Title:	NON-PERTURBATIVE SIMULATIONS OF QUANTUM FIELD THEORIES USING COMPLEX LANGEVIN DYNAMICS
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Abstract:	Non-perturbative formulations of field theories are essential to capture numerous intrigu- ing physical phenomena, including confinement in quantum chromodynamics, spontaneous supersymmetry (SUSY) breaking, and dynamical compactification of extra dimensions in su- perstring theories. Regularizing field theories on a spacetime lattice provides a robust frame- work for studying their non-perturbative features. The underlying theory can be quantized on a spacetime lattice using Euclidean path integrals. Conventionally, these path integrals are evaluated using numerical methods based on Monte Carlo importance sampling, where generating field configurations requires the Boltzmann factor to be interpreted as a proba- bility weight. However, various interesting physical systems have complex actions, rendering the Boltzmann factor complex, and thus, path integral Monte Carlo encounters the sign problem. The complex Langevin method (CLM) based on stochastic quantization aims to overcome the sign problem by analyzing the associated Langevin dynamics to evaluate com- plex integrals. This thesis employs the CLM to investigate various non-perturbative aspects of field-theoretic systems with complex actions. Physicists have long sought a unified description of all fundamental interactions of nature, and SUSY is now widely accepted as a necessary ingredient for such unifying approaches. However, since experimental evidence suggests that low-energy physics is manifestly non- supersymmetric, SUSY must be spontaneously broken at some energy scale. This thesis probes the possibility of spontaneous SUSY breaking in the simplest realizations of super- symmetric field theories. These systems generally have complex actions arising from a com- plex determinant of the fermion operator, and the phase of the determinant plays a critical role in determining the correct vacuum. We studied various interesting classes of, in gen- eral, complex superpotentials, including the ones exhibiting PT -symmetry. Non-Hermitian PT -symmetric theories are fascinating because they have real and below-bounded energy spectra. We first considered zero-dimensional supersymmetric systems with one bosonic and two fermionic variables. In the case of spontaneous SUSY breaking, the partition function (Witten index) vanishes, and the normalized expectation values encounter an indefinite form. We overcome this difficulty by using twisted boundary conditions on fermionic fields and then taking the vanishing limit of the twist parameter. Our CLM simulations reliably predictedthe presence or absence of SUSY breaking for various superpotentials. We then considered N = 2 supersymmetric quantum mechanical models with appropriate lattice regularization. Here also, we overcame the indefinite form of normalized observables by using twisted bound- ary conditions. While applying the CLM, we noticed that some models suffered from the singular-drift problem. In such cases, we introduced appropriate deformation parameters such that the CLM correctness criteria are respected and then recovered the original theory by taking the vanishing limits of the deformation parameters. Our analysis demonstrated that the CLM could reliably probe dynamical SUSY breaking in various quantum mechanics models with real and complex actions. We then extend our zero- and one-dimensional anal- ysis to two-dimensional field-theoretic systems. As a warm-up, we first laid out the lattice construction for bosonic field theories, including PT -invariant potentials. We then intro- duced fermions and considered the N = 1 Wess-Zumino model, a two-dimensional model with minimal fields. We then applied the CLM for double-well superpotential and examined the relationship between parity symmetry and supersymmetry. Another exciting aspect of non-perturbative physics we explore in this thesis is the dy- namical compactification of extra dimensions in superstring theories. Superstrings are the most promising theories for unifying all interactions, including gravity. However, these the- ories are consistently defined in ten dimensions. The connection to the real world, where only four dimensions are macroscopic, is realized in the non-perturbative definition of su- perstrings via compactification of the six extra dimensions. Matrix models in the large-N limit are conjectured as non-perturbative formulations of superstring theories. In this the- sis, we study a constructive formulation of the type IIB superstring, the IKKT (type IIB) matrix model. A smooth spacetime manifold is expected to emerge from the eigenvalues of the ten bosonic matrices in this model. When this happens, the SO(10) symmetry in the Euclidean signature must be spontaneously broken. The Euclidean version has a severe sign problem due to the inherently complex nature of the Pfaffian. This thesis probes the pos- sibility of spontaneous rotational symmetry breaking in the Euclidean version of the IKKT matrix model. We resolved the singular-drift problem associated with CLM by introducing supersymmetry-preserving deformations with a Myers term. The original IKKT model can be recovered at the vanishing deformation parameter limit. Our preliminary analysis indi- cates that the phase of the Pfaffian indeed induces spontaneous SO(10) symmetry breaking in the Euclidean IKKT model. The investigations performed in this thesis suggest that the CLM can successfully sim- ulate the non-perturbative aspects of quantum field theories by taming the associated sign problem.
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