SONIFICATION OF MONOPOLES AND CHAOS IN QCD

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Sonification is defined as the use of non-speech audio to extract information from data and it represents the sound analogue to graphical visualization. The method is applied in several disciplines from economy to medicine to physics. Sonification might also help in analyzing data of lattice QCD. It could assist, together with graphical display, to examine the behavior of lattice observables as a function of parameters like gauge coupling, quark mass, etc. Sonification might further be used to identify unique characteristics of single gauge-field configurations out of many such as, for example, the topological content. In order to demonstrate the methodology for quantum chromodynamics we analyze the monopole order parameter from the confinement to the deconfinement phase. We further produce a sound file for the Lyapunov exponents of classical $U(1)$ and $SU(2)$ gauge theory. The studies are also part of the development of program packages for audio browsing within the interdisciplinary research project SonEnvir (http://sonenvir.at/).

Keywords: Lattice QCD; Sonification.

1. Visualization and Sonification

In modern science and economy a vast amount of relevant data is stored and made available for evaluation. Techniques to locate the numbers of interest like data warehousing and data mining have been developed together with program packages for visualization in order to extract the hidden information. The question arose if methods of auditory display could help to get further insight into the structures behind the data. This discipline is called sonification, and a definition can be found in the wikipedia: Sonification is the use of non-speech audio to convey information or perceptualize data.[1] The International Community for Auditory Display (ICAD) [2] was established in 1992 and has been organizing international conferences since then. At the request of the NSF, in 1997 the ICAD also provided a Sonification Report.[3]

Sonification needs a realization on software and hardware platforms. We shall first provide a short description of the program package SuperCollider developed by James McCartney from Austin, TX. It originated as proprietary software and was released in 2002 under the free software GPL license. The name SuperCollider is said to have its origin from the Superconducting Super-Collider (SSC) in Waxahachie, TX, which was planned and begun to be constructed but was then abandoned and never finished.

The SuperCollider environment consists of two applications, a client *sclang* (being the language) and a server *scsynth* (being the audio) which communicate using Open Sound Control. The SuperCollider language (*sclang*) is an interpreter language and

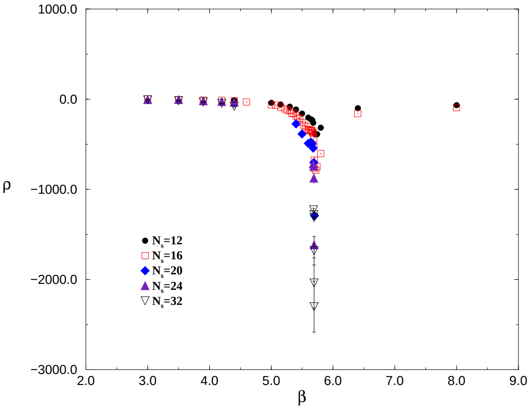

Fig. 1. Monopole disorder parameter ρ computed by the Pisa group as a function of β for different spatial sizes at fixed $N_t = 4$ with Polyakov projection and abelian generator F^3.

combines the object oriented structure of Smalltalk and features from functional programming languages with a C programming language family syntax. SuperCollider runs on the platforms Mac OS X, Linux, and Windows. We mention that beside this professional solution there is a simple sonification tool implemented in newer versions of Mathematica. Also MATLAB supports treating data vectors as if they were audio signals and thus allows to play them.

2. Application to Monopoles in Lattice QCD

To learn about the possibilities of sonification in lattice field theory,[4] we took as an example the phase transition to deconfinement which occurs at an inverse gluon coupling around $\beta = 5.7$.[5] Crossing the transition point the topological charge and the monopole density exhibit drastic changes and disappear. We are interested to sonify the (dis)order parameter for magnetic monopoles on the lattice developed by the Pisa group. Fig. 1 displays the derivative of the logarithmic monopole density with respect to β. The kink of the monopole density is thus transformed to a clearly visible spike, which becomes more pronounced with increasing lattice size and

Fig. 2. Screenshots of the zero-value for small couplings and of the spike of the monopole disorder parameter at the transition point.

stays practically independent of the abelian projection.[6]

We took the monopole data for spatial lattice size $N_s = 16$ from Fig. 1 and mapped them onto the audible regime. In Fig. 2 we present screenshots of the disorder parameter ρ around $\beta = 4$ and at the critical point $\beta = 5.7$. Listening to the sound file one can hear that the melody is dropping clearly to lower tones around criticality. This means that one can hear the phase transition to the quark-gluon plasma where the monopoles vanish. These sample results are stored on the SonEnvir server and can be accessed there.[4]

3. Lyapunov Exponents in Classical Gauge Field Theory

The study of chaotic dynamics of classical field configurations in field theory finds its motivation in phenomenological applications as well as for the understanding of basic principles. The role of chaotic field dynamics for the confinement of quarks is a longstanding question.[7] Here, we analyze the leading Lyapunov exponents of compact $U(1)$ and of $SU(2)$-Yang-Mills field configurations on the lattice. The real-time evolution of the classical field equations was initialized from Euclidean equilibrium configurations created by quantum Monte Carlo simulations. This way we expect to see a coincidence between the strong coupling phase and the strength of chaotic behavior in lattice simulations.[8]

Chaotic dynamics in general is characterized by the spectrum of Lyapunov exponents. These exponents, if they are positive, reflect an exponential divergence of initially adjacent configurations. In case of symmetries inherent in the Hamiltonian of the system there are corresponding zero values of these exponents. Finally negative exponents belong to irrelevant directions in the phase space: perturbation components in these directions die out exponentially.

The general definition of the Lyapunov exponent is based on a distance measure $d(t)$ in phase space,

$$L := \lim_{t\to\infty} \lim_{d(0)\to 0} \frac{1}{t} \ln \frac{d(t)}{d(0)}. \qquad (1)$$

We utilize the gauge invariant distance measure consisting of the local differences of energy densities between two field configurations on the lattice:

$$d := \frac{1}{N_P} \sum\nolimits_P |\mathrm{tr}U_P - \mathrm{tr}U'_P| \,. \qquad (2)$$

Here the symbol $\sum_P$ stands for the sum over all N_P plaquettes, so this distance is bound in the interval $(0, 2N)$ for the group $SU(N)$. U_P and U'_P are the familiar plaquette variables.

Figure 3 exhibits the averaged leading Lyapunov exponent between the strong and the weak coupling regime. The smoother falloff of the $SU(2)$ Lyapunov exponent reflects the second order of the finite temperature transition to a Debye screened phase of free quarks. The more pronounced behavior of $U(1)$ theory is indicative of a first order transition to a non-chaotic Coulomb theory in the continuum. Both for QED and QCD we find

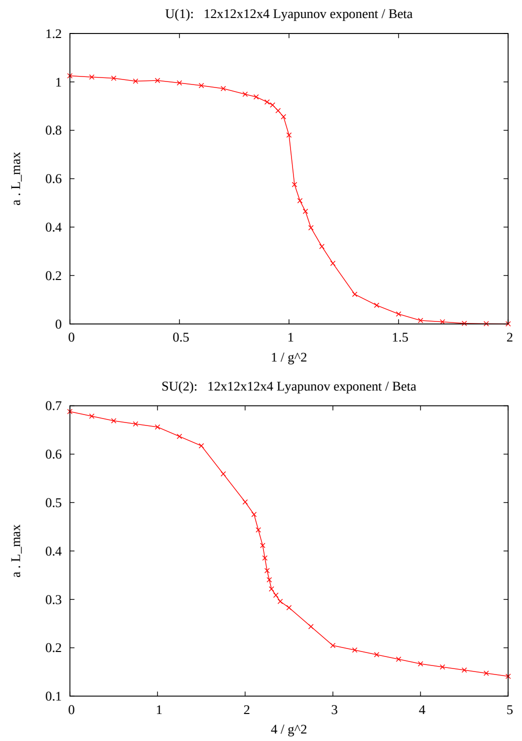

Fig. 3. Comparison of the average maximal Lyapunov exponent in $U(1)$ gauge theory with $\beta = 1/g^2$ (top) and in $SU(2)$ gauge theory with $\beta = 4/g^2$ (bottom) when crossing from the strong to the weak coupling phase.

that configurations in the strong coupling phase are substantially more chaotic than in the weak coupling regime. The results demonstrate that chaos is present when particles are confined, but it persists partly also into the Coulomb and quark-gluon-plasma phase. Already on the finite volume of the 12^3 lattice the first order of the $U(1)$ transition and the second order of the $SU(2)$ transition become visible.

Turning to the preparation of the audio files, we multiplied the raw data by a factor of 1000 and added the standard pitch of 440 Hz. In Fig. 4 we depict the frequencies of the Lyapunov exponent in $U(1)$ gauge theory and in $SU(2)$ gauge theory from the confinement to the deconfinement phase. Listening to the corresponding sound files of $U(1)$ and of $SU(2)$ one can hear that the melody is

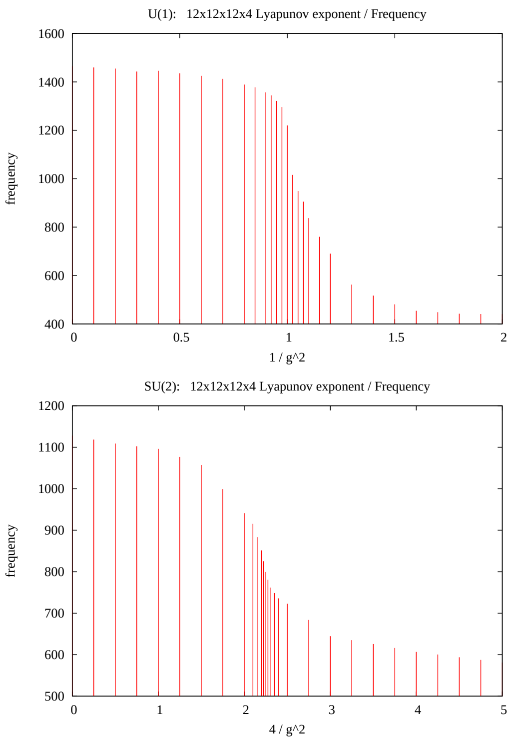

Fig. 4. Comparison of the audible frequencies of the Lyapunov exponent in $U(1)$ gauge theory (top) and in $SU(2)$ gauge theory (bottom) when crossing from the strong to the weak coupling phase.

changing clearly to lower tones. Both Lyapunov exponents behave similarly. Unfortunately, it is difficult to hear the difference between the 1^{st} order of the $U(1)$ transition and the 2^{nd} order of the $SU(2)$ transition. Those sound files can also be downloaded from the SonEnvir server.[4]

4. Concluding Remarks

This contribution reports on further attempts of applying auditory display to data from lattice QCD. The aim has been to find possible advantages in the data analysis through sonification. Using the examples of the monopole disorder parameter and of the Lyapunov exponent some exploratory sound files have been generated that allow to hear evident features, which have been familiar already from other kinds of data analysis, in particular, from graphical visualization. In this regard, sonification as applied here can be seen as an additional tool of data representation. Of course, one should find more refined means of auditory display in order to make further qualities apparent in some given data sets. Sonification offers the chance to detect structures in the data sets that have been hidden to the methods applied so far. Data analysis through sonification might especially be useful for displaying results depending on multiple parameters and/or belonging to higher space-time dimensions. In the context of lattice QCD one could think, e.g., of the investigation of the topological content of certain gauge field configurations.

Acknowledgments

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