Final Report

Geometry and Elementary Particle Physics

Sponsor: DOE – Chicago

Sponsor ID: DE-FG02-88ER 25066

1) Introduction: It is a pleasure to write this final report summarizing the support by the Department of Energy, for our activities in "Geometry and Elementary Particle Physics.

In 1988 the interaction between geometry and high-energy theoretical physics was small. Few realized the impact each subject would have on the other. In our original 1988 proposal we wrote: "Today, quantum field theories of a geometric nature and string theory portend another major development in physics. Although the requisite mathematics is unclear, and may have to be invented, mathematics and physics continue to interact fruitfully. It is time to formalize the liaison of modern mathematics and high energy theoretical physics."

"We propose to initiate a program that will stimulate research in this new area and to train young people to become experts in both subjects."

We had proposed to foster the interaction between geometry and physics by:

(a) Running a mathematics physics seminar featuring research scientists in both geometry and physics.
(b) Supporting postdocs in both fields.
(c) Training graduate students, and
(d) Doing research at the interface of geometry and string/M-theory.

We emphasize that our purpose was to stimulate close contact between mathematicians and high-energy theorists, as well as to promote research in geometry and physics. We could hardly have imagined how rapidly the interaction of modern mathematics and high-energy theory would grow and how much impact it would have on mathematics. Three of the four Fields medals awarded at the International Congress for Mathematics in Kyoto in July 1990 were for work closely related to the subject matter of this proposal. The impact of quantum field theory on mathematics continues unabated. Our predictions are being realized, "… not only will the constructive interaction be sustained, but in fact, there is a new branch of mathematical physics developing – an abstract theoretical physics – which brings more sophisticated mathematical methods to bear on problems of physical origin …"

The years 1990 – 2000 witnessed increased collaboration between high-energy theoretical physics and modern mathematics. The effect on mathematics has been remarkable. Mirror symmetry has revolutionized enumerative geometry, and Seiberg-Witten invariants have greatly simplified the study of four manifolds. And because of their application to string theory, physicists now need to know cohomology theory, characteristic classes, index theory, K-theory, algebraic geometry, differential geometry, and non-commutative geometry. Much more is coming. We are experiencing a deeper contact between the two sciences, which will stimulate new mathematics essential to the physicists' quest for the unification of quantum mechanics and relativity.

Our grant, supported by the Department of Energy for twelve years, has been instrumental in promoting an effective interaction between geometry and string theory.

We summarize our activities in the following sections:

2. The Mathematics Physics Seminar.
3. Postdocs supported by the grant.
4. Visitors and collaborators supported by the grant.
5. Graduate students supported by the grant.
6. Selection of research papers

I.M. Singer
Institute Professor
M.I.T.
[CV in Appendix 1]

2) THE MATH/PHYSICS SEMINAR

This seminar, organized by Arthur Jaffe and I.M. Singer, was in existence from 1984 to 2002. Visitors (mathematicians or physicists) gave their talk Tuesday afternoons. At dinner, interested members of the audience had ample time to discuss the talk. Frequently visitors came on Monday and stayed through Wednesday, to exchange views and information on topics of mutual interest. Occasionally, speakers gave a series of lectures spread over a week or more.

LIST SEMINAR SPEAKERS

Name of Lecturer	# of Lectures	Lecture Titles
Alvarez, O.	(1)	"Some geometrical aspects of target space duality"
Atiyah, M.F.	(1)	"The Geometry of Classical Particles"
Baulieu, Laurent	(2)	"Gauge Theories and QCD4 Seen from Five Dimensions" "Seiberg-Witten duality from the point of view of topological field theory"
Carey, Alan	(1)	"Some Novel Geometric Invariants"
Chamblin, Andrew	(1)	"Gravity on the brane"
Connes, Alain	(2)	"Non Commutative Gauge Theory" "Noncommutative Geometry and Matrix theory"
Cornalba, Lorenzo	(1)	"Matrix representations of holomorphic curves in M(atrix) theory"
Dijkgraaf, R.	(5)	"Five Lectures on The Mathematics of M=theory"
Douglas, Michael	(2)	"D-Branes on a Noncompact Calabi-Yau" "D-Branes on a noncompact Calabi-Yau"
Ellwood, David	(1)	"Principal actions in non-commutative geometry"
Etingof, Pavel	(1)	"Alegebras and Varieties Related to Finite Subgroups of Sp(2n)"
Freed, Dan	(2)	"Ramond-Ramond Fields, K-Theory, and D-Brane Anomalies"
Gottesman, Daniel	(1)	"Correcting Quantum Errors"
Hitchin, Nigel	(1)	"The geometry of 3-forms in six dimensions"
Hopkins, M.J.	(1)	"On an invariant of Kervaire and Witten"
Hori, Kentaro	(1)	"Mirror Symmetry"

Name of Lecturer	# of Lectures	Lecture Titles
Jaffe, Arthur	(1)	"Hidden Symmetry"
Julia, Bernard	(1)	"Beyond U-Duality"
Kac, Victor	(2)	"Operator Product Expansion and Conformal Algebra" "Classification of Simple infinite-dimensional groups of supersymmetries and quantum field theory"
Katz, Sheldon	(1)	"Mirror Symmetry of D-Branes and Superpotentials"
Kostant, Bertram	(1)	"A Cubic Dirac Operator and a Generalization of the Bott-Borel-Weil Theorem"
Kreimer, Dirk	(2)	"Feynman Diagrams, Renormalization, and the Hopf Algebra of Rooted Trees" "On the use of Hopf algebras in quantum field theory"
Krichever, Igor	(1)	"Hamilton Theory of soliton equations and Seiberg-Witten solution of N=2 SUSY gauge theories"
Lafforgue, Vincent	(1)	"Survey and Status of the Baum-Connes Conjecture"
Leung, Naichung	(1)	"Multiple cover formulas for nongeneric rational curves in Calabi-Yau Three Folds"
Marcolli, Matilde	(1)	"Quantum Hall Effect on the Hyperbolic Plane and Fractional Quantum Numbers"
Meinrenken, Eckhard	(1)	"Duistermaat-Heckman formulas for group valued moment maps and moduli spaces of flat connections"
Mickelsson, Jouko	(1)	"Functorial QFT. Dirac boundary value problems and gauge anomalieis"
Moore, Greg	(2)	"Donaldson=Coulomb + Higgs" "Superconformal Symmetry and the Geography of 4-Manifolds"
Morrison, David	(1)	"An introduction to F-theory"
Nair, Parameswaran	(1)	"(2+1)-dimensional Yang-Mills theory: Vacuum state, string tension, etc."
Nappi, Chiara	(1)	"Quantized Branes"
Nekrasov, Nikita	(1)	"Instantons on non-commutative space"
Ovrut, Burt	(1)	"Heterotic M-theory and Holomorphic Vector Bundles"
Pioline, Boris	(1)	"Eisenstein Series, String Thresholds and Triality"
Polyakov, A.	(1)	"Gauge Fields and String Theory"
Ramadas, T.	(1)	"Faltings' construction of the KZ connection"
Schomerus, Volker	(2)	"Branes Geometry and Quantization" "Brane Charges in Background Fluxes"
Schwarz, Albert	(2)	"Noncommutative geometry and duality of gauge theories." "Lie algebra homology, quantum observables and topological invariants"
Segal, Graeme	(1)	"Poincare Duality and the Cohomology of the Moduli Space of Curves"
Shubin, Mikhail	(1)	"Pseudo differential operators and the C*-algegbra of singular integral operators."

Name of Lecturer	# of Lectures	Lecture Titles
Silverstein, Eva	(1)	"Instanton moduli spaces and Six dimensional RG fixed points"
Singer, I.M.	(8)	Lectures on Operator Algebras, Noncommutative Geometry, and K-Theory. (Series)
Strominger, Andrew	(1)	"Supersymetric Deformations of the Hermitian Yang-Mills Equations"
Szenes, Andras	(1)	"On Kontzevich's deformation quantization"
Tamarkin, Dmitry	(1)	"KZ Equation, Little Disk Operad and Kontsevich Formality"
Taylor IV, Washington	(1)	"Is there a Born-Infeld extension of U(N) super Yang-Mills theory?"
Thomas, Richard	(1)	"Moment Maps, Monodromy and Mirror Manifolds"
Vafa, Cumrun	(2)	"Knot invariants as Gromov-Witten invariants at Large N" "Large N-Duality as a Geometric Flop"
Varghese, Mathai	(2)	"B-fields and twisted K-theory" "Twisted K-theory, II"
Witten, Edward	(2)	"Integration Over the U-Plane in Donaldson Theory" "D-branes charges and K-Theory"
Zwiebach, Barton	(1)	"$\hat{E}_g$ and $\hat{E}_{10}$ in type IIB superstrings"

3) POSTDOCS SUPPORTED BY THE GRANT

We have been fortunate in the postdocs who have been supported by the DOE grant. For three of them we include a list of papers completed while supported by these grants, and curriculum vitae as well.

a) Scott Axelrod is presently a research associate at IBM working on algorithms for speech recognition.

Papers completed at MIT 1991-1994

(1) S. Axelrod, *Overview and Warmup Example for Perturbation Theory with Instantons*, Geometry and Physics (Lecture Notes in Pure and Applied Mathematics Series, Number 184), Marcel Dekker, New York, 1997.

(2) S. Axelrod and I.M. Singer, *Chern-Simons Perturbation Theory*, Proceeding of XXth International Conference on Differential Geometric Methods in Theoretical Physics, 1, World Scientific, Singaport (1992).

(3) S. Axelrod and I.M. Singer, *Chern-Simons Perturbation Theory, II*, J. Diff. Geom 39 (1994) 173-213.

His CV is Appendix 3a. We include it because it demonstrates how training in geometry and physics is fruitful in applications to concrete societal problems.

b) T. Ramadas is a Professor of Mathematics at the University of Montpellier II and a research scientist at the International Centre for Theoretical Physics (ICTP) in Trieste, Italy. In 1998 he won the Bhatnagar Prize, India's most prestigious science prize.

Paper completed while at MIT 1988-1990

(1) (With I.M. Singer and J. Weitsman) *Some comments on Chern-Simons Gauge theory*. Commun. Math. Phys. 125, 409-420 (1989).

(2) *Chern-Simons gauge theory and projectively flat vector bundles on Mg. Commun*. Math. Phys. 128, 421-426 (1990).

His CV is Appendix 3b.

c) Washington Taylor IV is a Professor of Physics at MIT.

Papers completed at MIT 1993-1995

(1) (With S. Carroll, M. Ortiz) *Spin/disorder correlations and duality in the c=1/2 string*, preprint CTP-2481, October 1995. To appear in Nuclear Physics B.

(2) (With S. Carroll, M. Ortiz) *A geometric approach to free variable loop equations in discretized theories of 2D gravity*, CTP-2465, hep-th/9510199, October 1995. To appear in Nuclear Physics B.

(3) (With M. Luty) *Varieties of vacua in classical supersymmetric gauge theories*, CPT-2465, hep-th/9506098, June 1995. To appear in Physical Review D.

(4) (With M. Crescimanno) *Large N Phases of Chiral* QCD_2, Nucl. Phys. **B437,** 3 (1995).

(5) *Counting* Stings *and Phase Transitions in 2DQCD*, preprint MIT-CTP-2997, hep-th/9494175, April 1994.

(6) (With J. Baez) *Strings and two-dimensional QCD for finite N*, Nucl. Phys. **B426**, 53 (1994).

(7) (With D. Gross) *Two-dimensional QCD and strings,* Proceedings of Strings '93 conference, Berkeley, May 1993, M.B. Halpern, G. Rivlis, A. Sevrin eds. 9World Scientific 1995) p. 214.

(8) (With B. Boghosian) *Renormalized Equilibria of a Schleogl Model Lattice Gas*, J. Stat. Phys. To appear (October 1995).

(9) (With B. Boghosian) *Correlations and Renormalization in Lattice Gases*, Phys. Rev. **E52**, 510 (1995).

(10) (With B. Boghosian) *Renormalization of Lattice Gas Transport Coeffiecients*, to appear in "Pattern Formation and Lattice Gas Transport Automata," A. Lawniczak and R. Kapral, eds., (American Mathemtaical Society) (1995)

His CV is Appendix 3c.

d) Two other postdocs who were on this grant are

1. A. Chamblin –Research Staff Member at the University of London
2. L. Cornalba – Faculty of Science Member at the University of Amsterdam

4) VISITORS AND COLLABORATORS SUPPORTED BY THE GRANT

a) O. Alvarez – University of Miami, Professor of Physics
b) L. Baulieu – LPTHE University of Paris, Director of the Laboratory
c) J. Cuntz – University Muenster, Professor of Mathematics
d) R. Dijkgraaf – University of Amsterdam, Professor of Mathematical Physics
e) M. Hopkins – M.I.T., Professor of Mathematics,
f) V. Mathai – University of Adelaide, ARC Senior Research Fellow
g) T. Ramadas – Professor, Department de Mathematiques, University of Montpellier II, and Research Scientist, International Centre for Theoretical Physics, Trieste.
h) P. Roche – Charge de recherché, CNRS in the Laboratory of Theoretical Physics in Montpellier, France.
i) J. Zinn-Justin – Professor of Physics and "Ingenieur CEA" at SACLAY, France.

We point out some collaborations of current interest:

1. "Beyond the elliptic genus" with O. Alvarez: in 1987, O. Alvarez et al [CMP, III; 1, 1987] and independently E. Witten CMP 109, 525, 1987 discovered the elliptic genus from the quantum field theory viewpoint. In the past few years, topologists have renewed their interest in elliptic cohomology, looking for a new object in elliptic topology, an anologue of K-theory in ordinary index theory. Alvarez/Singer extending the sigma model viewpoint from the torus to Riemann surfaces of higher genus gives some insight to the new search.

2. "Special Quantum Field Theories in Eight and Other Dimensions" with L. Baulieu: In a series of papers, Baulieu/Singer derive some interesting quantum field theories by gauge fixing topological quantum field theories. Seven dimensional manifolds are of current interest, particularly the relationship between supersymmetry and topological BRST. We are currently exploring the implications of our eight dimensional theory.

3. "Quadratic Functions in Geometry, Topology, and M-theory" with M.J. Hopkins: This paper introduces and develops "generalized differential cohomology." Adding "differential" to the

usual concepts in topology is essential for the study of chiral anomalies in string/M-theory, a topic of great interest currently in geometry and physics.

4. "The Index of Projective Families of Elliptic Operators" with V. Mathai and R. Melrose: Twisted K-theory, an extension of ordinary K-theory, turns out to have some uses in string theory. We extend the Atiyah-Singer families index theorem to the case of twisted K-theory whose cohomological invariant is torsion.

5) GRADUATE STUDENTS IN GEOMETRY/PHYSICS

a) Naichung Leung is presently an Associate Professor in the mathematics department at the University of Minnesota.
The title of his doctoral dissertation was: "Differential geometric and symplectic interpretations of stability in the sense of Gieseker." 1993

b) Huazhang Luo is an Assistant Professor in the mathematics department at the University of California, Los Angeles.
The title of his doctoral dissertation was: "Stability of algebraic manifolds." 1971

c) Richard Stone
The title of his doctoral dissertation was: "2-loop perturbative invariants of lens spaces and a test of Chern-Simons quantum field theory." 1996

d) Serguei Piunikhin has his own Internet Company.
The title of his doctoral dissertation was: "Quantum and Floer cohomology have the same ring structure." 1996

e) Lenhard L. Ng is an instructor in the mathematics department at Stanford University. He is also a fellow of the American Institute of Mathematics.
The title of his doctoral dissertation was: "Invariants of Legendrian links." 2001

f) Radu Constantinescu is an Associate at J.P. Morgan Chase & Company in Moreno Valley, California.
The title of his doctoral dissertation was: "Circular symmetry in topological quantum field theory and the topology of the index bundle." 1998

6) Selection of research papers

a) Topological Yang Mills, *Nucl. Phys. B* (Proc. Supple.) **5B** (1988) 12 (with L. Baulieu)

b) The Topological Sigma Model. *Commun. Math. Phys*., **125**, 227-237 (1989) (with L. Baulieu).

c) Some Comments on Chern-Simons Gauge Theory. Commun. Math. Phys., **126**, 409-520, (1989) (with T.R. Ramadas and J. Weitsman).

d) Conformally Invariant Gauge Fixed Actions for 2D Topological Gravity. *Commun. Math. Physics*, **135** (1991), no. 2, 253-265 (with L. Baulieu).

e) The Supersymmetry σ-model and the geometry of the Weyl-Kač Character Formula. *Nuclear Physics*, **373B**, (1992), 647-687 (with O. Alvarez and P. Windey).

f) Chern-Simons Perturbation Theory. Proceedings of XXth Conference on Differential Geometric Method s in Theoretical Physics, Vol. 1, 2 (with S. Axelrod) (1992)

g) The New Mathematical Physics, *Elementary Particles and the Universe*, 187—191 Cambridge University Press (1991).

h) Chern-Simons Perturbation Theory II, (with S. Axelrod), *Journal of Differential Geometry*, **39**, 173-213 (1994).

i) On the Master Field in Two Dimensions. *Functional analysis on the eve of the 21st century. Vol., 1* 263-281 (1995) Birkhäuser, Boston**.**

j) Special Quantum Field Theories in Eight and Other Dimensions, Commun. Math. Physics 194, No. 1, 149-175 (1998).

k) Beyond the elliptic genus, (with O. Alvarez) *Nuclear Phys. B* **633** (2002), no. 3, 309--344.

l) Twisted K-homology theory, twisted Ext-theory (with V. Mathai) hep-th/0012046…

m) The Index of Projective Families of Elliptic Operators (with V. Mathai and R. Melrose), submitted for publication. math.DG/0206002

n) Quadratic Functions in Geometry, Topology, and M-Theory (with M.J. Hopkins) submitted for publication. math.AT/0211216

INDEX

Geometry and Elementary Particle Physics

FINAL REPORT

Curriculum Vitae for Isadore M. Singer

Degrees/education:	B.S. University of Michigan, 1944 M.S. University of Chicago, 1948 Ph.D. University of Chicago, 1950
Positions:	C.L.E. Moore Instructor, MIT, 1950-52 Assistant Professor, University of California, Los Angeles, 1952-54 Professor, MIT, 1956-70 Norbert Wiener Professor, MIT, 1970-79 Professor, University of California, Berkeley, 1979-83 Miller Professor, University of California, Berkeley, 1972-83 John D. MacArthur Professor of Mathematics, MIT, 1983-87 Institute Professor, MIT, 1987-
Visiting positions:	Assistant Professor, Columbia University, 1955 Member, Institute for Advanced Study, Princeton, 1956 Professor, University of California, Berkeley, 1977-79
Memberships:	National Academy of Sciences, 1968 American Academy of Arts and Sciences, 1959 American Philosophical Society, 1983
Awards and prizes:	Bôcher Memorial Prize, 1969 National Medal of Science, 1983 Eugene Wigner Medal, 1988 Chair of Geometry and Physics, Foundations of France, 1988–89 AMS Award for Distinguished Public Service, 1993 Steele Prize for Lifetime Achievement, 2000 Abel Prize, 2004 James Rhyne Killian Faculty Achievement Award (MIT), 2005
Honorary degrees:	Tulane University, 1981 University of Michigan, 1989 University of Illinois at Chicago, 1990 University of Chicago, 1993 University of Miami, 2002
Presidencies:	Vice-President AMS 1970–72

Scott Axelrod
Research Staff Member
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EDUCATION

Princeton University (Princeton, NJ) 1986-1991
Ph.D. in Mathematics
Thesis: *Geometric Quantization of Chern–Simons Gauge Theory*
Thesis Advisor: Professor Edward Witten
Field of Specialization: Quantum Field Theory, Differential Geometry, Gauge Theory

Rutgers University (New Brunswick, NJ) 1982-1986
B.A. in Mathematics and Physics
Highest Honors, General Honors Program, Departmental Honors in Mathematics and Physics

SELECTED FELLOWSHIPS, GRANTS, and AWARDS

Alfred P. Sloan Research Fellowship	1994–1998
Alfred P. Sloan Doctoral Dissertation Fellowship	1989–1990
National Science Foundation Graduate Fellowship	1986–1989
Richard T. Weidner Physics Prize from Rutgers	1986
Henry G. Sanders 1925 Memorial Prize in Mathematics from Rutgers	1986
Joseph Bradley Prize in Mathematics from Rutgers	1986
National Merit Scholarship	1982

WORK HISTORY

Research Staff Member, IBM	1999–
Visiting Scientist, IBM	1998–1999
Consultant at Schlumberger-Doll Research	1997–1998
Assistant Professor, MIT Mathematics Department	1992–1998
Joint Postdoctoral Position at Harvard and MIT Mathematics Departments	1990–1992
Computer Programmer, Energy for America, Inc.	1984–1986
Computer Programmer, AM Cable TV Corp.	1982–1984

TEACHING

- Taught calculus, discrete math, linear algebra, probability and statistics, analysis, differential geometry, graduate geometry of manifolds, graduate topics courses, and organized mini-course on applications of mathematics.
- Ph.D. thesis advisor, one student graduated in 1996.
- MIT undergraduate advisor, 1996-1998.
- MIT mathematics graduate instructor trainer, 1996-1997.
- Developed linear algebra course teaching materials in Matlab.

SELECTED INVITED LECTURES at CONFERENCES and WORKSHOPS

- "Geometric applications of quantum field theory and functional integration" — Oct. 1999
  Lecture series at conference in honor of 35^{th} anniversary of Atiyah-Bott theorem
- "Generalized Chern–Simons Invariants" — March 1998
  Conference in honor of Jim Simons 60^{th} birthday, Stonybrook, NY
- Lecture series at workshop on Four Dim'l Geometry and Quantum Field Theory — Dec. 1996
  Newton Institute, Cambridge, England
- "Riemann-Roch from Duistermaat-Heckman" — Nov. 1996
  AMS special session on Lie Groups and Physics, Columbia, Missouri
- "Equivalence of Various Definitions of 2-loop Chern-Simons Invariants" — Oct. 1995
  AMS meeting, Boston, Massachusetts.
- "Quantum Field Theory and Geometry" — June 1995
  Science & Engr. Program for Middle & High School Teachers, MIT, Boston, MA.
- Lecture series in Geometry and Physics conference in Aarhus, Denmark — Aug. 1995
- "Chern-Simons Perturbation Theory with a Moduli Space" — March 1995
  AMS meeting, Hartford, Connecticut.
- "Instantons and Perturbation Theory" — Jan. 1994
  Geometry and Physics Conference, MSRI
- "Manifold Invariants from Chern–Simons Perturbation Theory" — March 1992
  Geometry and Quantum Field Theory Conference, Baltimore, MD
- "Generalized Lagrangian Field Theory" — July 1991
  AMS Conference on Mathematical Aspects of Classical Field Theory, Seattle, WA.
- "Chern–Simons Perturbation Theory Below 2 Loops" — May 199l
  Conference on Topological and Geometrical Methods in Field Theory, Turku, Finland.
- "Connections on the Space of Conformal Blocks via Geometric Quantization" — April 1989
  Conference on Links Between Geometry and Physics, Schloss Ringberg, W. Germany.

RESEARCH SUMMARY

My research has spanned several different fields. Here I will briefly and incompletely summarize some of my results in the various fields, hoping the reader has, or is willing to imagine, the required background material. I will finish with a brief closing comment.

Work on Geometrical Quantum Field Theory

To begin with, my graduate training and first area of research was in a very dynamic area of mathematical physics at the intersection of geometry and quantum field theory. One of the striking developments of this field was the advent of "topological quantum field theories", which are functorial maps from a category of manifolds with certain operations to a category of vector spaces with certain operations. An early result I had in this area was a definition of a "cohomological field theory" associated with a broad class of moduli problems. My construction unified and generalized several examples of Witten's (and caught an error in one) and is overviewed in *Cohomological field Theories* by Edward Witten, International J. Modern Physics, A6, 1991.

A significant development in the field of topological quantum field theory was Witten's solution of the three–dimensional topological quantum field theory whose classical action is the Chern-Simons invariant of gauge theory. Based on physically motivated, but non-rigorous manipulations of functional integrals, he showed that the observables of the theory define invariants of three-manifolds with embedded links and are completely determined by a set of axioms for their behavior under surgery and some generating data given by conformal field theory. These invariants were later put on a rigorous footing by *a posteriori* verifying that they do indeed define invariants. Much of my published work in the field is devoted to a rigorous treatment of aspects of the theory in a way that develops the physical intuition into a rigorous tool.

In my thesis I give a definition of a "generalized Lagrangian field theory" (which satisfies the classical analogues of the axioms for a topological quantum field theory) and present a large family of examples of such theories, of which the theory based on the Chern–Simons invariant is one example. To every Riemann surface, this determines an action of the mapping class group on a prequantum line bundle over the space of gauge fields on the surface. Choosing a complex structure on the surface, one can perform geometric quantization and obtain a "quantum" Hilbert space. To show that the quantum Hilbert space is independent of the choice of complex structure, we [1] construct a natural projectively flat connection on the quantum Hilbert bundle over Teichmuller space. The construction is motivated directly by field theoretic reasoning. We thus arrive at one of the fundamental ingredients of Witten's exact solution: a diffeomorphism invariant definition of the Hilbert space, together with an action of the mapping class group.

In further work on three-dimensional Chern–Simon quantum field theory, Isadore Singer and I [2, 3] prove that the perturbation series about an acyclic flat connection on a closed three-manifold is finite and invariant under diffeomorphisms, thus defining a new family of three-manifold invariants. I extended this further [4] to the case when one perturbs not around an isolated flat connection, but any (non-degenerate) component of the moduli space of flat connections.

Work on NMR

Starting in 1997, I did consulting work on signal processing and the physics of NMR at the research division of Schlumberger-Doll, an oilfield services company. The principal result [7] of this research was a framework for deriving the asymptotic behavior of the Nuclear Magnetic Resonance (NMR) echo response to the standard Carr-Purcell-Meiboom-Gill pulse sequence applied to spins diffusing in a bounded region in the presence of magnetic field inhomogeneities. The nature of the attenuation of the spin echoes is governed by three length scales: the sample size, the "diffusion length" which measures the distance traveled by a spin between applied pulses; and the "dephasing length" which measures the distance a particle needs to travel to incur appreciable spin decoherence due to the effects of field inhomogeneities. There are in fact three different asymptotic regimes corresponding to the cases where one of the length scales is much smaller than the other scales. The regimes are: the "short–time regime" (where the diffusion length is small); the "motionally averaging regime" (where the system size is small); and the "localization" regime (where the dephasing length is small). In each of these cases, we provide asymptotic formulas for the echo response which extend previous results in the literature. In particular for the important short time case, we show how the entire perturbation theory can be formulated and rigorously understood using results from the asymptotic analysis of partial differential equations. These results are not only of theoretical interest, but also provide a crucial ingredient needed for further developing NMR technology to better characterize a sample such as an underground rock formation external to a borehole in which the magnetic resonance equipment resides or a human subject inside a magnetic resonance imaging machine.

In "Geometry, Quantum Field Theory, and NMR" [8], I discuss the parallels between some of the problems in NMR and geometrical quantum field theories. On the one hand, knowledge of the techniques used in grappling with geometrical quantum field theories opens up a much more expansive view of NMR problems (for example our full characterization of the short–time perturbation theory). On the other hand, results for the problem of NMR actually provide practical and mathematically accessible starting points to address some of the basic question about geometrical quantum field theory. For example, in [8] I propose a non-perturbative exponential correction to the subleading "boundary" term in the short-time asymptotic formula derived in [7]. I verify in a simple case that it does provide a good fit to the exact value of the echo sequences. I believe that this is a good starting point for understanding perturbation theory for field theories defined on manifolds with boundary. As another example, their is an approximate duality between regimes in the NMR problem, provable by the Poisson resummation formula, which is reminiscent of the mysterious dualities recently discovered in string theory and M-theory.

Work in Human Language Technologies

In 1998 I started at IBM in the Human Language Technologies group in a new area of research for me, using computers to perform natural language tasks. I have worked on document classification, natural language generation and understanding, speaker identification, audio-visual speech recognition, active learning, and acoustic modeling for speech recognition. One of my main accomplishments was developing and implementing techniques for natural language generation and dialog management which were part of IBM's airline travel reservation system for the DARPA Communicator program [9]. The IBM system performed best in the final DARPA competition.

One piece of work that I have done in human language technologies that makes direct contact with my background in physics was for the application of speaker identification. A standard approach to speaker identification is to find, for each speaker, the probability distribution (in the form of a mixture of Gaussians) which maximizes the likelihood of some training data for the speaker. Given a test utterance, the speaker hypothesized is the one for which the test utterance has maximum likelihood. In [10], I show that one can obtain more accurate identification results if the model for each speaker is adapted by being evolving by the diffusion equation for a time chosen so that the test utterance has maximum likelihood under the diffused distribution.

A final program of work [12, 13, 14, 15, 16, 17, 18] that I will mention is in the area of acoustic modeling for automatic speech recognition. Most state of the art speech recognition systems consist of: (i) a frontend, which maps raw input acoustic data into a sequence of acoustic features vectors $X = [x_1, ..., x_T]$, where x_t is the vector associated with time "frame" t; (ii) a language model, giving a prior probability distribution $P(W)$ over possible word sequences $W = (w_1, ..., w_n)$; (iii) a Hidden Markov Models which gives a conditional probability distribution $P(X|W)$; and (iv) a search strategy for finding the hypothesized word sequence $\hat{W}$, which is just that maximizing the joint likelihood $P(X,W) = P(X|W)P(W)$. A central ingredient of the Hidden Markov Model is a probability distribution $p(x|s)$ for an acoustic vector x at a given time given a phonetic context state s. For reasons of robustness and computational simplicity, one standard approach is to take the distributions $\{p(x|s)\}$ to be mixtures of Gaussians with diagonal covariance matrices. It is also, by now, standard to obtain significant gain at minimal computation cost by using a Maximum Likelihood Linear Transformation (MLLT) to define the basis in which the Gaussians are diagonal. In our work we generalize this much further. We take the model to be mixtures of full covariance Gaussian written as exponential models with a subspace constraint on the exponential model parameters. That is, we write:

$$p(x|s) = \sum_g \pi_g \, p(x|g) \tag{1}$$

$$p(x|g) = e^{<\theta_g, F(x)>}/Z(\theta_g) \tag{2}$$

$$\theta_g = B\phi_g \ , \tag{3}$$

where g is a label for an individual Gaussian component, which has prior π_g; $F(x)$ is the vector consisting of the degree 1 and 2 monomials in the components of x; θ_g is a vector of exponential model weights which is constrained to belong to the subspace spanned by the columns of B; and $Z(\theta_g)$ is a normalizing factor (which physicists would call a partition function). In our work, we given efficient algorithms for training all the parameters (B and $\{\pi_g, \phi_g\}$) to maximize total likelihood on a training corpus. In fact, we give algorithms both for the case of "generative" likelihood (maximizing $P(X,W)$) and discriminative likelihood (maximizing $P(W|X)$). We find that we are able to obtain significant accuracy gains at minimal cost compared to the MLLT models (which already have similar improvements over naive diagonal models).

Because the dimensions of the B matrix (and other choices we will not elaborate on here) are free to vary, our subspace exponential models provide quite a large parameter space of models over which the developer can optimize for any desired combination of computational efficiency and speech recognition accuracy. As in the cases of both string theory and NMR, we are once again in the situation of finding it advantageous to consider an entire parameter space of systems at one time.

Closing Comment

In this summary I have tried to give a flavor of some of my research. Although the fields of research are somewhat disparate, geometrical quantum field theory, nuclear magnetic resonance, and human language technologies, I have found that a solid mathematical grounding combined with physical intuition has been a common thread that has helped me in my work in each of these fields separately and in my efforts to find and exploit connections between them. I have found it fascinating to be involved in a range of work, varying from very sophisticated and abstract theorizing trying to explore what might be the foundation for an understanding of ultimate physical law, to very concrete experimental work trying to engineer practical systems that can perform human-like tasks.

Publications

[1] Scott Axelrod, Steve Della Pietra, and Edward Witten, "Geometric quantization of Chern-Simons gauge theory," *J.Diff. Geom.*, vol. 33, pp. 787–902, 1991.

[2] S. Axelrod and I. M. Singer, "Chern–Simons perturbation theory," in *Proc. XXth International Conference on Differential Geometric Methods in Theoretical Physics (New York, 1991)*, S. Catto and A. Rocha, Eds., pp. 3–45. World Scientific, New York, 1992.

[3] S. Axelrod and I. M. Singer, "Chern–Simons perturbation theory, II," *J. Diff. Geom.*, vol. 39, pp. 173–213, 1994, received special featured review by Mathematical Reviews.

[4] S. Axelrod, "Overview and warmup example for perturbation theory with instantons," in *Geometry and Physics (Aarhus, 1995), Lecture Notes in Pure and Appl. Math*, Jørgen Ellegaard Andersen, Johan Dupont, Henrik Pedersen, and Andrew Swann, Eds., pp. 321–339. Dekker, New York, 1997.

[5] P. N. Sen and S. Axelrod, "Inhomogeneity in local magnetic field due to susceptibility contrast," *J. Appl. Phys.*, vol. 86, pp. 4548–4554, 1999.

[6] P. N. Sen, A. André, and S. Axelrod, "Spin echoes of nuclear magnetization diffusing in a constant magnetic field gradient and in a restricted geometry," *J. Chem. Phys.*, vol. 111, pp. 6548–6555, 1999.

[7] S. Axelrod and P. N. Sen, "Nuclear magnetic resonance spin echoes for restricted diffusion in an inhomogeneous field: Methods for asymptotic regimes," *J. Chem. Phys.*, vol. 114, no. 15, pp. 6878–6895, 2001.

[8] S. Axelrod, "Geometry, quantum field theory, and NMR," in *The Universality of Physics: A Festschrift in Honor of Deng Feng Wang, the Proceedings of the Deng Feng Wang Memorial Conference, Princeton, NJ, August 12, 2000*, Ramzi R. Khuri, James Liu, Feng Chen, and Wenbiao Gan, Eds., pp. 67–84. Kluwer Academic/Plenum, 2001.

[9] S. Axelrod, "Natural language generation in the IBM flight information system," in *Proc. of the ANLP/NAACL 2000 Workshop on Converstional Systems*, Seattle, Washington, pp. 21–26.

[10] S. Axelrod, "Speaker identification using online, frame dependent, and diffusive variance adaptation," in *Proc. ICASSP 2002*, Salt Lake City.

[11] G. Gravier, S. Axelrod, G. Potamionos, and C. Neti, "Maximum entropy and MCE based HMM stream weight estimation for audio-visual ASR," in *Proc. ICASSP 2002*, Salt Lake City.

[12] S. Axelrod, R. Gopinath, and P. Olsen, "Modeling with a subspace constraint on inverse convariance matrices," in *Proc. ICSLP 2002*, Denver, Colorado.

[13] S. Axelrod, R. Gopinath, P. Olsen, and K. Visweswariah, "Dimensional reduction, covariance modeling, and computational complexity in ASR systems," in *Proc. ICASSP 2003*, Hong Kong.

[14] K. Visweswariah, P. Olsen, R. Gopinath, and S. Axelrod, "Maximum likelihood training of subspaces for inverse covariance modeling," in *Proc. ICASSP 2003*, Hong Kong.

[15] S. Axelrod, V. Goal, B. Kingsbury, K. Visweswariah, and R.A. Gopinath, "Large vocabulary conversational speech recognition with a subspace constraint on inverse covariance matrices," in *Proc. Eurospeech*, Geneva, 2003, To appear.

[16] K. Visweswariah, S. Axelrod, and R. Gopinath, "Acoustic modeling with mixtures of subspace constrained exponential models," in *Proc. Eurospeech*, Geneva, 2003, To appear.

[17] V. Goel, S. Axelrod, R.A. Gopinath, P. Olsen, and K. Visweswariah, "Discriminative estimation of subspace precision and mean (SPAM) models," in *Proc. Eurospeech*, Geneva, 2003, To appear.

[18] B. Kingsbury, L. Mangu, G. Saon, G. Zweig, S. Axelrod, V. Goel, K. Visweswariah, and M. Picheny, "Toward domain-independent conversational speech recognition," in *Proc. Eurospeech*, Geneva, 2003, To appear.

Curriculum Vitae
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Education :Ph.d.(Mathematics),Univ. of Bombay, 1982.
M.Sc. (Physics), Indian Institute of Technology, Kanpur, 1977.

Appointments:

Research Scientist, International Centre for Theoretical Physics, Trieste, Present
Professor at the University of Montpellier, France. 2000-2003
Professor, School of Mathematics, TIFR. 2002
Visiting Professor at the Scuola Normale (Pisa) May 2000.
Visiting Professor at MIT (Cambridge, USA) during Fall 1997, and Visiting Scientist during Spring 1998.
Visiting Scientist, MIT (Cambridge, USA) 1988-'89.
Member, Institute for Advanced Study, Princeton 1987-'88.
Visiting Professor, Laboratoire de Physique Theorique at des Hautes Energies, University of Paris VII, for two months in 1985, one month in 1989.
Visitor, Mathematical Institute, Oxford, January-June, 1981.

Affiliations & Awards:

Fellow of the Indian Academy of Sciences.
Bhatnagar Prize of the CSIR for Mathematics (1998).

I am Associate Editor of the Proceedings (Math. Sciences) of the Indian Academy of Sciences

In addition I have been a visitor at the Institut Fourier (Grenoble), University of Montpellier, the MPIM (Bonn) MSRI (Berkeley), the University of Nice, the University of Kaiserlautern, the ICTP, the SPIC Science Foundation (Madras), the University of Kyoto, and the University of Paris VII for periods of up to two months. I have given seminars and lecture courses at these places, of course.

Selected Publications

1) The ``Harder-Narasimhan Trace" and Unitarity of the Hitchin Connection: genus 0 (to appear in Annals of Math.)
2) (With V.B. Mehta) Frobenius splitting and invariant theory. Journal of Transformation Groups. 2, 183-195 (1997).
3) (With V.B. Mehta) Moduli of vector bundles, Frobenius splitting, and invariant theory. Annals of Math. 144, 269-313 (1996).
4) Factorisation of generalised theta functions II. Topology 35, 641-654 (1996).
5) (With M.S. Narasimhan) Factorisation of generalised theta functions I. Invent. Math. 114, 565-624 (1993).
6) (With I.M. Singer and J. Weitsman) Some comments on Chern Simons gauge theory. Commun. Math. Phys. 126, 409-420 (1989).
7) (With P.K. Mitter): The two-dimensional O(N) nonlinear sigma model: renormalisation and effective actions. Commun. Math. Phys. 122, 575-596 (1989).
8)(With M.S. Narasimhan): Geometry of SU(2) gauge fields. Commun. Math. Phys. 67, 121-136 (1979).

Invited Talks

Invited talk in Conference in honour of Vikram Mehta, June 2006, Mumbai.

Invited talk in the Conference on "Moduli Spaces", Cortona, June 2003

Invited talk in the Conference in honour of M.S. Narasimhan, Trieste, December 2002

Invited talk at the Conference on "Symplectic Geometry", Cortona, Italy, June 1999

Invited talk at the Conference on "Analysis and Probability", New Delhi, January 1997.

Invited talk at the Conference on "Topology and Geometry", Bangalore, December 1996.

Invited talk at the Conference on "Geometry and Physics", Warwick, March 1996.

Invited talk at the Conference on "Topological and Geometrical Problems of Quantum Field Theory", Trieste, March 1995.

Invited talk at the Conference on "Symplectic Geometry of Moduli Spaces", Luminy, March 1994.

Invited talk at the Conference on "Vector Bundles on Curves - New Directions", Bombay-Madras, December 1993.

Two invited talks at the MSJ Conference on "Topology of Moduli Space of Curves", Kyoto, September 1993.

Invited talk in the "Algebraic Geometry - Theoretical Physics" Seminar Series of the Academia Nazionale dei Lincei, Rome, April 1993.

Invited Talk at the ICMS Conference on "Geometry and Physics", Edinburgh, March 1991.

Invited talk at the MSI Conference on "Construction of Quantised Gauge Fields", Cornell, June 1988.

I have given invited seminar talks at Harvard, Zaragoza, Erlangen, Tokyo, Singapore, Lille, Orsay, Jussieu, Madras, Kyoto, Osaka, Amherst, Chapel Hill, Columbia (Missouri), Ljubljyana, and Urbana-Champaign and colloquia at Bangalore, Chicago, Kaiserslautern, Virginia and St. Louis.

I have lectured at several summer/winter schools.

For completeness, I mention the following invitations, which I was unable to accept:

``Geometry and Physics", Aarhus, 1995.

Professeur Invite, Universite Paris VII, during 1995.

Centre Emile Borel, IHP, 1995.

Institute of Mathematics, Academia Sinica, Taipei 11529, Taiwan.

Congress AMS/SMF, Lyon, 2001.

Some more background

My Master's degree (in Physics) was from the Indian Institute of Technology at Kanpur. This was a five-year course - in ten semesters - integrating a large amount of engineering (and subsuming the Bachelor's degree), and extremely rigorous. Since the IIT background may be relevant, I mention that I joined the B.Tech

(Electrical Engineering) program and later switched to Physics.

I have taught at all levels undergraduate upwards, a wide range of subjects.

I have been involved in the organisation of four international conferences in India. The first of these was the International Colloquium on ``Geometry and Analysis" (Bombay, January '92), the second, the International Colloquium on ``Lie Groups and Ergodic Theory" (Bombay, January '96) and the third, a conference on ``Differential and Algebraic Geometry" (Bombay, July 1997). The fourth, in which I had a central organisational role, was a meeting on ``Vector Bundles on Curves - New Directions" held in Bombay and Madras during December '93.

At Montpellier, I co-organised a meeting on "Arithmetic Quantum Chaos" in January 2004. At the ICTP, I was Local Organiser of a School/Conference on Commutative Algebra in 2004. I organised a School on Automorphic Forms in 2007.

I was on the National Organising Committee of the International Mathematical Olympiad, 1996.

At the ICTP, I have been Chair of the ICTP Prize Committee. I was Chair of a committee appointed to design an Applied Mathematics Diploma. Together with Claudio Procesi, I organise a series of Schools on Algebra and Geometry in East Africa. I am the organiser of the weekly Math seminar.

Curiculum Vitae for Washington Taylor IV

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Education: B.A. in Mathematics, Stanford
PhD in Physics, UC Berkeley 1993

Appointments:

Professor of Physics, MIT, 2002- Present

Assistant Professor of Physics, MIT, 1998-2002

Assistant Professor, of Physics ,Princeton University, 1995-1998

Postdoc, Center for Theoretical Physics, MIT 1994

Selected Publications:

Review Papers:

"D-branes, tachyons, and string field theory"; lectures on D-branes and recent developments in string field theory, by W. Taylor and B. Zwiebach; to appear in proceedings of TASI 2001, Boulder, Colorado, July 2001; hep-th/0311017.

"M(atrix) Theory: Matrix Quantum Mechanics as a Fundamental Theory"; review article on the M(atrix) model of M-theory, Rev. Mod. Phys. 73, 419-462 (2001); hep-th/0101126.

Research Papers

"Nongeometric flux compactifications", J. Shelton, W. Taylor, and B. Wecht JHEP 0510:085 (2005); hep-th/0508133.

"Type IIA moduli stabilization", O. De Wolfe, A. Giryavets, S. Kachru and W. Taylor JHEP 0507:066 (2005); hep-th/0505160.

"Enumerating flux vacua with enhanced symmetries", O. De Wolfe, A. Giryavets, S. Kachru and W. Taylor JHEP 0502:037 (2005); hep-th/0411061.

"A perturbative analysis of tachyon condensation", W.Taylor JHEP 0303:029 (2003); hep-th/0208149.

"Open string field theory without open strings", I.Ellwood and W.Taylor Phys. Lett. B512, 181-188 (2001); hep-th/0103085.

"Multiple Dp-branes in weak background fields", W.Taylor and M.Van Raamsdonk Nucl. Phys. B573, 703-734 (2000); hep-th/9910052.

"Linearized supergravity from Matrix theory", D.Kabat and W.Taylor Phys. Lett. B426, 297-305 (1998); hep-th/9712185.

"D-brane field theory on compact spaces", W.Taylor Phys. Lett. B394, 283-287 (1997); hep-th/9611042.

"Two-dimensional QCD is a string theory" , D.Gross and W.Taylor, Nucl. Phys. B400, 181-210 (1993); hep-th/9301068.

Presentations

"Counting flux vacua with special properties", talk given at Kavli Institute for Theoretical Physics (KITP), March 10, 2005; [PDF transparencies], [audio] and [video].

"String field theory and cosmology", informal talk given at KITP string cosmology workshop, August 27, 2003; [audio] and [time-lapse video].

"Emergent geometry and string field theory", talk at strings 2003, Kyoto, Japan, July 11, 2003; [PDF transparencies] and [audio].

"Computing tree and loop amplitudes in string field theory", talk at strings 2002, Cambridge, England, July 18, 2002; [transparencies], [audio], and [video].

"Gauge invariance and tachyon condensation in open string field theory", talk at strings 2001, Mumbai, India, January 7, 2001; [transparencies] and [audio].

"Tachyon condensation in open string field theory", talk given at PIMS Pacific Northwest seminar on string theory, March 17, 2001; [audio] and [video].

Research Interests

Washington Taylor is primarily working on the problem of unifying quantum mechanics and gravity. String theory is currently the most promising candidate for a framework in which to understand quantum gravity. It is still not possible, however, to define string theory in a space-time background compatible with the physics we see around us, and string theory cannot yet be used to make specific predictions. Taylor's research focuses particularly on the problem of finding a nonperturbative and background-independent definition of string theory and M-theory, and on the related problem of analyzing solutions of this theory. The goals of this research are to understand the basic principles of quantum gravity and to understand the consequences of these principles for cosmology, the physics of the early universe, and high-energy particle physics.

Over the last decade, Taylor has worked on different approaches to finding a fundamental formulation of string theory and on understanding the physics of the new mathematical structures suggested by string theory. Taylor has made important contributions to our current understanding of the connection between gauge theories and string theories, as well as to D-brane physics, the matrix model of M-theory, and string field theory.

Currently Taylor is working on the string vacuum problem. As discussed below, the experimental observation of a positive cosmological constant and the apparent existence of a vast plethora of string vacuum solutions pose major challenges to the program of constructing a string vacuum compatible with observation and using such a vacuum to make physical predictions. Taylor's current work focuses both on the construction of new string vacua and on analyzing the space of known vacua for correlations which may lead to testable predictions.