<u>String Field Theory: Formulation and Analytic Solutions – Final Report</u>

String theory is currently our most prominent candidate for a unified theory of nature. However, we do not know what string theory is. The standard formulation of string theory is in terms of single interacting strings. It is known from the experience with particle physics that much of the physics is left obscured by such a treatment. It is also known from particle physics that a formulation in which particles are represented as excitations of some underlying fields is much more complete. It is not obvious that a generalization of this idea to string theory should work, since there are many fundamental differences between the point particle and the string cases. Nonetheless, it is certainly a direction of research not to be missed.

The idea of defining string theory as a field theory of strings is almost as old as string theory itself. However, in order for it to work at the fundamental (i.e., at the non-perturbative and quantum) level, the field theory must respect the underlying symmetries of the theory. Those are most clearly treated using the BRST formalism. A first interacting string field theory, based on the BRST description of the string, was proposed in 1986 by Witten for the open bosonic string.

The bosonic string is the simplest among the string theories. However, it is usually considered to be merely a toy model of string theory, with the superstring, which includes both bosons and fermions, being the (potentially) physical formulation. The superstring is usually described using the Ramond-Neveu-Schwarz (RNS) formalism. The open string case includes the bosons in the Neveu-Schwarz (NS) sector and the fermions in the Ramond (R) sector. Closed RNS strings are defined in terms of a product of two sectors describing waves that propagate clockwise and counterclockwise around the loop which forms the closed string. The (NS,NS) and (R,R) sectors include bosons, while fermions live in the (NS,R) and (R,NS) sectors.

It is very natural to attempt a generalization of Witten's construction to the RNS string. Indeed, Witten himself tried to construct such a theory immediately following his construction of the bosonic theory. Unfortunately, it was soon shown to be inconsistent. Two other formalisms appeared later, namely the "modified" theory and the "non-polynomial" theory. While the former suffered from much criticism, the latter did not fully incorporate the Ramond sector.

During the first phase of this project, I performed a critical study of these formalisms. The results of this study appeared as three papers. I showed that while some of the criticism against the modified theory is unfounded, its incorporation of the Ramond sector is inconsistent. Hence, I concluded that a fully RNS string field theory is yet to be derived.

The problems with the construction of a reliable RNS string field theory are related to the choice of "picture numbers" for the string fields. A "picture number" is a quantum number peculiar to the RNS string, which signals a redundancy in the description of the physics: Each physical state can be described in infinitely many different ways, one for each "picture number". In all previous attempts towards an RNS string field theory this redundancy was resolved by choosing a single picture number for each string field. In all those cases, it turned out eventually that the proposed choices are inconsistent.

In order to overcome these problems, I developed a new RNS string field theory, in which the redundancy related to picture number is treated as a gauge symmetry. That is, all possible picture numbers are included in the formalism and the physical objects are defined to be equivalence classes of string fields. In this “democratic RNS string field theory”, it is not only possible to consistently include the Ramond sector, but it is also naturally unified with the NS string field. Furthermore, in a following paper, I showed that when restricted to the NS sector, it is possible to “fix the gauge” in different ways, and obtain as a result both the modified and the non-polynomial theory.

An important alternative to the RNS formalism comes in the form of the pure-spinor formalism. It has some advantages over the RNS formalism, but it is also known that it should be modified before a reliable string field theory could be based on it . Nonetheless, a pure-spinor string field theory exists. In order to examine whether this theory makes sense classically, I studied analytical solutions of its equation of motion. I managed to find several desirable solutions. It seems that the existence of these solutions suggests that a proper modification of the pure-spinor formalism could lead to a fully consistent string field theory.

All of the projects described above were carried out by me as a single author. However, the construction of superstring field theories and the study of their solutions are just two aspects of the understanding of these theories. Another important research direction is concerned with disentangling the physical degrees of freedom from the spurious (gauge) ones. For the projects described below, I chose a powerful collaborative approach.

Until recently, the gauge structure of the non-polynomial string field theory was not known. I studied this issue together with some of the world-leading string field theory experts. My collaborators on this subject are Nathan Berkovits from São Paulo, who constructed the non-polynomial theory, Yuji Okawa and his student Shingo Torii from Tokyo, Martin Schnabl from Prague and my MIT host Barton Zwiebach. In two papers, we presented the full non-linear gauge structure of the non-polynomial theory as well as its propagator. We also managed to construct parts of the master action that describe the gauge symmetry in a BRST language.

All this work led to a significant improvement in the current understanding of open superstring field theories. Moreover, it enables new research directions that can potentially lead to the construction and simplification of closed string field theories.