EXPLORATION OF 4D-DATA SPACES. SONIFICATION IN LATTICE QCD.

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ABSTRACT

We describe a pilot study on the sonification of data from lattice Quantum Chromodynamics, a branch of computational physics. This data is basically 4-dimensional and discretized on a lattice. The implementation allows interactive navigation through the data via different interfaces. Two different sonification schemes have been applied, giving information on small regions of the lattice. In real data sets we searched for structures that are hidden by quantum fluctuations. First results have been achieved with simplified data sets.

1. INTRODUCTION

In the course of the project SonEnvir, different sonifications have been developed in the field of physics. We did research on energy spectra of baryons (e.g. the proton or neutron; refer [1, 2]) and spin models, the Ising and Potts model ([3]). A smaller project was done on the chaotic double pendulum (see [4]).

In the last phase of SonEnvir and its aftermath, a pilot study on the sonification of data stemming from lattice QCD was done. Lattice QCD is the numeric calculation of problems of Quantum Chromodynamics (QCD). This part of theoretical physics describes the dynamics of quarks and gluons, the most fundamental building blocks of nature known today. The data sets stemming from numeric treatment of this theory are huge and multi-dimensional. In this project, we aimed at sonifying such data.

The data is in principle 4-dimensional - thus it cannot be visually displayed. It was our goal to display it aurally, without *getting lost in the map* for reasons of perceptual dependencies, as discussed in [5]. The resulting tools can be applied to any 4-dimensional and discrete data.

In the following section, we will give the background to lattice QCD, focusing on possible structures in the data. Also, research questions of this study are formulated.

In Section 3 we describe the sonifications. First the properties of the data are presented. Then the implementation in SuperCollider 3 is described. Strategies for sonification are discussed in Section 3.3, including sequentialization, interaction and the generation of pseudo data. Then, sound examples are described in Section 3.4. These can be found at http://sonenvir.at/data/lattice/sounds.

In Section 4 we give answers to the research questions and an outlook.

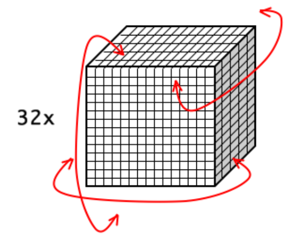

Figure 1: *Scheme of a 32x16x16x5 lattice; only three (space-like interpreted) dimensions are drawn. The time-like dimension has an extension of 32. The arrows indicate that the lattice has periodic boundary conditions: it is a hyper-torus, where e.g. the right neighbor of the last column on the right is on the first column of the left.*

2. QCD DATA AND RESEARCH QUESTIONS

2.1. Quantum Chromodynamics and Lattice Simulations

Since about the 1990s, the classical physics disciplines – experimental physics on the one hand and theoretical physics on the other – have a new counterpart: *computational physics* is implementing pure abstract theory and 'testing' it numerically; thus it belongs neither really to the theoretical nor to the experimental branch. With growing CPU power, results of simulations meet more and more the results of real measurements in physical experiments. One major implementation of computational physics is lattice QCD. In view of the reader community we will not go in depth with the theory here. Only the main characteristics of the data set shall be illuminated.

Typical lattice sizes nowadays contain 16x16x16x32 sites. Such a lattice consists already of 131072 lattice sites and is very computationally intensive (See figure 1). As this was a pilot study, we broke down the complexity of the data and had only real numbers on every latttice site instead of matrices. That way we also avoided theoretical problems.

We aimed at displaying such 4-d lattices in a meaningful and intuitive way, and compared the raw data with numerically treated data, revealing hidden structures from the statistical background (this method is called smearing and can also not be explained in detail here).

The data sets we were exploring in this pilot study consist of different configurations, each available as raw data and three different degrees of smeared data. Fig.s 2 a-d show 2-dimensional cuts of the 4-d-lattice of such data. The analysis of smearing reveals a structure, that is hidden in the background noise in the raw data. These so called excitations are what we searched for.

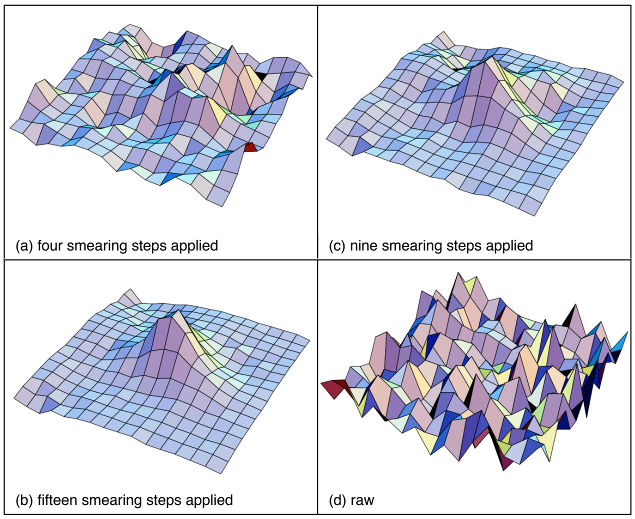

Figure 2: *Two dimensional cut through the 4-d lattice with data of the topological charge density of one configuration.*

2.2. Research questions

The questions we wanted to answer in this pilot study are:

4D auditory display: Is it possible to display a 4-dimensional structure by auditive and visual modalities such that it is better imaginable?

Orientation in a 4D space: How to not get lost in a 4-dimensional lattice? Does an interactive sonification scheme helps, or should it be passive?

Structure observation: Can the local structures be observed by listening to a direct sonification of the raw data, thus allowing a new direct approach excluding the possibility of physical artifacts?

Application: In how far could physicists or other scientists benefit of such a method?

3. SONIFICATION

3.1. Properties of the data

In this section, we list the main characteristics of the data (i.e., the lattice and the structures searched for). The properties of the lattice are:

- The lattice is hypercubic (4-dimensional) and discretized (16x16x16x32 sites), as drafted in Fig. 1.
- On each lattice bond, we deal with real numbers.
- Neighbors on a quadratic lattice in 4 dimensions means that there are 8 nearest neighbors per site.
- The structure is torus-like, that is the boundary conditions are periodic (the end of one line is next to its beginning).
- A basic premise for the discretization is a frequency cut-off: only freqencies bigger than the lattice spacing a and smaller than one side (e.g. $16a$) are representable on the lattice (this is called the infrared and ultraviolett cut-off of the lattice).

Especially the last property is interesting for a sonification design, since it determines the frequency range in the data set. Its values has to be considered esp. when rendering audifications.

Properties of the structures (topological excitations) we are searching for are:

- they are 4 dimensional objects,
- they are highly localized (their size being in the order of $4a$ in every dimension),
- they are masked by quantum fluctuations that behave randomly; topological excitations can be found by different methods, e.g., smearing, but this might produce non physical artifacts,
- the number of such a structure per configuration is $n \in [0, 1, (2, \ldots)]$ with decreasing probability (it is less probable to have many structures).

3.2. Implementation

Since the working process was interdisciplinary, we did not follow the usual software development cycle of design, implementation and testing. Programming was done in parallel to the discussion of the data and sonification approaches.

Therefore, we developed a QCD representation in SuperCollider ([7]), which, apart from its main application as a system for sound controlling and rendering also features an object-oriented, full-featured programming language well suited for implementing data exploration and complex sonification systems.

Due to the fact that the QCD data is large and complex, we implemented a class *QCD*, taking care of all bookkeeping such as loading, saving, selecting, preprocessing, etc. Besides these standard file handling, an option to save and load binary versions of the data was implemented - allowing to load a data set about ten times faster than by parsing the provided text-based files. Taking advantage of this it is possible to switch between sonifications of different data sets and easily compare their structure against each other. An overview of the class structure is given in Fig. 3.

Though this work clearly focuses on auditory displays, we decided to add a graphical user interface as shown in Fig. 6 to the system. It provides a rough overview of the current point of interest in the data and gives the possibility to navigate, e.g., by point and click via mouse. This relocation of the focus-point triggers an action, which by default is set to preprocess and sonify the current region as described in Section 3.3.

Apart from presets for all sonifications described in Section 3.3, the QCD environment features user-programmable slots allowing for future development of additional interactive- sonification related surveys of QCD data. E.g., it is possible to change the used sequencing algorithm, the color scheme of the data visualisation, and the sonification algorithm. For a more in-depth discussion of object modeling approach, please confer to [8].

```
QCD
classvar <>serTypes;
classvar <>knownTypes;
var <name;
var <data;
var <types;
var <>specs;
var <>action;
var <shape;
---
*read (name, shape, filenames, types, specs)
*load (path)
*new (name, data, types, specs)
valueAction (i, pos, mod)
serialize (index, pos, extent = 8, how = \hilbert)
gui ()
write (path)
findInstantons (allowedDevFromMean, minExt, degreeOfNeighbourhood)
findNonInstantons (maxSize)
```

```
QCDgui
var <aQCD;
var <win;
var <>colorFunc;
var <pos;
var views;
---
*new (aQCD)
focusToIndex (which, index)
evalInTrack_(val)
```

Figure 3: *UML diagram of essential parts of QCD-related Classes. GUI components are separated according to the model-view-controller concept. Since the functionality of both, interactive control and auditive display depends on the particular application, its implementation is not part of a class. Instead, they are developed in the interactive mode of SuperCollider. See Section Implementation for details. Interfaces provided for controlling and auditive display are: QCD:serTypes (place to put serializing algorithms), QCD:action (used for sonification processes).*

3.3. Strategies for the sonification

As the data was so complex, we firstly discussed possibilities and constraints of possible sonification processes.

3.3.1. Basic considerations

4 dimensions: We cannot imagine 4 dimensions. It may help to extrapolate from 2 to 3 dimensions for a better understanding; it may also be better not to imagine 4 dimensions at all for the human mind, as was stated by readers of the rather odd but interesting book "The forth dimension" by C. Hinton, written in 1912 [9].

Huge data: Also the size of the lattice is usually under-estimated. Trivially - a power of 4 behavior grows much more rapidly than a power of 3. If we assume our topological excitation (and a sub-cube) being of the size $4^4a = 256a$, and the whole lattice consisting of 131072 sites, the chance to find the sub-cube of interest is only $\sim 0.19\%$. Thus a random choice of data will probably not step over the excitation, and if the whole configuration is used to generate a sound, a configuration with excitation will hardly be different than one without.

Time and space: One dimension is interpreted as time-like, the other three as space-like; thus we may utilize that we are able to display three space-dimensions with auditory spatialization, and treat the time-dimension differently.

3.3.2. Sequentialization

In the sonification, we started out with a simple audification. The lattice is sequentialised and every value taken as the momentary sound pressure level of a sound signal.

The sequentialization has been done in two ways: first, the lattice is read along the torus, in the same way the configuration is generated. In a second attempt, we read it out along a Hilbert curve: this is a space filling, not-self intersecting curve for cubic structures, see Fig. 4 We implied two Hilbert-hypercubes of 16^4 dimensions. (This sequentialization has already been used in the sonification of the Ising and Potts model, refer to [3]. For further information on the Hilbert curve in the context of sonification see [10]).

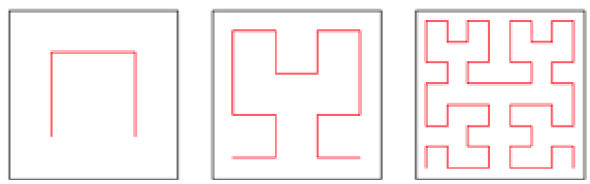

Figure 4: *The Hilbert curve in 2 dimensions. It fills a square completely without intersecting with itself. It preserves locality and can thus be ideally used for searching local structures.*

3.3.3. Sonification approaches

The audification approach gives a short overview, but is too simple for the very noisy data of quantum fluctuations. Thus we implemented another concept: sub-regions of the lattice should be sonified. The idea was to use something like an Emsi-Aura ([11]) or chose sub-hypercubes of the approximate size of the topological excitations searched for. They can either be chosen interactively or the whole lattice is read through on a sequentialized path. They are sonified in two ways:

The first sonification was done with an audification as input signal, which was amplified using different (e.g., random) frequencies. This already leads to a better perception of different data structures, as they are non-linearly amplified. Obviously, the resulting sound depends on these resonator frequencies. The scheme is plotted in Fig. 5 on the left side. We called it *resonated audification*.

In the second approach we put the cart before the horse: again, one sub-hypercube after the other is sonified. Each lattice site in the sub-hypercube provides a value of the topological charge. These values are taken as resonator frequencies for a white noise

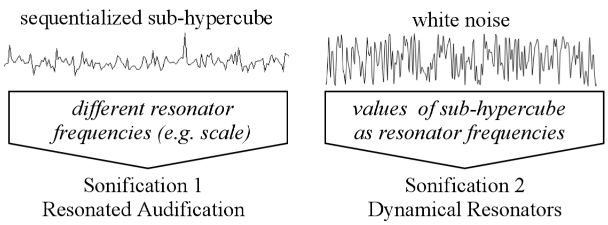

Figure 5: *Schemes of the two basic sonification approaches.*

input signal. This sonification scheme is plotted on the right side of Fig. 5 and we called this approach *dynamical resonators*. The resulting sounds are very interesting.

3.3.4. Interaction with the data

As discussed in [12] and [13], interaction is important in sonification. We also found interaction to be a key to the study and sonification of 4-d objects. Different interfaces can be used in order to enhance imaginability. The haptic interaction is very apt to build up an inner map of the data, see [14], thus we experimented with different interfaces. At first we used a graphic tablet, where the plane of 2 dimensions was mapped, and each point on the tablet represented a matrix of the other two dimensions. Then we used a simple GamePad with 2 push sticks, each having 2 axis representing two dimensions. Also an audio equalizer with 4 slides was used, which had the advantage of being able to stay at one spot without holding the interface. All interaction modes improved the imaginability and perception of the lattice by highlighting different aspects of the grounding structure.

Also, our system lets the user adjust parameters of the sonification interactively, in order to take into account the structure searched for. The path and extent of the sequentialization are very determining for the resulting sound, as well as the frequencies used for the resonators.

3.3.5. Pseudo data

The real lattice QCD data is highly complex, and a complete analysis of this data with other methods was not possible within the pilot study. Also, for presentation purposes we needed simple data. Thus we decided to generate pseudo data that would mirror the data properties very clearly. Our *pseudo instanton* is a 4-dimensional Gaussian structure, localised within $4a$. The masking quantum fluctuations were given as Gaussian noise. The - trivial - extreme cases were only pseudo-instanton vs. only noise. The two other data sets show their overlap, thus masking the structure with less or more noise - in the first case the amplitude of the noise being in the same order of magnitude as the one of the structure, in the latter case one magnitude bigger. This data is shown in the GUI in Fig. 6.

It was also used to generate the audio example described below.

3.4. Sound Examples

The sound examples described here can be found at:
http://sonenvir.at/data/lattice/sounds.

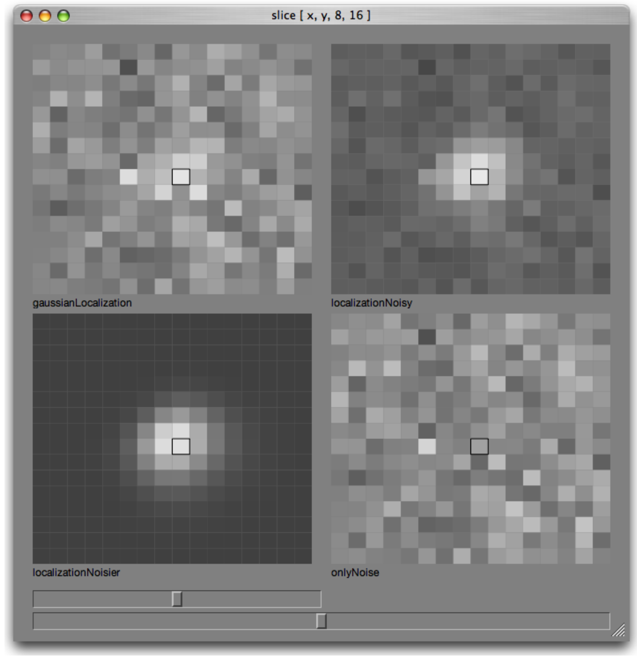

Figure 6: *GUI of a test configuration of 4 data sets. The x-y-planes of the z and t-indices (given in the header) are shown. Moving through the GUI is done by shifting the sliders or clicking onto the two dimensional slices.*

Audification: The first examples are audifications, as shown in Fig. 7. The advantage of this is, that the huge data set can be quickly scanned through. It works well to get an overview for smeared data. Though, the highly noisy data of the topological charge is much too complex for this approach. The *sound* is noise-like, with basic frequencies stemming from the sequentialization of the lattice. Single and rhythmic clicks give evidence of structure in the data.

Example 1: SmearedDataStruct.mp3 (see Fig. 7).

Example 2: SmearedDataNoStruct.mp3 (on the contrary to the first example this is rather uniform noise)

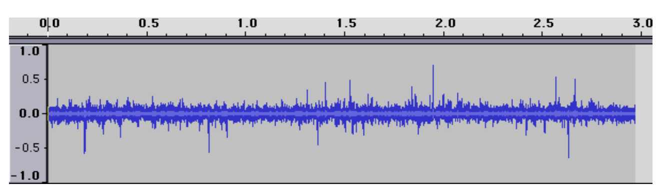

Figure 7: *Audification of the smeared topological charge data, sequentialized on a torus and used as a sound signal. The repeated structure indicates an excitation, and can be clearly heard as rhythmic clicks over a background noise.*

In the next examples, we hear a sequence of sounds. It is done by going over the *pseudo instanton* (that is, taking 16 steps in the middle of the data from left to right). All data sets are played one after the other in the order of the GUI, Fig. 6: first the very noisy set, then the noisy set (both with the underlying strucutre), then the pure structure and pure noise. Between the data sets, there is a pause of 2 seconds.

Resonated Audification: The sounds in this case are bell-like. If the strokes are played quickly after another, the acoustical information is not very clear.
Example 3: (Slow) ResAudif-Paus-0.5sec.mp3
Example 4: (Fast) ResAudif-Paus-0.1sec.mp3

Dynamical Resonators: These are steady, rather spherical sounds. The transition from one to the other data set sometimes causes overmodulation and is thus faded in/out in the examples. The information on the neighborhood in 4 dimensions is very clear, and even the heavily masked structure can be found.
Example 5: (Slow) DynRes-Paus-0.1sec.mp3
Example 6: (Normal) DynRes-Paus-0.25sec.mp3
Example 7: (Fast) DynRes-Paus-0.5sec.mp3

4. CONCLUSIONS

4.1. Answers

The questions raised in Section 2.2 can now be answered.

So far, we could achieve a meaningful exploration tool for 4-dimensional data spaces. Interaction is a key for a better imaginability. The problem is, that the data set is huge, and a consequent interactive exploration takes a lot of time - even for just one data set. Still, this is a proper *ansatz* if one really wants to explore the data.

For a short overview (e.g., for the smeared data) the audification gives reasonable results. This method allows to decide on the presence of topological excitations. Though, information on the position of this object has to be searched for interactively again.

So far we could not perceive topological excitations in the raw data sets. During the study, the question was raised, if the data theoretically does include the information we searched for at all. This could, so far, not be exhaustively clarified, even consulting specialists in the field.

In the pseudo data, the hidden structure can easily be found. The acoustical method is superior to searching for it in the GUI, because all neighbors in four dimensions are taken into account, whereas in the visual approach only two dimensions can be displayed.

As this pilot study had promising results, the question remained, in how far physicists could (and would!) profit of such a method. A first presentation was done in March 2006, where several professors and PhD students of theoretical physics of the University of Graz could also try the sonifications themselves. The general interest was big, but the concrete applicability was more or less seen as a toy (surely enhanced by the interaction interface being a gamepad for this presentation). For physicists, the sonification would have to be linked to other programs, that allow the immediate comparison with other numeric methods. Until then, the developed tools nevertheless can be used by interdisciplinary physicists for exploration purposes.

4.2. Outlook

The sonification tools developed are a good starting point to study different data of lattice QCD. Also, they may provide an abstract framework for sonification of n-dimensional numeric data sets.

A sonification approach that has been discussed shortly above but which is not yet implemented, is the following: The time-like dimension should be taken as real physical time in the sonification and the three space dimensions as spatial mapping of physical place. The soundgrains for each value (or each sub-hypercube) can be played shortly after one another, either randomly distributed and leading to a whole sound impression or as an interactively explorable space. The problem is, that the time-like dimension is smeared, because one soundgrain starts while an other is still playing. It can be encountered by a simultaneous triggering of parallel sounds.

A continuation of this pilot study is planned by implementing other data: the whole Gauge field should be taken into account. A sonification of quantum fluctuations may allow in a way to hear their underlying structure.

A more complete testing and evaluation of the presented study is in progress, but could not be completed until the deadline of the paper. The testing encompasses a systematic hearing of the available data sets, and other data shall be taken into account as well. The evaluation will be done informally by interviewing single experts in the field.

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