String theory provides the most promising framework in which to pursue an eventual unification of physics. It bridges the gap between the geometry of gravity and the quantum fields of particle theory while also inspiring developments in each subject individually and making major contributions to mathematics. However, the theory remains unconfirmed: the natural energy scale of fundamental strings is far beyond the reach of direct experiments. Any test will require us to understand the theory in enough detail to make indirect predictions.

My research involves various ways of looking beyond string theory's known perturbative structure, whether by explicit calculation of non-perturbative corrections or by studying the dualities that relate different limits of the theory. My particular work often combines advanced techniques from quantum field theory with comparatively simple ideas from geometry: portions of each calculation can be understood without mastering the full theory. That means that 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.

My primary research program at the moment is a study of new perspectives on T-duality, taking as my starting point a system with which I have special expertise. T-duality is the statement that string theory in a universe where one dimension is curled up as a circle of radius R (in string units) is completely equivalent to the case when the radius is $1/R$. Only our descriptions of the states change: each string's quantized momentum around the circle is exchanged with its integer winding number around the circle. This equivalence leads to an intricate web of relationships between the various objects in the theory.

Although these relationships are now fundamental to our understanding of string theory, a number of important questions about T-duality remain unanswered. In a paper with Jeff Harvey [1], I addressed a puzzle in the T-duality of the Kaluza-Klein monopole. The T-dual of this object is the NS5-brane, but their physical behaviors are qualitatively different even after exchanging string momentum and winding. We resolved this apparent contradiction by showing that non-perturbative corrections due to worldsheet instantons change the geometry of the Kaluza-Klein monopole and bring its physics in line with T-duality.

However, some of these changes are difficult to make sense of in conventional formulations of string theory because they involve both the geometric coordinate around the circle and the non-geometric coordinate around the T-dual circle. I am currently preparing for publication some recent work [2] relating our results to the "doubled geometry" formalism introduced by Hull [3] in which these two coordinates are treated in a symmetric manner. Although neither the Kaluza-Klein monopole nor the NS5-brane satisfy the standard assumptions of this formalism, when they are considered together it can be successfully applied.

That feature makes this system an important example and test case for the doubled formalism, and my next projects will build on this current work. One major open question is quantization: thus far I have only applied Hull's quantization procedure from [4] to this case, but that method explicitly breaks the duality symmetry and is only valid for one "polarization" of this doubled system. Other approaches to quantizing doubled geometry have been proposed, and I plan to see what they can teach us about this example. This may even give insight into what quantization schemes will be most successful.

Another short term question involves the background field equations for the doubled formalism. In the standard formulation of string theory, the beta functions of renormalization must vanish, and this turns out to imply that Maxwell's equations and Einstein's equation must hold for the background fields. Recent work has generalized this to doubled geometry [5], but only under conditions even more limited than the usual assumptions of the formalism. In [1] Harvey and I suggested that similar generalizations would be necessary, but these recent results would need to be extended to check and correct our conjecture. That could in turn provide further insight into the KK-monopole/NS5-brane system.

Looking farther into the future I expect related research to continue to be fruitful. Other objects in the string duality web may experience instanton corrections similar to those that I studied for the Kaluza-Klein monopole. A first step will be to find the "membrane instanton" corrections to the Kaluza-Klein monopole of M-theory that correspond to those we already found in string theory: slightly different mathematical tools will be required, but I have already laid some of the necessary foundation. That solution might then be used to explore ideas such as Hull's conjecture in [3] of additional "doubled" coordinates in M-theory. The corrected M-theory monopole will also lead directly into a study of analogous results for D-branes; it would be interesting to see whether doubled geometry alone is sufficient to describe those cases.

A secondary research program is related to the search for a holographic string model for quantum chromodynamics (QCD). In such a model, the physics of string theory in a five-dimensional space would match the physics of QCD living on the four-dimensional boundary of that space. This would not be a "theory of everything", but it would give new insight into the strong nuclear force and could lead to experimental tests of the mathematical technology of string theory.

In work with Jeff Harvey, David Kutasov, and Eduard Antonyan [6], I showed that a particular configuration of intersecting D-branes is equivalent in a weak coupling limit to a non-local version of the Nambu–Jona-Lasinio (NJL) model [7] of dynamical chiral symmetry breaking in field theory. In the opposite strongly coupled limit, the physics is described by D8-branes living in the near-horizon geometry of a stack of D4-branes. A third region of parameter space in this model corresponds to large N QCD. Our results thus provide a framework interpolating between the NJL model and QCD: this may explain the NJL model's success in approximating observed physics. Another interesting feature of this model is that the energy scales of confinement and chiral symmetry breaking can be independently tuned.

Although these results have already attracted considerable interest, there is room for refinement of our work. In the strongly coupled limit we neglected the backreaction of the branes on the geometry, but as these are D8-branes (charged domain walls) I expect that approximation to fail when their separation becomes large. Checking at least the leading correction should be feasible, and it would be useful to know what additional restrictions this imposes on such models.

A more involved but more important question involves next order corrections in the weakly coupled field theory limit. Our attempt to demonstrate dynamical chiral symmetry breaking in this limit was inconclusive as the leading order contributions canceled to zero. There are quite a few sources corrections at the next order in perturbation theory, but it should be possible to assemble them and find at least a numerical solution. Beyond these specific projects, I am following a number of related models that have appeared in the literature; I expect opportunities for interesting work in this area to multiply.

In addition to these established research directions, I will of course monitor the literature and consult with colleagues to find new opportunities to explore. Those may relate to other areas that I have worked in, including objects in M-theory and heterotic M-theory, dark energy in cosmology, or solitons and tachyon condensation in noncommutative geometry, but I am open to entirely new directions 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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