time.

From the time, they are hit by the collision particles, the electrons move (ideally) on a continuous trajectory with a constant drift velocity towards the read-out chambers. Thus the information on their impact time and location on the circular read-out chamber suffices to reconstruct the particle path exactly. Hence the name *time projection* chamber.

Figure 30: The cavern of the ALICE experiment - a 50 m high dome located 50 m underground. The photo is taken from a position which is impossible today: the huge magnetic doors are closed and the beam pipe is mounted and shielded today, as particle beams have been circulated since November 2009 from where the photo was taken. The TPC was installed in the middle of the detector - one read-out chamber at the front, where the doors are, the other at the back. *Photo: A. Saba, http://aliceinfo.cern.ch.*

The energy deposit on the wires and the shape of the tracks are sufficient to deduce which particles caused the tracks. Three steps of pattern recognition algorithms are needed. First, individual signals from the read-out pads behind the wires have to be combined to find the center of a freed electron cloud (cluster). These clusters are then grouped to a complete track. Finally, the analysis of the curvature of the track (due to an additional

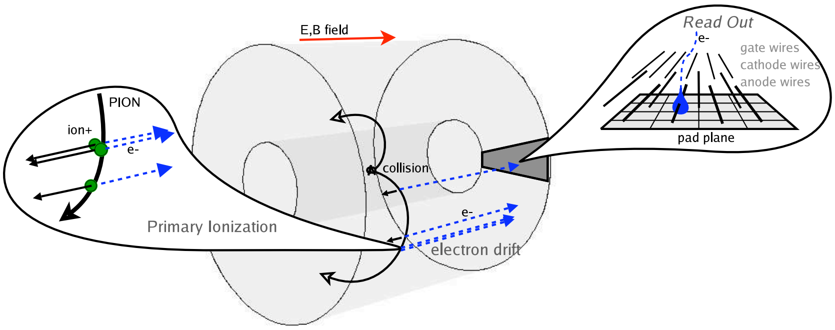

Figure 31: Schematic plot of the working principle of a TPC, on the basis of the example of a pion track. Charged particles transverse the volume of the drift chamber and ionize the gas. The created electrons follow the applied electrical field (E) and are collected in the wire chambers, where they are read out. Three layers of 656 fine copper and tungsten wires each are strained on top of each other with some mm between the layers (gate wires, cathode wires and anode wires). All technical details of the ALICE TPC can be found in [Ali00]. Source: [Ros09]

exterior magnetic field) permits conclusions concerning on the particle type.

The algorithms for these highly sophisticated pattern recognition tasks have been developed and tested with the help of simulations. The results have been integrated into the detector design and real-time data taking, without which no such measurement would be possible.

3.6 DATA PROPERTIES OF COMPUTATIONAL PHYSICS

All the simulations discussed above have at least structural similarities in common. Even if the physical and mathematical background is complex, these data properties enhance the understanding of sonification design.

Dynamic & discrete: The data are structured on discrete lattices that typically evolve in simulation time (which is not necessarily equivalent to ‘physical time’). The dynamic evolution of the models is fascinating, as they are built from simple microscopic interactions but show emergent macroscopic behavior.

No inherent perceptual dimension: The data are only represented abstractly in a computer. As discussed in Sec. 3.2.1, this can be considered as a new class of scientific data, but beyond that a perceptualization is needed in any case to extract meaningful information from the simulations.

High dimensional data: Many data sets are 4-dimensional, thus full visualization is not possible. Conceptually, the forth dimension also poses a problem, as we cannot imagine it, and any perceptualization of a four-dimensional system will remain abstract.

Large data sets: Many data sets stemming from simulations are huge, even if the basic dimensions appear to be rather small at first view. E.g., lattices in lattice QCD calculations typically *(by mid 2010)* contain 48 sites per 'space-like' dimension and 96 in time dimension, thus $48^3 \cdot 96 = 10,616,832$ sites, where each link is equipped with complex 3x3 matrices.

Moreover, the configuration space, the potential number of different data configurations, is infinite (uncountably infinite for continuous models).

Stochastic data: The physical observables derived from MC simulations, are bulk entities of statistical nature. Usually, many configurations have to be taken into account for the mathematical analysis.

Symmetry: One of the basic concepts of 20th century physics is symmetry: different physical systems can be described in the same formulations as long as they have the same underlying symmetry. Phase transitions are often manifested in a spontaneous breaking of these symmetries, which changes the behavior of the model more or less suddenly. The transformation may be identifed by observables that are variant under the symmetries, e.g. 'bulk quantities' like averages of the whole configuration, and sometimes also by a change of topological structures.

Part II

THEORY

4

STEPS IN SONIFICATION DESIGN

On the basis of my experiences of the research projects SonEnvir and QCD-audio, I present a framework for sonification design. Contrary to the various different design frameworks discussed in Sec. 4.1, the following section of Part II contains an *a posteriori* analysis of the design decisions that *have* to be taken for any (lattice) sonification on three different levels: *meaning, structure, and elements*, both for a sound model and a data model. I provide a *toolbox* – or rather boxes of tools – that have proved useful in these decisions (Sec. 4.2). In the research projects, *bottom-up* and *top-down* approaches were pursued. One detailed example of a top-down approach, given in Sec. 4.3, proposes *metaphoric sonification*. Finally, quantitative and qualitative *evaluation* approaches are discussed in detail (Sec. 4.4). As one outcome, a set of criteria for the evaluation of sonification is suggested.

4.1 SUPPORTING FRAMEWORKS FOR SONIFICATION DESIGN

In a survey of sound experts in different fields, Frauenberger found more skepticism than positive statements about the use of audio in human-computer interaction [Fra09]. As main problems he cited gaps in the documentation of the design process and in the reasoning behind it, the multi-disciplinary nature of the process, and limited awareness of contextual properties, e.g., usability and interaction design. Additionally, he argues that it is hard to sketch or mock up the solution for an AD problem. Simple draft sounds do not suffice, as they do not give a meaningful idea of the impression of the final sound. He reports that *"the context of the work often dictates the stages in the design process"* [Fra09, p. 38]. This was also true for the research projects SonEnvir and QCD-audio.

Several approaches to design guidelines for AD have been proposed. For an overview, see [Fra09]. For auditory icons and earcons, standard guidelines exist (see [Fra09]). For continuous AD, or generally for AD (continuous and discrete methods), guidelines are more difficult to define. I will summarize three alternative approaches: a systematic questionnaire (TaDa), an iterative data base of design patterns (paco), and a map of quantitative data characteristics (SDSM).

TaDa

One systematic approach to developing sonifications is *TaDa*, the task and data analysis of information requirements by S. Barrass [Bar97]. For designing a useful AD, an AD expert usually has to work together with a domain expert. The TaDa approach helps to clarify the communication between those two. It is a questionnaire that begins with an open space for a *'story'*: the domain expert is asked to describe shortly what the sonification should deal with. Then, key features should be given, identifying the open question of the AD, possible answers to it, the subject who will use the AD, and possible sounds. Then, the task, the information included in the data, and the technical representation of the data itself should be described in terms of the criteria in Tab. 4.1.

The TaDa method provides a detailed and systematic way of approaching a sonification design. It proved useful, e.g., in the interdisciplinary workshops SBE 1 and 2, mainly as a systematic description of all important aspects before the design process starts. The completion of the form caused some confusion for the domain scientists. The underlying problem might be the abstract generalization in categories. Further criticism of the approach includes the disregard of the context environment and the bias towards data sonification [Fra09].

The TaDa is a very practical tool for preparing the groundwork for a sonification, in the form of an easily distributable questionnaire. It does not help in the design decisions per se. (For this task, Barrass developed 'EarBenders' (Sec. 4.3.1)).

paco - pattern design in the context space

Frauenberger [Fra09] investigated an iterative approach to pattern design in the context space, called *paco*. It allows sound experts and newcomers to develop auditory displays mainly as a part of human computer interfaces and technical applications.

paco is a design framework that uses generic design patterns because they are flexible, abstract, and allow multi-dimensional access to design knowledge. The context space is a multi-dimen-

task:	
generic question	local, (subject *"it"*), intermediate (*"they, which"*), global (*"everything"*) (e.g., who is it? what is it? where are they? what is happening?)
purpose	*one of:* analyze, confirm, identify, judge, compare, navigate, track, alert, relax, remember, engage
[attention] mode	interactive, focus or background
type	discrete/procedural, continuous/tracking or branching/decision
style	exploration or presentation
information:	
level	local (single element), intermediate (several elements) or global (all elements involved)
reading	conventional (is learned and varies among individuals) or direct (cross-cultural, e.g. Geiger counter)
type	boolean, nominal, ordinal, ordinal-with-zero, ordinal-bilateral, interval, ratio, unknown or none (no information is involved)
range	[for exploratory contexts usually unknown]
organization	by categories, time, location, alphabet, continuum (e.g., ordered by magnitude)
data:	
type	none, nominal, ordinal, interval or ratio
range	(defined by data)
organization	category, time, location, mnemonic (e.g., alphabet), continuum (continuous order)

Table 3: Overview of the TaDa method by S. Barrass [Bar97]

sional space that is implemented with 6 basic dimensions: user, environment, device, application domain, user experience, and social context. Along with these dimensions, patterns (as well as design problems and solutions) can be *tagged*, thus appearing localized in the space and linked to each other.

When creating a pattern, a designer starts by localizing the context of the problem in the context space by assigning tags and describing concrete implementation examples. From this 'seed pattern' the designer iteratively generalizes a design pattern. The more often a pattern is visited, the higher its rating becomes, while low-rated patterns will lead to dead ends in the paco process. Because the concept is based on a self-organizing and community-driven process, it will only prove useful if it is accepted in the community. In tests, the approach worked out, but iterative design cycles were not used extensively.

In general, the approach of Frauenberger and other generic design approaches he cites operate on an abstract level. They support designers in building up or systematizing their own expertise, some approaches also for whole teams, which is probably the best aid there is in a generalized framework. Still, for concrete design decisions, transfer from experiences gained from other research projects is desirable.

Sonification Design Space Map

An objective method that goes into this direction is the *Sonification Design Space Map* (SDSM) by A. de Campo [dC09], see Fig. 32. Referring to M. Leman's concept of proximal and distal cues, de Campo describes sonification and the exploration context: *"sound design decisions inform details of the created streams of sound, i.e. they determine the proximal cues; ideally, these design decisions lead to perceptual entities ('auditory gestalts'), which can create a sensation of plausible distal cues behind the proximal cues"* [ibid, p.10]. The SDSM enables the sonification expert to choose the appropriate type of sonification depending on quantitative data properties. The aim is to provide a general guideline that facilitates the emergence of perceptual entities, which are expected at a certain order of magnitude.

De Campo differentiates three sonification types on the basis of their quantitative behavior. *Continuous data representation* treats data as quasi-analog continuous signals with equal distances along at least one dimension and a sufficient sampling

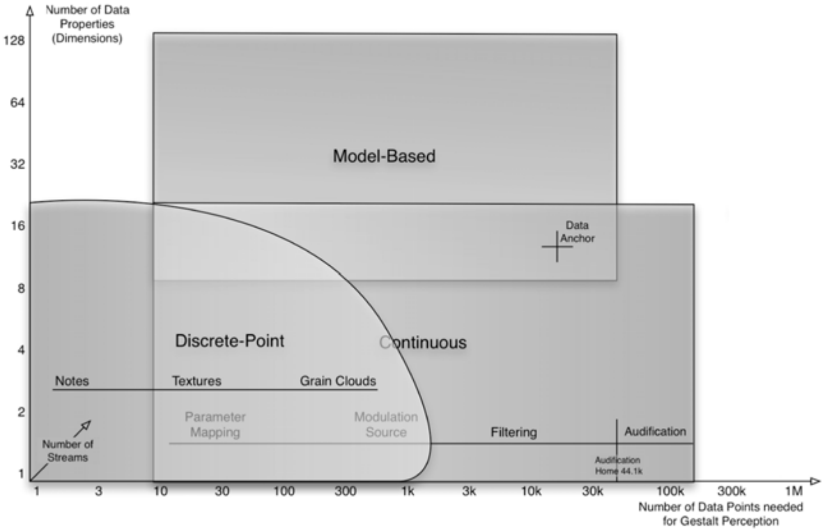

Figure 32: Sonification Design Space Map by de Campo. [dC09]

rate. Simple audification and parameter mapping belong to this category. Secondly, *discrete point data representation* creates individual events for each data point, e.g., sound grains. Finally, *model-based sonification* introduces a model for rendering the sound. The model properties depend on the data. Absolute numbers on the map are based on psycho-acoustical limits: on the one hand, it is difficult to discern sounds lasting less than 100 milliseconds, on the other hand, gestalts should 'fit' into the short-term memory, thus range as a rule of thumb within 1 to 3 seconds.

The map can be consulted iteratively in the design process. A data anchor is set as a first step. It is placed depending on the properties of the expected patterns in the data. In the development of the sonification, it can be shifted, e.g. due to a mathematical treatment of the data values (decimation, interpolation, etc.).

When used as an auxiliary tool in the design process, the SDSM gives a good overview of the perceptual space depending on the number of single information entities which can be used for sonification. But it can only be a complementary tool, as it builds on quantitative data features and neglects qualitative aspects. Data properties from incoherent categories are subsumed on a single axis of the map. For instance in simulation data, the data space and/or time provide *structural* dimensions, whereas there is also a domain of values (defined e.g., by number types and symmetries). A map taking these features into account would have to be multi-dimensional, and thus no longer provide a good overview. In addition, the SDSM does not help in the concrete sound implementation, but gives an idea of the method to choose.

4.2 MEANING, STRUCTURE, ELEMENTS

The guidelines cited above provide general strategies supporting the sonification design process. They range from rather abstract guidelines (e.g., paco) to codes of practice (e.g., TaDa, SDSM), and collective concepts (e.g., EarBenders). Even if they treat important aspects of the design process, none of them provides a complete framework for general AD design. It seems likely that such a framework can only be established within the consolidated progress of the community that is achieved in tandem with a standardization in the field.

Along the way towards standardization, the expertise of AD design gained from research projects has to be distilled in a systematic way. Therefore, I draw general conclusions from the process of designing sonifications of lattice data during two research projects: SonEnvir and QCD-audio.

The data for which these considerations apply are lattice simulation data. As discussed in Sec. 2.4, such data are structurally ordered on a discrete lattice, e.g. they are 2- to 4- dimensional and have an additional value dimensionality. Different symmetries can be found in their structure and value dimensions. In general, these criteria apply to many more data sets than just simulations of computational physics.

In introducing sonification, different standard methods are often presented, as I did in Sec. 2.3. Audification, parameter mapping, and model-based sonification are mentioned repeatedly. This classification scheme is practical for getting initial insights into the range of possibilities for sonification. In practice, however, the borders between these paradigms are harder to define, and the approaches are often hybrids, so there is some overlap between the categories. Therefore, further analysis of the methodology, for instance depending on special data features, is of limited use, and another viewpoint is needed.

Several different decisions *have* to be made in a sonification design process. The decision making is the driving factor for the development of a sonification model. I split the sonification model into the *sound model*, which concerns the sound and listening aspects, and the *data model*, which of course exists independently of the sonification process but evolves during the design process. The evolution of a data model is important, for preoccupation with the sonification leads to a deeper understanding of the data. Additionally, the *implementation* and the *evaluation* also influence the design process.

The design process trivially starts with the choice of the *data set*, and with the (not so trivial) motivation of *(hypothesized) observables* in the data that are in the focus of interest. The following decisions have no *a priori* chronological order, but often take the form of a bottom-up approach: a fundamental decision is the choice of the elementary data values, the *'display units'* that are actually used in the sound synthesis. They can be the raw data values, but also mathematically treated, and they may even depend on a structured accessing procedure. Determination of the overall *structure of the data* is a precondition on the global level, but decisions regarding the focal structure, e.g., whether only special regions or topologies of interest are displayed, must also be made. On the sound side, one obligatory decision concerns the coping with time as a *fundamental structure in sound*, and generally with some 'sonic space' that maps the lattice structure, e.g. a spatialization or timbre space. Equivalent to single display units in the data model, there are also elementary sound units – the perceived *'gestalt units'*. And finally, there is also meaning in the sound model, as any sound has *metaphoric content* on a global level. Ideally, the sound has also special meaning on the focal level, thus exhibiting *'audiables'*. Audiables are auditory *gestalts* of higher cognitive level that are emphasized against a possible sound background and give meaningful, non-trivial information about the data. Audiables are the sound analog to observables in physics.

Thus three distinct levels of decisions should be taken into account in the design process, both in the sound model and in the data model: meaning, structure, and elements, see Fig. 33. There are interdependencies between them, and also often trade-offs. The three levels have an intrinsic hierarchy. In sound, auditory perception starts from single entities, builds an internal map of a sound structure, and finally forms the audiables as higher-level cognitive entities. In the data, the mathematical treatment of the models starts with microscopic elements that are organized in

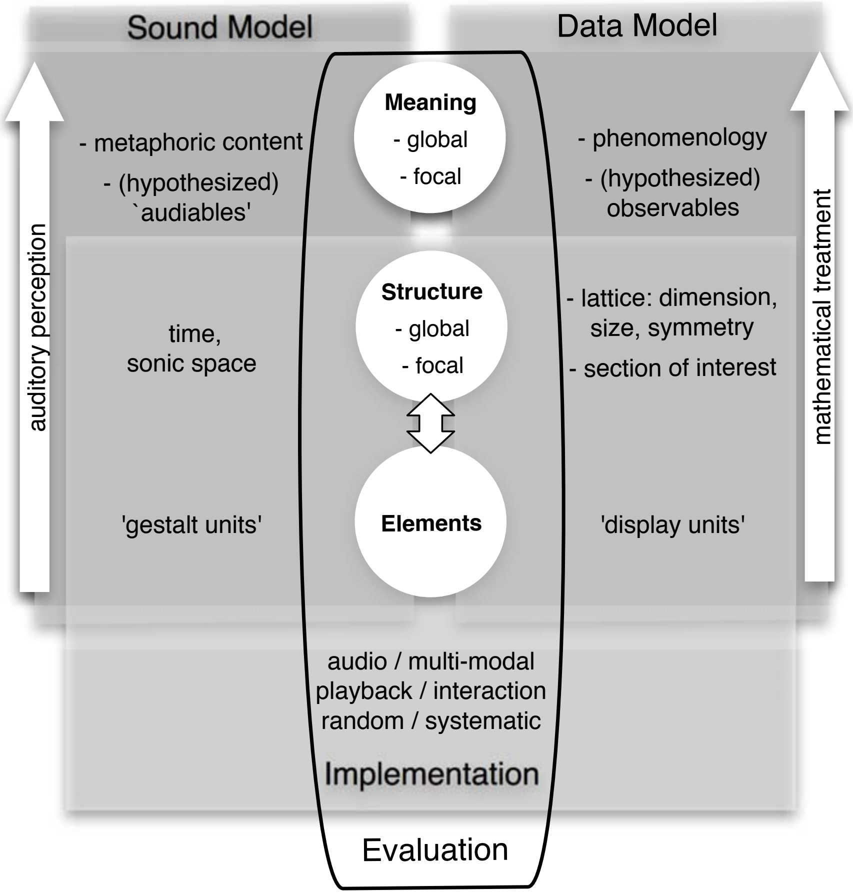

Figure 33: Meaning, structure and elements: in both the sound model and in the data model, decisions at these three levels have to be made. The levels are ordered hierarchically, along the auditory perception, on the sound side, and the mathematical treatment, on the data side.

The metaphoric content of the sound should fit the phenomenological meaning of the data. Hypothesized 'audiables' face observables. In structure, sound and data decisions differ from each other; sound is at least always structured in time and in some sonic space, while the simulation data is defined globally on a lattice, and often has local entities of interest. Also the elements, the 'gestalt units' as smallest perceivable entities, and the 'display units' that are actually used in the sonification, are not necessarily equivalent to each other.

For structure and elements, also the implementation (choice of interface, playback mode and interaction possibilities) plays a role. Finally, evaluation should influence all decisions in an iterative design process.

a specific structure and aggregated in macroscopic, meaningful observables.

The decision-making process is also influenced by practical considerations of the implementation of the sonification model. These must not be neglected, as the usability of the interface is an important factor for the actual application of sonifications. The implementation involves soft- and hardware issues and has interdependencies to the elementary and structural level of decision making, but usually not to the level of meaning.

Finally, the outcomes of evaluations at different stages of the design process should influence the sonification design.

In the following, I will discuss the six design decisions with a corresponding collection of *tools* that have proven to be especially useful in the context of simulation data, see Tab. 4.2. For the sake of emphasis, the tools are described in boxes.

Design decision	Tool	see
Data Meaning:	*different for each data set*	
Data Structure:	Path follower	p. 77
	Space-filling curves (Hilbert curve)	p. 78
Data Elements:	*different for each data set*	
Sound Meaning:	Soundfile manipulation	p. 80
	Metaphoric sonification	Sec. 4.3
Sound Structure:	Simulation time and physical time	p. 81
	Spatialization	p. 81
	Timbre space	p. 82
	Shepard scales	p. 83
	Digital waveguides	p. 84
Sound Elements:	Granular synthesis	p. 85
	(Distorted) modulation	p. 85
Implementation:	Graphical User Interfaces	p. 86
	Interactive motion-tracking	p. 86

Table 4: Overview of the design tools amassed in this thesis

4.2.1 *Data Meaning*

On a *global level*, a data set has a general meaning, for instance as a description of a physical field. The *focal level* in the sonification process is the observable that one is interested in. It can be an entity of a part of the data set, or an aggregated entity built from the entire data. Some observables are hypothetical, and have not yet been observed, but in many examples of Sec. 6 the observable is known, and the sonification is just a different method of displaying it.

Achieving intuitive equivalence between data meaning and sound meaning should not be disregarded. This topic will be discussed in the context of metaphoric sonification (Sec. 4.3).

It is striking that, early in the decision process, the meaning of observables is often broken down into structural questions; the task of displaying an observable can be re-formulated as a search for a special geometry or topology, e.g., clusters or closed loops of different sizes.

4.2.2 *Data Structure*

The global structure in the data model is mainly determined by the data set in the following categories:

- *lattice dimensionality*: $d \in [1, 2, 3, 4, ...]$
- *lattice size*: The lattice size is given by n_d sites per dimension and the lattice spacing a between adjacent sites (a links the discretized lattice to physical measures).
- *lattice symmetry*: Many geometries of lattices are conceivable; our models were mainly (hyper-)cubic, and in one case cylindrical.

The focal structure depends on the observable; it can consist, e.g., of a reading condition of the lattice (e.g., only closed loops).

In general, coping with the structural dimensions means one of the following decisions:

- the structure can be *(partly) ignored*; for instance, no local observables are expected and the statistical nature of the model is predominant;
- *sequentialization* can be used in order to map the higher dimensional space to a (usually) 1d curve and map it to

the sonification time (e.g., space-filling curves and a path follower, as discussed in the tool boxes below);

- structural information can be *spatialized* in the physical listening space (Sec. 4.2.5),
- or it can be mapped to an abstract *sonic space* (e.g., pitch or timbre space) that allows the listener some orientation (e.g., Shepard tones, Sec. 4.2.5);
- the structure can be used *implicitly*, which is the case for model-based sonification (e.g., waveguides, Sec. 4.2.5);
- and of course all approaches can be mixed.

Path follower

An automatic sequentialization rule is the following of a certain structure. This can be interesting when, e.g., loops have to be found or the locality of an audiable is of interest. Different path following rules are possible depending on the data. In a spin system, the spins can be interpreted as arrows pointing towards the site to follow. In the research project QCD-audio, a path follower has been implemented in the XY model, but it did not prove useful in this context due to the topological structure; the algorithm quickly runs into a dead end of 2 sites or a cycle of sites, pointing towards each other. Even when averaging over the last n steps of the path, a dead end cycle occurs that is not a priori congruent with the vortices and anti-vortices.

For cluster data, the random choice of one of the neighboring sites carrying the same value as the starting point, is a simple possibility. Such a path follower was implemented in the course of the SBE 2 workshop for monopole loop data [qcd] and the appendix.

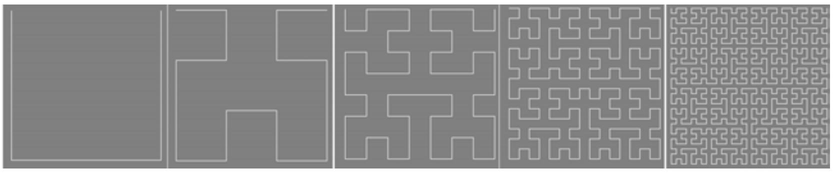

Figure 34: The first five steps towards a Hilbert curve in two dimensions. The endpoints of the basic U shape are at opposite lattice sides. (The *Moore curve* is built from the same basic structure, but its endpoints are at neighboring sites, thus the curve can easily be closed.) [wikc]

space-filling curves (Hilbert curve)

In the context of audification (e.g., Sec. 6.1.2) or the task of systematic navigation through the whole lattice (Sec. 6.4), a sequentialization rule is needed – the mapping of a n-dimensional structure to a 1d data stream. This can be achieved by simply reading out the data line by line, which makes perfect sense for a, e.g., toroidal structure.

A different sequentialization rule is given by space-filling curves, e.g., the Hilbert or Moore curve in a (hyper-)cubic structure. These curves are also known as *FASS curves* [Sag94]: space-Filling, self-Avoiding, Simple, and self-Similar. They are one-dimensional objects that fill an $n-$dimensional space completely, visiting each site only once and not intersecting. They are constructed iteratively from a basic shape (e.g., the "U" in the Hilbert curve, as shown in Fig. 34). Thus they are self-similar on different scales and have fractal dimension.

The best known example of a FASS curve is the Hilbert curve, which can be used in any object with square shape. Actually, there are 1536 different Hilbert curves in a cube, using different rotation rules of the basic 'U'.

space-filling curves have been introduced by F. Grond in the context of sonification of images [Gro07]. They are proving very useful for the audification of discrete lattices, as they preserve locality more than the simple toroidal sequentialization does. The curve only moves slowly from one region to the next. The main drawback is the arbitrary positioning of the curve. Consider the following example. A 2d lattice contains a 2d observable with a diameter of one half of the lattice size. If the observable is placed in the center of the lattice, the Hilbert curve will dissect it into 4 pieces of equal distance along the curve. But if it is placed in one quarter of the lattice, the time scale of the same structure is totally different, as it appears in the first quarter of the curve.

Nevertheless, space-filling curves are an important tool for structural decisions in sonification design.

4.2.3 *Data Elements: 'display units'*

As it is true for the data structure, the elements can also be basically described in categories:

- *data type:* Numbers are usually classified in natural numbers $\mathbb{N}$, integers $\mathbb{Z}$, rational numbers that can be expressed as a quotient $\mathbb{Q} = m/n$, irrational numbers $\mathbb{I}$, real numbers $\mathbb{R} = \{\mathbb{Q} + \mathbb{I}\}$, and complex numbers $\mathbb{C} = a + bi$. Data elements in computational simulations can also consist of vectors, matrices or tensors.
- *data range*: The data range of each data dimension is given by its minimum and maximum.
- *data symmetry:* Many of the studied data have local and global symmetry conditions, e.g. the data are angles $\in [0, 2pi)$ or a global transformation as the multiplication of all data by a factor is allowed.

A general decision must be made whether all the data or only parts of it are displayed. At any rate one has to decide, which data values are actually displayed:

- the use of *raw data* is the most direct approach is, as for instance is the case in an audification or simple parameter-mapping;
- *filtering* is a simple data treatment that is often useful in context of sound;
- *relations* between data points can be interesting (e.g., differences of neighboring values);
- *statistical entities*, e.g. mean values of regions, are interesting especially in Monte Carlo models;
- *derived values*, finally, follow from a more complicated mathematical treatment.

General tools for these decisions cannot be proposed, as they depend on the data meaning.

4.2.4 *Sound Meaning*

'Meaning' in a sound refers to the associations and metaphors that are evoked when listening to it. Any sound involves meaning. Additionally, the 'audiable' is that part of the sound that ideally comes to the fore and says something non-trivial about the data.

The metaphors in sound meaning can be shaped in a top-down process of sonification design, as discussed in detail in Sec. 4.3. A simpler approach is soundfile manipulation, starting with a ready-made sound and modifying it.

Soundfile manipulation

As a top-down process of sonification design, the first step can be the choice of a sound, for instance a soundfile of music or spoken text. In monitoring contexts, the soundfile can be used to display a distinct state of the data. In the example of the Ising gestalts (Sec. 6.1.2), a prepared soundfile is decomposed in different frequency bands that are triggered with delays and amplitudes determined by the data. Thus the original gestalt only appears in a certain data setting that is aimed to be emphasized. In other data settings, the file is fragmented. The change in the sound is perceived instantaneously, and this also has metaphoric meaning: some sort of 'disintegration' or 'decay'.

A similar approach was taken with data from a completely different context: physiotherapy. The correctness of a certain training movement can be monitored via a motion-tracking system. In the project *PhysioSonic* [VPK$^+$09] an additional auditory feedback system for the patient has been implemented that plays a chosen soundfile correctly only if the right movement is performed.

4.2.5 *Sound Structure*

Sound is always structured in time and can be additionally structured in a sonic space:

- *time* is the central structural element in sound – if there is no time, there is no sound neither.
- *spatialization* is the mapping of a 3d data space to the physical space;
- *a sonic space* can be used as well, where different sound dimensions (timbre, pitch, etc.) are 'orthogonalized' according to the auditory perception and used as dimensions of a sonic space. A particular example is the Shepard scale, an example for a rotational symmetrical 1d pitch space. More

abstractly, waveguides construct physical spaces by modeling sound propagation.

Simulation time and physical time

An important factor in the design decision is the choice of the sonification time, and it is often obvious to map the data time to the sonification time.

Simulations usually exhibit two independent time scales: the *simulation time* depends on the algorithm, e.g., the update between different configurations of the model. It has a priori no direct link to the *physical time*. The dynamics of the model is often interesting, but some types of models in this thesis are computationally very demanding and cannot be implemented as a real-time system. A fallback procedure is the pre-computation of configurations with systematic changes of a model parameter, which are then sonified.

Spatialization

Sound spatialization serves as a direct tool for mapping data structure to sound structure (but can also be used for data parameters in a less direct mapping approach).

The localization feature of the auditory perception (Sec.2.1) can be used to create virtual sound sources. The actual technique depends on the playback device and the software effort. With headphones, binaural rendering creates a full illusion of virtual sound sources, but simple stereo panning is also effective and simpler to implement. The same is true for a multi-speaker setup vs. stereo speakers.

In the examples described in Sec. 6, spatialization worked best with an additional perceptual input, e.g. a graphical user interface or the real movement in a tracked virtual surrounding (e.g., Sec. 6.3).

Timbre space

Timbre can be used to display structural information. Close points in a timbre space should be perceived as similar, while remote places should sound differently. The mapping of percepts to stimuli is important for sonification, but also needs a broader perspective than reduced variables in laboratory conditions. An attempt to create a perceptually scaled sonic space made by Barrass [Bar05b] originally appeared in the ICAD proceedings in 1994. He used pitch, brightness and (circular) timbre as space dimensions, derived from the Hue-Saturation-Lightness perceptual color model. In a review [Bar05a], the same author admitted that *"the step from color space to sonic space was not as straightforward as [he] had thought"* due to the lack of orthogonal sound axes and he called the mapping *'bumpy'*. A subsequent effort for a timbre space has been undertaken by Nicol et al., see [NBG04]. A complete perceptual sound-space model would be invaluable for sonification but is not within reach, also due to the complexity of cognitive processes involved in auditory perception.

If no complete orthogonal timbre space is available, simpler drafts can still be useful. For instance, each site of a 3-dimensional space can be mapped as a chord of three notes at different scales. Small movements are perceived as similar sounds, while remote places will also sound 'remotely'.

Shepard scales

In 1964, R. Shepard published a paper describing an interesting auditory illusion – an ever-rising scale. Analogously to optical illusions, like the circular staircase illusion by M. C. Escher, Fig. 35, he created a scale that the human ear perceives as constantly rising. It consists of several frequencies in exact octave pitch, $f_n = 2^n f_0$. The amplitudes of these frequencies are distributed with a peak around the central frequency, as shown in Fig. 35 on the right-hand side. While the pitch of all frequencies is raised, the amplitude distribution stays the same. Thus higher frequencies slowly fade out, while lower frequencies fade in. The assignment of the main frequency shifts in the perception, without the jump being explicitly realized.

The Shepard scale is an interesting tool for the display of periodic data, as can be seen using the example of an angle: while the sound continuously changes by increasing or decreasing the angle, there are clear differences for opposite angles.

The concept of the Shepard pitch scale can be generalized also to other sonic attributes. For the sonification of TPC data described in Sec. 6.5, a simple version of a Shepard *timbre scale* was implemented. Even and odd overtones of a basic frequency are faded in and out. Also a rhythmic variation is possible, as worked out by J.-C. Risset based on the work of K. Knowlton, [Ris98]; for a listening example see and hear [wike].

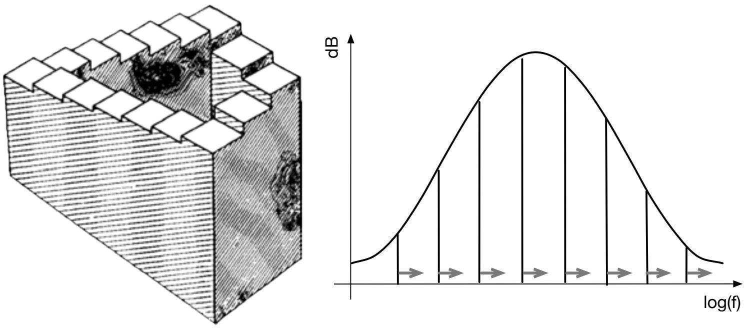

Figure 35: *left figure* – Escher's optical illusion of rising stairs. [She64] *right figure* – The Shepard scale. The x-axis shows the logarithm of the frequency, the y-axis the amplitude distribution (in dB).

Digital waveguides

The digital waveguide mesh is an efficient method of simulating wave propagation numerically [Smi06]. Physical space is discretized, and at each mesh site left- and right-going wave functions are summed up in a traveling-waves solution approach.
In the example described in Sec. 6.4.2, a digital waveguide model is used for a sonification of cluster data. Large clusters form large caves of uniform 'material' in the mesh, small clusters small caves. If the mesh is excited at one end, e.g. using white noise or an impulse, a wave will propagate in the caves and produce resonances depending on the cave size. The resulting sound gives information on the cluster structure that can easily be understood from everyday experience with spatial sounds.

4.2.6 *Sound Elements: 'gestalt units'*

Elements in the sound model are harder to define than in the data model. They are determined by the sound synthesis, but the real sound elements are the smallest perceived psycho-acoustical *gestalts* (Sec. 2.1), the 'gestalt units'. The elements can be single sounds, as for instance single grains in granular synthesis, but can also refer to a larger entity, e.g., a resonance frequency in the spectrum of the waveguide example cited above, or frequencies determined by phase modulation.

Concepts that have to be taken into account in the sound element decision are basic psycho-acoustics, such as masking effects, and higher level psycho-acoustics, similar to the 'echoic memory time frame' used by de Campo in the context of the SDSM [dC09].

Granular synthesis

Sound grains live on a *microsound* time scale, between the time scale of audiables (or, in the musical context, of notes) and the sampling time scale. Grains differ, e.g. in their envelope, waveform, duration, spatial position and triggering onsets, and are played simultaneously and/or sequentially. This leads not to perceived single events, but to an overall impression, which is called a grain cloud or characteristic texture. [wika]
In a statistical context, granular synthesis can be used to recreate a sort of *psycho-acoustical averaging* of the data. The perception receives many single events, but acquires an overview of the data. For an example of an application see the Ising grain clouds in Sec. 6.1.2.

(Distorted) modulation

Modulation is another basic method of sound synthesis, where three types can be distinguished: amplitude, frequency and phase modulation. Modulation can be used together with audification; the audified data is, e.g., used to modulate a basic sine wave, as in the Ising audification (Sec. 6.1.2). The sound is more controllable than with audification only, as the basic frequency and the modulation sampling rate can be set.
A more refined approach has been implemented with the XY model data (Sec. 6.2). The phase of a basic sine wave is modulated with closed loops of the data, the data values being interpolated in order to achieve a pitched sound. The interpolation can be used to feature certain aspects of the data. In the XY model a cosine interpolation was used. The original signal was distorted and normalized in order to get a resulting phase where large changes in the data are amplified and small changes suppressed.

4.2.7 *Implementation*

Implementation also plays a role in the development of the sound and data model. It consists of the playback and interaction possibilities of the hardware, on the one hand side, and the programming of the software, on the other.

- The most basic decision is the choice of the interface: *audio only* or *multi-modal* (with a visual, haptic, or some other interface).
- The interface can be *interactive* or an automatized *playback*, depending also on the data model and the expectations and possibilities of the domain science.
- Finally, in either an interactive or a playback scenario, there are *systematic* or *random* displays: the data is played systematically according to some pre-defined rule, or random data values or regions are chosen.

The implementations of the sonification designs described in Sec. 6 are all multi-modal, mostly using graphical user interfaces (GUIs) or an interactive tracking system.

Graphical user interfaces

GUIs proved to be an important part of implementation in sonification design. They make it possible to interact rapidly with the data and to change the sound parameters. The visual display can be used as a second modality to display additional information or the same information redundantly. (Of course this does not apply if the target group of the sonification are visually impaired people or if there are other contextual objections to the use of visual display).

Interactive motion-tracking

The CUBE [ZRS03] is the performance hall of the Institute of Electronic Music and Acoustics. It is equipped with both a multi-speaker array and a VICON motion-tracking system [vic], which was used to create virtual auditory environments. While this set-up demands a high technical outlay, it provides remarkable interaction possibilities, as for instance was achieved with the data listening space (Sec. 6.3; see also the discussion of the evaluation, Sec. 4.4).

4.2.8 *Conclusion*

In a synopsis of the final sonification designs described in Sec. 6, two general approaches to the design decisions can be found. While all start with the 'data meaning', a *bottom-up approach* works first with data elements mapped to sound elements. On the other hand, a *top-down approach* defines a sound metaphor before the actual synthesis is tackled, see Fig.36.

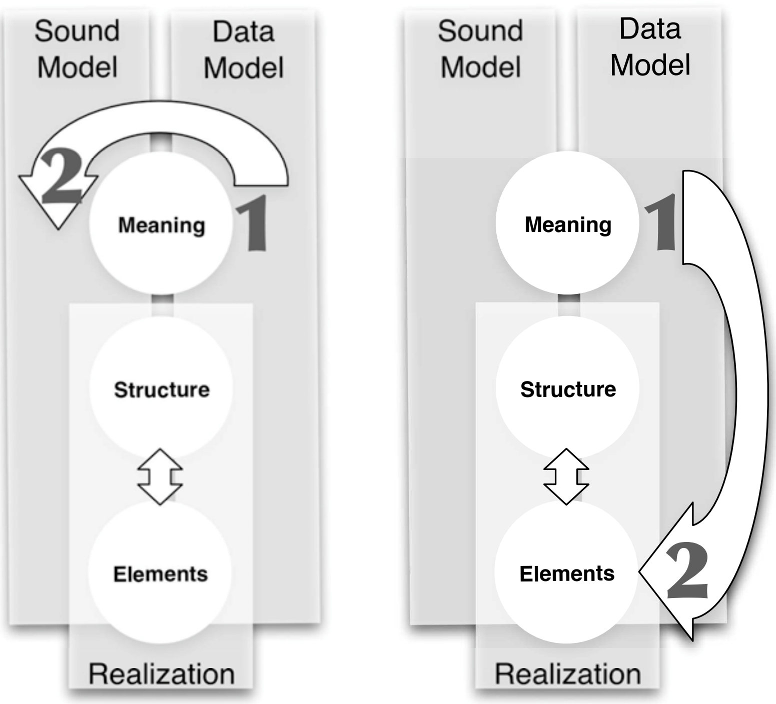

Figure 36: Course of action in the design process. On the left-hand side, a 'metaphorical' top-down process is shown. On the right-hand side, the process starts with the data meaning as well, but then continues with the elaboration of a concept for sonifying individual data elements.

In a bottom-up process, the first design decision concerns the display units: which data elements are used for the sound synthesis, and how they are transformed into gestalt units. Only then is the structural organization of data and sound taken into account, and audiables and a sound meaning emerge from the process.

For many exploratory contexts, the bottom-up approach is the only possible way, because the audiable and its meaning are unknown. In some cases, at least the global sound meaning can be shaped. For monitoring tasks, the sound meaning should in any case be chosen equivalently to the data model, as sonifications are better accepted by a community if the 'sound language' is understood from the beginning. A metaphoric sonification method as top-down design process is discussed in detail in Sec. 4.3.

4.3 METAPHORIC SONIFICATION

4.3.1 *Metaphors and sonification*

Conceptual metaphors have been discussed, e.g. by G. Lakoff and M. Johnson [LJ80]. Metaphors help us understand an idea in a target domain by citing another one in a source domain. Even more fundamentally, they shape our perception of reality. Science also builds on existing experiences: *"So-called purely intellectual concepts, e.g., the concepts in a scientific theory, are often – perhaps always – based on metaphors that have a physical and/or cultural basis. The high in 'high-energy particles' is based on* more is up. *[...] The intuitive appeal of a scientific theory has to do with how well its metaphors fit one's experience."* [LJ80, p. 19]

For a *good* sonification design, it would thus be enough to know about the underlying metaphors of a scientific theory *and* the metaphors for the sounds of basic experiences. By mapping, e.g., higher energies to what people in our culture perceive as *higher* in sound, a completely intuitive sonification could be created. Already in 1995, B. Walker and G. Kramer [WK05b] wondered whether there is something like best auditory mappings for certain data properties and what they might be. They tested different mappings which they had assessed as *good* or *bad*, and were surprised by the actual outcome of the test, because the 'bad' mappings actually led to best results. The same authors pointed out that *"interface designers have usually implemented what sounds 'good' to them"* and concluded that testing with the final users is crucial. An effective mapping cannot be predicted a priori and the polarity of mapping has to be taken into account as well. The results are also interesting in the specific context of our data, as they found for instance *"that increasing mass is generally best represented by decreasing pitch"*.

B. Walker conducted several studies in this direction [Wal02, Wal07]. He implemented magnitude estimates between sound attributes and conceptual data dimensions. Magnitude estimation is a standard psycho-acoustical procedure for studying the dependancy of an acoustic variable on its perceptual correlate (e.g., frequency and pitch). Walker extended the method to conceptual data variables. For data-to-display pairs he found positive or negative polarities (the increase in a data dimension is reflected by the increase or decrease of the sound attribute), and scaling functions, giving also the slope of the dependency. In extensive experiments he showed that polarity and scaling functions matter for the quality of AD, and a priori predictions about the best choice are often difficult, but can be determined empirically. For some mappings, the analysis showed unanimous polarities, as, e.g., for velocity to frequency. For most mappings, the positive polarity was dominant. While these results are highly valuable for sonification design, a complete analysis of the sound metaphors of any scientific theory is beyond the scope of creating an AD. Therefore, I tried a similar but more focussed approach, in response to the pragmatic needs of finding mapping choices for a particle physics sonification (Sec. 4.3.2).

S. Barrass argues that sonifications should be done in the 'world of sound' that the end-users know. In a physics' related context, e.g., the sound of a Geiger counter is one that can easily be understood, even if the data have nothing to do with radiation at all. *"The Geiger-counter schema also seemed to reduce the amount of time it took naïve users to learn to manipulate the [...] data, and provided a context for interpreting the sounds in terms of the geological application domain."* [Bar05a, p. 405] Also in the experiments cited above, different listener groups (e.g., blind and sighted people) chose different polarities as the best data display. Walker concludes that *"sonification must match listener expectance about representing data with sound"* and that it *"is also important to consider the perceptual reactions from a more diverse group of listeners"* [Wal07]. While the latter argument referred mainly to individuals differing in listening expertise, I argue that also differences in the conceptual understanding of data dimensions play a role. Energy in the context of macroscopic objects might mean something completely different to engineers than it might mean in the microscopic view to particle physicists. In agreement with Walker, we assume that general metaphors that are valid in any context can never be achieved. It will not be possible to produce a general table that a sound designer can simply read out for any sonification problem. *"As with any performance data that are used to drive interface guidelines, care must always be taken to avoid the treating the numbers as components of a design recipe." [Wal07, p. 596]*

Motivated by these assumptions, we developed a metaphoric sonification method, *metaphor*, Fig. 37. The basic idea is to ask scientists in the field about the sounds or metaphors they use or what they expect special data properties to sound like. The method is a sensible starting point for sonification design because it permits the designer to make informed parameter mapping choices. It can also be used for event-based methods as earcons or even for model-based sonification, where at least parameter tuning can be adjusted to fit the sound results to the intuition of the domain scientists. The method does not deliver a ready-made sonification design, but rather leaves creative space for the specialist who – by questioning the domain experts – gains insight into their possible 'world of sound'.

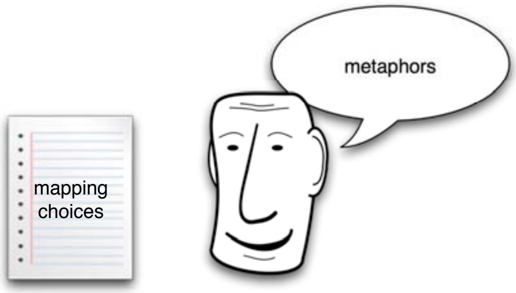

Figure 37: Metaphor sonification method. A questionnaire on sound metaphors and possible mapping choices.

One current approach to support the sonification design process is EarBenders, a database of stories about everyday listening experiences by S. Barrass [Bar97]. He suggested this method in analogy to classical case-based design from human-computer interaction because the sonification community still lacks a sufficient amount of case studies of ADs. The database can be accessed when a new sonification design is needed for a field in which the designer has no previous experience. One method of searching the database is a metaphorical one. Barrass argues that a *"metaphoric design can help when sounds are not a natural part of the design scenario, which is often the case in computer-based applications."* [Bar97, p.51] But even with a large data base, a search for a new sonification problem often does not deliver exact matches. Several general sonification design methods have been elaborated, and these are discussed in Sec. 4.

The power of metaphors

A comment is appropriate here on the human nature of sensorial metaphors. Mappings of conceptual data variables and auditory percepts are rarely homogeneous, i.e., judged similarly by different people. This may partly be a result of learning, but it may also be intuitive in the sense that cross-modal metaphors are found in common language (e.g., a *tone* color). Martino and Marks [MM01] suggest that this as a form of weak synesthesia compared to strong synesthesia, where associations between an inducer in one modality cause induced percepts in another (e.g., seeing absolute colors when hearing corresponding tones). While correspondences in strong synestehsia are systematic and absolute, in weak synesthesia they are defined by context. The authors suggest a *'semantic-coding hypothesis'*: high-level sensory mechanisms are involved, which are developed from experience with percepts and language. Thus also language can cause percepts, and these are rather homogeneous within a group of people from the same cultural background.

4.3.2 *A metaphoric sonification method*

Our metaphoric guideline on sonification design is similar to that of EarBenders, but for the case that no a priori sound examples exist. It allows the sonification designer to gain insights into the field from a meta-level point of view. The method is based on asking potential sonification users about which sounds they would expect or associate to the data and the task. Different kinds of metaphors in the answers are then re-interpreted to the sound domain. The procedure can be generalized as M–ET–APH–OR:

MATERIAL: Become acquainted with the data. Define which features should be covered by the sonification. A TaDa (see above and [Bar97]) may help in this task. Set-up a questionnaire, which may give you cues for the most important metaphors of the domain science. Include a free, associative part and a part with suggested mapping choices including the polarity. Define number and (the professional/ personal) background of the interviewees.

EXPERTS TALKS: Interview domain experts face-to-face and record the interviews.

ANALYZE PHRASING: Take notes on the questionnaire, extract and describe the sounds of the recordings. (For instance, intra-personal fits or misfits between language metaphors and the produced sounds can be interesting.) Collect the sonification ideas that have come up during the interviews. If there is enough data material, do some statistical analysis. Find common (inter-personal) metaphors. List also differing metaphors or cases where, e.g., the polarity of the mapping seems unclear.

OPERATE WITH RESULTS: Based on the results of the questionnaire, decide on the best mapping choice and implement it.

The main outcome of this procedure is knowledge about the specific metaphors and associations of scientists (or others) in their specific field. As a side effect, ideas for the basic sonification design can come up during the interviews – more than a single sonification designer would have thought of. In addition, if a domain scientist contributes to a sonification in this way, s/he will have already spent time with it and will be curious about the outcome. Thus the sonifications may be more widely disseminated.

It is important to record the questionnaire, because it is hard to speak about sounds, especially for people who have never done so before. Firstly, the recording allows the interviewees to *make* sounds rather than describing them. Secondly, misunderstandings can be avoided, especially when the interviewee and/or the sonification expert are not native speakers of the same language. It has to be taken into account that most test persons can think of more sounds than they can actually produce. The personal interview is very important because it helps the designer get information about the metaphors behind the sounds. Finally, the recordings of the discussions can confirm the decisions of the sonification designer.

A disadvantage of the metaphor procedure is the additional effort. In addition, for a purely exploratory sonification, the metaphors collected in the interviews do not help much, because the main purpose is to uncover new, unknown data features. But for any sonification design effort where at least some known structures involved, this method helps toward a good mapping choice and more acceptance in the domain community.

In developing the method, a short online questionnaire was conducted which is described in Sec. 4.3.3. Then, a larger study was done following the *metaphor* concept defined above. It is discussed in Sec. 4.3.4.

4.3.3 *Preparatory questionnaire*

A small internet survey on the topic *'physics and sound'* was performed between March and June 2009 at the University of Graz. Thirteen physicists, of whom five had completed the questionnaire, were invited to join the survey. According to the feedback, the response took up to one hour. All participants were male, all but one were part-time musicians and all had been working (including studying) in the field of physics for around ten years. Four were majoring in theoretical physics and one in experimental physics. All of the subjects were already familiar with the term sonification.

Several concepts were tested in the questionnaire. The first part was open and asked the subjects to describe sound phenomena that they knew in the field of physics. The second task was to describe simple everyday sounds. In the third section, they were asked to find acoustic metaphors for physical principles or entities. Finally, some personal information was elicited.

The most prominent answer in the first, open part was the Doppler effect.[1] Computer noise was mentioned several times. Also some physics experiments involving sound were described.[2]

In the second part, six simple and familiar physical phenomena involving sound in some way were given, and the subjects were asked to describe them. The phenomena were boiling water, Chladni figures (vibrating plates), the Doppler effect, rolling objects, a string and a running computer. Everyone was familiar with boiling water, rolling objects and a running computer and stated that they had a clear idea about the sound they make. One person was not so sure about the Doppler effect and the string, and two persons were not familiar with Chladni figures.

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[1] One test person made an interesting remark about the Doppler effect: *"Movement of objects can be measured using only one ear."*

[2] An interesting example was the following, as it used sound to illustrate an effect in optics: *"I remember an experiment where sound (a simple sine wave) was scattered at a big model (made out of metal sticks and plastic spheres) of a crystal lattice. The same effect occurred as with light at a real crystal. Walking around the crystal model there where regions with loud and calm noise. So the wavelength of the sound and the lattice constant of the crystal model fitted in the same way as light and a real crystal does."*

The third part discussed more abstract physical phenomena and asked for metaphors for them: *temperature, symmetry vs. asymmetry, a lattice structure, confinement, a phase transition and different particle types*. The answers were valuable suggestions for further work, but not systematic due to the small number of participants.

In total, the questionnaire had a few shortcomings. It was probably too long, thus only few people completed it. Questions seemed not to be phrased clear enough. This was a trade-off to the intention of leaving as much space for free associations as possible, and also led to some unexpected interesting statements. It was striking that many examples of physical phenomena such as the Geiger counter were *not* mentioned during brainstorming or were not recognized in the descriptive part as for instance Chladni plates. The internet provided easy handling for the distribution of the questions and the collection of answers, but proved to be unsuited for a questionnaire on sound. In any case, the questionnaire method was further developed.

4.3.4 *Towards an intuitive particle display*

In particle collision experiments, e.g. at CERN, different kinds of particles are measured. The most common visual display shows colored tracks of particles that are produced by a collision, sometimes as a movie. In a short term project in autumn 2009, I conducted a questionnaire on data from CERN that supported the design decisions for an 'acoustic standard model' of particle physics. The description below follows the *metaphor* procedure described above, even if the experiences from the survey were used to create the method.

Material

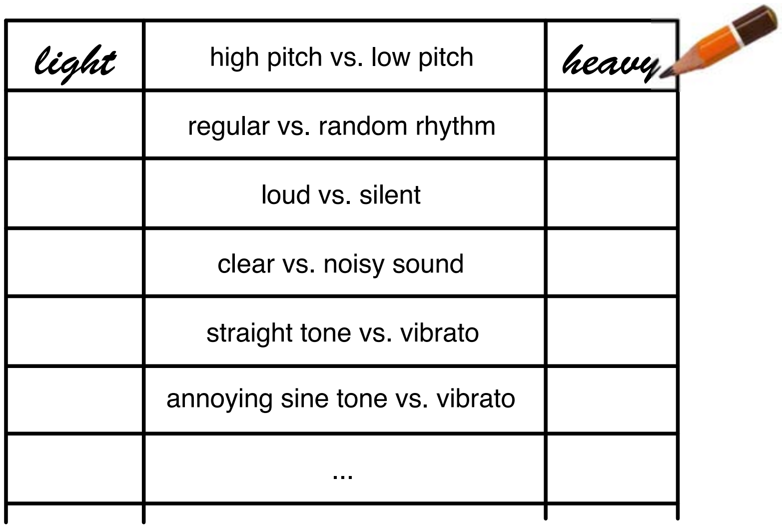
Hundreds of particles have been predicted by the Standard Model of elementary physics and observed in experiments, often referred to as a *'particle zoo'* (Sec. 3.1).

We elaborated a questionnaire on particles, including a short introduction and 3 other parts. The participants were chosen from employees at CERN who have studied physics.

Proton	p	*baryon (constituted of two up-quarks and a down-quark), charge: +e, mass: 938 MeV/*c^2*, fermion*
Anti-proton	p-	*anti-baryon (constituted of two anti up-quarks and a anti down-quark), charge: -e, mass: 938 MeV/*c^2*, fermion*
Electron	e	*lepton (elementary), charge: -e, mass: 0.5 MeV/*c^2*, fermion*
Positron	e+	*='anti-electron', lepton (elementary), charge: +e, mass: 0.5 MeV/*c^2*, fermion*
Muon	μ	*lepton of* 2^{nd} *generation (elementary), charge: -e, mass: 105 MeV/*c^2*, fermion*
Pion	π	*meson (constituted of an up-quark and an anti down-quark, , charge: +e, mass: 134/139 MeV/*c^2 *[*$\pi^0/\pi^{\pm}$*], boson*
Kaon	$\kappa^{\pm}$	*meson (constituted of a down-quark and a strange quark, one of them matter, one anti-matter, charge:*$\pm e$*, mass: 493 MeV/*c^2*, boson*
Higgs	h	*boson (elementary, theoretical), mass: 115-150 GeV*

Table 5: List of particles in the CERN questionnaire with a list of abbreviations and short explanations. (For more information see Sec. 3.1.)

After a short introduction, free associations for eight different particles were elicited, see Tab. 5. The particles were the most common (in our data from CERN), and covered the most important features, including mass, matter (vs. antimatter), charge, and quark content (for hadrons). We included the Higgs' boson as the only imaginary particle, because it was a 'hot topic' at the time at CERN and in the media. This part of the questionnaire was recorded.



light	high pitch vs. low pitch	heavy
	regular vs. random rhythm	
	loud vs. silent	
	clear vs. noisy sound	
	straight tone vs. vibrato	
	annoying sine tone vs. vibrato	
	...	

Figure 38: CERN questionnaire - I: Schematic plot of the table of sound properties with an example mapping choice.

The second part of the questionnaire was not shown until the free associative part had been completed. A table of sound properties with pairs of extreme positions was given (see Fig. 38). We tried to phrase these properties in a general, rather musical wording, avoiding technical terms. The list was open-ended and could be complemented by the interviewees if they had additional ideas.

Then, different particle properties were listed: mass (*heavy vs. light*), matter (*matter vs. anti-matter*), charge (*positively/ negatively charged vs. neutral*), quark content (*up, down, charm, strange, top, bottom*), particle type (*mesonic/ baryonic/ leptonic*), and excitation, again in an open-ended list. They could be chosen and filled into the left or right hand side of the sound properties' table, see Fig. 38. Properties not associated with any sounds were left out.

Finally, personal information including total years working in the field (including studying), name of the field, years working at CERN, gender, and whether the persons ranked themselves as (partly) musicians, music lovers, or none of these, was collected.

Experts talks

All interviews were conducted personally by mysef and had no time limit. In the open part, no additional information was given other than a short introduction to the project. If the test persons were comfortable with this, they were asked to mimic sounds they imagined, or else to speak about their associations.

Twenty-four people ranging from a diploma student to a Nobel prize laureate were interviewed (according to [Wal07, p.596], this number is appropriate for such an experiment). Three participants were excluded from the analysis, as it emerged during the interviews that they had not studied physics. One person did not want to be recorded or complete the questionnaire, but made some general remarks. One interviewee completed only the first, associative part, but not the fill-in part. Thus, 19 questionnaires were included in the analysis, of which two were completed by females and the remaining 17 by males. Five interviewees ranked themselves as *(partly) musicians* and three as *none*, the rest as *music lovers*. The length of the interviews averaged around 15 minutes.

The reactions of the interviewees were very diverse. The task of thinking about the sound of particles, or even mimicking them, was too demanding for some: such responses as *"I am shocked"* clearly reflect that. Many people reacted by saying that they were not the right person to ask: *"You know better than we do what to choose"*, or *"What you need is a synesthete!"* Many participants established a relationship to their actual field of work. For instance, experimental detector physicists would say, *"I am thinking of layers because I am working with detectors and their layers"*. One even extended the notion of a particle detector to the human ear, and suggested the use of very high sounds for particles which are hard to detect: *"I am already hard of hearing with high-pitched tones"*. Those, who did try to mimic the sounds they thought of, experienced problems with the task. *"I hear my sound and I think - 'Ahh, that's not exactly what I meant'. I cannot produce all the sounds that I imagine."* One participant tried his sounds out several times in order to improve fitting his actual vocalizing to his imagination.

Nevertheless, 12 people did produce sounds and three participants even suggested specific sounds for all eight particles on the list. The recordings of the free questionnaire part for all particles are available at http://qcd-audio.at/tpc/quest. An overview of all answers of this section can be found in the Appendix (Fig. 69).

Analyze Phrasing

For the analysis of the metaphoric sounds, the particle sounds were cut from the recordings and normalized. The spoken descriptions were also collected, and general ideas for the sonification design were extracted. The approaches in the recordings can be summarized as follows:

- Most people started systematizing already during the free, associative part – they are trained physicists. A clear majority suggested to map mass to pitch as the very first association.
- Phonetic or spearcon approaches following the particles' names were often applied. For instance the Higgs' sound was associated with a *"higgs"* or just *"igs"*, or proton became an *"ooo"* and the pion an *"iii"*.
- Many comparisons to the measurement were drawn. E.g., heavy particles collide *loudly*, or particles behave differently in various layers of the detector.
- Some suggestions were very concrete. (The examples cited here were taken into account in the display.)
  - Tone patterns, like J. S. Bach's famous b-a-c-h fugue theme, would make it possible to recognize particles. Simple particles, like protons, can become something like a bass line.
  - Each quark flavor can have a certain pitch assigned to it, meaning that hadrons are played as chords (thus baryons would sound like triads, for instance).
  - Matter is a normal sound and anti-matter is its reversed playback.
  - Particles sound like *cars passing by*, with their passing time and pitch variation depending on their speed.

Some statistical analysis was done, but as only 19 people were taken into account, no significant results were found regarding different backgrounds. Fig. 39 shows how often particles were mimicked with sound or described (in words) in the associative part of the questionnaire. The Higgs' particle was treated most often, possibly because it was a popular topic at the time. The Higgs' sounds were often meant to be funny, e.g., *"tadaa"* or *"kaboom"* for some earth-shaking discovery. Neglecting the Higgs', the figure shows that well-known particles as electron and proton are cited most often. There were much fewer associations for rare particles.

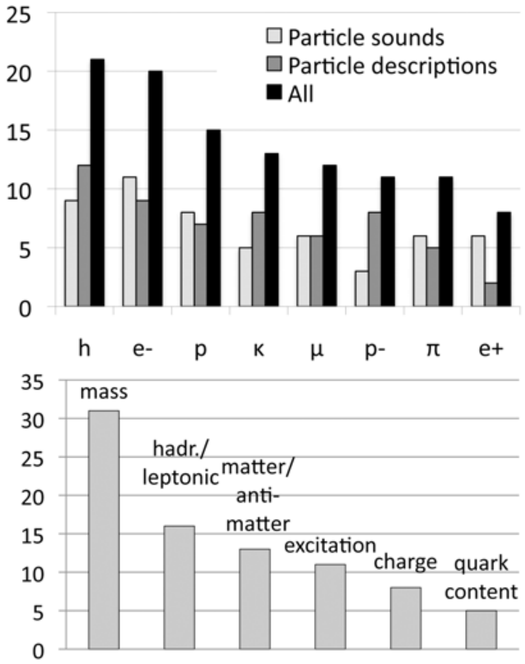


Figure 39: Quantitative results for the CERN questionnaire:
Upper figure: Overall number of particle descriptions and sound associations, sorted by their sum.
Lower figure: Number of entries of the particle property into the table of sound properties.

Some particle properties were used much more often for mapping suggestions. Many subjects linked mass, the general particle type or matter (vs. anti-matter) to sound properties. Mass, for instance, has a macroscopic meaning that can easily be associated with sounds. The particle type (e.g., hadronic or leptonic) is more abstract. For anti-matter, many explanatory metaphors exist - e.g., an anti-particle was described as its particle *"seen in a mirror"*. The quark content, at the end of the table, is an abstract property and was only cited a total of five times in all interviews.

Proton:	*low pitch, resonant, round and rather dull sound, 'fat and heavy', ordinary, 'thick' sound*
Anti-proton:	*reverse to or similar to p+*
Electron:	*high pitch, quick sounds,"ping", light and bright sound, "like lasers in Star Wars"*
Positron:	*reverse or similar to e-*
Muon:	*is lower than but similar to e-*
Pion:	*is low-pitched and/or falling in pitch, but similar to p+, "a wavy collective thing"*
Kaon	*similar to other mesons, lower pitched than π, sounds harder*
Higgs:	*spearcon and phonetic approaches ("hicks", fanfare), impressive, crazy* *or monotonous background noise (e.g., "like a foghorn")*

Table 6: Distilled list of features for the eight particles as described in the free part of the CERN questionnaire.

The qualitative analysis of the particles led to metaphors and associations shown in Tab. 6. Non-congruent adjectives were previously omitted.

The most obvious mapping choice was pitch with mass, heavy mass meaning low pitch. *All* answers in the table were given accordingly (only the direction of the mapping was *once* given contrariwise, high mass being mapped to high pitch). These results are in line with experiments of Walker [Wal07], where also a few (2 out of 19) participants chose opposing polarity for mass to frequency. In general, increasing sound frequency corresponds to decreasing mass.

The results of the sound property table are shown in Tab. A.1 in the Appendix. The most prominent choices were used for basic mapping decisions:

Mass, as a central particle feature, clearly was linked to *pitch*, which is a salient auditory percept. Charge was suggested for *amplitude* second most often after pitch. In general, *rhythm* was associated more with the experiment, measurement or data. There was no clear mapping choice for *noise*, due to inconsistent polarities. Vibrato was the favorite mapping for excitation.[3] *Timbre*

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[3] However, it should be mentioned that the term 'excitation' was ambiguous. While it refers to the excited state of the particle as opposed to the ground state, the notion was misleading because this cannot be seen directly in experiments.

had only few total number of suggestions, possibly because this concept is too complex.

Operate with Results

In general, each particle should be displayed as a recognizable sound of varying length, which can be transformed according to the dynamics dictated by an experiment. With all knowledge from the above, we worked out the following sonification [KH10]:

Mass is mapped to pitch, and each elementary particle (quark/ lepton/ boson) has an assigned pitch. First generation quarks (up and down) form a small, regular interval (a third). The strange quark is a *strange* mistuned fourth, and the charm is the *charming* octave, all in relation to the p quark, which is lightest and thus highest pitched. Bottom and top quark follow, each an octave lower. Perceptual grouping between different quark generations is difficult, but such composite particles are rarer in any case.

The leptons are separated from the other particle sounds into higher registers, and have a *light*, e.g. a flageolet sound. The corresponding neutrinos follow as clear sine tones an octave above the leptons. The pitches vary slightly for every observable around these frequencies. In Fig. 40, some examples are shown.

Every sound has a clear attack and decay. For anti-matter, the sound is reversed.

Hadrons are composites of 2 or 3 quarks - the corresponding pitches are played successively as a tonal pattern, always starting at the highest pitch. Also the tone lengths of the quark sounds vary with mass, resulting in a polyrhythmic structure.

Charge is given by a crescendo (positive charge) and a decrescendo (negative charge) on the whole structure (the tonal pattern for hadrons or single sounds for the other particle types). A neutral particle is steady in amplitude.

Each observable (hadron or lepton) is played by one musical instrument. This assures the perceptual grouping of the individual quark sounds into one coherent particle and allows it to have a certain characteristic timbre. Surely, more hadrons exist than perceptually distinguishable instrumental timbres are available, but they rarely all appear together in one measurement. A violin sound can be used for the frequently occurring proton, as it is the dominant instrument of the orchestra. A viola sound is chosen as the more 'neutral' instrument in comparison to the proton-violin; the viola represents thus the neutron.

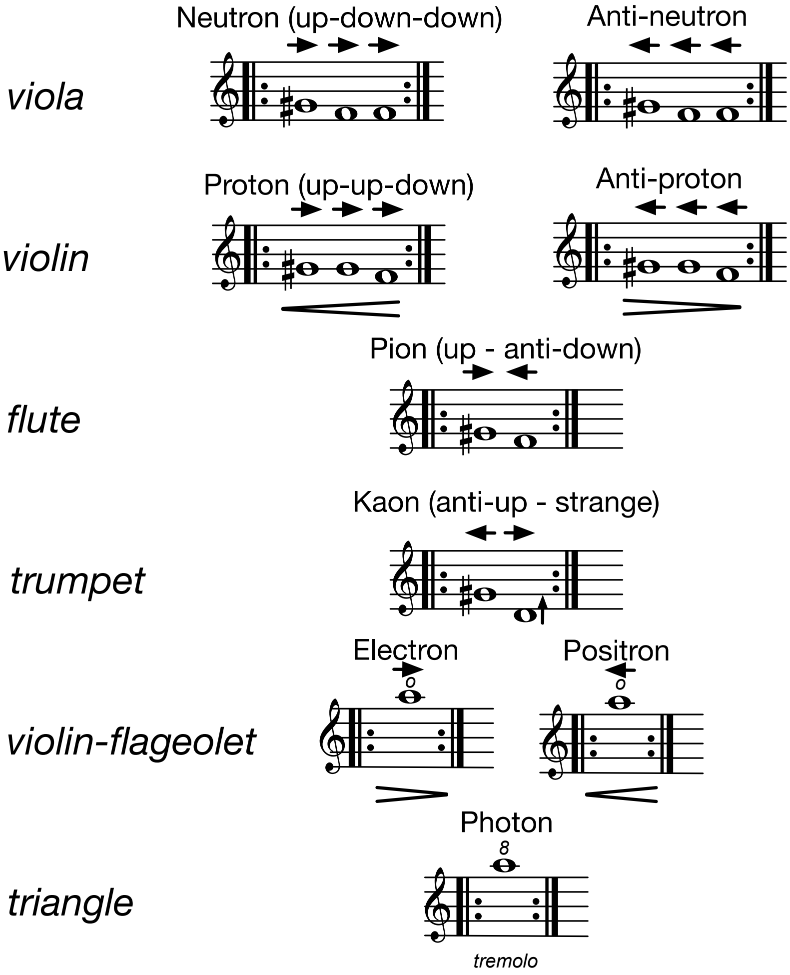

Figure 40: Example for the acoustical standard model. The forward and backward arrows denote the forward or backward playback time for each elementary sound.

The dynamics of the experiment can be implemented as spatialization and/or the Doppler effect, using the passing car association mentioned above. Oher particle displays are possible with this basic scheme: e.g., the sonification of 'static' Feynman graphs.[4]

Discussion

The metaphor procedure proved to be helpful for our purpose, and the resulting sonification design is coherent and possibly intuitive. Although a free, associative approach was rather demanding for the subjects, I was surprised with their many interesting sonification ideas and the sounds they were ready to make.

Some outcomes may not be surprising to those who have previously studied intuitive mappings. As cited above from [WK05a], high mass is normally linked to low pitch, which also makes perfect sense from a macrocosmic experience point of view. Still, I found it interesting to ask physicists about microcosmic structures, where high mass equals high energy, and could in principle be mapped to pitch with a different polarity (high energy to high pitch). The analyses showed that the high mass - low pitch metaphor is so strong that it also holds for microcosm and is even mentioned as the first association in open questions.

There is a trade-off between *open* and *concise* questions. While the sonification expert should not include too many of her/his own ideas into the questions, this lack of structure might also led to some misunderstandings. Misinterpretations probably occurred with the sound parameters, as they were explained in 'non-technical' terms. This could be – and should be – solved by *playing* actual sound examples for the participants.

Some conclusions can be drawn about the particle data set and the participants. 'Everyday' properties, such as mass, are cited much more often than abstract properties, like quantum numbers. Two explanations can be thought of: first, imagination is limited when the participants are accustomed to treating their problems only mathematically; second, the metaphorical shift from mathematics to a perceptual quality is too demanding for a simple questionnaire. Analysis also showed that the concepts of particles become clearer, the longer people work in the field.

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[4] Feynman graphs are complete schematic representations of equations describing particle decays among other processes.

This can be a benefit, because strong metaphors emerge from professional experience, but also a drawback, because there is a lack of flexibility with new modalities, such as sound.

The method in general helps with basic design decisions, but also restricts it. Because the sonification of complex data is already very demanding, another condition has to be taken into account. Although the metaphor method is quite easily applicable for parameter mapping, the possibilities for metaphoric sound design for model-based sonification are rather limited. Metaphors can still be implemented in the model design (rather than in the sound design).

An open question not directly covered by the proposed method is the evaluation of the sonification. This has to be done using other methods, as will be discussed in the following section (Sec. 4.4).

4.4 QUANTITATIVE AND QUALITATIVE EVALUATION

Evaluation of sonifications is a challenging problem. On the one hand, the goal of sonification in research is exploration and gaining new insights. When this goal is reached, evaluation is no longer needed. In order to reach it, sonification methods have to be further developed, and evaluation is one important step to do this. On the other hand, 'classical' survey research can usually not be applied. It is hard to find a cohort that is large enough for statistical analysis, that is willing to really engage with first sonification approaches, and has sufficient interdisciplinary knowledge to assess the sonification for both its sonic and domain science value.

Several different evaluation methods were tested by myself and collaborators in the research projects SonEnvir and QCD-audio. As a quantitative approach we used multi-criteria decision analysis (MCDA, [Oma04]), where a set of criteria was established for the evaluation of sonifications, and several different sonifications could be compared with each other during a workshop. A qualitative approach was tested for data listening space, following T. Bovermann [Bov09] using video analysis of participants interacting with the system complemented by qualitative feedback and the evaluation of the same criteria as above. Before these methods are discussed, an overview of evaluation in the ICAD community is given.

4.4.1 *Evaluation in the ICAD community*

In a screening of all ICAD papers between 1992 and 2009 that had *evaluation* in their title, keywords and/or abstracts, I found the following meanings and concepts of evaluation within the ICAD community (as there are some 70 papers in the list, only those are cited which have evaluation as part of their title):

USER INTERFACES AND DISPLAYS: By far most of the evaluation examples stem from tests with user interfaces and displays. This category is very diverse, including the use of technical applications (from phones to cockpits [BS08] and train cabs [ZS98]), sonified graphical user interfaces [Wer09], auditory displays for visually impaired or blind people [SBWE94, Wer08] (e.g., auditory graphs and spreadsheets [Sto04]), sonic interaction design [PH07], auditory tool palettes [BC97, CB98], auditory icons and earcons [Luc94], and alerts. For these applications, efficiency assessments have been used, asking how long it takes to receive a certain information from the user interface; sometimes in comparison to other modalities, as visual display. In general, some sort of quantitative analysis is used as evaluation tool in this context.

PSYCHO-ACOUSTICAL ASPECTS: Psycho-acoustical aspects are evaluated. These provide insights into the relationship between stimuli and percepts, e.g. timbre or synthetized sound [MW01]. E.g., cross-modal influences between vision and audio [DRF07, RW07] or even multi-modal systems [MB02] are studied. Cross-cultural studies, cognitive factors and learning are evaluated as well. As for psycho-acoustics in general, classical auditory tests are possible [MR97]. Questions are, e.g., which two stimuli are different out of a set of three or how stimuli should be sorted or rated amongst each other (ABX test). (Methods of perceptual audio evaluation are discussed in [BZ06].) All these evaluations are done in the context of simple sounds in testing conditions, thus the methods can hardly be used for the evaluation of sonifications with complex sound phenomena involved.

AUDIO TECHNIQUES: This category unites both audio hardware and software technology, e.g., spatial audio quality [GLCB07, SBC07], binaural rendering, auralisation [LJ01] or HRTF design [MNT08, YIS08]. It includes also higher levels of techniques, as semantic categorization of audio and audio-augmented reality [JSF05]. In most of these cases, evaluations compare the objective, technical level to the psycho-acoustical level (see previous item).

SPECIFIC SONIFICATIONS AND OTHERS: A few examples of specific sonifications were evaluated, e.g., of stock market data [NB02]. These evaluations are often explicitly called *subjective*, e.g. in [Mar02], because usually the sonification designer and her or his colleagues evaluate the AD.

Some papers were located in music, aesthetics or design theory and dealt mainly with the theoretical aspects of evaluation.

Other evaluation concepts also emerged in the field. Bovermann [Bov09] recently conducted a small survey with experts on how to evaluate a software system for its interaction quality. He found four important modules of interaction quality, namely the *scenario* (in which environment the device is tested), the *material* (e.g., audio/video, questionnaire, or time-measurements), the applied *methodology* (qualitative, quantitative, questionnaire, comparison, heuristics) and *indicators* for the evaluation (qualitative, quantitative or correlation-based indicators). However, the survey did not produce homogeneous suggestions for a specific method of evaluating interaction quality.

Bovermann criticizes the inadequacy of quantitative approaches in the context of exploratory data analysis. In an exploratory data display, the task is unknown and cannot be measured. Assessing the participants' individual performance does not make sense, as an exploratory interface can prove to be *good* even if it works only for one single person who obtains scientifically innovative results with it. Therefore Bovermann suggests a qualitative evaluation approach, based on *grounded theory* [wikb] and (in his case) video analysis of people using the interface. Grounded theory allows for generating hypotheses during the analysis process, in contrary to defining them beforehand. Several examples of tangible auditory interfaces were evaluated with this approach and findings are discussed by Bovermann. I used the method for evaluating the data listening space (Sec. 4.4.4).

4.4.2 *Multi-Criteria Decision Aid*

In the evaluation approaches mentioned above, an objective comparison of the different sonifications cannot be achieved. Nevertheless, this would be preferable, especially if sonifications of completely different data sets are taken into account. More general rules for successful sonification design might be deduced from the comparison of such diverse examples. The sonification designer is usually the only, but at least the primary tester. S/he surely has most expertise, but the final users of the sonification are others – in exploratory data analysis, the domain scientists. For various reasons, sonifications are often not used in scientific routines. General limitations are discussed in Sec. 2.3.3, but to better understand the problems in the specific context, the grounded theory approach cited in Sec. 4.4.1 can give qualitative insights. Quantitative methods are also needed, as the effort is comparatively smaller, larger test groups can be taken into account than in the qualitative approach, and the results focus on the aspects in question. Finally, the conception of a grounded theory evaluation approach of the mainly cognitive processes of listening to a sonification in an exploratory context is a real challenge. As a side benefit, the preoccupation with a sonification of a large group of domain scientists during an evaluation can increase the acceptance of this method in general.

During the workshop Science by Ear II (SBE2) that took place at the Institute for Electronic Music and Acoustics in Graz in February 2010, I tried another evaluation method for ADs. The Multi-Criteria Decision Aid (MCDA, [Oma04]) has been developed for political and economic contexts where different options need to be assessed and several criteria play a role. It may be the case that some criteria have trade-offs between each other (e.g., the need for energy supply in our society vs. an increasing ecological awareness). The MCDA incorporates consensus methods that communicate between different groups (in the economic context, these are stakeholders). For an overview of MCDA methods in the context of sustainable development see [Oma04].

I used one method of MCDA, the *weighted sum* approach. For the context of the workshop, each sonification approach was one option O, to be rated. The stakeholders were the participants of the SBE2, thus domain scientists from physics or related subjects, sonification experts, media-scientists and media-artists. A set of criteria c_i was established and will be discussed in detail below. These criteria were ranked according to their importance, individually and in a group process, and weights w_i were calculated for each criterion (see below). This set of weighted criteria was kept constant for the workshop, but the analysis of the results showed that it partly led to misunderstandings. Therefore I suggest a slightly refined set of criteria at the end of this section. For each sonification, each participant filled out a questionnaire and rated the AD according to each criterion. The rating r_i was averaged and multiplied by each weighting factor, then all weighted ratings were summed up to one final number W:

$$W_O = \sum_i w_i \bar{r}(c_i) \tag{4.1}$$

During the three-day workshop, 11 sonification approaches to 4 different data sets were developed and rated. A total of 189 questionnaires were analyzed.

Set of criteria

I suggested a set of criteria at the beginning of the workshop, an this set was then extended in a discussion. Taking into account the results of the evaluation (e.g., a correlation analysis between the criteria, see Fig. 41) and feedback of the evaluation of the data listening space (Sec. 4.4.4), a final set of criteria is proposed in Sec. 4.4.5. The discussed criteria were *aesthetics/amenity, intuitiveness, learning effort, clarity, potential, efficiency, 'contextability', complexity,* and *technical effort*. (As the discussion during SBE2 took place in the German language, the original terms are given in square brackets in the following.)

The term *aesthetics* referred to the sound quality. This term was replaced with *amenity* [Annehmlichkeit] in the discussion, as aesthetics is a broader concept from artistic research. The criterion itself was rather clear and was accepted by the participants. Amenity of the sound is important, as listeners are very sensitive to what they hear, and the level of annoyance is usually reached more rapidly than with visual displays.

Intuitiveness [Intuitivität] was one of the disputed criteria. One criticism was that intuitiveness is always achieved by learning – any AD becomes 'intuitive' after a while. The notion *familiarity* might be more appropriate in characterizing how well the sound fits the data or whether the mapping choices make sense to the listener. But the main criticism was that intuitiveness/ familiarity is not applicable to all cases, as most abstract data have no 'intuitive' sound equivalence.

Learning effort [Lernaufwand] was taken into account because sonifications need to be comprehended within a rather short amount of time, otherwise domain scientists will not start using them. The criterion was rather clear in the discussion.

Clarity [Deutlichkeit] refers to sounds, and how easy it is to perceive the structures of interest against a given sonic background.

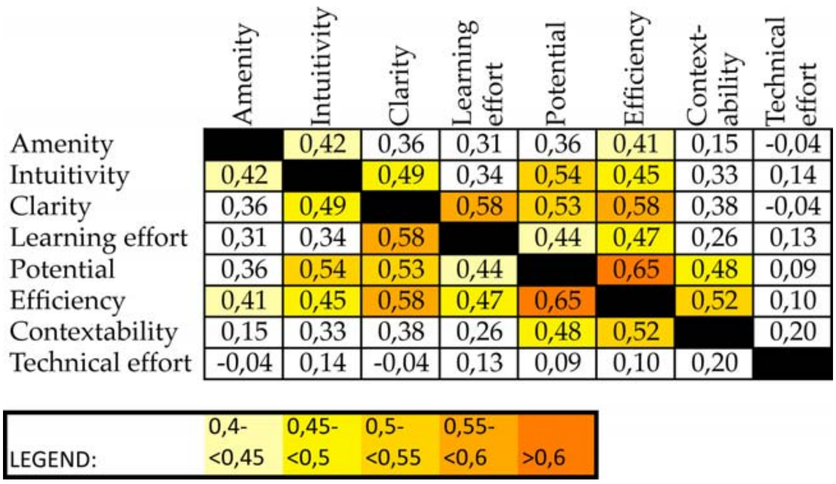
Potential Originally called benefit [Gewinn], this criterion was renamed potential [Potential] during the workshop. A sonification shows potential if it achieves some added value, e.g., in comparison to classical displays, mathematical or numerical treatment, or for special applications. The criterion was unanimously accepted.

Efficiency [Effizienz] was added to the criteria in the discussion, but perhaps not clearly enough defined, as discussed below. It was introduced by one of the domain scientists as a measure of efficiency in competition to classical strategies, such as visualization or mathematical treatment.

'Contextability' [Kontextfähigkeit] is a neologism for the ability of the sonification to work in certain context, defined usually in reference to the physical surrounding. Depending on the application tasks, this could be, e.g., the ability to complement a visual display, or, in laboratory condition with other sounding measurement devices, the distinctness of the AD.

Complexity [Komplexität] was a measure of the 'non-triviality' of the sonification task. I suggested it in the first place because it is one thing if simple data are sonified (like the trend of temperature values over time), but another if 4d data are sonified from QCD. While the first example might be rated as a perfect sonification according to many criteria (amenity, learning effort or clarity), this is much harder for the latter. The weighted sum also needs a measure of difficulty for the task and data in order to balance the result. In the discussion this criterion was rejected for the workshop, as it measures an independent quantity - the data - , and not the sonification.

The *technical effort* [Technischer Aufwand] was suggested by participants of SBE2. It is a measure of the applicability of a sonification, and of course it influences the probability that it is used.



	Amenity	Intuitivity	Clarity	Learning effort	Potential	Efficiency	Context-ability	Technical effort
Amenity		0,42	0,36	0,31	0,36	0,41	0,15	-0,04
Intuitivity	0,42		0,49	0,34	0,54	0,45	0,33	0,14
Clarity	0,36	0,49		0,58	0,53	0,58	0,38	-0,04
Learning effort	0,31	0,34	0,58		0,44	0,47	0,26	0,13
Potential	0,36	0,54	0,53	0,44		0,65	0,48	0,09
Efficiency	0,41	0,45	0,58	0,47	0,65		0,52	0,10
Contextability	0,15	0,33	0,38	0,26	0,48	0,52		0,20
Technical effort	-0,04	0,14	-0,04	0,13	0,09	0,10	0,20	

LEGEND:	0,4-<0,45	0,45-<0,5	0,5-<0,55	0,55-<0,6	>0,6

Figure 41: Correlation matrix showing correlation probability of pairs of criteria, calculated from all questionnaires of the SBE2 according to Eq. (4.2).

For the analysis of the criteria, a correlation matrix of all criteria pairs was calculated according to Eq. (4.2), where x and y are the mean samples of two matrices X and Y. The results are shown in Fig. 41. Efficiency shows dependencies with most other factors. As expected, learning effort and clarity are linked, as clearer *gestalts* are learned more readily.

$$K(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \tag{4.2}$$

I also analyzed non-ratings, i.e. responses made by ticking *"don't know"* and/or *"not relevant"*. Results are shown in Fig. 42. Contextability, efficiency, and technical effort were often not rated. While efficiency was unclear (as seen from the correlation analysis), the other two criteria seemed to be only secondary and not always applicable. Potential is the only criterion that was *always* relevant, but was quite often hard to assess (*"don't know"*).

Weighting of criteria

Normally, there are more and less important criteria. A central step of the MCDA is the weighting of the criteria. In SBE2, two different methods were tried out. One was the classical assessing of individual opinions by questionnaire. Every test taker had to specify percentage rates for the criteria according to their importance for the evaluation of sonifications in general. The an-

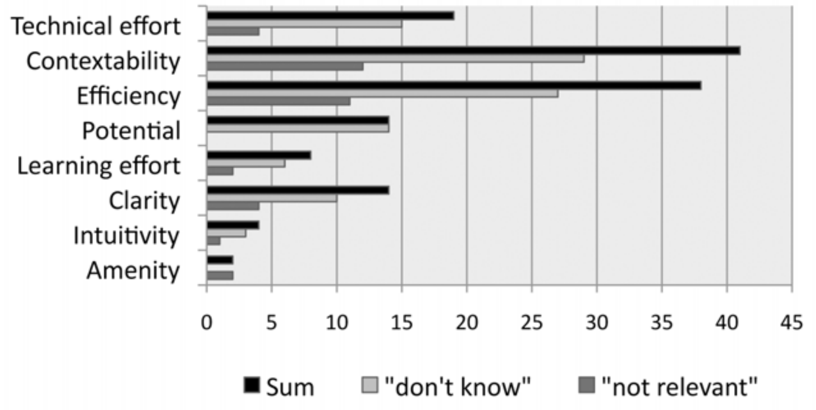


Figure 42: Number of tickings *"don't know"* or *"not relevant"* and their sum over all questionnaires of SBE2.

swers were collected and averaged. The second approach was the *silent negotiation* technique of the MCDA, that achieves a consensus weighting for the whole group. All group members gather around a table, on which cards with the criteria have been placed. One side of the table is designated as "high-ranking", the opposite as "low-ranking". One by one, each person places a criterion card where s/he thinks it belongs. This procedure is repeated until no additional significant changes are made (or until a repeated pattern of changes occurs). The procedure is supervised by a moderator who does not take part in the silent negotiation, and stops the process. During the whole procedure, no discussions are allowed, but the focus on the cards allows for an intensified non-verbal 'discussion'. A photo of the silent negotiation in SBE2 is shown in Figure 43.

From the ranking R_i of the silent negotiation method, weights w_i were deduced for each criterion. In a short discussion, the group agreed on a weight difference of 1:5 from the least important to the most important criterion. The scaling is linear in our case.

$$w_i = R_i \frac{HighestRank}{NumberOfCriteria} = R_i \frac{5}{8} \tag{4.3}$$

The weights were ultimately normalized to the range of 0 to 1, and used to calculate the weighted sum as given in Equation 4.1. The resulting weights found during SBE2 are shown in Fig. 44. Potential and clarity were rated first ex aequo, followed

Figure 43: A group of the SBE2 test takers during the silent negotiation process of weighting the criteria for the MCDA.

by a gap and the other criteria, the last being intuitiveness. Interestingly, averaging over the individual assessments of criteria criteria led to very similar results which suggests the robustness of the consensus approach. Only two criteria were rated differently: intuitiveness and learning effort. The others had results within ±2.5% (!) of the consensus' weights. intuitiveness was correlated with other criteria (see correlation in Fig. 41) and was extensively discussed before and during the silent negotiation (the 'intuitiveness' card was displaced demonstratively). Its final position was largely influenced by the group decision of when to stop the ranking process. Learning effort was assessed as much less important in the individual rating (9.4 vs. 16.7%).

MCDA Results

The final quantitative results of the weighted sum approach are shown in Fig. 45, in chronological order. The sonifications are briefly described in the appendix (Sec. A.2) but some general conclusions are drawn below.

There was a slight trend over the three days of the workshop, that ratings became generally higher. Moreover, 'threesomes' were observed for each data set, where one of the three developed sonification approaches was rated best. Thus, the three 'winning' sonifications stem from one data set each. (This must have been partly accidental, as the questionnaires were filled out immediately after the presentation of the sonifications.)

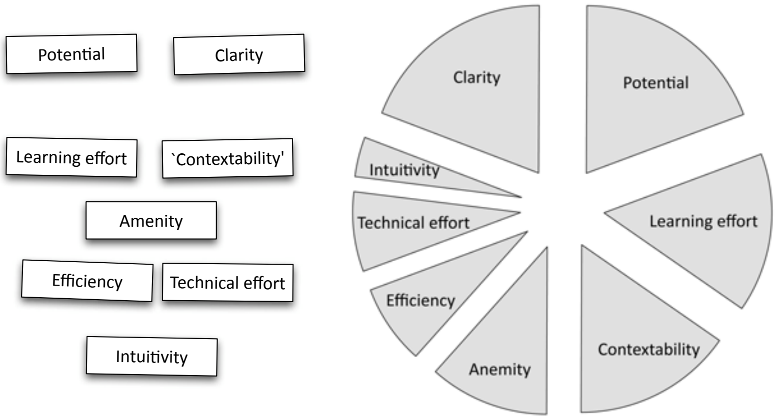


Figure 44: The ranking of the cards in the silent negotiation process in SBE2 is shown on the left-hand side, the resulting relative weights for the criteria on the right-hand side. Potential and clarity were ranked highest. The normalized weights according to Eq. 4.3 are given as (rounded): Potential 20,8%, Clarity 20,8%, Learning effort 16,7%, Contextability 16.7%, Amenity 12,5%, Efficiency 8.3%, Technical effort 8.3%, and Intuitiveness 4.2%.

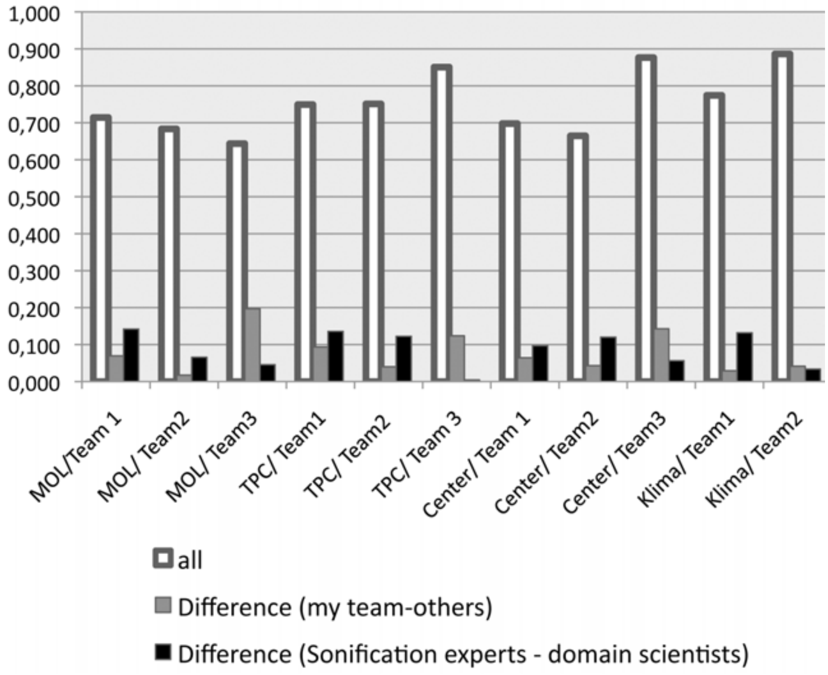


Figure 45: Weighted sums of the ratings of all sonifications developed during SBE2. The three best rated sonification approaches were 'Klima/ Team1', 'Center/ Team3', and 'TPC/ Team3', referring to the name of the data set and the number of the group. Furthermore, the differences between the ratings of the own team results to others and the differences between the evaluation of sonification experts and domain scientists are shown.

Two more indicators are shown in Fig. 45: firstly, the difference between the rating of the sonification of the 'own team' vs. the 'other teams' is shown. For all sonifications, the own team was rated higher than the others. Two factors probably influenced this rating behavior. Firstly, there was often too little time to finish the sonifications properly, thus the presented results only partly reflected the real potential of the approach. Only if the idea is well understood can the real value of the sonification be assessed by people who have not been involved in its design. Secondly I noticed tendency to rate one's own work better than that of others.

The third columns shown in Fig. 45 show the differences between the ratings made by the sonification experts and those made by the domain scientists. In all cases, the sonification experts rated higher than the domain scientists. It can also be observed that the differences in the ratings given to the highest rated sonifications by the two groups were negligible. In general, the differences are not large and the groups rated rather homogeneously.

The 'winning sonification' was elaborated for the climate data set ('Climate/ Team 2'). It received high ratings throughout, including by far the most points for intuitiveness, and clearly highest for amenity. The sonification sounded like wind and thus evoked a climate metaphor, and it was also rated the least annoying sound of the whole workshop. In general, the climate data were also probably easiest to understand.

A sonification of numerical physics data, 'Center/ Team 3', was ranked second. Coherent clusters of different size and shape were to be found in 3-dimensional data sets. The sonification was creative and sounded funny: while amassing sites of a cluster following neighbor by neighbor, the sonification plays in parallel. The longer the cluster was, the more rapid the search became (the sound becoming quicker and higher pitched), to be then suddenly stopped and re-started slowly with a new cluster.

A sonification of the TPC data set, 'TPC/ Team 3', was ranked third. Particle tracks from the time projection chamber from CERN were provided as data. This approach was well implemented, and easy to understand – outliers in the tracks that suddenly changed direction were given high amplitude, thus the quality of a reconstructed track could be assessed with the sonification.

The overall results make it possible to compare sonifications, but a qualitative discussion of the criteria should follow. The sonifications of SBE2 were developed in an intensive workshop on a tight schedule. The teams had only 2-3 hours to understand the data and task, develop a sonification and implement it. Only a short period of time remained for the presentation in the plenum. Therefore in analyzing the results of the workshop, other factors besides the general criteria had to be taken into account as well. The most 'successful' sonifications were generally those whose implementation was advanced and the idea easily grasped by the other plenum members. A more thorough engagement with each sonification would be necessary for a full evaluation. The set of criteria is not complete owing to a bias caused by the specific setting. I suggest a slightly refined set of criteria based on these experiences in the following.

4.4.3 *Revised set of criteria for evaluating sonifications*

A correlation analysis showed that some notions were unclear or interpreted differently by the participants.

Amenity was a clear concept, exhibiting hardly any correlations with other criteria. *Intuitiveness* was much discussed. Although I claim that intuitiveness still should be a criterion for sonification design in the sense of the *metaphor* procedure (Sec. 4.3.2), it showed some correlation with learning effort and clarity and thus might be disregarded as an evaluation criterion. The more intuitive/familiar a display sounds, the quicker it can be learned and the clearer the *gestalts* are perceived. *Learning effort* showed some correlation with intuitiveness and clarity. I wish to retain learning effort as a criterion because the term seems to be unambiguous, and the success of a sonification is influenced by the effort it takes to learn to use it. *Clarity* is also related to the mapping choices (in the case of parameter mapping), and thus should be taken into account for sonification design. In the weighting of the criteria, clarity was ranked first ex aequo with potential and is an obviously important criterion for sonification. *Potential* was ranked at the highest level. In the evaluation of the data listening space (Sec. 4.4.4), participants were confused by the term potential, as it can also suggest the possibility of amelioration (also by changing the sonification!). As a more univocal term, I therefore suggest *gain* [Gewinn] for this criterion, which was suggested during the SBE2 as well. The correlation analysis also showed that the notion of *efficiency* was unclear, possibly because efficiency may mean economy of time either for the sonification itself or compared to classical displays. Because the correlation matrix showed that efficiency was quite highly correlated to potential, I wish to exclude it from the final set of criteria.

The next three criteria are rather secondary for the evaluation of sonifications, and apply only if they are appropriate: *Contextability* might not play a large role in exploratory data analysis. *Complexity* stands for non-triviality, and an refers to the 'challenge' set by the data and task. The *technical effort* is ambivalent, as technical issues may be solved differently (and will become easier in the future) while the sonification design remains the same. Still, the criterion showed the lowest correlation with other factors and is all clear cut.

The proposed final set of criteria for the evaluation of sonifications is shown below, with questions defining the terms more detailed:

Gain	How much is gained by the sonification, e.g., in comparison to other displays or classical methods?
(Gestalt) Clarity	How clearly can differences and interesting structures be perceived in the sonification?
Learning effort	How long does it take to comprehend the sonification and to be able to make use of it?
(Sound) Amenity	How aesthetically pleasing (as opposed to annoying) is the sound?
Additional criteria can be added if useful:	
'Contextability':	Is the sonification applicable in its context (e.g., scientific exploration, public outreach, work environment, etc.)
(Task&data) Complexity:	How complex (or 'non-trivial') did you think the task or underlying data were (<u>not</u> the sonification or sound!)?
Technical effort:	How much technical effort did the sonification require?

Table 7: Criteria for evaluating sonifications.

Because the revised set of criteria differed from the one used during the SBE2, I re-analyzed the data with different weights. I omitted efficiency, which had shown high correlation with potential, and also other criteria. Furthermore, I took the gap between the cards ranked first and second into account, which was not done in the first analysis. The second card then is given rank '3'. These modification of the weights did not change the overall result: in all different assessments, the final weights for each criterion changed only slightly, and there were hardly any effects seen in the final relative weighted sums. The revised set of criteria and the one used during the workshop are so similar that the weighted sum results of the workshop data is still valid even with new criteria.

4.4.4 *Evaluation of the data listening space*

The data listening space was created for a sound installation of quantum physical data in MUMUTH (House of Music and Music Drama, Graz) in November, 2009 [qcd]. One listener at a time could explore a sonified lattice QED model. S/he was equipped with headphones and a 'hand target', both tracked by a VICON motion-tracking system. The installation was evaluated in a brief study with 6 male participants from the scientific or technical staff at IEM. None of them had known the data listening space before, and none were experts in physics, but in sound-related issues. The evaluation took place at the IEM in March 2010.

The participants received only a brief orientation beforehand, which should serve as introduction also here. Then, they were told to focus their comments mainly on the interface and sound of the installation, as they were not experts in the field of quantum physics:

The data listening space is a 6x6 m square, where data of a model from computational physics, namely a configuration of lattice QED, is virtually placed. The data are discrete, thus some spots act as virtual sound sources. You can move freely around with headphones whose position and rotation are tracked, and with a second, handheld tracking target. We used its distance from the listener axis (no matter in which direction!) as a further interaction possibility. A change in the second target triggers a change in sound only with a preset delay of a few seconds. What you hear is different pitches, looping rhythms and intensities, all of which give information on the energy in the configuration.

Physicists usually aggregate all information about such a configuration to one single number. The open research question was -and is- whether local structures in the data configuration can be found, e.g., emerging from the individual data sounds.

Each participant was filmed for about 5 minutes. Then, I elicited short feedback in personal interviews, asking first for open feedback. Second, I asked for a qualitative and quantitative assessment of the criteria developed in SBE2. Afterwards I analyzed the videos. The following foci were found and compared among the participants: first movement (any); first head movement; first hand target movement; eyes (open/ shut); head (separate movements); body (position); movement of arm/ handheld tracking target; location/ range in the room; general strategy of the exploration of the physical space (that I assumed in the analysis). The following behavior was repeatedly noticed:

Many participants did not test all possible interaction possibilities. Three out of the six never recognized the possibility of using other layers besides the 'head plane'. Two of these three never bent down and one 'detected' it only after several minutes. Three participants did not attempt to locate the sounds by explicit head movements, but all may have oriented themselves unconsciously by moving about (participants reported generally good orientation in physical space). The hand target was used by all participants, but in different ways (e.g., shifting between minimum and maximum position; mostly constant at a certain distance).

From this I conclude that the high degree of freedom in the interface might be a problem rather than a benefit. In a more restricted interface, such as a GUI, the user has several different options 'at hand' and one can try out all the buttons or sliders. In our case, the 'buttons and sliders' are hidden, and the interaction possibilities have to be explored creatively.

Often, three vertical layers were assumed. The data had 10 vertical layers, but three were induced by the possible (or more pleasant) body movements, i.e. standing, bowing, and crouching. For this setting these three layers of listening were sufficient, as the whole data range could still be assessed. Two neighboring planes were always played together with the central one. The approximately three body layers times where 3 neighboring ayers are actually played simultaneously results in approximately nine of a total of ten layers for the effective listening range.

In general it has to be taken into account that the listeners are not only limited by the interface (which is, in this case, completely free in three dimensions), but also by their bodies. Some people might be more flexible than others in using the three body levels.

Different scalings are disturbing. The QED lattice is equidistant but was compressed in the vertical axis, as a person cannot move 6 meters up. Therefore small changes of the head altitude by only a few centimeters could cause dramatic sound changes, even if there was no intent to go up or down. Horizontal changes were perceived more continuously along some 60 cm of displacement. This discontinuity was also mentioned in the feedbacks, and is not equivalent to the initial data dimensions. Therefore, this setting is not recommended for future installations.

Furthermore, the different reaction times of the head target and the hand target caused confusion. The hand target had a (deliberate) delay of a few seconds whereas the displacement of the head target caused immediate sound changes. This was meant to keep the person longer at a place, forcing her or him to become immersed in the wider and more complex soundscape. The listeners thus had to take their time, but were displeased with it, because it slowed them down. The auditory memory might also have been challenged more by this setting, as direct comparisons between sounds with short and long head-hand distances were artificially separated in time by several seconds.

The handheld target caused confusion in general. Even against initial information that only the radial distance from the head target played a role, most participants tested different orientations and some even tried rotations of the object. Another interface, such as perhaps a slider held in the hand, might have been more appropriate for the interaction task.

The data listening space allows the listener to be immersed in the data. This was reported as feedback, but could also be observed by the level of concentration and the reduction of the visual sense shown by the participants. Most participants reported a good orientation in the space, and two explicitly reported that they liked to walk 'in' data.

During the open feedback discussions subsequent to the video taking I asked the participants questions following to the criteria from the SBE2 (Sec. 4.4.2). This part of the questionnaire followed the MCDA approach.

The qualitative responses were very diverse. While some participants said the sound was intuitive and appropriate, for others it was too simple and limited. The fact that many did not perceive the task as complex is interesting because finding yet unknown structures in QED might well be a called complex task. Obviously, the translation of abstract, unknown entities to parameters well-known to the participants, and the rather simple mapping (pitch, rhythm and location), made the task subjectively simple. Also 'contextability' was rated diversely, as some said it would be appropriate for installations but not for scientists, and one person stated exactly the opposite.

The quantitative feedback was more uniform. Even with only six participants, the weighted sum gave nearly the same result as during SBE2 (using the weights found there and replacing intuitiveness, which had been omitted in the meantime, with complexity as least important criterion). The value for the evaluation of IEM members was 0.67 as compared to the SBE2 result of 0.66. The *mean rating for each criterion* and its standard deviation can be found in Fig. 46.

The grounded theory evaluation approach revealed some general guidelines for this type of installation:

Equal scalings between dimensions/ parameters. There should be no artificial discontinuities between dimensions (such as different distances in the vertical and horizontal plane) and interaction parameters (such as delay times), if they are not predefined by the data.

There are three vertical 'body layers'. Because the body dimensions of standing, bending, and crouching are constant, a similar kind of interface should be used with data that have a dimension with three inherent layers (for example, the atmosphere, with a troposphere, stratosphere and mesosphere). But even than, the most important or interesting region should always be at the 'head plane'.

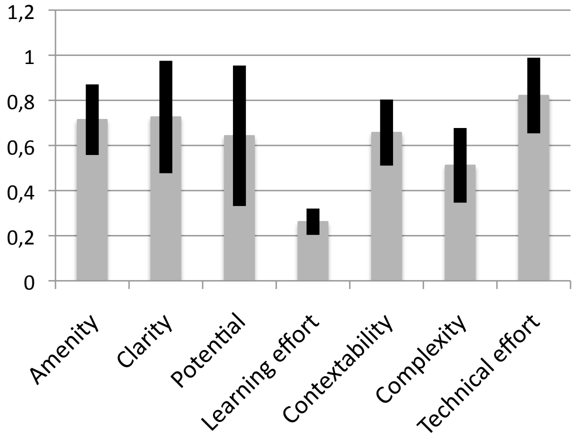


Figure 46: Quantitative results of the evaluation of the data listening space for each criterion. The black lines give the standard deviation. Amenity: 0.71 ± 0.16; clarity: 0.73 ± 0.25; potential: 0.64 ± 0.31; learning effort: 0.26 ± 0.05; contextability: 0.66 ± 0.15; complexity: 0.51 ± 0.17; technical effort: 0.82 ± 0.17.

A free interface needs an extensive introduction. The use of very free interfaces, such as an empty space with the listeners only wearing headphones, should be supported by any means. We used light as a visual indication of the boundaries of the data listening space. Additionally, a simple schematic documentation of interaction types should be provided, or a simple test set during which the listener is guided through different possible movements.

It has to be noted that participants might behave differently in front of a camera and/or an observer. In addition, the participants had different approaches to gathering information. Some asked many questions before the video was taken, while others immediately started to explore the space. Finally, the binaural rendering may have influenced the results, as it did not work very well for locating sounds from below or above.

This kind of grounded theory approach is an illuminating method for evaluating ADs, but it focuses on 'external' features, such as the handling of the interface. It is a challenge to transpose the method for evaluating 'internal' features, such as a better understanding of a certain data set.

4.4.5 *Conclusions regarding the evaluation approaches*

An exploratory sonification will always be ultimately evaluated on the basis of its exploration gain, i.e. new insights in a field that have been supported or inspired by the sonification. Nevertheless, evaluation is needed until sonifications can become that successful.

In general it can be concluded that the MCDA is a useful method for comparing different sonifications quantitatively. It objectifies the evaluation to a certain extent. Nevertheless, a qualitative analysis of *why* some approaches are rated better than others has to follow. Such an analysis can be used to improve future sonification designs. The evaluation process itself is fruitful for the sonification designer, because it includes the domain scientists in a discourse across different criteria.

The weighted sum approach has also drawbacks. The first is inherent: completely different categories, 'apples and oranges', are summed to one final number. However, this is also a distinct benefit of the method. Second, while the theoretical scale of results is one over the highest possible rating ($1/\mathrm{rating}_{\mathrm{max}}$) to 1, its *effective scale* seems to be much smaller. On the one hand, *some* of the criteria will always be assessed as good, and the effective minimum will lie much higher. On the other hand, hardly ever will *all* criteria receive maximal ratings (from all participants!), thus the maximum lies below 1. For SBE2, the results lay between 0.6 and 0.9, which leaves only small differences between the options.

5

TRANSLATING SONIFICATIONS

Sonifications *translate* from a domain science to the auditory perception, thus also mediate usually between domain scientists and sound experts. To make this mapping more explicit and less prone to misunderstandings, a sonification operator has recently been suggested by J. Rohrhuber [Roh10]. In the examples described in Sec. 6, data from physics have been taken that are naturally described in mathematical terms. It is therefore straightforward to describe also the sonification, or at least the mapping to the sound synthesis, in mathematical terms. In Sec. 5.2, I suggest notation modules that are needed for such a linkage and are used in the description of the examples.

5.1 THE SONIFICATION OPERATOR

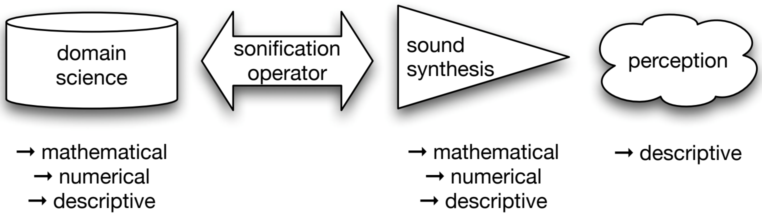


Figure 47: Process of translating sonifications

In general, sonification is the translation of some scientific domain to a sonic domain and, as a further consequence, to perception and cognition (see Fig. 47). The formulation of the domain science is usually given in a descriptive and (concisely) in a mathematical and numerical form. The sound synthesis domain is also denoted descriptively, mathematically, and numerically, but usually follows notation conventions that differ from the domain science. The perception of the final sonification cannot be described in mathematical or numerical terms, but is characterized phenomenologically.

As intermediaries, sonifications are usually described in words, and implemented as numerical algorithms. The mapping can also be made more explicit as an operator in a mathematical formulation, as was recently suggested by J. Rohrhuber [Roh10]. The sonification operator $\mathring{S}$ formalizes a concise link between a domain science (given below as any $\mathcal{A}(d)$) and an algorithm of sound synthesis. This linkage can lead to a better understanding between the domain scientists and sonification experts. It introduces a sonification time $\mathring{t}$[1] and a sonification signal $\mathring{y}$ that depends on $\mathring{t}$, on the data d, and the sound parameters p that are set in the sonification, Eq. (5.1).

$$\mathring{S} : \mathcal{A}(d) \rightarrow \mathring{y}(\mathring{t}; d, p) \tag{5.1}$$

Note that this formalization gives a clearer picture of the linkage between domain science data and sound synthesis, but the actually perceived auditory *gestalts* cannot be explicitly written in a formal way.

5.2 NOTATION MODULES FOR CONTINUOUS SONIFICATION

In order to define a specific sonification operator, various general modules of notation are needed that mainly follow conventions in sound synthesis. In this chapter, all of the topics are discussed that are needed in order to describe the examples in Sec. 6. The list is thus not complete, and may be extended by adding other sonification techniques.

5.2.1 *Essentials of sound synthesis*

Sampling

Although the sonification (listening) time $\mathring{t}$ is continuous, the implementation of the sonification algorithm takes place in discrete time. This transformation is achieved via digital-to-analog conversion and auditory perception, and is thus not described within this formalization.

For any sound synthesis, the sampling frequency f_s is important. The 'sampling' time t_s can be explicitly transformed using

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[1] The superscripted ring, as in $\mathring{t}$, denotes a sonification variable, as distinguished from a physics variable, e.g., t.

the sampling frequency f_s (samples per second), Eq. (5.2). The continuous sonification time corresponds to the discrete sampling time via the samples n in this notation.

$$t_s = \frac{n}{f_s} \qquad n \triangleq \mathring{t} \tag{5.2}$$

Up-sampling, down-sampling, and interpolation

Often, a signal is read out from the data, and has to be up- or down-sampled by a factor s, see Fig. 48. If it is up-sampled, the signal usually has to be interpolated as well. Up-sampling by a factor of s is notated as $\uparrow_s$, down-sampling as $\downarrow^s$. The interpolation is an operator called $\mathrm{Int}[x]$, and can be specified by additional parameters, e.g. $\mathrm{Int}[x]^{cos}_{N}$ for a cosine interpolation between the (original) N samples.

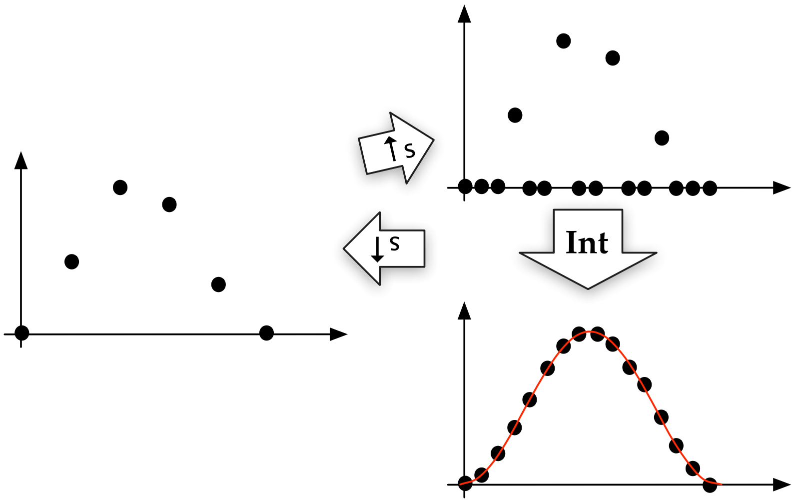


Figure 48: Up-, down-sampling, and interpolation. The factor of the sampling in the example is $s = 3$. The red curve shows the perceived function. The x-axis shows time/samples, the y-axis the signal function.

Periodic signals

The simplest periodic sonification signal is a sine function of amplitude a, frequency f, and phase ϕ,

$$\mathring{y}(\mathring{t}) = a \cdot \sin(2\pi f \mathring{t} + \phi). \tag{5.3}$$

Modulation

The signal in Eq. (5.3) can be modulated in three different ways. In an amplitude modulation, $a = a(\mathring{t})$:

$$\mathring{y}_{AM}(\mathring{t}) = a(\mathring{t}) \cdot \sin(2\pi f\mathring{t} + \phi). \tag{5.4}$$

If $\phi(\mathring{t}) = \phi_0 + M_p\phi'(\mathring{t})$, a phase modulation is described, with the phase changing over time in addition to the constant phase shift ϕ_0 (the modulation strength is denoted as M_p):

$$\mathring{y}_{PM}(\mathring{t}) = a \cdot \sin(2\pi f\mathring{t} + \phi_0 + M_p\phi'(\mathring{t})). \tag{5.5}$$

The argument of Eq.(5.5) is abbreviated as $\xi(\mathring{t}) = 2\pi f\mathring{t} + \phi_0 + M_p\phi'(\mathring{t})$. For a frequency modulation, frequency varies over time: $\omega(\mathring{t})$ is introduced as the instantaneous angular frequency, $\omega(\mathring{t}) = d\xi(\mathring{t})/d\mathring{t} = 2\pi f + M_f\omega'(\mathring{t})$; vice versa $\xi(\mathring{t}) = \int \omega(\mathring{t})d\mathring{t}$. The frequency modulation can thus be written as

$$\mathring{y}_{FM}(\mathring{t}) = a \cdot \sin(2\pi f\mathring{t} + \phi_0 + \int M_f\omega'(\mathring{t})d\mathring{t}). \tag{5.6}$$

Timbrel characteristics

Every non-artificial sound has overtones. Any periodic sound can be described by a Fourier series as the sum of simple sine functions with $f_k = k \cdot f_0$:

$$\mathring{y}(\mathring{t}) = \sum_k a_k \sin(2\pi f_k\mathring{t} + \phi_k). \tag{5.7}$$

f_0 is the fundamental and $k = (1,2,3,...)$. The amplitudes of the harmonic partials determine the timbre of the sound.

As a special case of simple timbre manipulation, even and odd harmonics can be distinguished, $f_{k,e} = 2kf_0$ and $f_{k,o} = (2k-1)f_0$, as implemented in the example in Sec. 6.5.

Formants are characteristic amplitude distributions of frequency bands, that make it possible to distinguish vowels in human speech. They can be denoted using the international phonetic alphabet, e.g. for the vowel [æ] as in

$$\mathring{V}_{[æ]}(\mathring{t}) = \sum_k a_{k[æ]} \sin(2\pi f_k\mathring{t} + \phi). \tag{5.8}$$

Noise and impulse

Noise is a signal to which no pitch can be assigned. Different noise signals are differentiated by colors, e.g. 'white noise' stands for a broadband noise with equally distributed spectral power density at all frequencies, or 'pink noise', where the spectral power density falls by 3dB per octave. I denote noise with $\mathring{\mathcal{N}}(\mathring{t})$, its amplitude being determined by a pre-factor, e.g. $\alpha \cdot \mathring{\mathcal{N}}(\mathring{t})$; different types of noise can be indicated in the subscript, e.g.,

$$\mathring{\mathcal{N}}_{white}(\mathring{t}).$$

Another sound without pitch is an impulse, ideally defined as a sound containing the whole frequency spectrum in $0-$time expansion. It can be used to excite a filter or to map information to rhythm, and is denoted as

$$\mathring{\mathcal{I}}(\mathring{t}).$$

Filtering

Filters can be described by a convolution with the signal, $y(t) * h(t)$, or with an operator conveniently indicating the main filter parameters (the filter type, e.g., low-pass filter (LPF), high-pass filter (HPF), band-pass filter (BPF), or Notch-filter (Notch), and the cut-off frequency or frequencies, denoted as, e.g. $cof/s = 100-200$Hz),

$$\mathring{\mathcal{F}}^{cof/s}_{type}[\mathring{y}(\mathring{t})].$$

5.2.2 *Granular synthesis and looping*

In granular synthesis, the signal $\mathring{y}(\mathring{t})$ consists of n_g individual grains with a length of about 1-100 ms. The grains can be played at different volume, pitch, timbre, speed, or phase. The superposition of many grains triggered at different times results into a characteristic sound texture.

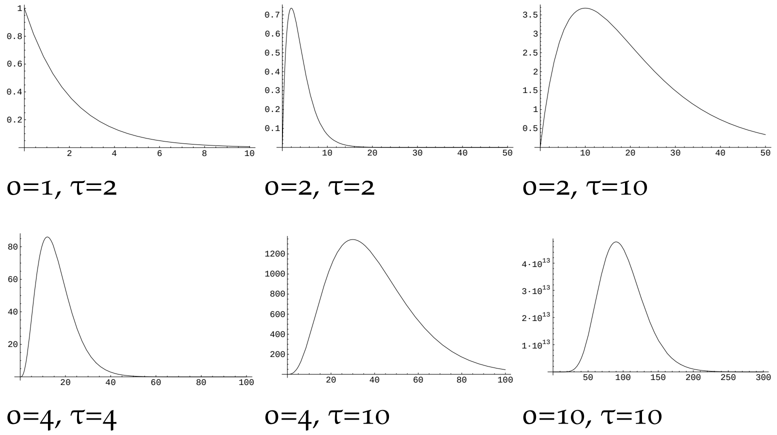
A grain $\mathring{y}_g(\mathring{t})$ consists of some 'content', which is modulated by an envelope $a_{env}(\mathring{t})$. The content can be a pure sinusoidal tone, a superposition of sine waves (harmonic or inharmonic) or any arbitrary sound snippet,

$$\mathring{y}_g(\mathring{t}) = a_{env}(\mathring{t}) \cdot \mathrm{content}(\mathring{t}). \tag{5.9}$$

Envelope

For granular synthesis, but not exclusively for this technique, an envelope is needed that controls the amplitude evolution of the sound grain depending on time $\mathring{t}$. One choice for an envelope is given in Eq. (5.10). It allows different attack and decay times that are respectively controlled by the orders $\mathcal{O}$ and the decay constant τ, see Fig. 49. Because the function decreases exponentially, a maximal time (sample) t_{max} is needed at which the function is truncated. As the amplitude then is close to 0, a smooth decay is perceived rather than a hard click.

$$a_{env}(\mathring{t};\mathcal{O},\tau,t_{max}) = a\mathring{t}^{\mathcal{O}-1}e^{-\mathring{t}/\tau}, \qquad \mathring{t} = (0,...t_{max}) \quad (5.10)$$



o=1, τ=2 o=2, τ=2 o=2, τ=10

o=4, τ=4 o=4, τ=10 o=10, τ=10

Figure 49: Envelope function proportional to the gamma distribution, Eq. (5.10). For $o = 1$, the attack time is 0; $o > 1$ controls the 'order' of the attack time. τ controls the decay time (note that the running index t, shown on the x-axis, as well as the maximum ordinate value, change in scale!).

The envelope can also be written in more general terms, at least defined by the grain duration t_g, the attack time t_a, the decay time t_d, and the maximal amplitude a_{max},

$$a_{env}(\mathring{t};t_g,t_a,t_d,a_{max}). \quad (5.11)$$

Triggering: onset time

The grains are triggered at different onset times $\delta\mathring{t}$, for (in total) n_T times, which can be formalized by a trigger operator $\mathring{T}^{n_T}_{\delta\mathring{t}}$,

$$\mathring{T}^{n_T}_{\delta\mathring{t}}[\mathring{y}_g(\mathring{t})] = \sum_{j=1}^{n_T} \mathring{y}_g(j)(\mathring{t} - \delta\mathring{t}(j)). \quad (5.12)$$

$\delta\mathring{t}$ is a series of times $\delta\mathring{t}(j) \overset{!}{>} 0$, where $\delta\mathring{t}(j)$ is either a fixed onset time, or a random number in a certain range, e.g., $\delta\mathring{t}_{rand} \in \{10;20ms\}$, and can be a cumulative sum $\delta\mathring{t}_{cum}$.

Looping

Looping is needed in various sonification methods, e.g. the looping of a modulator phase, a whole soundfile or sound grains. A looping operator $\mathring{L}^{n_L}_{s_L}$ can be defined that loops a signal $\mathring{y}(\mathring{t})$ with a loop period of s_L samples for n_L times (e.g., ∞). Note that according to Eq. (5.2), the samples n are equivalent to $\mathring{t}$,

$$\mathring{L}^{n_L}_{s_L}[y(t)] = \sum_{i=1}^{n_L} \mathring{y}(n - s_L \cdot i). \qquad (5.13)$$

5.2.3 *Model-based sonification*

Model-based sonification cannot be formalized in a general manner, but by specifying the dependencies of the model function, Eq. (5.14). Indices i and j denote some local dependence of the model space and $input$ is usually some sort of excitation signal applied at location i. The $readout$ condition, applied at location j, also determines the sound.

$$\mathring{y}(\mathring{t}) = \mathring{\mathrm{MBS}}_{readout(j)}[input(i)] \qquad (5.14)$$

5.2.4 *Spatialization*

Spatialization is an important factor for sonification. In the following, the notation modules for stereo, binaural rendering and multi-channel expansion are briefly discussed. For a stereo sound, the signal is split into a left signal $y_L(t)$ and a right signal $y_R(t)$,

$$\mathring{y}(\mathring{t}) \rightarrow \begin{pmatrix} \mathring{y}_L(\mathring{t}) \\ \mathring{y}_R(\mathring{t}) \end{pmatrix}, \qquad \mathring{y}_{Stereo}(\mathring{t}) = \mathring{y}(\mathring{t}) \cdot \begin{pmatrix} a_L \\ a_R \end{pmatrix}. \qquad (5.15)$$

Binaural rendering can be achieved by convolution with the head related transfer function (HRTF) depending on the position of the sound source relative to the listener's position. 'Ω' indicates that the listener has to wear headphones.

$$\begin{aligned} \mathring{y}(\mathring{t}) &\rightarrow \begin{pmatrix} \mathring{y}_L(\mathring{t}) \\ \mathring{y}_R(\mathring{t}) \end{pmatrix}^{\Omega} \\ \mathring{y}_{Binaural}(\mathring{t}) &= \mathring{y}(\mathring{t}) * h_{HRTF}(\mathring{t}, pos) \end{aligned} \tag{5.16}$$

Multi-channel expansion simply indicates the use of a speaker setup with n_C channels.

$$\mathring{y}(\mathring{t}) \rightarrow \begin{pmatrix} \mathring{y}_{n_1}(\mathring{t}) \\ ... \\ \mathring{y}_{n_C}(\mathring{t}) \end{pmatrix} \tag{5.17}$$

5.2.5 *Data, mapping, and interaction*

Lattice and data

The lattice is given by a lattice-spacing a, linking to physical units (if a continuous theory has been discretized), and the number of lattice sites per dimension, $n_{Lattice}$ for a cubic lattice, or $n_{Lattice,i}$, ... if individual dimensions need to be differentiated.

The data are generally denoted as d.

Sequentialization rules

A sequentialization is a mapping from a higher dimensional space to (usually) 1d. One possibility is the Hilbert space-filling curve (Sec. 4.2.5). In a formal way, it can be written as an operator on data d with dimensionality D, e.g. given by the indices x, y, z in three dimensions,

$$Hil[d_{x,y,z}](i) \ .$$

The running index i is then only over one dimension. Other sequentialization paths can be defined if necessary, e.g., a toroidal operator

$$Tor[d_{x,y,z}](i).$$

Smoothing

One practical smoothing tool is the moving average. The mean value of the current value and of the K predecessor values is used to determine the new value,

$$d_{smooth}(i) = \frac{1}{K}\sum_{k} d(i-k). \tag{5.18}$$

Mapping and binning

Often, data are mapped non-linearly onto sound parameters, e.g. in a range between x_1 and x_2. To indicate an exponential or linear mapping, $\in [x_1, x_2]^{exp}$ or $[x_1, x_2]^{lin}$ can be used.

An explicit exponentiating and re-normalization of data values is given below. The data are distorted by an exponent k, thus the values $d(i) << max_i(d)$ are suppressed.

$$d_{distort}(i) = \frac{d^k(i)}{max_i(d)}, \qquad k \in 2,3,4,... \tag{5.19}$$

Often, there is no one-to-one correspondence in a mapping, but instead an aggregation of values in bins. The range between a minimum and maximum value of a bin is expressed as $[b_{min}, b_{max}]$, and the number of all values d_i that fall into this bin accordingly as

$$m(d; [b_{min}, b_{max}]) = number(\{d_i \,|\, b_{min} \leqslant d_i < b_{max}\}).$$

A histogram is the plot of m for every bin.

Cluster

In many examples of Sec. 6, clusters must be found. These are coherent regions of equal data values linked as nearest-neighbors. i stands for the data dimensions (thus is an index or array of indices), and a path of equal data values exists from i to $j = l \cdot (i+1)$, where l is a number of – or an array of numbers of – sites $l < n_{Lattice}$,

$$c = \{i \,|\, \exists\, d_j = d_i, j = l \cdot (i \pm 1)\}. \tag{5.20}$$

Interaction

In many cases, the parameters of a sonification are controlled interactively. The symbol to denote interactivity is ↻.

5.2.6 *Table of notations*

a		amplitude;
$a_{env}(\mathring{t})$	Eq.s (5.10, 5.11)	envelope;
$a_{k[æ]}$ (etc.)	p. 128	amplitude distribution of partials that shape the formant '[æ]';
c	Eq. (5.20)	set of indices of a cluster;
d		data;
f_k	p. 128	vector of frequencies;
f_s	Eq. (5.2)	sampling frequency;
$\mathring{\mathcal{F}}^{cof/s}_{type}[\mathring{y}(\mathring{t})]$	p. 129	filter operator of a certain type and cut-off frequency/ies;
$h(\mathring{t})$	p. 129	filter (for convolution in the time domain);
$Hil[d_D](i)$	p. 132	Hilbert curve sequentialization operator; mapping from $\mathbb{R}^D \rightarrow \mathbb{R}^1$;
$\mathring{\mathcal{I}}(\mathring{t})$	p. 129	impulse;
$Int[x]$	p. 127	Interpolation of a function depending on the original function, x;
$\mathring{L}^{n_L}_{n_S}[\mathring{y}(\mathring{t})]$	Eq. (5.13)	looping operator, loops a function y n_L times over s_N samples;
M_p	Eq. (5.5)	modulation strength of the phase modulation;
M_f	Eq. (5.6)	modulation strength of the frequency modulation;
n	p. 127	sample index;
$n_{Lattice}$	p. 132	lattice size (sites per dimension);
$\mathring{\mathcal{N}}_{type}(\mathring{t})$	p. 129	noise of a certain type;
$\mathring{\mathcal{S}}$	Eq. (5.1)	sonification operator;

t_s	Eq. (5.2)	(discrete) sampling time;
$\mathring{t}$	Eq. (5.2)	(continuous) sonification time;
$\mathring{T}^{n_T}_{\delta\mathring{t}}$	Eq. (5.12)	trigger operator, triggering n_T times at different onset times $\delta\mathring{t}$;
$\mathrm{Tor}[d_D](i)$	p. 132	toroidal sequentialization operator; mapping from $\mathbb{R}^D \rightarrow \mathbb{R}^1$;
$\mathring{y}(\mathring{t})$		sonification signal;
$\mathring{y}_{AM}(\mathring{t})$	Eq. (5.4)	amplitude-modulated signal;
$\mathring{y}_{FM}(\mathring{t})$	Eq. (5.6)	frequency-modulated signal;
$\mathring{y}_{PM}(\mathring{t})$	Eq. (5.5)	phase-modulated signal;
$\mathring{y}_{Stereo}(\mathring{t})$	Eq. (5.15)	stereo frequency vector;
$[x_1, x_2]^{exp}$ (etc.)	p. 133	range of values between x_1 and x_2, with exponential scaling;
$\mathring{V}_{[æ]}(\mathring{t})$	Eq. (5.8)	formant signal ('V' for vowel);
α, β		free parameters;
ϕ		phase;
Ω	Eq. (5.17)	indicates the use of headphones;
$\uparrow_s$	p. 127	up-sampling by a factor of s;
$\downarrow^s$	p. 127	down-sampling by a factor of s;
$\circlearrowright$	p. 133	denotes interactive control of parameter;

As sonification operators are often complex, they are written as an array of equations. For the larger examples, the following structure is used in Sec. 6:

1 Calculate display unit
2 Set sonification parameters
3 Synthesize gestalt unit
→ Overall sonification operator

Part III

SHOWCASES AND CONCLUSION

6

SONIFICATION EXAMPLES

With all the foregoing background and theoretical considerations, concrete sonifications of simulation data from computational physics can now be described. These examples were elaborated during the research projects SonEnvir [son] and QCD-audio [qcd]. The respective collaborators and publications are cited in the beginning of each section. Listening and code examples can be found on the accompanying CD and at www.qcd-audio.at; the corresponding files are listed at the end of each section.

The data are described here only on a technical level (for physical background see Sec. 3). The sonifications are also formulated in mathematical form, built-up from the notation modules in Sec. 5.2. The description of the specific sonification operator $\mathring{S}$ is indicated by a sonification signal $\mathring{y}(\mathring{t})$, depending on the data d for each of the examples. The following examples are presented[1]:

ISING NOISE TO ISING *gestalts*

- Ising noise
- Ising grain clouds
- Ising *gestalts*

VORTICES AND ANTI-VORTICES IN THE XY MODEL

- Spin quartets

QUANTUM ELECTRODYNAMICS

- *data listening space*

QUANTUM CHROMODYNAMICS

- Searching for topology in QCD
- Waveguide meshes of center symmetry

PARTICLE DETECTION SIMULATION AT CERN

- A sonic time projection chamber

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[1] Additional examples from the SBE2 workshop are summarized briefly in the Appendix, Sec. A.2

Implementation

The sonifications were implemented with the audio synthesis software SuperCollider3 (SC3) [McC02]. This is an object-oriented language and programming environment under the free GPL license. It was originally developed by James McCartney as a real-time sound synthesis language, and it is continually being enhanced by a growing community of users in the electronic music domain and the sonification community. In addition, graphical user interfaces and simpler, less time consuming models have been implemented using SC3.

Often, the raw data was very complex, and testing of the sonification design or fine-tuning its parameters with this data was not useful. Thus, simpler 'pseudo-data' were generated that reflected the patterns expected in the data.

6.1 FROM ISING NOISE TO ISING *gestalts*

Simple spin models, such as the Ising or the Potts model, have been used in many scientific contexts. They remain interesting for physics as well, as they can describe different physical systems, in principle even lattice QCD in some limits. Within the research projects SonEnvir and QCD-audio, spin models have been studied for two reasons. First, they are the oldest and best-studied statistical models. Even if no real new physics is to be discovered, a sonification can enhance the imagination of the model and it can be used as a didactic tool. Second, the developed sonification techniques can be applied to other, more demanding models, and might lead to new insights there.

6.1.1 *The Ising and the Potts model*

The Ising model is the most basic spin model, with each spin having only two orientations $(+1,-1)$. One simple extension of it is the q-state Potts model, which allows more possible spin states (e.g., $q = 3,4,5,\ldots$). They are dynamic and rather easy to implement but still show complex behavior with emerging properties. Spin models are usually exploited by abstraction, suppressing details, and an intuitive understanding is not attainable. The standard approaches aim at a quantitative and – mainly for didactic reasons – visual exploitation of results. At any rate, only in the 2-dimensional case is a full visualization possible.

Several interesting sonification problems are posed by the Ising model. Firstly, an *'acoustic overview'* of a complete configuration cannot be easily achieved. While vision gives us a quasi-instantaneous idea of the state of a phenomenon, sonification needs time. A second problem is the basic property of the Ising model as a statistical model. A single configuration is only typical for an overall temperature with a certain probability – it *might* be completely a-typical. Therefore the sonification should provide an *'acoustical averaging'*, which enables the listener to go quickly through many configurations. Due to the global symmetry (for vanishing external field), absolute spin values do not play a role, but their *relative behavior* is important. The most challenging tasks are discerning the phase of the model and finding unambiguous *acoustic properties for the phase transition* itself. For the Potts model, it should furthermore be possible to compare *different orders of phase transitions* for various different numbers q of possible spin orientations.

In most sonification approaches data pre-processing was avoided, and raw data was used, because this is also the approach taken in the explorative setting of more complex models.

6.1.2 *Ising: Sonification approaches*

'Ising noise'

This sonification was elaborated during the SonEnvir project by Katharina Vogt, Alberto de Campo, Christopher Frauenberger, and Willibald Plessas. [VdCFP07]

The most direct approach in sonification is an audification, which requires a sequentialization path from the n-dimensional lattice to a 1-dimensional data stream. We implemented two possible choices: a *toroidal path* reading line-by-line, and the *Hilbert curve*, preserving partly locality (Sec. 4.2.2), see Fig. 50. A simple audification of such a randomized system with two discrete states results in noise. In the hot temperature phase, where $T > T_{crit}$, the sound is rather homogeneous. This fits the intuitive assumption that a hot system, with a lot of 'Brownian' movement, sounds noisy. The more clusters there are and the bigger they are, the more temporally structured and 'unstable' the sound be-

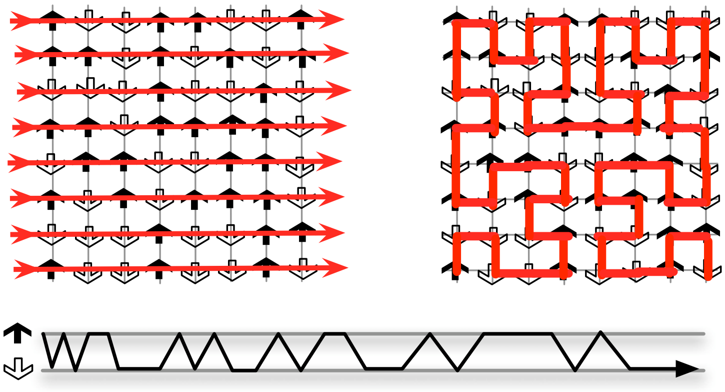


Figure 50: *upper figure* – Scheme of sequentialization of the lattice used for the audification. Either a torus path is read line-by-line (left figure) or a Hilbert curve is followed (right figure).
lower figure – Example of a sequentialization path of the Ising model in the high temperature phase. Such a value sequence is audified with a sampling rate of, e.g., 44.1 kHz, leading to a noisy sound.

comes . When the temperature is still lowered, the audification falls silent, as one spin orientation prevails throughout the lattice at $T < T_{crit}$.

As a refinement, we used audification for phase modulation of a sine wave with a basic frequency f_0. Thus, for $T < T_{crit}$, the pure sine wave remains, while for $T > T_{crit}$ the sound is noisy. The sonification operator for this phase-modulated sine wave with a Hilbert sequentialization path is given in Eq. (6.1).

$$\mathring{y}(\mathring{t}) = a \cdot \sin(2\pi f_0 \mathring{t} + M_p \mathrm{Hil}[d_{x,y}](n)) \tag{6.1}$$

Demonstration & Code:
Examples_Ising_audification.mov
Examples_Ising_Audification_SC3.rtf, requires HilbertIndex.sc and Pturtle.sc as classes
The sequentialization path in the example files is a Hilbert path.

Ising grain clouds

This sonification was elaborated during the SonEnvir project by Katharina Vogt, Alberto de Campo, Christopher Frauenberger, and Willibald Plessas. [VdCFP07]

For a 3d Ising model evolving in real-time, a granular parameter mapping sonification has been developed that allows for a more pleasant soundscape than that achieved by audification. Two or three sound parameters (pitch $f(d)$, noisiness $\mathring{\mathcal{N}}(\mathring{t})$ and, in the multi-channel setting, spatial location with n_C channels) manipulate the character of a sound grain. When many of these sound grains are played in a short time frame, a characteristic '*texture*' is perceived as a whole *gestalt* rather than as individual sound events.

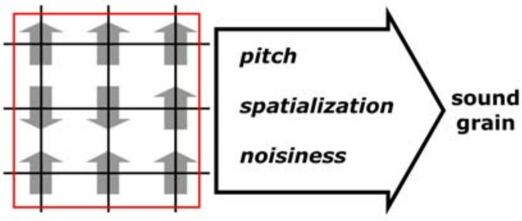


Figure 51: Two-dimensional scheme of the sonification of randomly chosen, averaged spin blocks in the Ising model.

Short sound grains, Eq. (6.2e) are played with a 10 ms time-lag, and last for about 20 ms. For a 24^3 lattice, we calculate *blockspins*, averages over 3^3 sites; see Fig. 51 and Eq. (6.2a). The entire configuration could be played within 10 seconds, each spin being part of a blockspin grain. The time span of 20 ms for the grain length is approximately the lower threshold of pitch recognizability. On the other hand, one would like to go through the entire configuration in less than ten seconds. As the model is a statistical one, it is not necessary to take the full frame into account.

Therefore, a few lattice sites $d_{x,y,z}$ are chosen at random for each configuration, and the average over the neighboring spins $\overline{d}_{x,y,z}$ is calculated according to Eq. (6.2a). This mean magnetic moment lies between -1 (all negative) and $+1$ (all positive), 0 would be a balanced ratio of spin orientations. This information is used to determine the pitch, Eq. (6.2b), and the noisiness, Eq. (6.2c), of a sound grain. The more the spins are alike, the clearer the tone, the less alike, the noisier the sound. A noise threshold is implemented, thus if there is a majority of one spin value within the neighborhood ($|\overline{d}_{x,y,z}| > 0.8$), the sound is a clear sine tone that is high- or low-pitched, respectively. The pitch range was chosen as an octave for the two spin values of the Ising model, reflecting the symmetry between the spins. The grains are triggered at random times $\delta\mathring{t}$, Eq.(6.2d).

In a multi-channel setting, the lattice position is given by the location in space, Eq. (6.2g), otherwise it is ignored. The full sonification operator is given in Eq. (6.2).

$$
\begin{aligned}
& && \text{Calculate display unit:} \\
& && (x,y,z)_{rand} \in \{n_{Lattice}\} \\
\overline{d}_{x,y,z} &= && \frac{1}{27} \sum_{\substack{\delta x,\delta y,\delta z= \\ -1}}^{+1} d_{(x+\delta x,y+\delta y,z+\delta z)} && \text{(6.2a)} \\
& && d_{x,y,z} \in \{-1,1\} \\
& && \text{Set sonification parameters:} \\
f(\overline{d}_{x,y,z}) &= && f_0 \cdot \frac{\overline{d}_{x,y,z}+3}{2} \qquad \text{thus}\, f(+1) = 2 \cdot f(-1) && \text{(6.2b)} \\
b(\overline{d}_{x,y,z}) &= && b_0(\cdot 0.8 - |\overline{d}_{x,y,z}|), \quad b(|\overline{d}| > 0.8) \equiv 0 && \text{(6.2c)} \\
\delta t &= && 10\,ms \rightarrow \delta\mathring{t}_{cum} && \text{(6.2d)} \\
& && \text{Synthesize } \textit{gestalt} \text{ unit:} && \text{(6.2e)} \\
\mathring{y}_g(\mathring{t};d) &= && a_{env}(\mathring{t};20\,ms) \cdot (sin(2\pi f(\overline{d}_{x,y,z})\mathring{t}) + b(\overline{d}_{x,y,z}) \cdot \mathring{\mathcal{N}}(\mathring{t})) \\
& && \text{Overall sonification operator:} \\
\mathring{y}(\mathring{t};d) &= && \sum_g \mathring{T}^{\infty}_{\delta t_{cum}} \left[\mathring{y}_g(\mathring{t};d)\right] && \text{(6.2f)} \\
[\mathring{y}(\mathring{t};d) &\rightarrow && \mathring{y}_{MultiChannel}(\mathring{t});d] && \text{(6.2g)}
\end{aligned}
$$

Even untrained listeners can easily distinguish the phases of the model with this sonification, but assessing the exact point of the phase transition is difficult due to the statistical nature of the model.

Demonstration & Code:
Examples_Ising_GrainCloud.mov
Examples_IsingGrainCloud_SC3.rtf
The example plays 5 random sites for each calculation step of the model; each sound lasts 0.02 seconds and starts 0.01 seconds after the last one

Ising gestalts

This sonification was elaborated during the QCD-audio project by Katharina Vogt and Robert Höldrich. [Vog08]

Auditory scene analysis, on the one hand, studies emergent features of sound, so-called *gestalts* (Sec. 2.1). On the other hand, the Ising model shows emergent behavior at the critical temperature T_{crit}, as clusters appear at all scales. Thus, we used perceptual grouping for displaying critical behavior, the number of clusters within cluster bins. This approach demands more pre-processing than the previous ones but is interesting for its metaphoric content. The formalization is shown in Eq. (6.3) and explained below.

Calculate display unit:

$$
\begin{aligned}
b &= 1,2,\dots 11 && \text{(6.3a)}\\
c &= (0,1,8,27,64,125,216,343,512,729,1000,4096) && \text{(6.3b)}\\
w_{crit} &= \overline{m}(d(T_{crit});[c_{b-1},c_b]) = && \text{(6.3c)}\\
&= (0.04,0.21,0.41,0.56,0.67,0.77,0.81,0.91,1.00,0.46,0.00)\\
m_{rel}(d) &= \frac{m(d(T);[c_{b-1},c_b])}{w_{crit}} && \text{(6.3d)}
\end{aligned}
$$

Set sonification parameters:

$$
\begin{aligned}
&f_{b+1} = \frac{f_b}{\sqrt{2}} \quad \text{with } f_0 = 6.4\,\text{kHz} && \text{(6.3e)}\\
&\delta t_b(d) = t_0 + \beta \cdot m_{rel}(d) && \text{(6.3f)}\\
&a_b(d) = \alpha \cdot m_{rel}(d) && \text{(6.3g)}
\end{aligned}
$$

Synthesize *gestalt* unit:

$$
\mathring{y}_b(\mathring{t};d) = a_b(d) \cdot \mathring{\mathcal{F}}_{BPF}^{[f_b,f_{b+1}]}\left[s(\mathring{t})\right] \tag{6.3h}
$$

Overall sonification operator:

$$
\mathring{y}(\mathring{t};d) = \mathring{L}_{s_{max}}^{\infty}\left[\mathring{T}_{\delta t_b(d)}^{11}\left[\mathring{y}_b(\mathring{t};d)\right]\right] \tag{6.3i}
$$

The sonification can be based on any soundfile $s(\mathring{t})$, e.g. music or speech. This soundfile is decomposed into 11 spectral bands indexed with b, Eq. (6.3a). Clusters are defined according to Eq. 5.20 in Sec. 5.2. The occurrence of different cluster sizes, $m(d;[c_{b-1},c_b])$, is determined for every configuration, using the Hoshen-Kopelman cluster-finding algorithm [HK76]. The cluster size distributions is grouped according to the borders given in Eq. (6.3b). As a strict binning would lead to sudden sound changes, the bins are actually overlapping and have a Gaussian shape as shown in Fig. 52. Thus, one cluster can belong to two or even more bins.

Hints for the equal distribution of clusters of different orders of magnitude at the phase transition are given by [Yeo92], but a weighting function is not given there. Obviously, very small clusters appear more frequently than larger ones, and it is highly unlikely that a cluster would fill a whole configuration. Thus a suitable cluster occurrence distribution was determined empirically by averaging over many configurations of the running model at the critical temperature, giving the (rounded) weight factors, w_b, in Eq. (6.3c). The weighted cluster occurrence, m_w, in Eq. (6.3d) is the 'display unit' for this sonification.

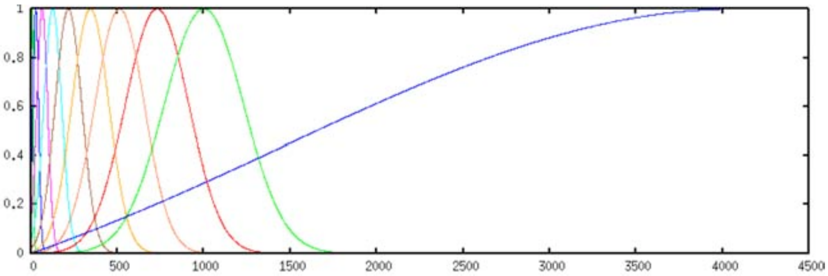


Figure 52: Gaussian bins for cluster sizes. For a 64x64 lattice, the maxima of the bins lie at cluster size 0, 1, 8, 27, 64, 125, 216, 343, 512, 729, 1000, and 4096. If there were no Gaussian overlap, a small increase or decrease in the cluster size could lead to a significant perceptual change.

Each cluster bin of the Ising model controls one frequency band of the soundfile in its onset time δt_b (Eq. (6.3f)) and its amplitude $a_b(d)$ (Eq. (6.3g)). Their cut-off frequencies follow a 'tritonus' function', Eq. (6.3e). The band-pass filtered signal is given in Eq. (6.3h).

If clusters of all orders of magnitude exist, according to the w_{crit} distribution all bands are triggered at the same time (t_0) and played at their original loudness. The soundfile is perceived as being unchanged, $\mathring{y}(\mathring{t}) = s(\mathring{t})$. Any deviation from this cluster distribution is used to delay the trigger of the bands and manipulate their amplitude. Thus the frequency bands lose their synchronicity in the temporal onset. They also lose their spectral proportions, as the amplitudes of the partials are distorted. Then the overall impression is blurred. In the high temperature region, mostly small clusters appear, accentuating only the higher parts of the spectrum of the soundfile. In the other extreme, a large uniform cluster allows only the low frequency bands to be played. Close to the critical region, most parts of the spectrum are played, but they are staggered in their on-set times; see Fig. 53. Due to the statistical nature of the model, some deviations of the soundfile's original *gestalt* will always be present, but the phase transition is played with a clear *gestalt*.

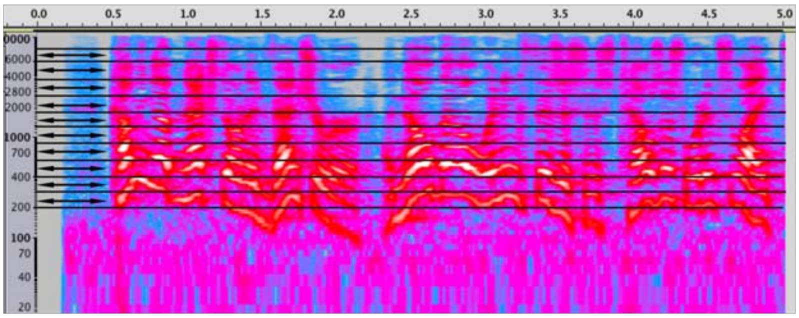


Figure 53: Scheme of the Ising *gestalt* sonification. The soundfile is split into frequency bands, each of which is mapped to a cluster size bin. The onset of the bands is controlled by the number of clusters found in the Ising configuration, as indicated by the arrows. Additionally, the amplitude of the frequency band is manipulated as well. Frequency is plotted on the y-axis vs. time on the x-axis, amplitude is color-coded. Note that averaging over time is done additionally: in order to achieve a smooth transition between different cluster occurrences, the previous configuration is averaged with the current one. Therefore there is an additional time lag in the reaction time of the sonification.

Demonstration & Code:
Examples_Ising_Gestalts.mov
Ising_Gestalts_loadAll.rtf (needs other files in the same folder).
The running model is used to control the parameters of a soundfile of an interview of Nobel prize laureate F. Wilczek.

6.2 XY MODEL - SPIN QUARTETS

This sonification was elaborated during the QCD-audio project by Katharina Vogt, David Pirrò, and Robert Höldrich. [VHPG10]

The main difference between the XY model and the Ising model is that the spins assume continuous values. When studied in two dimensions this results in an interesting topological structure that consists of vortices and anti-vortices (Sec. 3.3.2) as opposed to the Ising model, which exhibits only 'bulk' observables.

Visually, these structures are hard to find in the raw data, see Fig. 54(b); cooling the configuration brings the structures to the foreground (Sec. 3.2.2), but also destroys information, see Fig. 54(c). As full visualization is possible in the 2d XY model, the sonification has to bring an additional benefit. The task of the sonification is, again, differentiating configurations below, above, and at the phase transition by making the local topological objects and their properties audible.

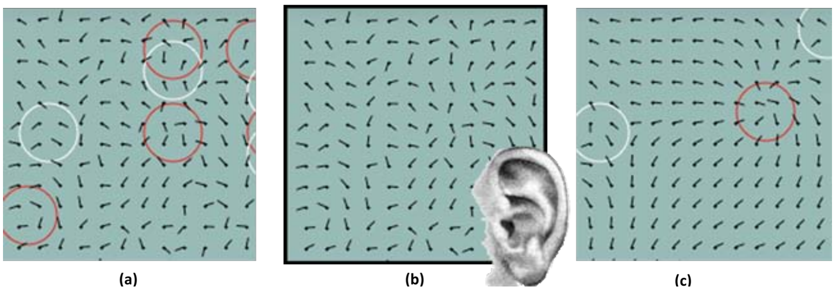


Figure 54: Detail of the XY model. (a) shows a typical configuration, where the positions of the vortices and anti-vortices have been calculated and are shown as red and white circles. If only raw data is shown (b), these structures are very hard to find visually – the ear indicates that this is the data used in the sonification. (c) shows the same detail after several steps of cooling, an algorithm that removes fluctuations, lowers the overall energy and leaves only the most stable vortices and anti-vortices.

Spin quartet sonification

For this sonification approach the plaquettes are the starting point – four neighboring sites on an elementary square, that carry the spin values s which form the topological structures. We refer to them as *spin quartets*, see Eq. (6.4a).

The differences between adjacent spin values in the plaquette $\delta s_{x,y,i}$ are calculated according to Eq. (6.4b) (assuring that the cumulation always continues in the same rotational direction). The $\delta s_{x,y,i}$ are added up in counter-clockwise direction to form a cumulative sum of the angles' differences $s'_{x,y,i}$, Eq. (6.4c). For an ideal vortex and antivortex, $\delta s_{x,y,i}$ is $+\frac{\pi}{2}$ and $-\frac{\pi}{2}$. The cumulative sum $s'_{x,y,4}$ is accordingly $+2\pi$ and -2π. Neutral spin quartets containing no anti-/vortex[2] show a total rotation of $s'_{x,y,4} = 0$. (Any configuration other than anti/-vortices has values between $-\pi$ and $+\pi$, but with a total rotation of 0.)

---

[2] This notation is used for 'vortex or anti-vortex'.

The resulting series s'_0 to s'_4 is used for phase modulation: the values are up-sampled by a factor of S between adjacent values, interpolated with a cosine function ($\mathrm{Int}^{\cos}$), and distorted by a cubic function, Eq. (6.4d). The distorted phase of an anti/-vortex still yields a final value of $\pm 2\pi$; see Fig. 55. Other configurations are suppressed.

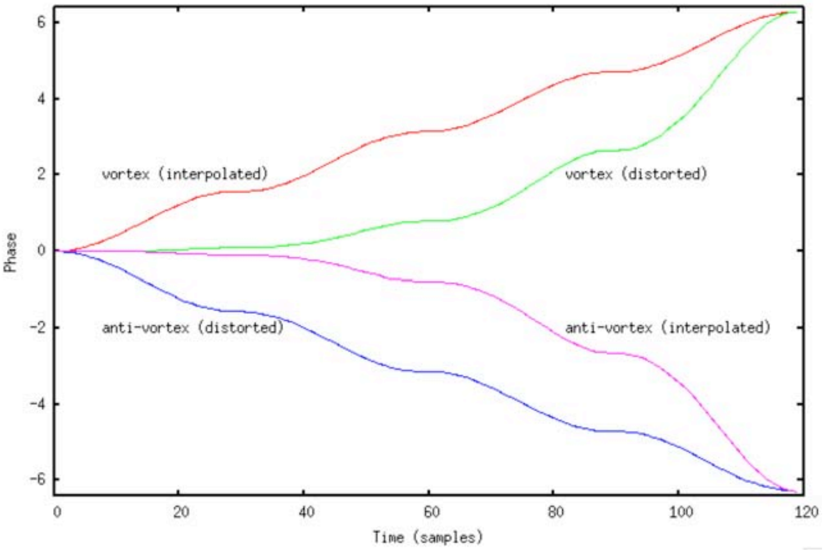


Figure 55: Phases of the ideal anti-/vortex for the XY sonification. The interpolated curves are depicted in red and magenta, the distorted curve according to Eq. (6.4f) in green and blue. The x-axis gives the number of samples. When the phase is looped, it is added smoothly to the last value; the base oscillation is periodic in 2π and does an effective modulo.

The resulting phase-distorted ramp is looped and controls the phase of a sine oscillator with the base frequency f_0, which is ultimately filtered out with a `Notch` filter. Thus, only the frequencies resulting from the phase modulation, f_p, and their overtones remain in the signal. In the case of a vortex, the phase rises by 2π and the resulting frequency increases. In the case of an anti-vortex, the frequency is lowered due to a negative phase slope. The number of samples between each of the spins was chosen to be $S = 30$. This results in a frequency of $f_p = f_s/4S = 44100/120 = 367.5\,\mathrm{Hz}$. We used a base frequency f_0 of $3f_p = 1102.5\,\mathrm{Hz}$. Thus, $(f_0 + f_p) : (f_0 - f_p) = 2 : 1$, and a vortex and an anti-vortex are one octave apart, Eq. (6.4e).

For each spin quartet at distance r (see below), a sound grain $\mathring{y}_r(\mathring{t}; d)$ is played, whereby a sine oscillator is modulated depending on the spin values, Eq. (6.4f). The full sonification operator is given in Eq. (6.4).

Calculate display unit:

$$
\begin{aligned}
s_{x,y} &= (s_{x,y}, s_{x+1,y}, s_{x+1,y+1}, s_{x,y+1}) && \text{(6.4a)}\\
\delta s_{x,y,i} &= s_{x,y,i+1} - s_{x,y,i} \quad i = 1,2,3 && \text{(6.4b)}\\
\delta s_{x,y,4} &= s_{x,y,1} - s_{x,y,4} &&\\
&= \begin{cases} \delta s_{x,y,i} & \text{if} \quad -\pi < \delta s_{x,y,i} < \pi \\ \delta s_{x,y,i} - 2\pi & \text{if} \quad \delta s_{x,y,i} > \pi \\ \delta s_{x,y,i} + 2\pi & \text{if} \quad \delta s_{x,y,i} < -\pi \end{cases} &&\\
s'_{x,y,i} &= \sum_{n=1}^{i} \delta s_{x,y,n} \qquad with\, s'_0 = 0 && \text{(6.4c)}\\
\phi_r(\mathring{t}; d_{x,y}) &= \mathring{L}_{4S}^{\infty} \left[\mathrm{Int}_S^{\cos} \left[\uparrow_S \left[\frac{(s'_{x,y,i})^3}{4\pi^2} \right] \right] \right] && \text{(6.4d)}
\end{aligned}
$$

Set sonification parameters:

$$
f_0(r) = \alpha(r) \cdot 3 \cdot f_p, \quad f_p = \frac{f_s}{4 \cdot S} \tag{6.4e}
$$

Synthesize *gestalt* unit:

$$
\mathring{y}_r(\mathring{t}; d_{x,y}) = \sin\left(2\pi f_0(r)\mathring{t} + \phi_r(\mathring{t}; d_{x,y})\right) \tag{6.4f}
$$

Overall sonification operator: (6.4g)

$$
\begin{aligned}
\mathring{y}(\mathring{t}) &= \sum_{r(\circlearrowright)} \mathring{L}_{s_L}^{\infty} \left[a_{env}(R, \mathring{t}_r) \cdot \mathring{\mathcal{F}}_{\mathrm{Notch}}^{f_0(r)} \left[\mathring{y}_r(\mathring{t}; d_{x,y}) \right] \right]\\
a_{env}(\mathring{t}; r) &= \begin{pmatrix} a_L(\mathring{t}(r), r) \\ a_R(\mathring{t}(r), r) \end{pmatrix} && \text{(6.4h)}
\end{aligned}
$$

The sonification is used interactively. Many spin quartets are played simultaneously around a central clicking point (x, y); their center and neighborhood range $r(\circlearrowright)$ can be chosen by the user, who thus determines the number of simultaneous quartets. A spotlight indicates all playing quartets in the GUI; see Fig. 56. Each sound grain is modulated by an envelope $a_{env}(\mathring{t}; r)$, Eq. (6.4h), and looped by the looping operator, $\mathring{L}$, until a new center site is chosen. The duration and loudness of the grain are determined by the distance to the clicking point, thus closer neighbors sound louder and quicker. This distance information is also encoded in a mistuning of the base frequency $f_0(r)$ by an adjustable parameter α (Eq. (6.4e)). Very close anti/-vortex pairs will have nearly the same base frequency in octaves. If the pair is further shifted, the interval is mistuned, resulting in a beating of varying frequency. This is a key feature of the sonification that allows a listener to distinguish the difference between bounded pairs and a vortex plasma. To give some orientation, left/right panning is also applied.

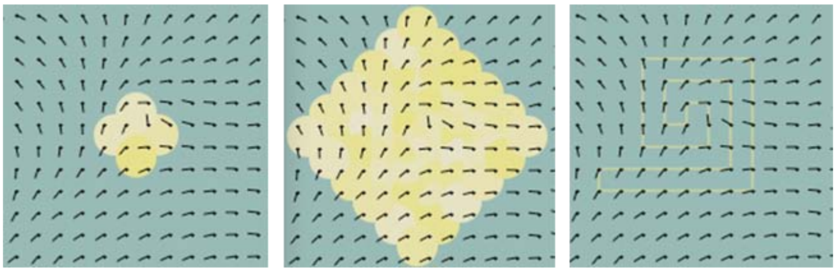


Figure 56: Interactive GUI of the XY model showing different listening range modes: In the neighbors mode (*left and medium figure*) a certain number of spin quartets around the clicking point is sonified. As an additional, more extensive mode of interaction, a spiral path was implemented. The spiral has variable length – order 1 gives a spin quartet. This setting is more exploratory, as the possible phase differences and the spectrum of the phase-modulated sine wave become more complicated. The sound of a vortex or anti-vortex depends on its position in the spiral, and several anti/-vortices can be encompassed in one spiral.

Documentation & Code:
Examples_XY_SpinQuartets;
XY_LoadAll.rtf (uses the files XY_FindVortices.rtf, XY_GUI.rtf, XY_Model.sc, XY_SonicPhases.rtf);
further online documentation at http://qcd-audio.at/results/xy.

6.3 QED *data listening space*

This sonification was elaborated during the QCD-audio project by Katharina Vogt, David Pirrò, Martin Rumori, and Robert Höldrich. [qcd]

Quantum electrodynamics (QED) is the quantum theory of electrodynamics, and lattice QED is a possible numerical approach. In the lattice formulation, the theory exhibits a phase transition which can be found by global observables of a whole configuration (Sec. 3.4.1). In the sonification of QED model data we created a possibility to search for local structures – the *'data* *listening space'*. The goal for the installation was to create an aesthetically interesting listening experience, that would allow a general public to assess this abstract data. The main challenge with this data was to display a 4d space plus an additional data dimension in a way that still permits orientation.

Data listening space

Data listening space [qcd] was a concept prepared for a public installation in November 2009, see Fig. 57. A person moves freely through space, and her/his position and rotation are captured by a motion-tracking system over a target attached to headphones. Each lattice point of the first three dimensions of the QED model has a fixed position in the tracking region, as depicted in Fig. 58. The height, as the third dimension, is compressed, thus all lattice points can be reached within the range of a person crouching down or stretching.

The data stemmed from a Monte Carlo simulation of lattice QED that was integrated in the SC3 source code. Single configurations of the model were stored beforehand and could be chosen in different temperature ranges. The configurations were typical in the sense that their action equalled the mean value of action of many configurations at that temperature. The lattice had 10^4 sites. The major restriction for the display unit was that only closed loops of values give physically meaningful entities (Sec. (3.4)).

A clear perception of localization of the lattice sites was reached via a binaural rendering. If the listener was exactly 'on' a lattice site, the according sound is played in mono, leading to in-head localisation. Otherwise, the sound was located virtually in space, by playing signals that slightly differ in their amplitudes and phases to the two ears. Maximally 5^3=125 points of the neighborhood were played simultaneously, with the nearest sites being dominant in amplitude. This range was chosen due to machine performance, but proved also sufficiently complex with listening 'performance'. The sonification operator is given in Eq. (6.5) and explained in detail below.

Figure 57: Foto of the data listening space installation in the MUMUTH Györgi-Ligeti-Saal in Graz, 8 November 2009. A listener explores the virtual data lattice, equipped with tracked headphones and a second tracking target.

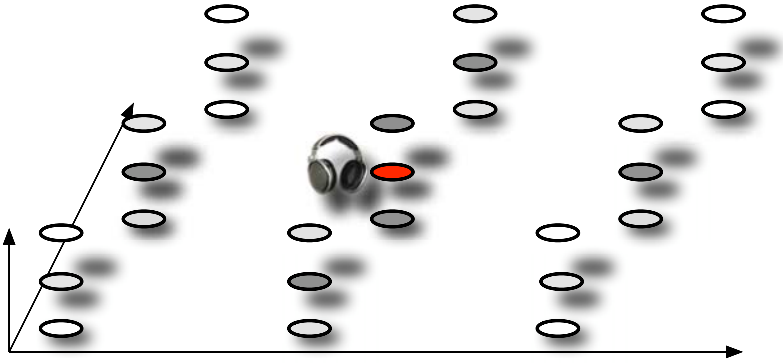


Figure 58: Schematic plot of the data listening space. Three space-like dimensions of the QED lattice are placed virtually in a real physical space. A listener can move freely about with headphones that are tracked with infrared cameras. Each dot represents the virtual position of a sound in the data listening space. The positions in the height dimension are compressed.

Calculate display unit:

(p is the series of links of the Polyakov loop (Eq. 3.17))

$$d_0([x,y,z];t) = p_0([x,y,z](\circlearrowright_1);t;r_L=0) \tag{6.5a}$$

$$d_{r_L}([x,y,z];t) = \begin{pmatrix} \{p_x([x,y,z](\circlearrowright_1);t;r_L(\circlearrowright_2))\,|\,x=1..r_L\} \\ \{p_y([x,y,z](\circlearrowright_1);t;r_L(\circlearrowright_2))\,|\,y=1..r_L\} \\ \{p_z([x,y,z](\circlearrowright_1);t;r_L(\circlearrowright_2))\,|\,z=1..r_L\} \end{pmatrix} \tag{6.5b}$$

$$d_0^{dist}([x,y,z];t) = \left(\frac{d_0([x,y,z];t)}{max_t(|d_0(x,y,z,t)|)}\right)^8 \tag{6.5c}$$

Set sonification parameters:

$$f_{r_L} = \alpha\cdot\left(1-\cos\left(\sum_t d_{r_L}([x,y,z];t)\right)\right) \tag{6.5d}$$

$$= \begin{cases} \in [220,440]\,\mathrm{Hz} & \text{if } r_L\text{=1} \\ \in [440,880]\,\mathrm{Hz} & \text{if } r_L\text{=2, 3} \\ \in [880,1760]\,\mathrm{Hz} & \text{if } r_L\text{=4, 5} \\ \in [3520,7040]\,\mathrm{Hz} & \text{if } r_L\text{=6} \end{cases}$$

$$s_L = \beta\cdot\sum_t |d_0^{dist}([x,y,z];t)| \qquad \in [0.07,0.28]\,\mathrm{s} \tag{6.5e}$$

Synthesize *gestalt* unit: (6.5f)

$$\mathring{y}_r(\mathring{t};d;[x,y,z]) = \sum_{r_L(\circlearrowright_2)} a_{env}(s_L)\cdot\mathring{\mathcal{F}}^{f_{r_L}}_{reson}\left[\mathring{L}^{\infty}_{10}\left[d_0^{dist}([x,y,z];t)\right]\right]$$

Overall sonification operator:

$$\mathring{y}(\mathring{t};d) = \sum_{(x,y,z)(\circlearrowright_1)} \mathring{L}^{\infty}_{s_L}\left[\mathring{y}_r(\mathring{t};d;[x,y,z])\right] \tag{6.5g}$$

$$\mathring{y}(\mathring{t};d) \rightarrow \begin{pmatrix} \mathring{y}_L(\mathring{t};d) \\ \mathring{y}_R(\mathring{t};d) \end{pmatrix}^{\Omega}$$

The sonification starts from the values used in a Polyakov loop $p_{x/y/z}$, sequences of numbers within $[-\pi,\pi]$, Eq. (6.5b). At each position ($[x,y,z](\circlearrowright_1)$) in the data listening space, the display unit is given at least by the '0-loop' (see below and Eq. (6.5a)) and the '1-loop': depending on the hand distance as a second interaction possibility, the loop range $r_L(\circlearrowright_2) \in [1,6]$ is set. For the display unit three times r_L loops are calculated, $p_{x/y/z}([x,y,z];t;r_L)$. The physical time dimension t is the running index of each of the series. The Polyakov loop series as a basic display unit are shown in Fig. 59.

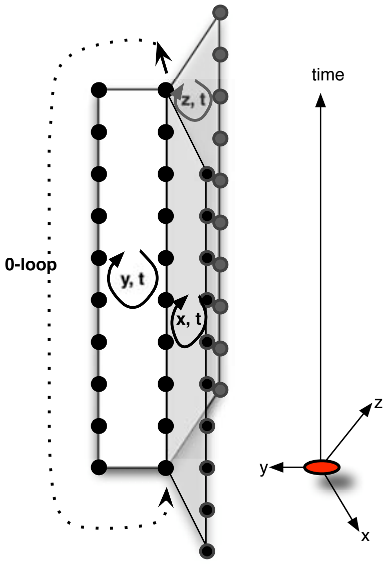


Figure 59: Schema of the sonification implemented for the data listening space. One lattice site is represented by at least the basic ‘0-loop’ and wider-ranging Polyakov loops (here the ‘1-loops’ are shown). They always encircle the whole time dimension and one space dimension with varying distances, respectively in the planes (x,t), (y,t) and (z,t).

As in the XY sonification, see Fig. 55, the 0-loop d_0 is distorted, but in this case by an exponent of 8 (Eq. (6.5c)), and normalized to 1 using the maximum t-link value of the entire configuration, Eq. (6.5c). The focus of interest thus lies on large changes in the 0-loop that remain after the distortion, while very uniform sequences fall automatically silent. The series d_{r_L} is used for pitch mapping into different frequency bands depending on the loop range r_L, Eq. (6.5d). The distorted 0-loop determines the looping time s_L of the display unit Eq. (6.5e), as explained below. Thus, the more changes are found in the 0-loop, the quicker the sound is looped.

The frequencies are used for resonant filters, $\mathring{\mathfrak{F}}_{reson}$, that are excited with the looped and distorted 0-loop signal, Eq. (6.5f). This is the *gestalt* unit modulated by an envelope a_{env}.

The overall sonification operator, Eq. (6.5g), is the loop of many sounds around the position $[x,y,z](\circlearrowleft_1)$. Their rhythm is determined by s_L, and their amplitude by the distance to the central position in a_{env}. The signal is rendered binaurally, thus the localization of the surrounding grains is displayed.

The resulting sound gives the following information. Silent sites are not interesting as there are hardly any changes in the 0-loop over time. Loud sites, on the contrary, indicate large fluctuations which can be interpreted as high energy. The pitch and the rhythm encode the energy: the more fluctuations in the lattice, the higher the pitches and the quicker the rhythm. Different loop sizes are distinguished by different frequency bands. Therefore, bigger loops can be compared to smaller ones. The overall impression gives an acoustic average of the different loops. This averaging which would be done in a numeric exploration as well.

Documentation & Code: A demo video was recorded at the IEM CUBE: 'QED_demovideo.flv'.

6.4 SONIFICATIONS IN LATTICE QCD

Lattice QCD is the numerical approach to problems of Quantum Chromodynamics (QCD) (Sec. 3.4). Two very different sonification tasks were studied: one for the topological charge density, the other for deduced data from local Polyakov loops. In both examples, the data are highly abstract and not fully visualizable. Thus, the purpose was to explore it.

6.4.1 *Searching for topological objects in QCD*

This sonification was elaborated during the SonEnvir project by Katharina Vogt and Till Bovermann, Philipp Huber, and Alberto de Campo. [VdCHB08]

For this sonification, the topological charge density, given by one real number per lattice site, served as data. Our research question was, whether local topological structures could be found in the data, e.g. instantons, which are hidden under random quantum fluctuations (Sec. 3.4.2). The sonification challenge was to display complex data locally in a 4d structure and allow some orientation. In addition to the real data, we generated simplified 'pseudo data' containing an 'ideal' instanton covered by noise with varying amplitudes, see Fig. 60. A pseudo instanton is a 4d

Gaussian-shaped bump, localized within $8a$. The lattice encompasses 16^3x32 sites and has periodic boundary conditions.

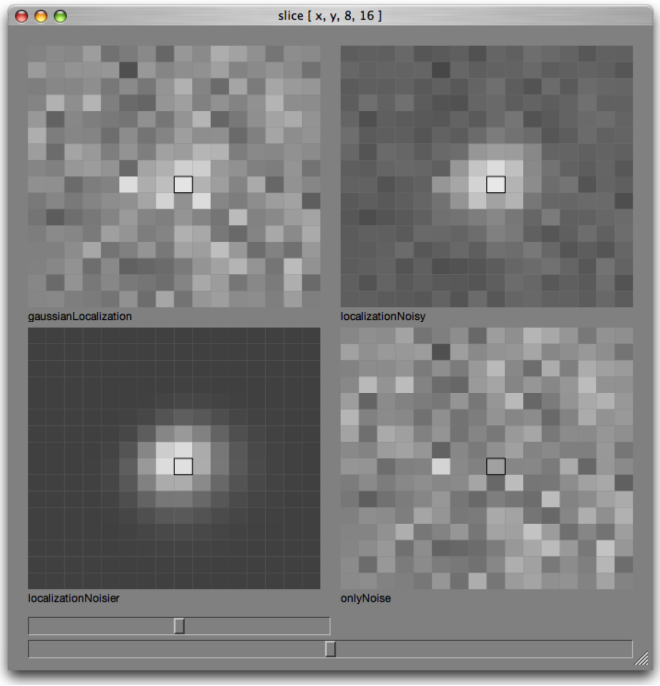


Figure 60: GUI of a test configuration of QCD with four data sets. The x-y planes of the z- and t-indices (given in the header) are shown. The data at the bottom left depict the pseudo instanton – a 4d Gaussian structure. On the contrary, the data set at the bottom right depicts only noise. The 2 top data sets are superpositions of the lower ones. The Gaussian structure is masked more (left side) and less (right side) by the noise data. Moving through the GUI is done by shifting the sliders or by clicking onto the 2d slices.

As the data are very large, we utilize 'sub-hypercubes', small regions around a chosen site, where $4^4 = 256$ neighboring sites are taken into account. We have implemented two sonification approaches: a 'resonated audification' and 'dynamical resonators', see Fig 61. They are similar in concept, as both excite resonator frequencies with a signal, but the roles of excitator and resonator are reversed.

In the resonated audification approach, $\mathring{y}(\mathring{t})_1$ (Eq. (6.6)) we use the Hilbert space filling curve to sequentialize the information of the sub-hypercube. This signal is used to excite different frequencies, f_i, in a filter bank. Depending on these frequencies the data can be probed to determine whether it contains peri-

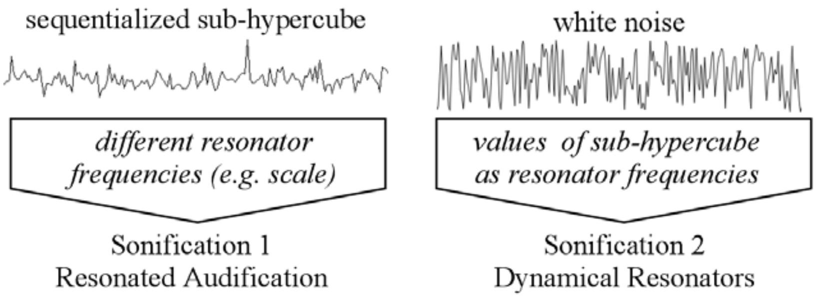


Figure 61: Schemes of the two basic sonification approaches for the topological charge in QCD.

odic structures on different scales. The sound is enclosed in an envelope. The sonification operator is given in Eq. (6.6).

$$\begin{aligned} f_i &= (f_0, f_1, f_2 ... f_n) \\ \mathring{y}(\mathring{t})_1 &= a_{env} \cdot \mathring{\mathfrak{F}}^{f_i}_{reson}\left[L^{\infty}_{256}\left[\mathrm{Hil}\left[d^{range=4}_{x,y,z,t}\right](i)\right]\right] \end{aligned} \tag{6.6}$$

In the second approach, $\mathring{y}(\mathring{t})_2$ (Eq. (6.7)), we put the cart before the horse: each data value of the sub-hypercube is directly mapped to a frequency f_i of a resonator, which is excited with white noise. The sonification operator is given in Eq. (6.7).

$$\begin{aligned} (x,y,z,t)_i &= \{[x+\delta x, y+\delta y, z+\delta z, t+\delta t]\}, \\ &\quad (\delta x, \delta y, \delta z, \delta t) \in [0,1,2,3] \\ f_i &= \alpha \cdot d(x,y,z,t)_i \\ \mathring{y}(\mathring{t})_2 &= \mathring{\mathfrak{F}}^{f_i}_{reson}\left[\mathring{\mathcal{N}}_{white}(\mathring{t})\right] \end{aligned} \tag{6.7}$$

Both implementations allow for interactive navigation through the data. A GamePad, equipped with two push sticks, can be used to navigate through the lattice. An alternative is simple sliders in the GUI. Automatic playback of a whole configuration is also possible, e.g. along two Hilbert curves of 16^4 sites (the two of them covering the shole lattice of 16^3x32).

Documentation & Code: 'QCD_TopologicalObjects.mov' is a demo video of the dynamical resonators with noisy pseudo data. The whole code is given in the file' QCD_TopologicalObjects' (start <1-PilotProjektPrograms_MasterGUI.rtf', and everything else starts from the GUI).

6.4.2 *The QCD waveguide mesh*

This sonification was elaborated during the QCD-audio project by Katharina Vogt and Robert Höldrich, David Pirrò, and Christof Gattringer.

A completely different data set from lattice QCD deals with center symmetry considerations derived from the Polyakov loop (Sec. 3.4.2). The data are three-dimensional and occur in four different states ($-1, 0, 1$, and 2; the latter referring to undecided states which are ignored). The configuration forms clusters, sites of identical states that are connected through links with same state Polyakov loops at their endpoints. A specific phenomenon is percolation, meaning that a cluster ranges from one lattice side to the opposite end. The size of the clusters and whether they percolate depends on the temperature.

In this sonification approach, we used a model in which the clusters of each state (excluding the '2') are regarded as caves of free wave propagation; the borders of the cave defined as hard reflections between different states. The 'caves' are excited by white noise or by an impulse at one side of the lattice, and the resulting resonant signal is recorded at the opposite side. The sound signal propagates through the lattice only if there is percolation. The model is based on a 3d waveguide mesh. A short introduction to linear waveguides and waveguide meshes is described below.

The digital waveguide mesh

The digital waveguide mesh is an efficient method of simulating wave propagation numerically (for an extensive introduction see [Smi06]).

To model a linear waveguide, a one-dimensional wave $y(x,t)$ propagates along the space dimension x at speed c (e.g., describing the transverse displacement of a vibrating string or the longitudinal sound velocity in an organ pipe). Following the d'Alembert solution of the wave equation, the wave can be decomposed in a left-going (y_l) and a right-going factor (y_r) :

$$y(x,t) = y_r\left(t - \frac{x}{c}\right) + y_l\left(t + \frac{x}{c}\right) \tag{6.8}$$

Physical space is discretized as $x_m = mX$ in the waveguide model, and time as $t_n = nT$. The traveling wave solution is thus sampled at intervals of T seconds, with the spatial expansion then given by $x = cT$. The wave travels to the left or right one waveguide site per time sample. The sampled form of the traveling-wave solution is then given by:

$$\begin{aligned} y(t_n, x_m) &= y_r[(n-m)T] + y_l[(n+m)T] \\ &\equiv y^+(n-m) + y^-(n+m). \end{aligned} \tag{6.9}$$

The term $y^+(n-m)$ corresponds to the output of an m-sample delay line, with an input of $y^+(n)$; thus the waveform is delayed by m samples. Correspondingly, $y^-(n+m)$ is the *input* to an m-sample delay line whose *output* is $y^-(n)$. The actual wave value (e.g., displacement or velocity) at each waveguide site is the superposition of the left- and right-going part.

This approach can be easily extended to two or more dimensions, resulting in a waveguide *mesh* as shown schematically in Fig. 62 for two dimensions. At each junction, incoming and outgoing waves are summed (denoted by '+') up to calculate the wave value.

In the free case, a wave triggered at some site(s) n_i is passed through the mesh without losses. If there are boundaries, or changes of the impedance, in the mesh, the wave is reflected at that point (partially) and the reflected part superimposes with the incoming wave. The impedances R_i at each site i result in the *reflection coefficient* $k_i(t)$ between adjacent sites in direction i,

$$k_i(t) = \frac{R_i(t) - R_{i-1}(t)}{R_i(t) + R_{i-1}(t)}. \tag{6.10}$$

The effect of R changes its sign depending on the wave direction. E.g. for transversal wave propagation on a string, the relation between the physical force density (or *stress*) f_i and the velocity $v(t) = dy/dt$ is given by:

$$\begin{aligned} f_i^+(t) &= R_i v_i^+(t) \\ f_i^-(t) &= -R_i v_i^-(t) \end{aligned} \tag{6.11}$$

Referring to Eq. (6.10), the stress can be derived for a normalized setting of variables (see [Smi06, p. 358ff]), and f is now denoted with a tilde. The normalized lossless scattering junc-

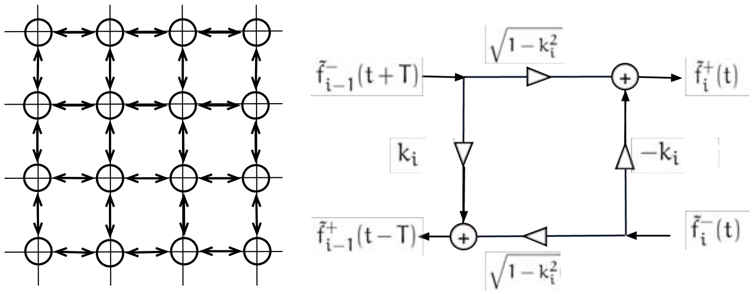


Figure 62: *left figure* – Scheme of a digital waveguide mesh in two dimensions.
right figure – A normalized scattering junction in the digital waveguide model.

tion is then the digital simulation of two neighboring sites with impedances R_i and R_{i+1} resulting in a reflection coefficient k_i:

$$\begin{aligned} \tilde{f}^+_i(t) &= \sqrt{1-k_i^2(t)}\tilde{f}^+_{i-1}(t-T) - k_i(t)\tilde{f}^-_i(t) \qquad (6.12) \\ \tilde{f}^-_{i-1}(t+T) &= k_i(t)\tilde{f}^+_{i-1}(t-T) + \sqrt{1-k_i^2(t)}\tilde{f}^-_i(t). \end{aligned}$$

The simulation diagram of a 2d mesh is shown in Fig. 62 on the right-hand side.

Errors in digital waveguides stem from a small numerical error, and a larger dispersion error: higher frequencies have a higher propagation velocity than lower ones, due to the geometrical characteristics of the mesh.

QCD Waveguides

Waveguide meshes have been used in the context of sonification by Lee et al. [LSB05] with high-dimensional data sets. In our example, we implemented a 3d waveguide mesh. Their data stem from the center symmetry clusters. The boundaries between the clusters are hard reflecting.

A sonification operator can only be formulated in general for model-based sonification. It is given in Eq. (6.13). The readout condition is to sum over all sites of the southern boundary plane ($[x,y]_{\mathrm{south}} \equiv [x,y,z]|_{z=0}$) of the mesh for all times, e.g. 30,000 samples. Two different excitation inputs have been used at time 0 at the opposite, northern plane ($[x,y]_{\mathrm{north}} \equiv [x,y,z]|_{z=n_{\mathrm{Mesh}}}$): one is a locally distributed 'noise' or random values, the other an impulse, where all boundary values are set to 1. The model is

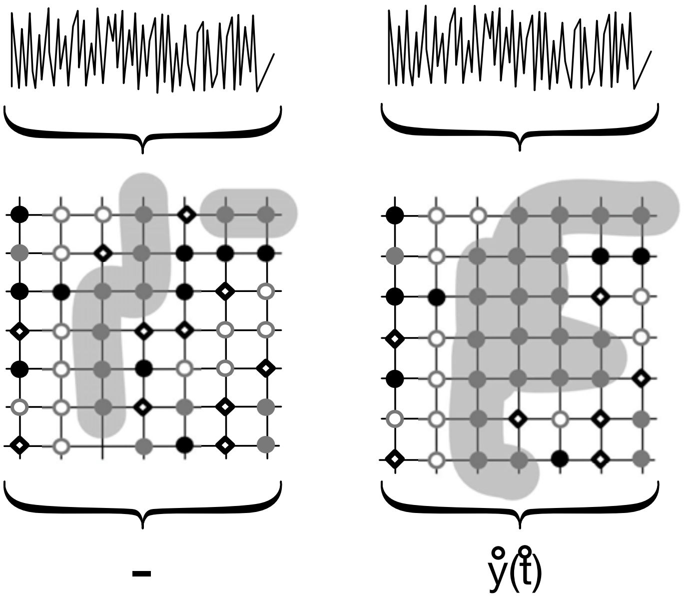


Figure 63: Two schematic examples of the center symmetry waveguide mesh, with clusters of the 'grey' states highlighted, excited by noise. As the left configuration is not percolating and the right one is, thus a sonification signal $\mathring{y}(\mathring{t})$ is recorded at the 'southern' end of the right configuration.

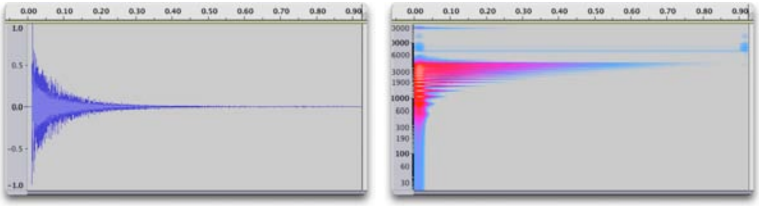
defined by free wave propagation inside the clusters, and hard boundaries between them. A schematic plot is shown in Fig. 63.

$$\mathring{y}(\mathring{t}) = M\mathring{B}S_{\sum_d d([x,y]_{south})}\left[\mathrm{Excite}([x,y]_{north}, \mathring{t} = 0)\right] \tag{6.13}$$

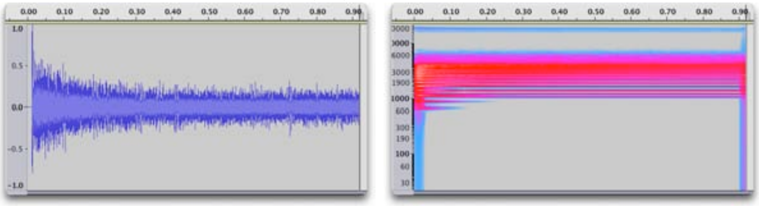
The waveguides are computationally demanding and are calculated in non real-time. For each state, a separate waveguide mesh is calculated. The three resulting soundfiles are played simultaneously on three channels or mixed in stereo to the left, the middle, and the right position. It is very unlikely that more than one state will show percolation. Thus, only the left, middle or right channel plays, and the assignment of the percolating state is unanimous.

If locally distributed 'noise' is used as an excitation signal, the resulting sonification signal is determined by random fluctuations of the input. Thus, for the following showcase examples, an impulse was used as excitation. Test 'clusters' were programmed as simple tunnels extending from north to south, with three varying extensions. The resonances in the sonification signal are determined by characteristic sizes of the tunnel. The smallest tunnel of 1x1x20 mesh sites loses its energy quickest, thus the sound decays, and the higher frequency components are the most distinct; see Fig. 64.

1x1 tunnel



9x9 tunnel



15x15 tunnel

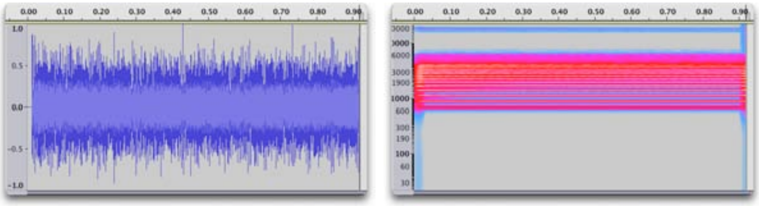


Figure 64: Examples of a 20^3 sites waveguide mesh, excited with an impulse (all values set to one) at time $t = 0$, and run for 20,000 samples. Three percolating tunnels of different sizes were programmed into the mesh as 'test clusters'. Small tunnels lead to the excitation of higher frequencies, and lose their energy quicker than large tunnels, which excite also low frequencies, due to longer distances of free wave propagation between adjacent (hard reflecting) cluster sides.

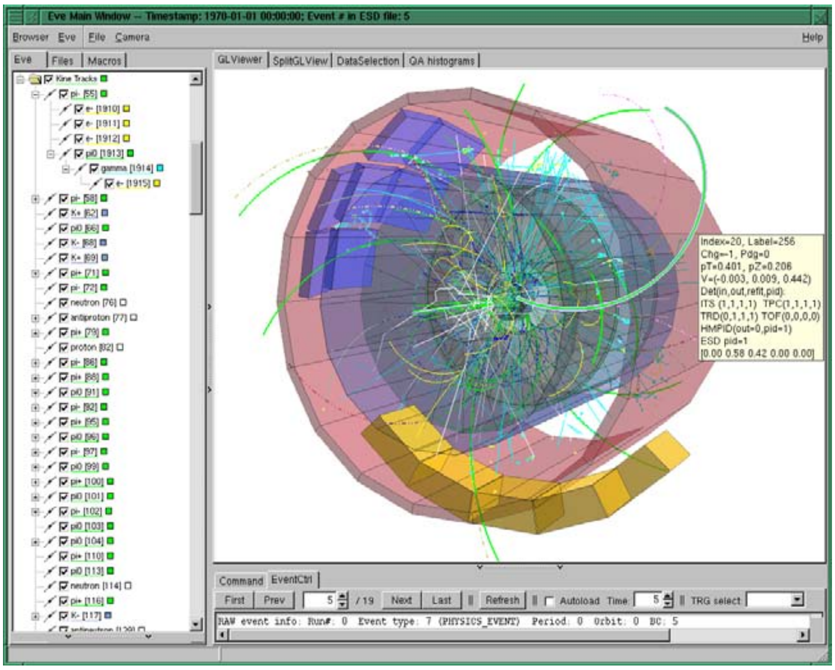
Documentation & Code: See the folder 'QCDWaveGuide' for test tunnel examples and real data examples.

6.5 A SONIC TIME PROJECTION CHAMBER

This sonification was elaborated during the QCD-audio project by Katharina Vogt, David Pirrò, Martin Rumori, Robert Höldrich, and was supported by scientists from CERN. [VHP+10]

Data for this example stem from simulations of the Time Projection Chamber (TPC) of the ALICE project at CERN (Sec. 3.5). Particle detection is based on pattern recognition algorithms, but is still today double-checked with visualization tools. An interactive visualization tool, AliEve [TMT00], exists for this data, see Fig. 65.

The provided data sets are simulated *events* of p-p collisions containing up to 35 tracks comprising a few hundred thousand individual electron impacts, each given at a certain time (t_i) and location (ϕ_i, r) with an energy deposit (e_i). These are the simulated raw data expected in the measurements; further information comes from a second level of pattern recognition, i.e. which individual electron impacts form a track caused by one particle.



```
Index=20, Label=256
Chg=-1, Pdg=0
pT=0.401, pZ=0.206
V=(-0.003, 0.009, 0.442)
Det(in,out,refit,pid):
ITS (1,1,1,1)  TPC(1,1,1,1)
TRD(0,1,1,1) TOF(0,0,0,0)
HMPID(out=0,pid=1)
ESD pid=1
[0.00 0.58 0.42 0.00 0.00]
```

5 ☐ Autoload Time: 5

```
RAW event info: Run#: 0  Event type: 7 (PHYSICS_EVENT)  Period: 0  Orbit: 0  BC: 5
```

Figure 65: Screenshot of AliEve [TMT00], the visualization tool of the ALICE offline group. The reddish surface gives the volume of the TPC (yellow and blue are other detectors). Each line is the track of a particle of this event.

The sonification is based on a parameter mapping that uses the raw data of single electron hits, allowing for a perceptual grouping into tracks following auditory grouping principles (Sec. 2.1 or [Bre90]).

Based on the fact that 'electrons' (in fact electron clouds) hit the wires with a certain charge (the number of electrons), the wires are taken as being analogous to *strings*, which are hit and resonate with their basic frequency depending on their length, see Fig. 66.

It was a natural choice to place the listener at the collision point and to let the time 'evolve' towards the left and right read-

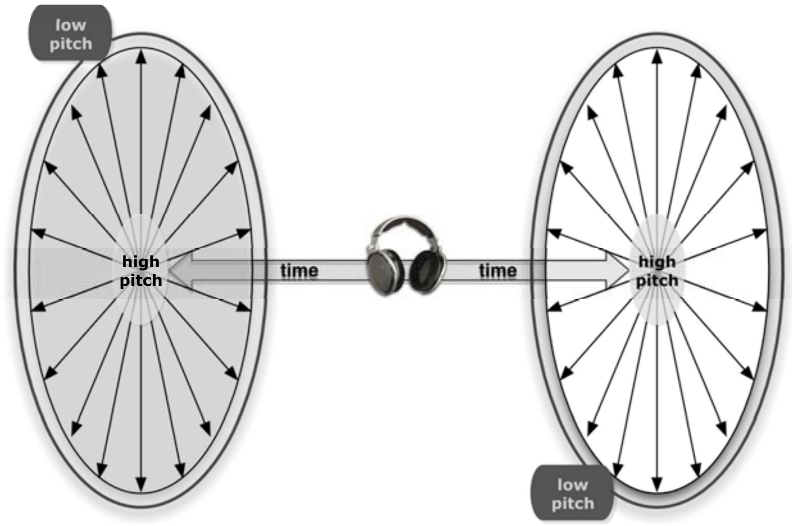


Figure 66: Scheme of the sonification of TPC data: the listener is virtually placed in the center of the detector, where the beams collide.

out chambers. The time in the raw data is given *reversely*, as it is the impact time of electrons freed by particles passing nearly at the speed of light. Those electrons reach the read-out chambers first that are closest to them. Thus, the time in the raw data thus evolves from outside back to the collision point. The sonification time is reverse to the data time, as it is more natural to follow the tracks from the collision point outwards.

In order to enhance the perceptual grouping and separation of tracks, it is necessary to disambiguate those events which take place in the same height of the radius but at a different angles (given by ϕ in cylindrical coordinates). Depending on this angle, we add different sets of overtones to the base frequency. In order to achieve different timbres, the base frequency is either played solely for $\phi = 0°$ (where the amplitudes of all even and odd overtones are 0), or with just one set of overtones (odds = 0, evens =1 for $\phi = 90°$, or vice versa if $\phi = 270°$), or as a full sound at $\phi = 180°$ (evens and odds = 1); see Fig. 67.

For angles in between these extreme positions, a linear interpolation of the partial's amplitudes is introduced as a weighting factor $w(\phi_i)$. Furthermore, all partials are weighted with $w_k = 1/n$, where n is the number of harmonics.

This differentiation of pitches and timbres allows the correct grouping in human perception: following the *gestalt* psycholog-

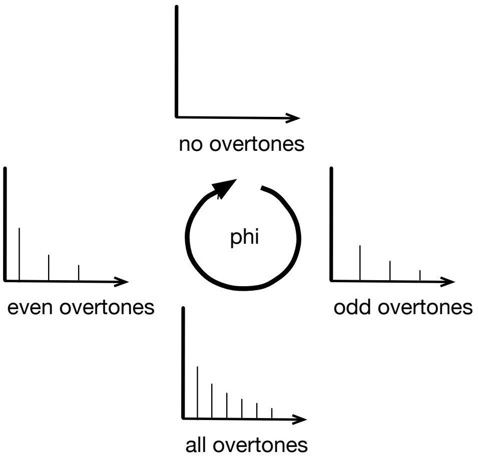


Figure 67: Simplified scheme of the overtone structure in the TPC sonification depending on the angle ϕ. The overtone structure helps disambiguating the correct grouping and separation for single sounds into coherent tracks, even if these tracks have similar pitches.

ical principle of *similarity*, similar sounds are grouped together and perceived as originating from the same track. As additional cues, similar sounds always follow close to each other (principles of *proximity* and *good continuation*).

Each electron impact is displayed as a sound grain consisting of resonator filters $\mathring{\mathfrak{F}}_{reson}$ with frequencies $f_{i,k}$ specified according to the pitch mapping. The filter bank is excited with an impulse and enclosed by an envelope $a_{env}(\mathring{t})$. The level of the impulse and thus the amplitude of the resulting sound are determined by the charge deposit of the electron. Tracks with only few single electron impacts or very weak ones fall silent.

The sonification operator is given as:

Display unit:

$$d_i = d(t_i, r_i, \phi_i, e_i) \tag{6.14a}$$

Set sonification parameters:

$$f_0(r_i) \in [200, 800]^{\exp}\ \mathrm{Hz} \tag{6.14b}$$

$$f_k(\phi_i) = \{fo(\phi_i), fe(\phi_i)\} \tag{6.14c}$$

Synthesize *gestalt* unit:

$$\mathring{y}_i(\mathring{t}; d_i) = a_{env}(\mathring{t}) \sum_k w_k w(\phi_i) \mathring{\mathcal{F}}^{f_k(\phi_i)}_{reson}[e_i \cdot \mathring{\mathcal{J}}(t)] \tag{6.14d}$$

Overall sonification operator:

$$\mathring{y}(\mathring{t}; d) = \sum_i \mathring{T}_{\delta \mathring{t}} \left[\mathring{y}_i(\mathring{t}; d_i)\right] \tag{6.14e}$$

$$\mathring{y}(\mathring{t}; d) \rightarrow \begin{pmatrix} \mathring{y}_L(\mathring{t}; d) \\ \mathring{y}_R(\mathring{t}; d) \end{pmatrix}^{(\Omega)} \tag{6.14f}$$

We rendered stereo files and a binaural version, but the latter seemed not to work well with 'imaginary' paths (perception has no fix references). Simple stereo panning required less effort but was perceived even more clearly in addition to the visual cues of the screenshots.

In the current setting, each event takes 10 seconds of sonification time. This time span can be shortened, of course, but is a good length to disambiguate tracks even in more complicated events.

As it is difficult to listen to many tracks at once, any track can be selected and played individually. Fig.68 shows a screenshot for one sound example on the homepage (see below). The marked track is played. In this case, the particle was not produced in the collision, but stems from background radiation or some secondary process of disintegration. It is a charged particle, as it is whirling around in the exterior magnetic field of the ALICE experiment. The pitch is rising and falling, which matches the idea of a rotating flying object.

Documentation & Code: Sound examples and further documentation can be found at http://qcd-audio.at/tpc/

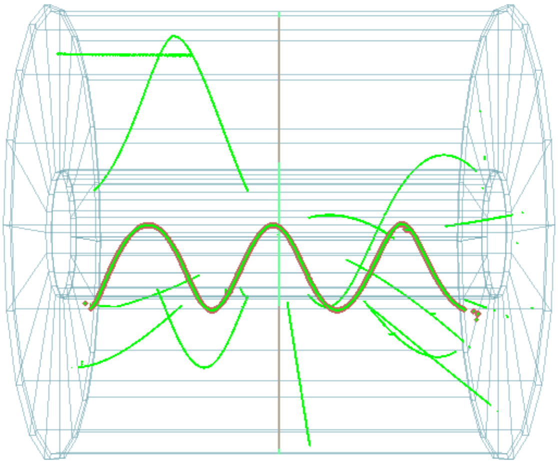


Figure 68: Screenshot of a sound example of a TPC sonification (event number 6), which can be listened to at www.qcd-audio.at/tpc.

6.6 CONCLUSIONS OF SONIFICATION EXAMPLES

The examples presented in this section represent a diverse collection of data and sonification approaches. Even if they all come from computational physics, this field is so segmented and highly specialized that the actual tasks varied significantly. The main similarity in the data sets is the re-formulation of a phenomenological task as a structural, sometimes topological problem: recurring entities that were aimed to be displayed were (closed) loops and clusters, and other localized structures (bumps in the topological charge density of QCD, anti/-vortices in the XY model, or continuous tracks in the TPC simulation).

The diversity of the data is reflected by the diversity in the sonification designs. There are no clear methodological borders; audification, parameter-mapping and model-based approaches are combined within single sonifications. An example is the data listening space: the sonification takes audified signals (of loops), that serve as input to filters with resonance frequencies determined by sums over other loops. Thus the data themselves serve as a model played by other parts of the data. Additionally, everything is 'classically' mapped as parameter mapping into physical space.

As discussed in Sec. 4.2, the sonification designs can be categorized as bottom-up or top-down. While purely exploratory sonification tasks are usually bottom-up approaches, the control of the metaphoric content of the sonification in top-down designs has also advantages, e.g. better intuitive understanding within the domain science. Into the first category of bottom-up design fall the Ising noise and Ising grain clouds, the XY spin quartets, the QED data listening space, and the topology search in QCD. The second category, where the metaphoric content is shaped from the beginning, comprises the Ising *gestalts*, the waveguide meshes of center symmetry (because the spatial audio paradigm matches the cluster idea), and the sonic TPC (because the detector *would* sound as our sonification does if the measurement process were audible).

What has been achieved on a practical level is general sonic solutions for many sub-challenges in different sonifications. Some tasks may be presumably simple, such as getting an idea about cluster sizes and shapes, providing a quasi-instantaneous overview in sound (which is, however, never instantaneous), or allowing for an 'acoustical averaging' over large, stochastic data sets; or the task can be more complex, such as providing orientation in a 4-dimensional space, or perceptualizing a hundred thousand data points in a sensible amount of time.

Evaluations have not been included in the examples' section because they were not done in a systematic way throughout the research projects (SonEnvir and QCD-audio). In general, most of the examples were evaluated in an informal way during the design process in cooperation with physicists from the Institute for Physics at the University of Graz. Furthermore, they have been presented in various forms to a broader audience of physicists. The general attitude towards sonification is characterized by curiosity, and the sonifications are often received as entertaining; however, the scientific attitude toward sonification as a method in computational physics is rather skeptical. Nevertheless, in general the new method is seen to have great potential.

7

CONCLUSION

It is important to pass on knowledge gained in sonification research to scientists across fields and to make the field of sonification accessible to newcomers. For this reason, the thesis starts in Part I with extensive background material that covers the basics of auditory perception, examples of *'spontaneous sonification'* in science, and the history and outcome of systematic research in sonification of the last 20 years. In addition, the basics of computational physics, the field that provides the data for this thesis, are introduced. Part II gives methodological guidelines for describing sonifications formally with notation modules and for designing them, and also provides a practical *toolbox*. The examples in Part III show how the tools have been used. They are described using the notation modules, but the codes and listening examples (or demo videos) are provided as well. Even if the data all stem from computational physics, the sonifications can be transferred to many other scientific domains.

I showed in Part I that certain kind of data might be more effectively studied using sonification rather than some other perceptualization method (usually visualization). Examples of *'spontaneous sonification'* give hints as to when or under what circumstance sonifications are useful. While some of these purposes might not be applicable to the data in this thesis (for instance, sound is surely not a *by-product* of simulation data), others match the tasks of computational physics. One of these is the recognition of *conceptual similarities* (e.g., when mapping the data time to sonification time), another one the *'let's see'* approach that shows promise due to the vast amounts of multi-dimensional and abstract data. This analysis has shown that sonification is very suitable for simulation data.

The data used in this thesis stem from Monte Carlo (MC) simulations. As a 'third quid' to theory and experiment, the MC simulation provides categorically new data that have no inherently perceptual dimension. They are dynamic (exhibiting a simulation time and a modeled physical time evolution), discretely structured on a lattice, often high-dimensional, and stochastic in nature. Furthermore, symmetries play an important role, which link many different real systems to each other as they are described by the same kind of simulation. Perceptualization is a central component of data analysis of simulations. However, perceptualization tools are usually not developed further in computational physics, but taken for granted following standard methods.

Even after some 20 years of research, sonification design is still a challenging task, due to various reasons. First, the perhaps most challenging aspect is the need for interdisciplinary knowledge. While sonification surely has the potential to provide new hypotheses in a domain science, the sonification community is still developing its basic methods and conventions. For this reason, information about the needs of a given domain science and about the possibilities of ADs has to be exchanged, and must often be combined within one 'integrative' person to a certain extent. Second, a major part of sonification research is not concerned with the exploration of scientific data, but with technical applications, e.g. monitoring of processes. Design frameworks and evaluation procedures that are general enough to cover both fields (exploration and applications) are lacking and perhaps not even possible. Third, examples of sonifications usually emerge from small projects in diverse domain disciplines. An institutional framework for continuous on-going sonification research is lacking worldwide, with few exceptions. Facing these challenges, the research projects SonEnvir and QCD-audio, as well as the Science By Ear workshops, stood out in at least two aspects. On the one hand, sonifications for various *different* disciplines were implemented by interdisciplinary teams within one project. On the other hand, sonification knowledge was gathered continuously and combined at the Institute of Electronic Music and Acoustics (IEM). The IEM serves as a *'trading zone'* (in the sense introduced by P. Galison) for the exchange of ideas from audio engineering, computer music, auditory perception, and mathematics, and provides an ideal environment for sonification research.

In this interdisciplinary arena it is necessary to facilitate the communication between sound experts and domain scientists. For this task, the thesis proposes *notation modules*. The mathematical formulation of a sonification operator is simple and concise. (Even though the formulations of the examples in Part III sometimes look quite voluminous, they are still much more compact than any verbal explanation). In the field of physics, this sort of formalization has even been expected, but 'softer' sciences than physics can also take advantage of it. The modules are not complete, but consist of what was needed to describe the sonification examples in this thesis. Even though many different methods are covered, ranging from granular synthesis to parameter mapping and model-based sonification, the modules will have to be extended by additional sonification methods.

A possible disadvantage of the sonification operator is the fact that it describes only the linkage between domain science and sound synthesis, but not how the sound is *perceived*. One has to keep in mind that a given sonification signal is interpreted by the listener on different levels of perception and cognition. The sonification operator does not 'solve' a problem, but only describes the sound synthesis in dependance on the data of the domain science.

Continuous sonification is usually classified as audification, parameter mapping, or model-based sonification. However, these methods are usually combined in sonification examples, and a different structure was needed to present the various tools developed in the research projects. For every sonification, decisions had to be made regarding the treatment of the data and the synthesis of the sound. For this, I suggested three levels: meaning, structure, and elements. Six design decisions follow from this analysis, concerning the phenomenological *meaning of the data*; the metaphoric *meaning of the sound* (including *'audiables'* that provide non-trivial new insights); the discrete and dynamic *lattice structure of the data*; the *structure of sound* (consisting at least of a time structure, but often also of some 'sonic space'); the *'display units'* as data elements that are actually used for the sonification; and the *'gestalt units'* as sound elements that are the smallest perceived entities.

The meaning of data is the starting point for any sonification. Every sound also has a meaning, and for an intuitive understanding of sound, metaphors should be taken into account. This can be achieved, e.g., by using the metaphoric sonification method, which is a *top-down* approach of sonification design. However, shaping the sound *ab initio* also leads to problems. Designing a useful sonification is already a complex task in which one has to come to terms with the display units, the data that are actually used for the sonification, and the data structure. Accordingly, many examples described in this thesis were designed following a *bottom-up* approach, where one first determines the mapping of display units to *gestalt* units. Following this classification of six design decisions and the implementation constraints, *boxes of tools* are provided which present solutions for sub-tasks of sonification design. Most of these tools have yet not been used in the context of sonification, or at least not in the way suggested in the thesis. They are applicable to different contexts than the presented sonification examples.

Because of their interdisciplinary and innovative nature, it is difficult to evaluate sonifications. In the ICAD community, few instances of comparisons of sonifications stemming from different backgrounds have been reported. New approaches are needed to determine objectively what a 'good' sonification entails. During the projects, most of the evaluation work was done directly by members of the interdisciplinary teams, but two approaches have been tested additionally. On the one hand, a qualitative evaluation was implemented for the *data listening space*. Video taking and its analysis that is following a grounded theory approach is very instructive. The example offers useful suggestions for the usage of a motion-tracking system or similar interfaces in the context of interactive sonification. However, in many contexts such a setting is difficult to envision. E.g., progress in understanding 'better' an already known model through an AD cannot be observed from the 'outside'. Some sort of interview or targeted testing is probably the only way.

On the other hand, as a quantitative approach, the Multi-Criteria Decision Analysis (MCDA), was pursued within the SBE2. It allowed to assess and directly compare the sonifications of the workshop. The MCDA in general gives significant results, but the motivations of subjects to chose one or the other option cannot be surveyed in detail. They must be concluded on the basis of further, qualitative analysis. Nevertheless, a *set of criteria*, such as that suggested in this thesis, can greatly enhance our ability to compare sonifications across application domains and it can also help us find successful shared strategies for the future development of sonification.

A

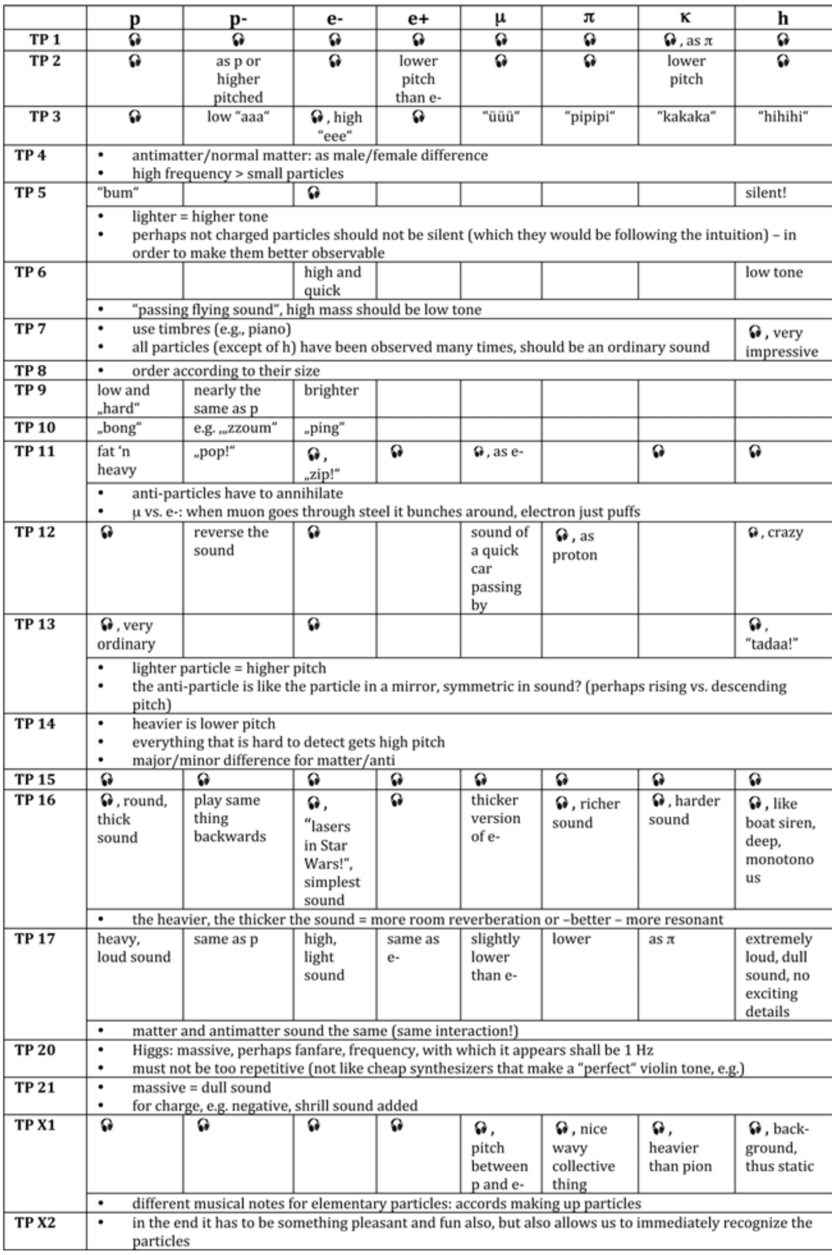
APPENDIX

A.1 QUESTIONNAIRE RESULTS

The table in Fig. 69 shows the results of the recorded part of the questionnaire of the metaphor procedure (Sec. 4.3).

Free associations for eight particles have been extracted. The symbol of the headphones indicate that a sound recording exists for this particle of the test person (TP). Three TPs have been excluded as they had not studied physics, 2 extra test persons (X1 and X2) only did parts of the questionnaire.

Resulting mapping choices of the fill-out part are shown below. (The number of mentions vs. the whole number of all answers for this property is shown in brackets):



	p	p-	e-	e+	μ	π	κ	h
TP 1	🎧	🎧	🎧	🎧	🎧	🎧	🎧 , as π	🎧
TP 2	🎧	as p or higher pitched	🎧	lower pitch than e-	🎧	🎧	lower pitch	🎧
TP 3	🎧	low "aaa"	🎧 , high "eee"	🎧	"üüü"	"pipipi"	"kakaka"	"hihihi"
TP 4	• antimatter/normal matter: as male/female difference • high frequency > small particles							
TP 5	"bum"		🎧					silent!
	• lighter = higher tone • perhaps not charged particles should not be silent (which they would be following the intuition) – in order to make them better observable							
TP 6			high and quick					low tone
	• "passing flying sound", high mass should be low tone							
TP 7	• use timbres (e.g., piano) • all particles (except of h) have been observed many times, should be an ordinary sound							🎧 , very impressive
TP 8	• order according to their size							
TP 9	low and „hard"	nearly the same as p	brighter					
TP 10	„bong"	e.g. „„zzoum"	„ping"					
TP 11	fat 'n heavy	„pop!"	🎧 , „zip!"	🎧	🎧 , as e-		🎧	🎧
	• anti-particles have to annihilate • μ vs. e-: when muon goes through steel it bunches around, electron just puffs							
TP 12	🎧	reverse the sound	🎧		sound of a quick car passing by	🎧 , as proton		🎧 , crazy
TP 13	🎧 , very ordinary		🎧					🎧 , "tadaa!"
	• lighter particle = higher pitch • the anti-particle is like the particle in a mirror, symmetric in sound? (perhaps rising vs. descending pitch)							
TP 14	• heavier is lower pitch • everything that is hard to detect gets high pitch • major/minor difference for matter/anti							
TP 15	🎧	🎧	🎧	🎧	🎧	🎧	🎧	🎧
TP 16	🎧 , round, thick sound	play same thing backwards	🎧 , "lasers in Star Wars!", simplest sound	🎧	thicker version of e-	🎧 , richer sound	🎧 , harder sound	🎧 , like boat siren, deep, monotonous
	• the heavier, the thicker the sound = more room reverberation or –better – more resonant							
TP 17	heavy, loud sound	same as p	high, light sound	same as e-	slightly lower than e-	lower	as π	extremely loud, dull sound, no exciting details
	• matter and antimatter sound the same (same interaction!)							
TP 20	• Higgs: massive, perhaps fanfare, frequency, with which it appears shall be 1 Hz • must not be too repetitive (not like cheap synthesizers that make a "perfect" violin tone, e.g.)							
TP 21	• massive = dull sound • for charge, e.g. negative, shrill sound added							
TP X1	🎧	🎧	🎧	🎧	🎧 , pitch between p and e-	🎧 , nice wavy collective thing	🎧 , heavier than pion	🎧 , back-ground, thus static
	• different musical notes for elementary particles: accords making up particles							
TP X2	• in the end it has to be something pleasant and fun also, but also allows us to immediately recognize the particles							

Figure 69: Overview of free associations for 8 particles

Pitch: mass (18/18), favorit: mass

Amplitude: mass (7/14), charge (4/14), matter (2/14), favorit: charge

(mass will be used for pitch, and does not need to be mapped twice, as pitch is a very strong mapping factor; charge was cited second most often)

Rhythm: lep/ had (3/12), mass(2/12), matter (2/12), individual suggestions (3/12), no clear favorite

in general, rhythm is more associated with the experiment, measurement or data

Noise component: lep/ mes/ bar (7/14), matter(3/14), quark content (2/14), favorit: lep/ mes/ bar

(but no clear mapping choice due to inconsistent polarities)

Vibrato: exc. (6/14), lep/ mes/ bar (4/14), matter (3/14), charge (2/14), favorit: excitation

(here the problem was different notions of excitation; we referred to ground state and excited states, but this is not reflected in measurements, and was thus often interpreted differently. Still, vibrato would be the favorite mapping for excitation.)

Timbre: matter (2/8), exc. (2/8), lep/ mes/ bar (2/8), no clear favorite:

and only few total number of suggestions (possibly, this is concept is too complex)

A.2 WORKSHOP: SCIENCE BY EAR 2

The 2nd 'Science By Ear' workshop (SBE2)[1] took place at the Institute of Electronic Music and Acoustics in Graz, from 25th to 27th of February, 2010.

Within the same workshop design as SBE1[2], interdisciplinary teams worked in parallel sessions on sonifications of different

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[1] http://qcd-audio.at/sbe2

[2] http://sonenvir.at/workshop

data sets. 20 people with backgrounds in sonification design, programming (SuperCollider3, SC3), physics and other domain sciences, sociology, and music were invited[3]. The data sets stemmed from computer physics (Institute for Physics, University of Graz), data from experimental physics (CERN/ALICE) and climatology (WEGCenter):

- Monopole Loops in lattice QED
- TPC simulations: Data from the Time Projection Chamber at ALICE (CERN)
- CENTER - Clusters in QCD: data from lattice quantum chromodynamics
- RO: Radio-occultation data from climatology

For each data set, a short introduction was given by a domain expert. Then, 2 or 3 teams were built, consisting of programmers, sonification experts and domain scientists. In sessions of 2 to 3 hours, they developed a sonification approach for the data set. In the plenum, these different sonifications were presented and discussed. An evaluation based on the Multi Criteria Decision Analysis (Sec. 4.4.2) was conducted.

Monopole Loops

The first data set were monopole loops stemming from lattice QED (see Sec. 3.4.1). Thus the data consist of one-dimensional closed loops in a four-dimensional lattice.

The sonification approaches consisted of two statistical approaches, a simple frequency mapping and the display of neighbor relations, and a 'topological' one following the loops.

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[3] The participants of the SBE2 were: Gerhard Eckel, Robert Höldrich, David Pirrò, and Kathi Vogt (IEM),
Christof Gattringer, Christian Lang, and Axel Maas (Institute for Physics, Department Theoretical Physics, University of Graz),
Bettina Lackner and Christoph Bichler (Wegener Center for Climate and Global Change, Graz),
Till Bovermann, Thomas Hermannt, and Florian Grond (Ambient Intelligence Group, Technical University of Bielefeld),
Alberto deCampo (Inst. f. zeitbasierte Medien, Berlin),
Marcus Schmickler (freelancer - media artist),
Florian Dombois and Iris Rennert (Y-Institute, Bern),
Stefan Rossegger(CERN, Geneva),
Julian Rohrhuber (Inst. f. Musik und Medien, Düsseldorf)

Team 1 tried to identify the phase transition temperature acoustically by simply summing over absolute values of each link. Below the transition, many '0' values can be found. The values were mapped to absolute frequencies. As a second attempt, mean values for each file have been calculated and played.

The second team used granular synthesis. The link variables of the lattice position controls the synthesis. A grain consists of simple sines with glissandos indicating the difference to the neighboring sites. Also a second approach with format synthesis has been developed.

Team 3 followed the loops. At first, a random point is chosen. The histogram of its neighbors is computed, giving the number of neighbors being a -/+2, -/+1 and 0 state. To each state, a frequency is assigned, where $[-2, -1, 0, 1, 2] \rightarrow [f_1, f_2, f_3, \epsilon f_2, \epsilon f_1]$, where $f_3 << f_2 < f_1$. The $\pm 1, \pm 2$ states are similar to a small mistuning factor of ϵ, because they are analog, indicating high or low loop density. The 'minuses' are panned to the left, and the 'pluses' to the right. Finally, the number in the histogram is mapped to the amplitude of the frequencies, and the loop path is followed. Short loops lead to a short repetitive sound pattern, while long ranged ones change in sound over long periods.

Center Clusters in QCD

Center clusters are discussed in Sec. 3.4.2. The task in this data set was to identify large and small clusters of 3 distinct states in a 3-dimensional lattice. At the phase transition, clusters start to percolate (there is a coherent cluster from one lattice side to the opposite one).

The sonification approaches mainly worked with cluster finding, that caused a lot of programming effort. Still, interesting sonification have been achieved.

Team 1 chose to implement granular synthesis with formants. Each sound grain is one step in the cube. Its base frequency, formant frequency, and panning position are mapped to the 3 lattice dimensions. (As a drawback, they experienced jumps, when modulo wraps around, even if the mapping should be toroidal).

Team 2 implemented a simple cluster finder (only finished correctly after the end of the workshop). A link lattice was deduced from the original one, where all neighbors with the same value are marked by a link '1', and all different ones by '0'.

Then, a random point is chosen, and continued along the '1' links. The lattice coordinates are directly used as triad, where $[f_1, f_2, f_3] \rightarrow ([x, y, z] \cdot 20 + 100)\mathrm{Hz}$ (resulting in a minimal frequency of $f_{min} = 100\,\mathrm{Hz}$ and a maximal one of $f_{max} = 900\,\mathrm{Hz}$. The idea was to find out when the starting point is reached again, and then (perhaps after a few cycles) choose new site; but this feature was not implemented.

Team 3 also used a cluster finder, but in a systematic way through all the lattice. They start with every valid site value (-1,0,1; the '2' were non valid and thus ignored), and flood the surrounding with a recursive *ClusterID* finder. The finder is accelerated successively up to a maximal velocity – and accordingly the pitch is raised. In between (new) clusters, a new ClusterID is assigned and a noise pulse played; new Clusters start at low pitch. The sonification allows to hear all the lattice in approximately 1 to 2 minutes. Percolating clusters have a long, rising tone. Before/ and or after the long clusters, many mini clusters are found.

RO Climate Data

Two radio occultation (RO) data sets have been provided by the Wegener Center for Climate and Global Change, University of Graz. The RO method is a remote sensing technique making use of GPS signals to retrieve atmospheric parameters (refractivity, pressure, geopotential height, temperature) in the upper troposphere-lower stratosphere (UTLS), which we define as region between around 5km and 35km height. The data, atmospheric monthly means, is given at 9 height levels (between 8.5 km to 28 km height), 18 latitudes (90° N to 90° S, 10° steps), and 96 months (intermittently 2001 to 2008, see below).

Temperature and refractivity data have been provided. Refractivity can be thought of as atmospheric density and is approximately indirectly proportional to temperature. The sonification should allow hearing the QBO (Quasi biennial oscillation), a stratospheric pattern of changing temperatures (wind directions), best pronounced in the tropics (10° N-10° S). An extratropical QBO signal can be probably found at higher latitudes with a different phase.

Two sonification approaches have been developed (For the RO data, there has been no third team):

Team 1 audified one lattice site (in time), which contains information about the seasons and the QBO as a bigger cycle. The seasonal and trivial looping information were filtered out (calculated as the loop freq of 88 months and 12 months seasonal frequency). The audification was played at slow rate using FM, thus rhythmic structures of the QBO and remaining seasonal structure could clearly be heard, as poly-rhythms. The system should allow to play different regions, that are panned on a multi-channel system, and zoom in into interesting places; but this feature was not implemented.

Team 2 also used real time as sonification time. The height levels of the data were mapped to pitch, and the temperature was used as the energy in the spectral bands of this mapping. As input to the filters, noise excitation was used, that was then band pass filtered. In the data, the 'NaNs' were replaced by mean values. The sonification allows to hear next to the yearly cycle also the 26 months rhythm.

TPC simulations

Data from the Time Projection Chamber was provided by the ALICE Offline group, and is described in Sec. 3.5.

Sonification approaches:

Team 1 argued that the existing visualization is so strong, that a sonification has no added value. Thus they would not sonify spatial information, but the listener should move through space along the z coordinate and listen to a characteristic signature of a track. Charge was mapped to 'roughness'. The implemented mapping was: charge → frequency modulation, ϕ is used in frequency modulation as $\cos(\phi)$ is scaled to 300-800Hz. The resonance $r \rightarrow$ LPF (low pass filter), and the boundary frequence is controlled by the phase ϕ (big r leads to a big quality Q of the filter). Data is sorted along z as new sonification time axis.

Team 2 also did not want to implement a monitoring system for the track reconstruction, but rather to characterize the event. Since an interesting signal from the physics point of view is the presence of collimated collection of tracks, the approach was to use as the basic data set the direction of the particles with respect to their origin, their identity and their energy. The sonification consisted of a mapping of the derived data (a four-tuple for each track, see below), in the following way: The angle ϕ is projected to the sonification time. Particle energy is assigned to the level and θ to both duration and brilliance of a sound to be played when the track is encountered during the phi sweep. To this end, the tracks were orderd in ϕ. The frequency is determined by the particle type (taken to be the particle type ID, an abstract number between 0 and roughly 500 in the data set). Whether the track is form a particle or antiparticle is mapped to the left or right channel of the stereo. With this sonification, the presence of collimated sprays in ϕ direction is clearly audible in the low-multiplicity proton-proton data available. The identification of the θ angle is, however, not very clear. This has to be improved to obtain a jet-finder on a sonification basis. Nonetheless, jets are audible structures in this approach, even their average energy. (The track information have only been partly processed in the available data. The team therefore approximated the remaining data by the available data. In particular, the direction is obtained from the angle phi and the atan of the z over r ratio of the point with smallest r of each track as theta, and the energy by the inverse charge (the later is erroneously in the code not normalized by the track length). The particle type is taken directly from the data.)

Team 3 aimed at finding 'weird' tracks, which have sudden changes in their direction. The tracks can be played individually one after the other or all in the same time. (Bigger) radius is mapped to (lower) pitch, achieving an intuitive 'departing' sound. The angle is mapped to the base frequency of a formant. The curvature is derived, thus sudden changes cause louder sound changes.

B

ACRONYMS

ASA	Auditory Scene Analysis
ALICE	A Large Ion Collider Experiment (Detector of LHC at CERN)
AD	Auditory Display
AFM	Atomic Force Microscope
CERN	European Organization for Nuclear Research [formerly 'Conseil Européen pour la Recherche Nucléaire'
EEG	Electroencephalography
ENIAC	Electronic Numerical Integrator and Computer
LHC	Large Hadron Collider (experiment at CERN)
MC	Monte Carlo
MCDA	Multi Criteria Decision Aid (*sometimes Analysis*)
TPC	Time Projection Chamber
QBO	Quasi biennial oscillation
QED	Quantum electrodynamics
QCD	Quantum chromodynamics
QFT	Quantum field theory
SonEnvir	Sonification environment (research project)

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