



Renormalization and Universality in Mathematical Physics

THIS WORKSHOP WAS AN EXCHANGE of ideas and recent results between physicists and mathematicians, experts in renormalization, scaling, and universality in statistical physics and quantum field theory. It was held at the Fields Institute October 18-22, 2005 as part of the fall thematic program, and was organized by Pavel Bleher and Dirk Kreimer.

The renormalization group (RG) approach to the theory of critical phenomena is one of the most important and influential discoveries in late 20th century physics. It provides a beautiful intrinsic description of the scaling and universality of critical asymptotics and critical exponents in the theory of critical phenomena, which had been a great mystery for many years. The RG approach dramatically influenced the theory of dynamical systems, probability, statistical hydrodynamics, and quantum field theory.

The original ideas of the RG approach to the theory of critical phenomena were developed in the physical papers of Kenneth Wilson, Leo Kadanoff, Michael Fisher, and others in the early seventies, leading to Wilson being awarded the Nobel Prize for his fundamental work in this area. Michael Fisher's lecture, which opened the

workshop, was an excellent overview of the basic ideas of scaling and universality, based on his recent work on the critical asymptotics in spherical models and their applications to the theory of fluids and solid state physics. Leo Kadanoff gave two lectures at the workshop, the core of which was the semigroup of real space renormalization transformations, and the calculation of thermodynamic scaling functions and critical exponents in terms of the RG fixed points.

Robert MacKay gave a nice review of recent work on classical and quantum spin chains related to the RG theory of Hamiltonian systems. David Brydges presented recent results based on difficult



Lai Sang Young

2005 Coxeter Lectures Oded Schramm and Lai Sang Young

As part of the fall 2005 thematic program on Renormalization and Universality in Mathematics and Mathematical Physics, participants heard two inspiring series of Coxeter Lectures, given by Oded Schramm (September 13-15) and Lai Sang Young (November 23-25).

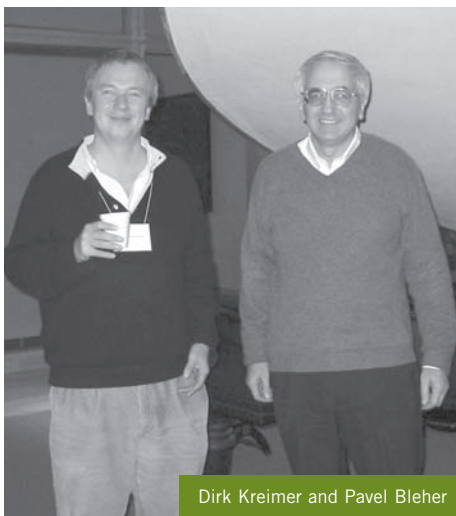
Oded Schramm, a Senior Researcher at Microsoft Research in Seattle, revolutionized the study of conformal invariance when he discovered SLE - a completely new class of stochastic processes - and used it to resolve a number of well-known conjectures. SLE stands for the Stochastic Loewner Evolution, though now other researchers refer to it as the Schramm-Loewner evolution. SLE represents a one-parameter family of conformally invariant planar processes. Many lattice models of statistical physics were conjectured to have conformally invariant scaling limits, such as critical percolation, the Ising model, or self-avoiding random walk. In some cases Schramm and his coauthors have now proved this, and have identified the limits as SLEs. Moreover SLE was used by Schramm, in collaboration with Greg Lawler and Wendelin Werner, to establish conjectured values for

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renormalization group estimates for self-avoiding random walks. Tom Spencer described a supersymmetric approach to band random matrices, developed in his work with Martin Zirnbauer.

The talks of Pavel Bleher, Vladimir Korepin, and John Palmer were devoted to exactly solvable models of statistical physics. Bleher reported on his recent results with Vladimir Fokin concerning the exact solution of the six-vertex model with domain wall boundary conditions and its applications to alternating sign



matrices. Korepin reviewed recent results on the exact solution for the von Neumann entropy in one dimensional quantum spin systems, Bose gas, and the Hubbard model. Palmer discussed the exact short distance asymptotics in the 2D Ising model.

Historically, a strong input to the development of the RG approach to statistical physics came from quantum field theory, a relation that is used for concrete calculations of critical exponents in the spin models of statistical physics. Jean Zinn-Justin gave a fascinating review of the works on the quantum field theory approach to the critical phenomena in 3D spin systems. His second talk described an impressive RG approach to the weakly interacting Bose gas.

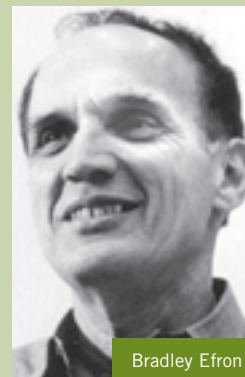
When it comes to comparing nature with established theory, quantum field theory still reigns supreme: it is unsurpassed in its ability to predict verifiable numbers in microscopic and macroscopic physics, covering more than twenty orders of magnitude in scale from critical phenomena to particle physics. Recent years have revealed fascinating connections to very modern developments and concepts in pure mathematics, notably number theory and geometry. About half of the talks reported on this. They included an overview of state of the art computational particle physics by John Gracey and Stefan Weinzierl which exhibited the many ways in which generalized polylogarithms and harmonic sums appear in calculations. Further applications of the renormalization group were exhibited in Gerry McKeon's talk.

The mathematics behind field theory was illuminated in a talk by Kreimer which reviewed the unifying language of Hopf algebras in field theory. Algebraic aspects of Rota-Baxter algebras in this context were covered by Li Guo. Stefan Hollands reported on progress with respect to quantum field theory in curved spacetime, whilst Tim Morris illuminated the structure of the exact renormalization group in gauge theories. Ivan Todorov managed to review the history of quantum equations of motion while introducing the audience at the same time to the structure of globally conformal field theories in four dimensions.

Quantum field theory constantly rejuvenates itself, staying at the forefront of conceptual work with novel insights into its mathematical and number-theoretic structure. At the same time it allows for the most precise comparison between theory and reality on a routine basis. The workshop proved a fitting tribute to these achievements emphasizing the concepts of renormalization and universality which are at the core of quantum field theory.

Pavel Bleher (IUPUI) and Dirk Kreimer (CNRS-IHES & Boston)

Efron: Statistics Lectures



On November 8 and 9, 2005, Professor Bradley Efron, Max H. Stein Professor of Humanities and Sciences and Professor and Chair of the

Department of Statistics at Stanford University gave an inspired and inspiring pair of lectures on empirical Bayes methods in modern statistical applications. Previous speakers in the "Distinguished Lecture Series in Statistical Science" include Peter Hall, Donald Fraser, Donald Dawson, and Sir David Cox. Professor Efron has been awarded the Ford Prize, the MacArthur Prize, and the Wilks Medal for his research work in computer applications in statistics, and is perhaps best known for his invention of the bootstrap, a computationally driven method for statistical inference.

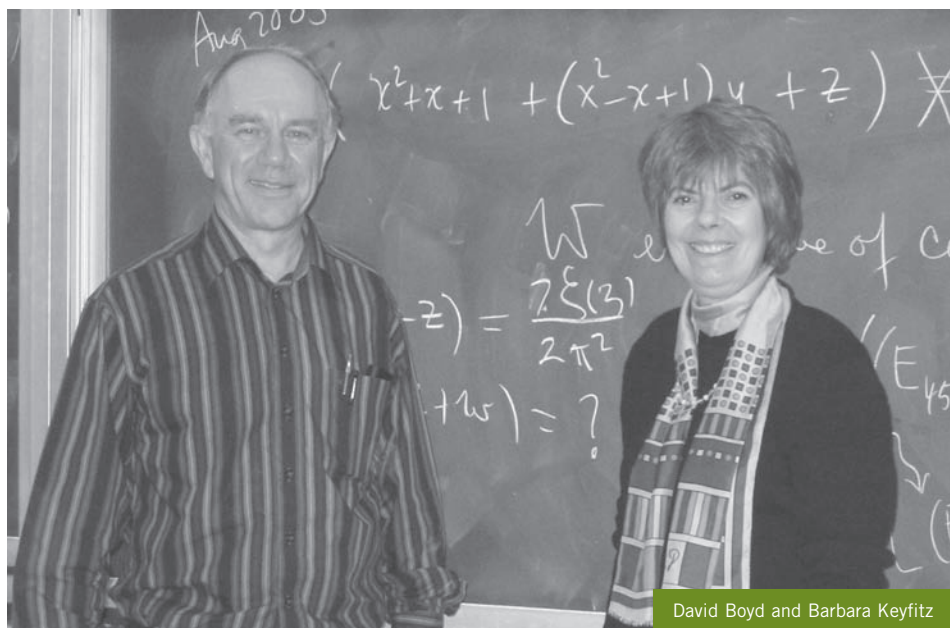
In the first lecture, Efron described the field of statistics as the most successful of the information sciences, and went on to illustrate this in the context of a number of applied problems that he has worked on during his career. In the process he gave a very accessible introduction to both Bayesian and frequentist approaches to assessing information. Empirical Bayes methods, suggested by Robbins in 1954 and extensively developed by Efron in a number of important papers, provide a type of compromise between Bayesian and frequentist methods by using data to estimate the prior distribution. Efron illustrated this first in the context of assessing for a friend, the probability that her expected twins would both be boys!, and next in the problem of the estimation of the number of unseen species. This problem also arose in 1976 by Efron and Thisted in the beautifully titled article "How many words did

CRM-Fields Lecture 2005: David W. Boyd

Shakespeare know?”. Efron and Thisted had an unexpected opportunity to evaluate their predictions in 1987, when a new poem, “Shall I Die”, was discovered in the Bodleian library; their conclusion, based on their use of empirical Bayes methods, was that the word usage in the poem was consistent with the Shakespearean canon. Efron then showed how empirical Bayes methods are very well adapted to data sets in which there are a large number of measurements on related entities. A famous illustration is the estimation of batting averages based on early season results, published by Efron and Morris in *Scientific American* in 1977. Most recently, the technical revolution in biology and medicine has led to massively parallel data sets; two examples are microarrays for measuring expression levels of thousands of genes and fMRI experiments that measure activation of thousands of voxels in the brain.

Efron’s recent work on this type of data was the subject of his second lecture. He used as a motivating example a gene expression array of study fifteen subjects, seven in one group and eight in another, with some 3000 measurements on each subject of gene expression. This leads to 3000 comparisons of the two groups, most of which would be expected to show no difference, either because the genes are not active, or are equally active across groups. The goal of the study is to find the needles in this haystack; the genes that do show expression level differences. Efron described his work on using the parallelism inherent in the problem to establish a baseline, an “empirical null hypothesis”, and look for the needles relative to that baseline. This leads to better results than the more standard approach of a “theoretical null hypothesis”, particularly when there is correlation among the genes that has not been expressly modelled. Characteristically for Efron, his approach seemed elegantly simple and almost inevitable, was clearly outlined with well chosen graphs, but on closer examination is seen to be built on ingenious and original mathematical arguments.

Nancy Reid (Toronto)



David Boyd and Barbara Keyfitz

IF P IS A POLYNOMIAL IN n VARIABLES, ITS Mahler measure, $m(P)$, is defined to be the average of $\log |P|$ over the product of n unit circles. This quantity appears naturally as an entropy in certain discrete dynamical systems and as a rate of growth in many other situations. A nice example of this, given in Boyd’s lecture, is some very recent work of Russell Lyons on the asymptotic enumeration of the number of spanning trees in growing central sections of the d -dimensional integer lattice. The Mahler measure is also of interest in connection with certain algebraic numbers, the P - V numbers and the Salem numbers, and, as such, has been of interest to Boyd for over a quarter of a century.

When $n = 1$, there is a classical formula of Jensen that expresses $m(P)$ in terms of the zeros of P , but for $n > 1$ there is no such general formula. In the late 1970’s, Chris Smyth proved some intriguing formulae for a few polynomials of 2 and 3 variables that showed that $m(P)$ can sometimes be related to special values of Dirichlet L -functions. Such a connection between an analytic object and an arithmetic object becomes possible once the polynomial has integer (or at least algebraic) coefficients and is always exciting when it occurs.

Experiments by Boyd led to the discovery of further such formulae and then, starting from an insight of Deninger, and in work partly on his own and partly joint with Rodriguez-Villegas, Boyd succeeded in proving and conjecturing such formulae for infinite families of Laurent polynomials in 2, 3 and more variables, relating the value of $m(P)$ to special values of L -functions of various kinds (or their first derivative in cases where the L -function vanishes), including L -functions of elliptic curves, Hecke L -functions and L -functions defined by modular forms. Although some of the formulae have been proved, most have only been numerically verified to many (e.g. 50) decimal places. The phenomenon is connected with the conjectures of Bloch and Beilinson from K -theory, as well as to earlier arithmetic conjectures of Stark and of Chinburg.

Boyd’s lecture presented a selection of many of these formulae, the history behind their discovery, and explained how some of them have been proved. It painted a very pretty picture and one which has plenty of room for further work.

John Friedlander (Toronto)



Mikhail Lyubich, Oded Schramm, Michael Yampolsky, Ilia Binder

Brownian non-intersection exponents, as well as to resolve the long-standing Mandelbrot conjecture on the dimension of the Brownian frontier.

In his Coxeter lectures, Schramm gave an introduction to SLE, as well as describing recent progress in the field and some related problems. The first lecture described the motivation for introducing SLE and the major ideas behind the proofs of existence for conformally invariant scaling limits in certain lattice models. He also gave an overview of the major conjectures in the field. In his second lecture he presented a more technical view of the theory of SLE. He explained the proof of the celebrated Cardy formula using SLE, and described the proof of the convergence of the harmonic explorer process to SLE(4). He devoted his last lecture to his recent joint work with Jeff Steif on dynamic critical percolation, presenting a more dynamics-related point of view on lattice models. He also described his recent work on this important model, and stated open questions about it.

Lai-Sang Young's lecture series was titled *A mathematical theory of strange attractors*. Located at the Courant Institute of Mathematical Sciences, Young studies the geometric and ergodic theory of dynamical systems, working to connect rigorous mathematical theory with systems of real-world interest.

The theory of strange attractors is motivated by observations in science and applied mathematics. Typically using a computer, one observes dynamical systems for which an open set in the phase space is contracted to a lower dimensional invariant object, the attractor. To be a "strange attractor", this invariant object must have sufficiently complicated, often fractal, geometry. Examples include the famous Lorenz attractor and Hénon attractor. However, without a mathematically precise definition it is nearly impossible to prove a meaningful theorem.

Young began her first talk with her precise definition of a *strange attractor*, a definition based on the practical belief that observable behavior and observable systems are those that occur on positive

Lebesgue measure sets of orbits and parameters. Young's definition of strange attractor is an object with five specific properties that are designed to conform with the naive notion of "strange attractor," as described above, and to have meaningful real-world properties, including a natural invariant measure and statistical fluctuations in the observables that are governed by the central limit theorem. She explained that existence of a strange attractor in a specific system requires knowledge of that system to an arbitrary precision, leaving as the only practical approach the proof that systems from a Lebesgue positive measure set of parameters have strange attractors.

Young defined *rank one* systems to be systems whose instability occurs in one dimension and contraction occurs in the remaining directions. Examples include limit cycles with periodic kicks, supercritical Hopf bifurcations with kicks, and real world systems such as the Hodgkin-Huxley model of a neuron, the Brusselator chemical reaction, Chua circuits, population dynamics, and (possibly) fluids. She concluded her first lecture stating a theorem that provides sufficient conditions for a family of rank-one systems to have strange attractors for parameter values in a positive Lebesgue measure set.

In her second lecture, Young described the properties needed to overcome *non-uniform hyperbolicity*, or informally stated, the lack of uniformly expanding behavior that is a result of folding. In her third lecture she showed how to use the "duality and similarity" between phase space and parameter space to obtain control on the Lebesgue measure of the set of parameters corresponding to strange attractors. She concluded by showing how to check the conditions from her theorem in two example systems: the kicked limit cycle and the kicked super-critical Hopf bifurcation.

Ilia Binder (Toronto) and Roland Roeder (Fields)

Official Opening of the Centre for Mathematical Medicine

THE INAUGURATION OF THE CENTRE FOR Mathematical Medicine (CMM) took place on Friday, September 2, 2005, at the Fields Institute. Opening remarks were made by the Directors of CMM, Amit Oza and Siv Sivaloganathan. Oza welcomed a full house of guests and remarked that it was a daunting task to address the distinguished audience with not only his “boss” (Chief Oncologist of Princess Margaret Hospital) but his boss’s boss (President and CEO of University Health Network) and his boss’s boss’s boss (President of the University of Toronto) all in attendance! He posed a question that many of his medical colleagues had been asking him recently: “What the heck is Mathematical Medicine?” Sivaloganathan outlined the long-term vision and goals of the Centre, stressing that CMM would have a dual role to play: In its pedagogical role the Centre would try to attract the best and brightest young researchers into this exciting interdisciplinary field. This would be accomplished via short courses, summer schools, and seminars at both undergraduate and graduate levels. In its research role, the aim is to develop CMM into the hub of a research network that stretches not only across Canada but worldwide. This would be accomplished through collaborative projects, workshops, conferences and eventually a Fields Institute thematic program.

Barbara Keyfitz (Director of the Fields Institute) endorsed the goals and mission of CMM. She said that the Fields Institute was very happy to nurture the Centre and help bring to reality the hopes and aspirations of CMM and its directors. She noted that biomedical science is a major field where mathematics has great potential to make significant contributions.

David Naylor (President of the University of Toronto) congratulated the directors on bringing the Centre into being. He reflected on some of



his own research which had involved extensive collaboration with mathematical scientists, and commented that these sorts of innovative ventures attract rising young stars as well as top established researchers.

Robert Bell (President and CEO of University Health Network) reiterated many of the points made by President Naylor. He hoped the Centre would foster true collaborative, interdisciplinary research and bridge the chasm between the disciplines of mathematics and medicine which clearly had much to contribute to each other.

These introductory remarks were followed by the two keynote speakers, both world-renowned researchers and authorities in their fields.

Tak Mak (Ontario Cancer Institute) gave a most refreshing and stimulating talk drawing analogies between the body’s immune system and Milton’s *Paradise Lost*, in which the latter was compared to the human body invaded by pathogens (antigens). He commented (in jest) that everything about immunology was contained in Milton and there was nothing left for him to do.

Jim Keener (Utah) focused on the impact of mathematics on medicine. He could not say exactly what the future would hold for the interaction between the two disciplines of mathematics

and medicine - but, if the past can be used as a barometer for the future, the interaction will be both mutually beneficial and dramatic. He illustrated this with examples from cardiology which could not have been seen (or resolved) without mathematics. Currently defibrillators, pacemakers and other devices are being designed, specifically using mathematics. He concluded by commenting that there is currently a ground swell of interest in the interdisciplinary field of Mathematical Medicine and that it was the right time and right place to establish CMM. The evening concluded with an excellent reception.

The Centre’s activities continued into the fall, with an ongoing seminar series, and a workshop on October 5, 2005 on the topic *Modelling in Oncology: Problems and Challenges*, co-organized with the Biomathematics and Biostatistics working group at the University of Guelph. Workshop talks focused on four themes: drug delivery, ovarian cancer, gliomas, and radiotherapy. For all themes, discussions addressed such issues as the level of detail to include in models, how to validate them, and areas suitable for new applications of the models.

Siv Sivaloganathan (Waterloo, CMM)

Fields Publications

THIS MONTH, THE INSTITUTE AND THE AMS are jointly publishing *The Coxeter Legacy*, an account of the talks at the conference “The Coxeter Legacy: Reflections and Projections” which took place at the Institute in May, 2004. This collection captures the essence of Donald Coxeter’s life and work – it is a mixture of surveys, research articles, history, story-telling, and personal memories, and includes a bibliography of all of his research publications.

The books described here, as well as all earlier Fields publications, are now available at the front desk of the Institute, free of shipping charges and also at a discount for AMS members.

The newest entry in our Monograph Series is *Modular Calabi-Yau Threefolds* by Christian Meyer of Mainz University. Its main theme is the connection between

“This collection captures the essence of Donald Coxeter’s life and work – it is a mixture of surveys, research articles, and history”

Calabi-Yau threefolds and modular forms, presenting the general theory and bringing together the known results. Hundreds of new examples are given of rigid and non-rigid Calabi-Yau threefolds, and the construction of correspondences between them which leads to conjectures about the modular forms involved. The author has compiled tables of newforms of weight four and large levels, which are included in the appendix.

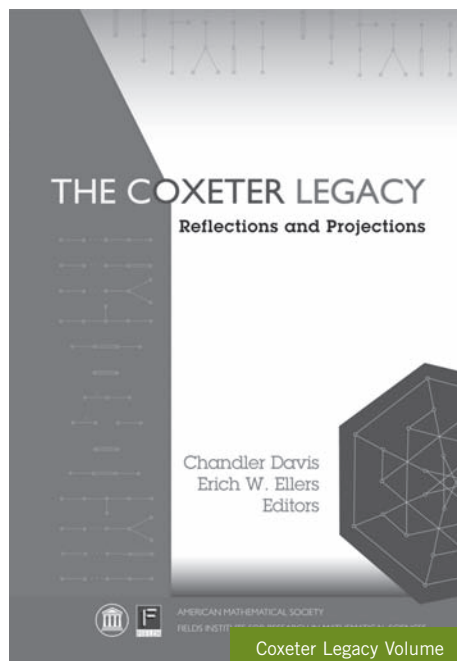
There are several new volumes in the Fields Communication Series. *Representations of Algebras and Related Topics*, edited by Ragnar-Olaf Buchweitz of the University of Toronto and Helmut Lenzing of the University of Paderborn, is a collection of research and survey articles, resulting from the “Tenth International Conference on Representations of Algebras and Related Topics” held at the Fields Institute in honour of Vlastimil Dlab’s seventieth birthday. It reflects state-of-the-art research in quantum groups, the theory of Lie algebras, the geometry and combinatorics of tilting theory, commutative algebra, algebraic geometry, homology theories, and derived and triangulated categories.

Topics in Kinetic Theory, edited by Thierry Passot (CNRS, Nice), Catherine Sulem (University of Toronto), and Pierre-Louis Sulem (Observatoire de la Côte d’Azur, Nice) will appear this month. This volume collects lectures given at a short course and workshop on kinetic theory held at the Fields Institute during the spring

of 2004, covering a variety of topics related to kinetic theory in neutral gases and magnetized plasmas with extensions to other systems such as quantum plasmas and granular flows. A comprehensive presentation is given for the Boltzmann equations and other kinetic equations for a neutral gas, together with the derivations of compressible and incompressible fluid dynamical systems, and their rigorous justification. Several contributions are devoted to collisionless magnetized plasmas. Rigorous results concerning the well-posedness of the Vlasov-Maxwell system are presented. Special interest is devoted to asymptotic regimes where the scales of variation of the electromagnetic field are clearly separated from those associated with the gyromotion of the particles.

Also appearing this month in our Communications Series is *Geometry and Topology of Manifolds*, arising from a conference held at McMaster University in May, 2004, and edited by Hans U. Boden, Ian Hambleton, and Andrew J. Nicas of McMaster University, and B. Doug Park of the University of Waterloo. It contains expository papers that give an up-to-date account of recent developments and open problems in the geometry and topology of manifolds, along with several research articles that present new results appearing in published form for the first time. The unifying theme is the problem of understanding manifolds in low dimensions, notably in dimensions three and four. The techniques include algebraic topology, surgery theory, Donaldson and Seiberg-Witten gauge theory, Heegaard-Floer homology, contact and symplectic geometry, and Gromov-Witten invariants.

Carl Riehm (Fields)



Workshop on Profinite Groups and Applications



Workshop Participants

THIS WORKSHOP WAS HELD AUGUST 8–11, 2005, at Carleton University. There were 34 participants including nearly 20 postdocs and graduate students. The organizers were Luis Ribes and Benjamin Steinberg. The meeting began with an introductory lecture by Ribes to provide the graduate students present with the background needed to follow the later talks. Minicourses were given by Moshe Jarden (Tel Aviv), Alex Lubotzky (Hebrew University) and John Wilson (Oxford). In addition to the lecture of Ribes and the minicourses, there were seven one-hour lectures by other experts in profinite groups and related fields.

Moshe Jarden's course explored the relationship between projective groups and pseudo-algebraically closed fields, stressing the connections between group theory and field theory and preparing the reader for the more advanced material in the book of Fried and Jarden. This theme was also taken up in the one hour lecture of Dan Haran (Tel Aviv). Similar themes, with an algebraic geometry flavour, also appeared in the lecture of Florian Pop (Penn).

Alex Lubotzky gave three very stimulating lectures. The first two were concerned with the relations between counting prime numbers (in particular the Riemann and Generalized Riemann Hypotheses), counting finite index subgroups (particularly of arithmetic groups) and counting covering spaces of Riemannian manifolds. In his third lecture, he turned to a different topic — profinite presentations, the Golod-Shafarevich theorem and the congruence subgroup problem. In particular he gave a conjecture that is nearly as strong as Thurston's conjecture on hyperbolic manifolds in that it implies most of the consequences of this conjecture, including the Serre conjecture on the congruence subgroup property. Some of these themes also appeared in the one hour lecture of Pavel Zalesskii (Brasilia) on profinite surface groups.

John Wilson delivered three lectures relating to subgroup separability that ranged from classical results about polycyclic and solvable groups, to very recent results on branch groups, including

the subgroup separability of the famous Grigorchuk group. Dani Wise (McGill) gave a related talk on residual finiteness and separability in groups arising from geometric group theory. In particular he gave the students some feeling for how the geometry of spaces that groups act on can be related to the structure of the groups in question. He also presented a plan of attack for several open questions including a conjecture of Baumslag on one-relator groups.

Wolfgang Hertfort (Vienna) gave a lecture on generalizations of Frobenius groups in the profinite context. There were two lectures on emerging applications of profinite groups to automata and monoid theory by Jorge Almeida (Porto) and Benjamin Steinberg (Carleton). Almeida showed how the dynamics of endomorphisms of free profinite monoids can be used to associate profinite groups to symbolic dynamical systems and under

“a conjecture that is nearly as strong as Thurston's”

certain primitivity assumptions obtain presentations for these groups, and in certain cases, as in the case of Sturmian systems, show that these groups are free profinite. Steinberg's talk gave an introduction to how the Ribes and Zalesskii theorem about free groups relates to automata and monoid theory and posed new problems about profinite groups coming from these connections.

Overall the meeting was very successful and fostered contacts between people working in diverse but overlapping areas of mathematics.

Benjamin Steinberg (Carleton)

Franco-Canadian Workshop on Combinatorial Algorithms



Workshop Participants

AIMED AT BRINGING TOGETHER A DIVERSE group of people working on both theoretical and applied aspects of combinatorics, this three day workshop was held August 18-20, 2005 at McMaster University. Although mostly Franco-Canadian in its orientation, the workshop was also attended by researchers from the USA, the UK, Belgium, Israel, Japan and Taiwan.

The conference featured a combination of theoretical and algorithmic

one-hour talks by distinguished invited researchers. Stephen Cook (Toronto) opened the conference with his talk on proof complexity and combinatorial principles. Later that day, Henry Wolkowicz (Waterloo) presented approximate and exact completion problems for Euclidean distance matrices using semidefinite programming. On the second day, Bruce Reed (McGill) surveyed a variety of results on the fractional chromatic number of a graph, Nantel Bergeron (York) discussed

the general theory of combinatorial Hopf algebras and presented a few examples, followed by Maxime Chocremore (Marne-la-Vallée) who emphasized the interplay between algorithms and combinatorics on words. On the third day, Bill Cunningham (Waterloo) spoke on his recent work on algorithms for disjoint path problems, and Jean Fonlupt (Paris VI) introduced the notion of good colorations of the vertices of a simple polytope and its relations to a theorem of Scarf.

The conference, with about 100 participants and 35 contributed talks, was hosted by the Department of Computing and Software at McMaster University and was co-sponsored by the Fields Institute, MITACS, and the Department of Computing and Software and the Faculty of Engineering at McMaster. For more details, see comal.mcmaster.ca

Antoine Deza (McMaster)

Quantitative Finance Conference on Credit Risk

A QUANTITATIVE FINANCE CONFERENCE ON Credit Risk took place on November 5, 2005 at the University of Western Ontario. This event attracted 85 people to London, of whom half were students and postdoctoral fellows. The others were equally split between professors and practitioners, helping achieve one of the aims of the conference, namely to generate substantial interaction between academia and industry. The topics covered ranged from new frontiers in credit-risk research to some important practical issues from industry.

Kay Giesecke from Stanford University started the day, speaking about a top-down approach for multi-name credit modelling and its application to the pricing of credit default swaps. Michael Walker from the University of Toronto, Alex Kreinin of Algorithmics, and Tom Hurd of McMaster University gave presentations describing different approaches to pricing various

Collateralized Debt Obligations (CDOs), currently a hot topic in credit risk research and practice. Michael Gordy of the U.S. Federal Reserve discussed how international regulators determined the new Basel II capital requirements that institutions must hold for their CDOs. Greg Gupton of Moody's/KMV considered the specification and fit of models for loss given default, a crucial component of any model used for pricing and managing credit products. Niall Whelan from Scotia Capital exposed some of the many computational challenges risk-managers face when dealing with a big portfolio having a large number of risk factors, including the risk of default. He also provided a practical simulation framework to overcome these challenges. Finally, Weidong Tian of the University of Waterloo looked at the issue of capital structure, default, and their relation to equity-linked debt products. Feedback the



Greg Gupton

organizers received from academics and practitioners alike suggested that these presentations provided something for everyone interested in credit risk modelling and pricing.

Fields, MITACS, and SHARCNet all provided generous financial support for the conference, with Fields and SHARCNet also providing significant organizational support.

Mark Reesor (Western)

Workshop on Current Issues in the Analysis of Incomplete Longitudinal Data

THIS WORKSHOP WAS HELD AT THE FIELDS Institute October 13-15, 2005, sponsored by the Fields Institute, the National Program on Complex Data Structures (NPCDS), the University of Waterloo, and GlaxoSmithKline Inc. who provided funding for graduate students' travel. The organizing committee consisted of Michal Abrahamowicz (McGill), Richard Cook (Waterloo), Paul Gustafson (UBC), Liqun Wang (Manitoba), and was chaired by Peter Song (Waterloo).

Statistical methods for the design and analysis of longitudinal and clustered data are critical for valid and efficient research in the medical, public health and social sciences. Such data are widely used to study causality, develop health policy, and carry out program assessments. In these settings, numerous statistical challenges have arisen which cannot be addressed by conventional linear or generalized linear regression techniques. This workshop focused on four important themes including longitudinal data analysis with missing values, measurement error models, joint modeling of longitudinal and survival data, and models for multi-state data.

Four invited sessions were scheduled, each a half day in length, followed by a fifth wrap-up session. A poster session was also held, involving 6 researchers from Canada and USA.

The first session on the theme of missing data problems covered a wide range of problems. K. Carriere Chough (Alberta) focused on the method of multiple imputations to deal with missing values in small sample repeated measures. Joan X. Hu (SFU) presented a new approach to improving the estimation of the population mean of longitudinal data with missing values. Lang Wu (UBC) was concerned with the inference problem in the linear/nonlinear mixed-effects models



with both dropouts and missing covariates. Jason Nielsen (SFU) presented a flexible semi-parametric model for the analysis of longitudinal panel data.

The second session featured four talks on measurement error issues in longitudinal data analysis, environmental health and social sciences. Paul Gustafson (UBC) used a flexible parametric modeling strategy to address the issue of consistent estimation of potentially non-identified models. Grace Y. Yi (Waterloo) gave an overview of approaches for longitudinal data models with missing data and for measurement error models. Roland Thomas (Carleton) gave an overview of the social science approach to latent variables modeling. Then Hyang Mi Kim (Alberta) presented a study on the impact of the use of grouping strategy for the mismeasured exposures in logistic and Cox proportional hazard models.

The third session's topic was the joint modeling strategies of survival and longitudinal data. Jeremy Taylor (Michigan) gave an overview of joint models for longitudinal biomarker data and event times. Xihong Lin (Harvard) presented a slightly different joint modeling problem. Todd MacKenzie (Dartmouth) talked about the use of

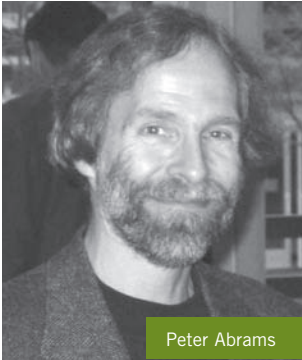
auxiliary variables or markers in clinical trials with a survival endpoint. James Robins (Harvard) presented recent results on robust and honest confidence intervals with longitudinal missing data.

The fourth session dealt with models for multi-state data. Jerry Lawless (Waterloo) spoke on problems arising in event history analysis. Vern Farewell (Cambridge) spoke of a large cohort study of cardiovascular health in the United Kingdom. Interest in this study lay in understanding the rates of non-fatal and fatal events with different censoring mechanisms operating for the two types of events. Paul Albert (NIH) reported on a wide range of multi-state models for the analysis of longitudinal binary data. Leilei Zeng (SFU) closed the session with a presentation on marginal methods for multivariate or clustered multi-state data.

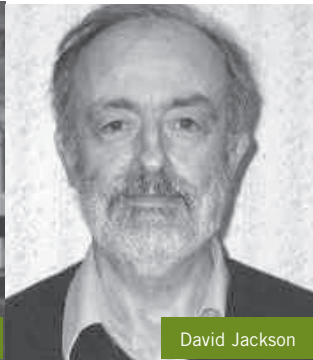
The fifth session began with Jamie Stafford's presentation on the past and future of the NPCDS. It was then led by the theme leaders who presented summaries of the talks given in the respective invited sessions as well as personal comments on the future research directions that this NPCDS project may take.

Peter Song (Waterloo)

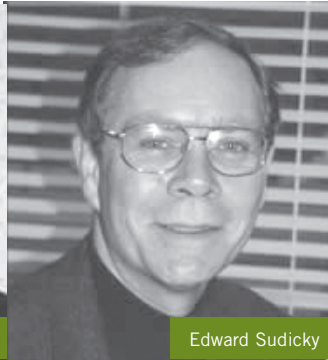
A Welcome to New Mathematics at the Royal Society



Peter Abrams



David Jackson



Edward Sudicky

ON NOVEMBER 14, THE FIELDS INSTITUTE celebrated the election of new Fellows of the Royal Society of Canada with three talks. This year's celebration was muted by the absence of one mathematical inductee in particular: We were saddened to learn of the death of Alberto O. Mendelzon of the Computer Science Department, University of Toronto.

The speakers this fall were Peter Abrams, Department of Zoology, University of Toronto, David Jackson, Department of Combinatorics and Optimization, University of Waterloo, and Edward Sudicky, Department of Earth Sciences, University of Waterloo.

Abrams' talk centred on the modelling of coexistence and diversification of competing species. Volterra formulated the "Principle of Competitive Exclusion" (the number of resources bounds the number of species). However, the hypotheses of this theorem are not satisfied by a number of real systems. Using more realistic models, Abrams can explain, in mathematical and ecological terms, some of the complex behaviour of evolving and adapting systems.

Jackson's talk was a reminder that mathematics can be applied to mathematics. His field of algebraic combinatorics uses algebraic tools to

recover geometric information. In his talk, he defined the map series and showed applications in string theory and moduli spaces of curves. The talk concluded with a discussion of Faber's top intersection number conjecture and the Virasoro conjecture.

With Sudicky's talk on *Simulating Integrated Surface-subsurface Flow*, the subject turned to hydrology. The novelty here is in combining the rather different mathematical approaches traditionally used to model surface water and groundwater flow. Sudicky's research includes dramatic examples at all spatial scales – local basins to North America – and time scales. For example, simulations demonstrate a greater exchange between surface and subsurface water than had been guessed – a conclusion with significance for contaminant transport.

Former Director of Mathematical Sciences at NSF Philippe Tondeur coined the phrase "fundamental and interdisciplinary" to describe the ability of mathematics to contribute to other sciences while simultaneously developing according to its own intrinsic structure. This theme was well illustrated by the FRSC Symposium.

Barbara Keyfitz (Fields)

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Graduate School Information Day

EACH FALL FIELDS ORGANIZES AN EVENT at which local graduate programs in mathematics, statistics, and computer science provide information to prospective graduate students. The sixth of these sessions took place November 5, 2005, and was attended by representatives from Alberta, Carleton, Guelph, McMaster, Ottawa, Rochester, Toronto, Waterloo, Western, and York. The day included two talks designed to introduce students to the kind of research they might encounter at graduate school. Students travelling from out of town received support, and even a bus where numbers warranted. Students came and went throughout the day, with about 60 students participating in total, about half of whom were present at 1pm prior to the start of the first talk.

The day's first speaker was Lucy Campbell (Carleton) who spoke on *Some Mathematical Problems in Geophysical Fluid Dynamics*. She described how PDEs arise in modelling atmospheric or ocean



Lucy Campbell and student

waves. By suitable approximations, these can be put in more tractable form, one example of which was a singular ODE of the type commonly encountered in undergraduate classes. While numerical solutions are more easily found from the original form of the equations, the analytical approximations help one understand the nature of the solutions. Particular attention was paid to the

consequences of nonlinearities in the equations, and to the large scale effect of rotation (eg the Coriolis force) and stratification (layering of the atmosphere).

Michael Yampolsky (Toronto) is one of the organizers of this fall's Fields thematic program. He gave the day's second talk, titled *Beautiful Fractals You'll Never See*. In it he described the dynamical system arising from iteration of a complex quadratic polynomial, and he discussed its associated Julia set. Turning to questions of computability, he defined what it means for an algorithm to "draw" a Julia set in an effective way, and gave a theorem (joint with M. Braverman) stating the existence of special Julia sets for which such algorithms will not exist. In effect, these give fractals that we cannot "see", even with the help of a sophisticated computer graphics program.

Tom Salisbury (Fields)

Fields Workshop on the Grand Mathematical Challenges in Medical Image Processing

THIS WORKSHOP WAS DESIGNED TO STIMULATE innovative thinking related to the mathematical aspects of medical imaging, to foster the exchange of information and insights among its participants, to identify future research directions in medical imaging and to seed new collaborations in areas of mutual interest. It was sponsored by the Fields Institute, MITACS, the Waterloo Institute for Health Informatics Research, and the University of Waterloo Faculty of Mathematics and School of Computer Science. Organizers were Jeff Orchard (workshop director), Edward Vrscay, Paul Fieguth, and Dominic Covey, all of the University of Waterloo.

There were 65 participants – professors, students, post docs, research scientists, software developers and engineers – from various universities, research institutes,

companies and hospitals. Pieter Vuylsteke, Senior Researcher at Agfa, came from Antwerp in Belgium, and found that his work (an image enhancement method known as MUSICA) was referred to in the keynote speech by Paul Babyn of Toronto's Hospital for Sick Children.

Each of the speakers gave inspiring presentations, with topics ranging from the use of partial differential equations in medical image processing, to "the current state of medical imaging: what's working, what's not". Each lecture was followed by a panel discussion that involved the audience. The workshop concluded with a half-day group brainstorming discussion.

Electronic copies of the speakers' talks are available online at the Waterloo Institute for Health Informatics Research website hi.uwaterloo.ca.



Based on the participant evaluations and comments, this workshop was a huge success. One participant stated "From a professional viewpoint, this is probably one of the very best conferences I have ever attended. The quality of the speakers and the brilliantly directed focus of the range of topics covered was exceptional." Others echoed this sentiment.

Jeff Orchard (Waterloo)

OTHER EVENTS



Percolation and SLE: Steffen Rohde, Vincent Beffara & Don Marshall

Since September, additional Fields activities took place that space limitations preclude reporting on in this issue. In the thematic program, this includes the workshops on *Percolation, SLE, and Related Topics* organized by Ilia Binder and Steffen Rohde (September 20-24, 2005), and on *Renormalization in Dynamical Systems* organized by Hans Koch, Misha Lyubich, and Michael Yampolsky (November 29 - December 3, 2005). The program also organized regular seminars, and a sequence of mini-courses.

Amit Bose and his colleagues organized an *Applied Probability Day* at Carleton University on September 17, 2005. A workshop on *Jordan Algebras and Related Fields* was held September 21-24, 2005 at the University of Ottawa (organizers E. Neher and M. Racine). The Centre for Mathematical Medicine mounted a Workshop on *Modelling in Oncology* on October 5, 2005. A *Data Mining* workshop took place November 10-12, 2005, sponsored by NPCDS and Generation5, following the success of a

workshop on that topic held the year before. The series of *Weekend Workshops on Algebraic Varieties* continued with a meeting November 5-6, 2005, organized by James Lewis and Noriko Yui.

The Institute's ongoing research seminars were active all fall. Practitioners and academics met regularly at the three commercial/industrial mathematics seminar series: *Quantitative Finance* (speakers Dmitry Kramkov, Mark Reesor, Marco Frittelli, Nizar Touzi, Steven Kou, and Mary Hardy), *PRMIA Risk Management* (speakers Allan Brender and Santiago Carrillo), and *Industrial Optimization* (speakers Stefan Karisch, Ellis Johnson, David Zingg, Natalia Alexandrov, Samer Takriti, and John Birge). The Fields Mathematics Education Forum continued its work, one theme of which was the ongoing review of the Ontario grades 11-12 mathematics curriculum. And our Scientific Advisory Panel and Board of Directors both met, to review and approve future Institute activity.

Tom Salisbury (Fields)

NOTED

JURIS STEPRANS will become the next Deputy Director of the Fields Institute on July 1, 2006. He was an organizer of the Fall 2002 program on Set Theory and Analysis.

JOHN MIGHTON has been awarded the Siminovitch prize and a Governor General's award for his play "Half Life". The mathematics tutoring organization JUMP he founded was based at the Fields Institute for several years. His achievements in the arts and sciences were honoured at an event at the Institute on December 5, 2005.

CORRECTION: The article "Schubert Calculus and Schubert Varieties" appearing in volume 6:1 of Fields Notes was attributed in error to Lisa Jeffrey. The correct author is Alexander Yong. The Fields Institute apologizes for this error.

Leo Kadanoff; Jean Taylor
continued from page 16

biological systems are too complicated to have arisen by evolution. A proponent of this theory, William Dembski, was a student of Kadanoff's, and in the second part of his talk, Kadanoff explained Dembski's reasoning: A search through a totally random landscape cannot possibly be efficient, and hence evolution through random mutation shouldn't itself have brought us to the complex forms of life we experience. Kadanoff pointed out that the landscape is not "random". Pattern formation and emergent systems give an alternate picture, which does not preclude Dembski's scenario, but suggests that it needs study and scrutiny.

Despite the violent image of "breaking a neck" (the separation of a jet of liquid into droplets), Kadanoff's approach to the controversial topic of intelligent design was gentle. "I applaud their work", he said; "Good skeptics make good science."

of industry-oriented software, and a goal of the seminar is to make this more widely recognized. In seminars like these, and in a number of industry-oriented workshops, Fields provides a window for academic mathematicians on the real world. The news is that current mathematical results are being applied to industry problems in exciting ways.

But beyond the mathematics, beyond the models, beyond the computed answers, there is a real world of risk-taking and decision-making that is economic and political, and that is linked to social pressures and human effects. To give just one example, the announcement of General Motors' downsizing of its Oshawa operations, despite their being star producers, came less than a month after the *Math for Industry* conference at which a good share of the participants were scientists working for GM. All of their good work was powerless to influence a decision that affects tens of thousands of workers' lives. In fact, the values of the "research

department" are probably invisible to the people who made that decision.

The mathematical contribution to commerce may be long-term, not immediate. And general, not company-specific. Hence investment in fundamental research may not appear to be cost-effective to a particular company, despite the bromide that research is essential to the well-being of the entire country in the long run. Could we be, in our academic culture, simply too insulated from the consequences of our research to understand the culture of industry? How can we have an impact on the real world without taking real risks ourselves?

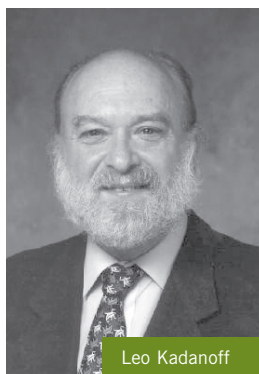
And yet, as everyone knows who has tried to write a grant proposal to "industrial" standards, and has puzzled over "milestones" and "timelines" – those markers that every manager seems to regard as essential and that few mathematicians can predict – there is little that is riskier than fundamental research. It may not be our fortunes that are at stake, but rather that most precious thing of all – our time. We often must choose research directions without being

confident of a successful outcome; we must take charge of our students' and of junior researchers' futures; we must predict which are productive avenues for research. And the concentrated time that one must spend to achieve a deep research result is not compatible with the daily pressure of meeting deadlines. In short, our culture, our "ivory tower", has evolved to meet the needs of advancing research in the mathematical sciences just as surely as the culture of the "real world" fits the mission of industry.

Perhaps the most valuable thing we learn from our "industrial outreach" is a respect for the way different modes of work suit different goals. Everyone who cashes a cheque or flies in an aeroplane – that is to say, *everyone* – appreciates the usefulness of the real world in the lives of mathematicians. Those same technologies – banking and flight – use mathematics in invisible but essential ways.

The question is not, "Does the real world need to invest in mathematical research?", but, "Can it afford not to?"

Barbara Keyfitz (Fields)



Leo Kadanoff

A few weeks later, the mood at Jean Taylor's Royal Canadian Institute *Science on Sundays* lecture, co-sponsored by the Fields Institute, was intrigued rather

than skeptical. Now on the faculty at NYU's Courant Institute, Jean has spent most of her career at Rutgers University. She has served as President of the Association for Women in Mathematics, and is a Fellow of the American Academy of Arts and Sciences. Her talk, *From Soap Bubbles to Crystal Growth*, presented a lively tour of the fascinating subject of minimal surfaces, and included a description of the fundamental problem Jean solved recently.

Fred Almgren and Jean Taylor changed the concept of a surface, as neither of the classical definitions (surface as a graph, surface as a mapping) provides a space of functions in which the minimization problem is guaranteed to have a solution. In the framework of Geometric Measure Theory, one can prove the existence of minimizers, and the problem becomes that of proving regularity. In her dissertation, Jean proved that the junction of three minimal surfaces is a curve of finite length. Her recent breakthrough is a proof that the configuration of twin bubbles is indeed a solution to a minimal surface problem.

"I'm always blowing bubbles ..." may not sound like serious science, but Plateau's problem is also fundamental in materials science, where it models phase boundaries in crystals. In a long collaboration with metallurgist John Cahn, Jean has investigated surprising

properties of crystal growth, for example rotation of immersed phases away from the crystal plane as they shrink.

The talk interwove the scientific and the personal. Jean pointed out her good fortune in often "being in the right place at the right time". She concluded with a thought-provoking analogy concerning the flood of computer simulations that may overwhelm theoretical mathematics. To Jean, one can take advantage of the information and insights offered by computation, while continuing to use geometry, as she plans to do with crystal formation.

After the talk, members of an enthusiastic audience of over 300 people peppered Jean with questions. We applaud the RCI's program and also their technology: A video recording of the talk, complete with slides, can be accessed from the Fields Web page by anyone who uses Windows.

Barbara Lee Keyfitz (Fields Institute)

Call for Proposals, Nominations, and Applications

For detailed information on making proposals or nominations, please see the website: www.fields.utoronto.ca/proposals

General Scientific Activities*

Proposals for short scientific events in the mathematical sciences should be submitted by March 15 or October 15 of each year, with a lead time of at least one year recommended. Proposals will be considered at other times as funds permit. Activities supported include workshops, conferences, seminars, and summer schools. If you are considering a proposal, we recommend that you contact the Director, Barbara Keyfitz (bkeyfitz@fields.utoronto.ca) or Deputy Director, Tom Salisbury (salt@fields.utoronto.ca).

Thematic Programs*

Deadlines for letters of intent and proposals for semester or year-long programs at the Fields Institute are March 15 and August 31 each year. Organizers are advised that a lead time of several years is required, and are encouraged to submit a letter of intent prior to preparing a complete proposal. They may consult the directorate about their projects in advance to help structure their proposal.

Postdoctoral Opportunities

Applications are invited for postdoctoral fellowship positions for the 2006-2007 academic year. The thematic program on Cryptography will take place at the Institute from August-December 2006, while the thematic program on Geometric Applications of Homotopy Theory will run from January-June 2007. Qualified candidates who have recently completed a PhD in a related area of the mathematical sciences are encouraged to apply. The fellowships provide for a period of engagement in research and participation in the activities of the Institute. They may be offered in conjunction with partner universities, through which a further period of support may be possible. One recipient will be awarded the Institute's prestigious Jerrold E. Marsden Postdoctoral Fellowship. Applicants seeking postdoctoral fellowships funded by other agencies (such as NSERC or international fellowships) are encouraged to request the Fields Institute as their proposed location of tenure, and should apply to the address below for a letter of invitation. Additional support is available (pending NSF funding) to support junior US visitors to this program. Applications are encouraged from all qualified candidates, particularly aboriginal peoples, persons with disabilities, members of visible minorities and women.

The deadline for postdoctoral applications for the 2006-2007 programs was December 9, 2005, although late applications may be considered.

***A note on diversity. In proposing any activity, applicants are requested to consider the mandate of the Institute to broaden and enlarge the community.** Applicants should explain how they plan to include women and members of visible minority groups in the proposed activity. As well, they should ensure that the proposed participant lists include scientists representing a range of career levels, types of institutions and geographical locations in Canada and abroad.

Please send applications, nominations, and proposals to:

The Director, Fields Institute
222 College Street,
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Fields Activities

Chalk it up to Mathematics



JANUARY TO JUNE 2006 *at Fields unless otherwise indicated*

FIELDS

Detailed information: www.fields.utoronto.ca/programs

Thematic Programs

HOLOMORPHIC DYNAMICS, LAMINATIONS, AND HYPERBOLIC GEOMETRY

Organizers: B. Kleiner, M. Lyubich, Y. Minsky, M. Shub and M. Yampolsky

JANUARY 2006

Graduate Courses

Holomorphic Dynamics (M. Lyubich)

Several Gems of Complex Dynamics (M. Yampolsky)

JANUARY 5–9, 2006

Workshop on Partially Hyperbolic Dynamics, Laminations, and Teichmüller Flow

JANUARY 9–11, 2006

Distinguished Lecture Series:

Gregory Margulis (Yale)

MARCH 7–11, 2006

Workshop on Holomorphic Dynamics

MARCH 27–29, 2006

Coxeter Lecture Series

Yair Minsky (Yale)

MAY 23–27, 2006

Workshop on Hyperbolic Geometry

CRYPTOGRAPHY SUMMER SCHOOL

JUNE 19 - JULY 7, 2006

Computational Number Theory and Applications to Cryptography

Rocky Mountain Mathematics Consortium, held at the University of Wyoming,

General Scientific Activities

JANUARY 13–15, 2006

Combinatorial Inverse Systems

JANUARY 22, 2006

RCI Public Lecture:

Miroslav Lovric (McMaster) held at the University of Toronto

FEBRUARY 9–11, 2006

Quantum Adiabatic Approximation

held at the University of Waterloo

MARCH 2006

Workshop on Lie Algebras held at the University of Ottawa

MAY 10–12, 2006

Numerical, Mathematical and Modeling Analysis Related to Fluid Dynamics in Hydrogen Fuel Cells held at the University of Ottawa

MAY 12–13, 2006

Ottawa–Carleton Discrete Mathematics Workshop held at Carleton University

MAY 14–16, 2006

Covering Arrays held at Carleton University

MAY 15–17, 2006

Probabilistic Symmetries and their Applications held at the University of Ottawa

MAY 15–20, 2006

Random Walks in Random Environments

JUNE 1, 2006

Actuarial Research Day held at the University of Western Ontario

JUNE 1–3, 2006

Workshop on Applied Probability held at Carleton University

JUNE 8–10, 2006

Xenakis Legacies Symposium held at the University of Guelph, Perimeter Institute, and Fields

JUNE 8–11, 2006

Digital Mathematical Performance held at the University of Western Ontario

JUNE 10–20, 2006

Summer School on Mathematical Modelling of Infectious Diseases held at York University

JULY 3–22, 2006

Summer School & Conference on Valuation Theory and Integral Closures in Commutative Algebra held at the University of Ottawa

From the Director: The Fields Institute and the Real World

FOR THE MOST PART, PARTICIPANTS IN OUR thematic programs come here to get away from the real world of academic duties, classes and committees. They come to spend a little time carrying out abstract research, talking about mathematics, learning new areas, renewing the excitement of working hard on a problem and thinking about nothing else for days at a time. A person unfamiliar with the nature of mathematical research might well consider that what is going on here is not very important.

Even what we call “applied mathematics” is not part of the real world of buying and selling, of manufacturing things, of making decisions on medical treatment or safety regulations – decisions that can help or harm real people. The chain that leads from mathematical models (for physical phenomena,



Jean Taylor and Barbara Keyfitz

engineering design, or professional decisions) to a commercial or societal outcome is long, and mathematicians, even in a business setting, often work close to the academic end of it.

Fields’ Commercial and Industrial Mathematics program is one attempt to bring both ends of the chain into view of each other. Our “Quantitative

Finance Seminar”, which has now been running for ten years, has achieved world-wide prominence. As well as serving as a conduit for the exchange of information, it has helped the financial world in Toronto to recruit stronger researchers and has helped those scientists to stay connected to research trends.

Our new Industrial Optimization Seminar plans to follow this model. This forum supports a variety of discipline based topics – aircraft design and the dynamics of energy markets were the subjects of two recent seminars – united by the property that they require the use of large-scale state-of-the-art optimization strategies. Mathematical techniques have the potential to contribute greatly to the development

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Leo Kadanoff *Makes a Splash*; Jean Taylor *Captures a Bubble*

“LIGHTING A FIRECRACKER” MIGHT BE A better metaphor for Leo Kadanoff’s Clay Math Institute public lecture. Kadanoff is a professor of Physics at the University of Chicago who has, among other honours, received the National Medal of Science from the President of the United States. He is participating in the Fall 2005 thematic program as a Clay Senior Scholar. On a rainy October evening a large crowd assembled to hear him speak on *Making a Splash; Breaking a Neck: The Development of Complexity in Physical Systems*. As one of the originators of the theory of universality, Leo Kadanoff

is uniquely qualified to talk about the emergence of complex behaviour and the development of complex patterns and dynamics.

The fundamental laws of physics can be written on “the top half of an ordinary piece of paper”, while the world about us, which we as scientists claim is derived from those laws, is “beyond the capacity of all of our libraries to describe”. The complicated smoke patterns of a candle flame, the mushroom-shaped plume of a nuclear explosion, the famous Edgerton milk-drop photograph, all illustrate

the dynamics of turbulence and its relation to the simple equations of fluid dynamics. A simple model, consisting of a dynamic game on a hexagonal lattice, in which pieces move following simple rules, produces an intricate pattern reminiscent of the evolution of turbulence from laminar flow. A number of other striking photographs defined what is meant by universality.

But the Master of Universality had a surprise: Kadanoff launched into a discussion of the scientific basis of “Intelligent Design”, the theory that

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