

The Impact of Lance Dixon's Work on String Theory

**LanceFest
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J. Harvey

OUTLINE

**Memories of Princeton and of Lance
1984-1990**

**The impact of Lance's work on string
theory**

What he accomplished

The later impact

Closing Thoughts

Princeton 1982-86 when Lance was a grad student was an exciting place to be. Before the 1984 string revolution:

D. Gross: Kaluza-Klein, Random Surfaces, Spin Glasses

C. Callan: Monopole/Fermion Dynamics, Anomaly Inflow

E. Witten: Large N QCD, WZW models, Susy Breaking, Gravitational Anomalies, Morse Theory...

There were many other great and influential faculty: Treiman, Lieb, Wightman, Peebles, Taylor, Anderson,...

Postdocs/Junior Faculty: I. Affleck, M. Perry, L. Yaffe, M. Srednicki
IAS: N. Seiberg, M. Dine,... G. Moore was an undergrad. Paul Ginsparg was the Society of Fellows visiting whatever.

Lance first approached me as a potential advisor in the fall of 1983 or winter of 1984. I was a new junior faculty member with no experience advising grad students and ignorant of string theory. I worked with Ed Witten and Ian Affleck on non-perturbative susy breaking and with Curt Callan on anomaly inflow and tried to keep up with the firehose of new results coming from Ed.

After my first proposal to Lance for a research project fell apart, I suggested a problem involving the quantum numbers of dyons in $SU(3)$ gauge theories. Lance solved the problem on his own in a month or so, and published his first paper.

Then, in the summer of 1984, the string revolution began.

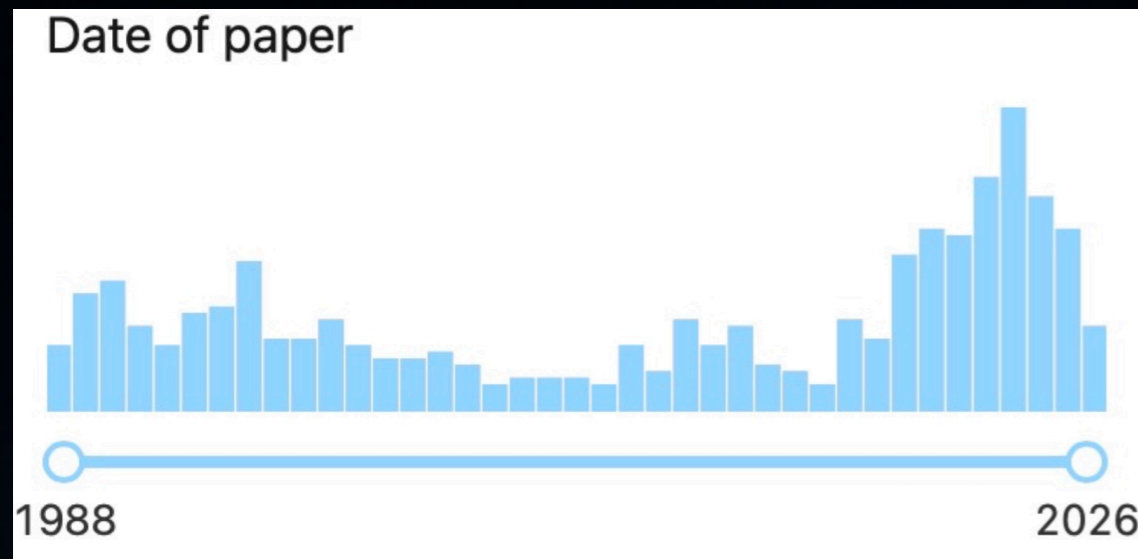
In the fall of 1984 David Gross taught a course on string theory at Princeton. Many people sat in on this course and struggled to learn string theory, including myself and presumably Lance, although my memory is fuzzy. I suspect he learned faster than I did.

It was an incredibly exciting and fun time, with new developments every month and the feeling of constructing (or discovering?) a new and profound theory of physics.

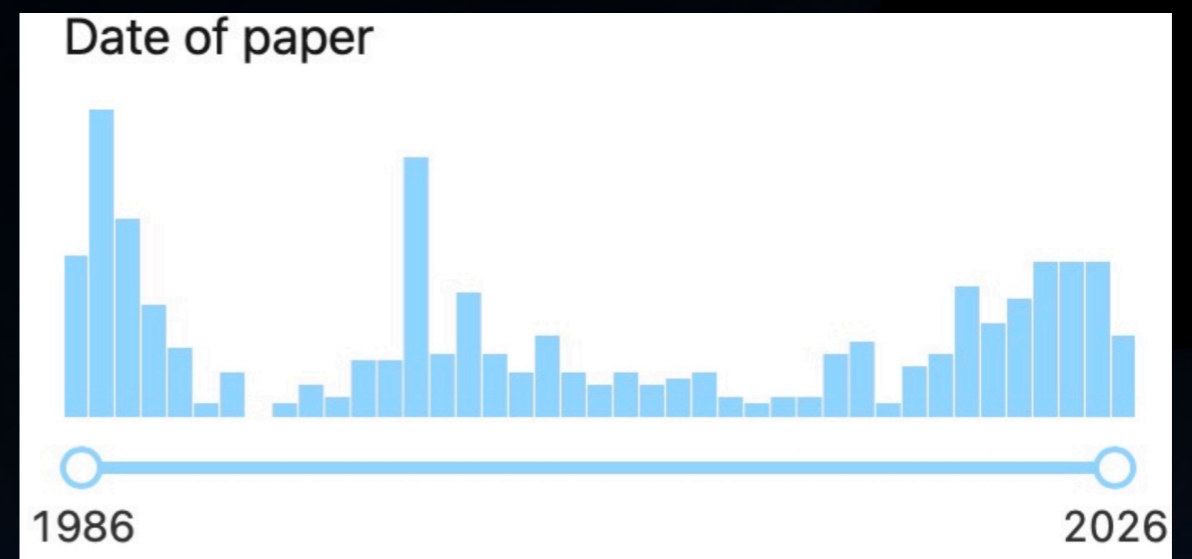
Between 1985 and 1990 Lance wrote 14 papers on string theory as well as several conference and summer school proceedings. I was a coauthor on 5 of these papers and I hope I will be forgiven if I say nice things about them.

These papers have had an enormous impact on string theory, phenomenology, cosmology and mathematical physics. All of them continue to be well cited, and some, 40 years later, are more heavily cited than they were originally.

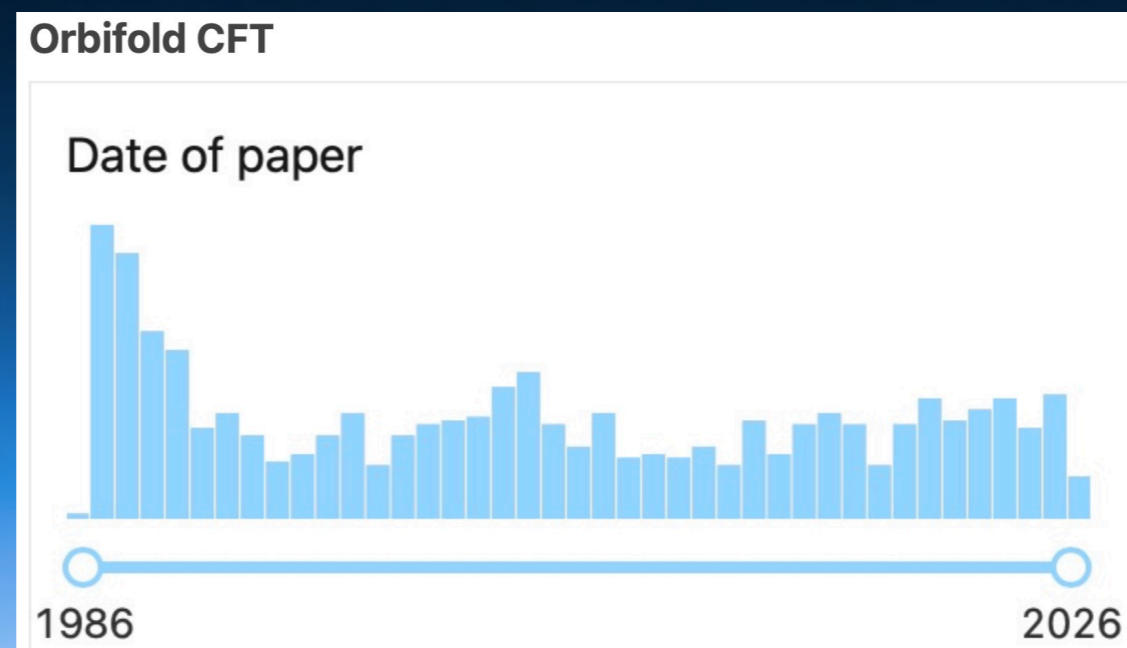
Banks and Dixon, Constraints on String Vacua with Space-Time Supersymmetry (563 citations)



Dixon and Harvey, String Theories in Ten Dimensions Without Space-Time Supersymmetry (511 citations)



Dixon, Friedan, Martinec and Shenker, The Conformal Field Theory of Orbifolds (1094 citations)



The things about Lance at that time that struck me most forcefully when he was a graduate student:

- ▲ He was interested in and knowledgeable about all areas of physics. Not just particle physics, but also condensed matter, astrophysics, etc.
- ▲ He was totally fearless when it came to difficult computations.
- ▲ He was generous with his time and open to sharing his ideas.
- ▲ He actively sought out new collaborators.
- ▲ He had exceptionally good taste in the problems he worked on.

This had a very negative impact on my future ability as a graduate advisor.

I will discuss his papers on string theory and their impact organized as follows:

Orbifolds

Conformal Field Theory

Strings Without Supersymmetry

Fayet-Iliopoulos Terms

Unification

Mathematical Impact

Orbifolds

Following work on the heterotic string and Calabi-Yau compactification, Lance and I started exploring ideas to “twist” the heterotic string d.o.f. to break the symmetry. Vafa and Witten were exploring similar ideas from a more geometric point of view so we decided to join forces. This led to two of Lance’s most important and most cited papers:

Strings on orbifolds ☆

[L. Dixon](#)¹, [J.A. Harvey](#), [C. Vafa](#), [E. Witten](#)

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Abstract

String propagation on the quotient of a flat torus by a discrete group is considered. We obtain an exactly soluble and more or less realistic method of string compactification.

Strings on orbifolds (II)

[L. Dixon](#)^{†1}, [J. Harvey](#)^{†2}, [C. Vafa](#)[†], [E. Witten](#)^{†3}

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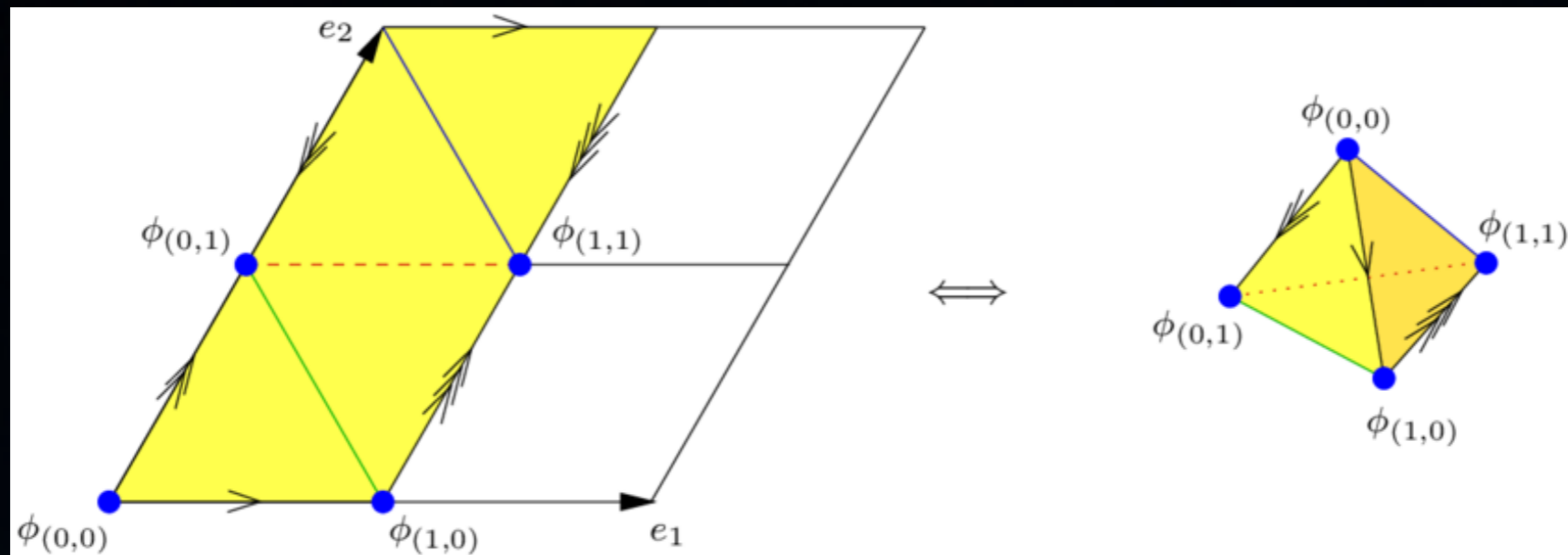
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Abstract

A general framework for analyzing string propagation on the quotient of a manifold by a discrete group is presented. The conditions necessary for modular invariance and absence of tachyons are discussed. Models with four or fewer generations which correspond to the standard embedding of the spin connection in the gauge group are analyzed. We all discuss some generalizations which may lead to more phenomenologically promising models.

$$T^2 / \mathbb{Z}_2$$



This construction showed that

String theory makes sense in the presence of quotient singularities

There are exact world-sheet CFTs describing limits of Calabi-Yau spaces

Became a valuable tool in string model building and in explicit one-loop string computations since the full string spectrum is computable

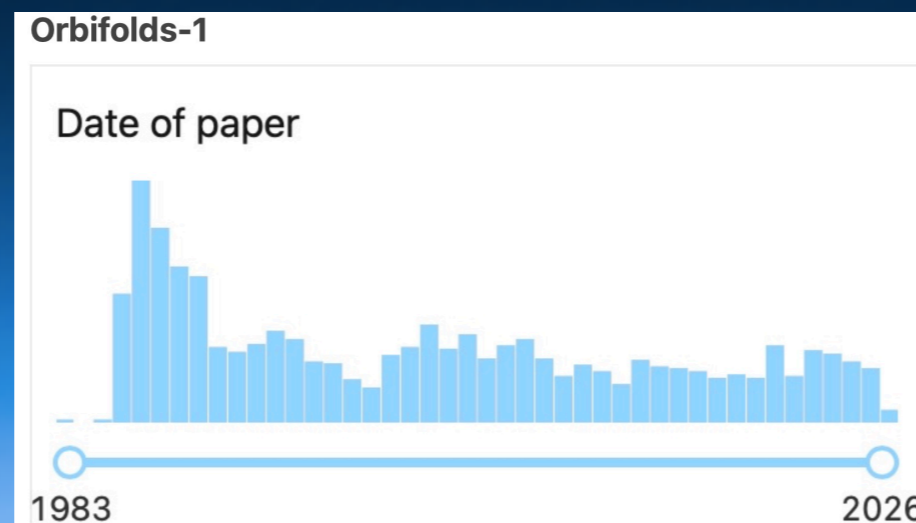
This construction has been generalized and incorporated into the modern view of symmetries in QFT.

Orbifold—Gauging of non-anomalous discrete symmetry of a CFT

Twisted sector of an orbifold by $g \in G$ — codimension-1 defect around which $X(\sigma + 2\pi) = gX(\sigma)$

Classification by $H^2(G, U(1))$ (discrete torsion)

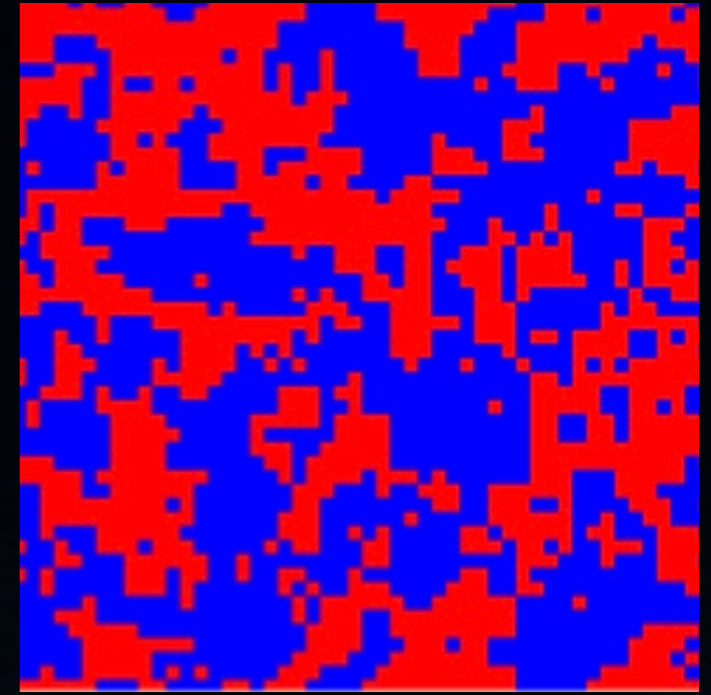
Broadly applicable even without a clear geometrical picture.



Orbifolds in principle provided an exact 2d CFT description of Calabi-Yau like compactifications of the heterotic string with $N=1$ supersymmetry in $d=4$ and chiral fermions in a representation of some subgroup of E_8 .

But, from a practical point of view, no one was exactly sure how to do explicit computations with these orbifold CFTs. What is the operator content? What is the structure of the OPEs? How does one compute correlation functions? Lance collaborated with experts on the use of CFT in string theory to answer these questions.

Conformal Field Theory



The conformal field theory of orbifolds

Lance Dixon^{1 2 7}, Daniel Friedan^{a b 3 7}, Emil Martinec^{4 7 5}, Stephen Shenker^{c d 6 7}

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Abstract

A prescription for the calculation of any correlation function in orbifold conformal field theory is given. The method is applied to the scattering of four twisted string states, which allows the extraction of operator product coefficients of conformal twist fields. We derive Yukawa couplings in the effective field theory for fermionic strings on orbifolds.

These techniques formed the foundation for many further developments, ranging from the abstract to the concrete. Here are two examples.

The operator content and OPE structure formed the basis for the determination of the “fusion algebra” of orbifold CFT, part of the categorical structure being explored in QFT.

The computation of entanglement entropy in QFT is both important and challenging. The Rényi entropy is computed using n copies of a CFT with a Z_n orbifold symmetry and utilizing orbifold techniques. This has been crucial in holography via the Ryu-Takayangai proposal and in condensed matter physics.

Strings Without Supersymmetry

After construction of the heterotic string it became important to know if there were any other $d=10$ strings that had been missed.

I think the general expectation was that string theories without supersymmetry contained tachyons (were unstable) and that anomalies were such a strong constraint that other possibilities were unlikely.

It thus came as a surprise when Lance and I (with related work by Seiberg&Witten and Alvarez-Gaume, Ginsparg, Moore & Vafa) discovered several new theories including a non-susy, tachyon free model with $O(16) \times O(16)$ gauge symmetry.

Given the lack of evidence for low-energy supersymmetry there has been renewed interest in string model building starting from non-susy string theories. Perhaps what once seemed to be a curiosity will become more important. My impression is that our understanding of such theories is still poor.

String theories in ten dimensions without spacetime supersymmetry

[L.J. Dixon](#)¹, [J.A. Harvey](#)²

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Abstract

We analyze the possibilities for new modular invariant ten-dimensional string theories without spacetime supersymmetry which are twisted versions of the closed superstring or of the heterotic string. The most interesting possibility is a tachyon-free theory with gauge group $O(16) \otimes O(16)$, chiral fermions, and a positive one-loop contribution to the cosmological constant.

Fayet-Iliopoulos Terms

$$c^{(a)} = \frac{g}{64\pi^3} \int \frac{d^2\tau}{(\text{Im } \tau)^2} \sum_i n_i q_i^{(a)} h_i = \frac{g}{192\pi^2} \sum_i n_i q_i^{(a)} h_i.$$

In $d=4$, $N=1$ susy gauge theory with a $U(1)$ gauge symmetry there is a famous term one can add to the action called the F-I D term.

$$c_a \int d^4\theta V_a$$

Such a term typically leads to a potential in otherwise flat directions and breaks supersymmetry. In field theory such a term can be induced at one-loop if the trace of the $U(1)$ generator over left-handed fermions is nonzero, and the coefficient is quadratically divergent.

Dine, Seiberg & Witten (1987): Such terms can be generated at one-loop in string theory, are finite, and can lead to vacuum instability.

Since these terms violate the usual susy non-renormalization theorems, it was important to perform explicit one-loop string computations to verify the DSW claim. This was undertaken by two groups:

Dine, Ichinose & Seiberg

Atick, Dixon & Sen

**STRING CALCULATION OF FAYET-ILIOPOULOS D -TERMS
IN ARBITRARY SUPERSYMMETRIC COMPACTIFICATIONS***

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Received 18 March 1987

We calculate the Fayet-Iliopoulos D -terms generated at one loop for the heterotic string in any background which preserves four-dimensional space-time supersymmetry and maintains $(2,0)$ world-sheet superconformal invariance. Although our calculation is performed in the full string theory, the result can be evaluated entirely in terms of properties of the massless spectrum. Furthermore it agrees with the result of a computation in the four-dimensional effective field theory using a stringy regularization. We also check our general result through a more explicit calculation in an orbifold background.

Both groups gave careful and correct arguments that such terms are generated at one-loop in string theory and are non-zero only then $\text{Tr } Q$ is non-zero.

However, Lance's group also did a completely explicit orbifold computation as well as a general SCFT analysis, and computed the precise numerical coefficient.

Impact:

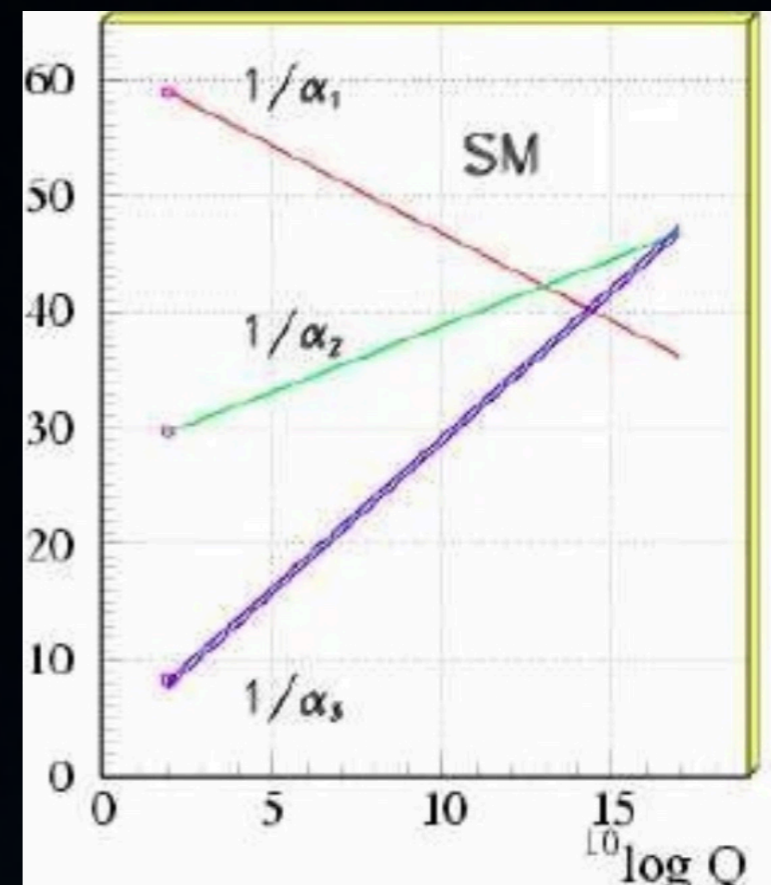
These models are a great test of our control of superstring perturbation theory because spacetime supersymmetry is maintained only by balancing tree and one-loop terms (see papers by Sen and by Witten)

They also play an important role in both string model building and in cosmological scenarios such as D-term inflation.

And there is also a one-loop correction to the masses of BPS string states as shown in a recent paper by Tai Wai Hu and JH.

Unification

(Does string theory really provide a unified theory?)



Lance wrote several papers that laid much of the foundation for connecting formal string theory to low-energy observable physics. These included

Phenomenology and Conformal Field Theory, or Can String Theory Predict the Weak Mixing Angle? With Banks, Friedan and Martinec.

This paper showed how to extract 4d physics directly from 2d SCFT bypassing much of Calabi-Yau technology.

Constraints on String Vacua with Space-Time Supersymmetry with Tom Banks

This paper established the precise conditions a world-sheet CFT must have to lead to $N=1$ spacetime supersymmetry. And as an aside it contained the proof that global symmetries in spacetime must actually be gauge symmetries, now a foundational conjecture in the swampland program.

Moduli dependence of string loop corrections to gauge coupling constants with Kaplunovsky and Louis

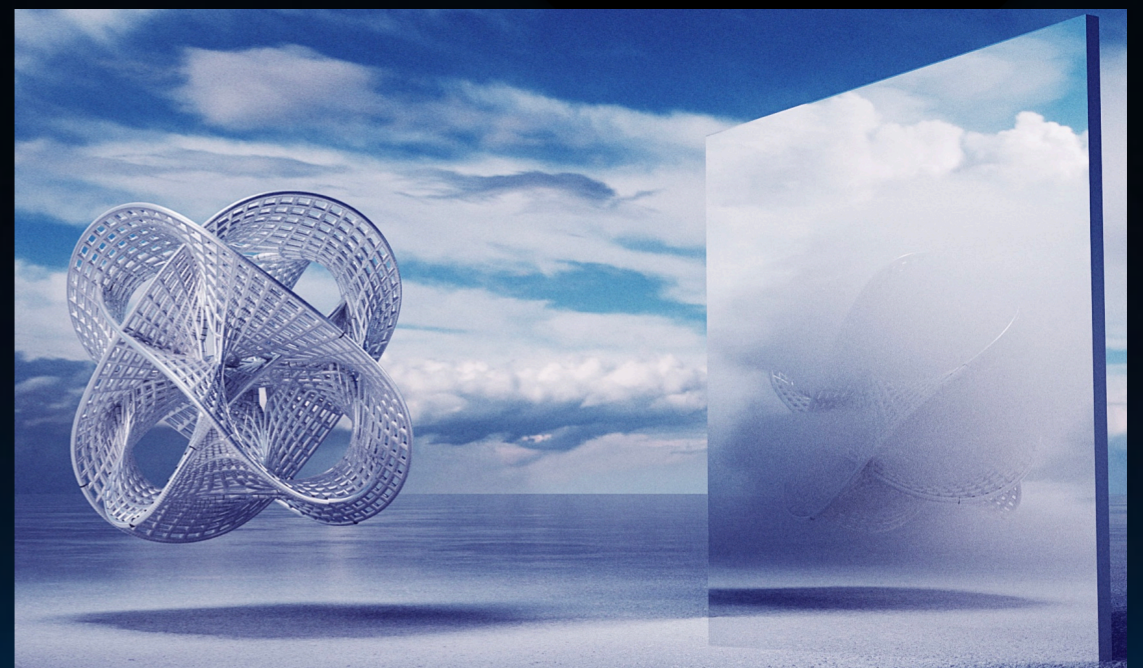
This paper contained the tools needed to study gauge coupling unification in string theory accurately and its dependence on the moduli of the compactification. It was also a technical tour de force.

Mathematical Impact

It is my impression that Lance has always been more interested in physics than in math, but some of his work has had a considerable impact on mathematics nonetheless. Here are a few brief examples.

In an unpublished paper Lance noted that two Calabi-Yau manifolds related by what is now called mirror symmetry would correspond to the same world-sheet SCFT. The existence and properties of mirror CY manifolds came as a complete surprise to mathematicians and is still an active area of research.

Mirror Symmetry



SOME WORLD SHEET PROPERTIES OF SUPERSTRING COMPACTIFICATIONS, ON ORBIFOLDS AND OTHERWISE

Lance J. Dixon (Princeton U.) (Oct, 1987)

Contribution to: Summer Workshop in High-energy Physics and Cosmology

Moonshine

Beauty and the Beast: Superconformal Symmetry in a Monster Module

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In this paper Lance, Paul and I translated the math VOA construction of a “Monster module” by FLM into the language of CFT. We discovered a super-conformal version of the theory, and provided a path for mathematicians to follow in constructing rigorous versions of other orbifolds of holomorphic CFTs

In the first paper on orbifolds we gave a path-integral computation of the Euler number of a Calabi-Yau manifold resulting from smoothing out an orbifold:

Orbifold Euler number formula

$$\chi(T^6/G) = \frac{1}{|G|} \sum_{g,h \in G, gh=hg} \chi(g, h)$$

Mathematicians made fun of us at first because they knew there was no such general formula. The Euler number depends on how you smooth out the singularities. Later they discovered a special kind of “crepant resolution of singularities” for which this formula is correct. Physically this is the resolution that preserves spacetime supersymmetry.

There are several other examples. The techniques Lance developed for computing the moduli dependence of threshold corrections were further generalized by G. Moore and JH and used to explain some results of R. Borcherds. Borcherds further generalized our results in a celebrated math paper.

Lance I developed an idea of Zamolodchikov for decomposing CFTs into CFTs with smaller central charge whenever the original theory has dimension $(2,0)$ primary operators. Lance persuaded me that it was not interesting enough to publish. It was rediscovered by mathematicians and led to a rich theory of framed Vertex-Operator-Algebras.

Presumably we will hear about other examples growing out of his post-string theory life.

Closing Thoughts

I don't recall any detailed conversations with Lance about why he stopped working on string theory. I presume it is because his focus has always been on physics, and he felt that he had better opportunities to connect his work to the real world working on other topics. Time has shown the wisdom of his decision.

Of course he hasn't really stopped working on string theory. He has written 14 papers related to N=4 Super Yang-Mills theory including one posted two days ago. Anyone who thinks N=4 SYM is not part of string theory has not been paying attention.

Lance has managed to find the sweet spot where he can both work on formal topics and have a profound impact on real world physics.



Happy Birthday Lance



Thank You For Listening

**And thanks to Lance for
choosing me as his
graduate advisor**