String theory is the most promising framework for the eventual unification of physics. It bridges the gap between the geometry of gravity and the quantum fields of particle theory, inspiring fruitful new research in each subject individually even as it develops toward its ultimate goal. I see this whole enterprise as one of the most exciting areas in science today, both for its long-term dream of understanding the fundamental structure of the universe and for its ongoing development of new tools and insight for practical models in particle physics.

In my research, I use a variety of non-perturbative techniques to solve problems of both types. My work combines techniques from quantum field theory with simpler ideas from geometry: portions of each calculation can be understood without mastering the full theory. I expect to be able to collaborate with undergraduates on cutting edge work; please see the included list of potential student projects for some of these plans. I also enjoy discussions and collaboration with colleagues outside my field; I have contributed ideas and even mathematical proofs to colleagues' research in solid state physics and other disciplines.

One of my recent projects is a model that I have studied with Jeff Harvey, David Kutasov, and Eduard Antonyan [1]. (Although we are still preparing this work for submission, our preprint has already received 57 citations.) This work is based on the search for a “holographic” string model of the strong nuclear force, quantum chromodynamics (QCD). In such a model, the physics of string theory in a five-dimensional spacetime would match a familiar theory of particle physics living on the four-dimensional boundary of that space. (This is analogous to encoding a three-dimensional image in a two-dimensional hologram.) Many longstanding puzzles in QCD field theory could be solved more easily in the string description.

The goal of our work is to better understand the mechanism by which the underlying chiral symmetry of quarks is broken in observed strong interactions. Because this effect occurs when QCD interactions are strong, analysis using field theory has been difficult. The phenomenon is better understood in other field theories such as one developed by Nambu and Jona-Lasinio [2] (based on an analogy with superconductivity), but there has been no reason to expect those results to apply to more realistic theories.

Our model is based on a particular configuration of extended membrane-like objects in string theory called D-branes. This model has two important parameters: the distance between the D-branes and the size of the extra fifth dimension. In one limit of those parameters it reduces to a Nambu–Jona-Lasinio model, while in another limit we can analyze the D-branes using string theory. We have argued that chiral symmetry is broken in both limits and thus is likely broken for all values of the parameters. The great significance of this result is that a third limit of the parameters gives QCD: we provide the first theoretical connection between these models of chiral symmetry breaking and realistic physics. Our model also allows the energy scale of quark “confinement” to be tuned independently of chiral symmetry breaking, which could give new insight into the longstanding puzzle of why quarks always form composite particles.

It will be interesting to strengthen and extend these conclusions in several ways. In the string theory limit we neglect the effect of the D-branes on the geometry, but for our model I expect that approximation to fail when their separation becomes large. It should be possible to find the leading correction and see what restrictions that places on the model. A more involved but more important task is to better understand the field theory limit. We have not conclusively demonstrated chiral symmetry breaking there because leading order contributions cancel out. There are multiple corrections at the next order in perturbation theory, but it should be possible to find at least a numerical solution.

A variety of related models have now appeared, and I expect opportunities for interesting work in this area to multiply. One direction that I find intriguing is computer simulation of models like ours using the tools of Lattice QCD. Some work in this direction has already appeared [3]; it could be fascinating to explore this myself.

My most active research at the moment seeks to shed light on a fundamental property of string theory called "T-duality", as applied to a system with which I have special expertise. T-duality is a remarkable symmetry of string theory in a universe where one dimension is curled up as a circle. Strings can have (quantized) momentum around the circle and can also have (integer) winding number around it. Incredibly, physical predictions are unchanged if the extra dimension's radius is inverted while the momentum and winding numbers are exchanged. This equivalence leads to an intricate web of relationships between the various objects in the theory.

In a paper with Jeff Harvey [4], I addressed a puzzle in the T-duality of the Kaluza-Klein monopole (a magnetic monopole that appears in theories with extra dimensions). The T-dual of this object is known, but differences in their physical behaviors are inconsistent with T-duality. We showed that non-perturbative effects change the geometry of the Kaluza-Klein monopole and bring its physics in line with T-duality. However, the necessary changes are ill-defined in conventional formulations of string theory because they involve both the monopole's coordinate around the actual circle and a more mysterious coordinate around the hypothetical T-dual circle.

I am actively preparing for publication a paper [5] that embeds those results in a powerful new formalism called "doubled geometry" [6] which treats these two coordinates in a symmetric manner. Although neither the Kaluza-Klein monopole nor its T-dual its usual assumptions, doubled geometry can be naturally generalized to handle their unconventional features. This system may be the first non-trivial example of the full potential of the doubled formalism, and my next projects will build on this current work.

One major open question in doubled geometry is the proper way to quantize the theory. My current work applies a method [7] that explicitly breaks the duality symmetry. Other methods have been proposed, and this example could help determine which will be most useful. Another important question is the form of field equations like Maxwell's and Einstein's equations in the doubled formalism. Harvey and I argued in [4] that our results made certain corrections necessary. These equations have recently been studied under limited conditions [8], but to test our conjecture and make it precise I will need to extend that work considerably. That would then provide further insight both into my system and doubled geometry as a whole.

Looking farther ahead I expect related work to continue to be fruitful and of broad interest. Other objects in the string duality web may experience non-perturbative corrections similar to those that I have studied for the Kaluza-Klein monopole. A first step will be to find the analogous corrections to the closely related Kaluza-Klein monopole of M-theory (a higher-dimensional limit of string theory): I have already begun to lay the necessary groundwork for this. That solution will serve as a gateway to extend these ideas to other parts of the duality web, as well as a test of a conjecture in [6] about the extension of doubled geometry to M-theory.

Beyond these established plans, I continue to pursue ideas in other areas of string theory (and physics) that I find interesting. I have recently explored connections between recent progress in M-theory and previous work that I did in that field. I also have experience with dark energy in cosmology and a variety of other topics related to string theory, and I enjoy learning entirely new topics in physics as well. I look forward to continuing to develop all of these ideas in a productive research program for myself and my students.

References

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