ESI **The Erwin Schrödinger International Institute for Mathematical Physics**

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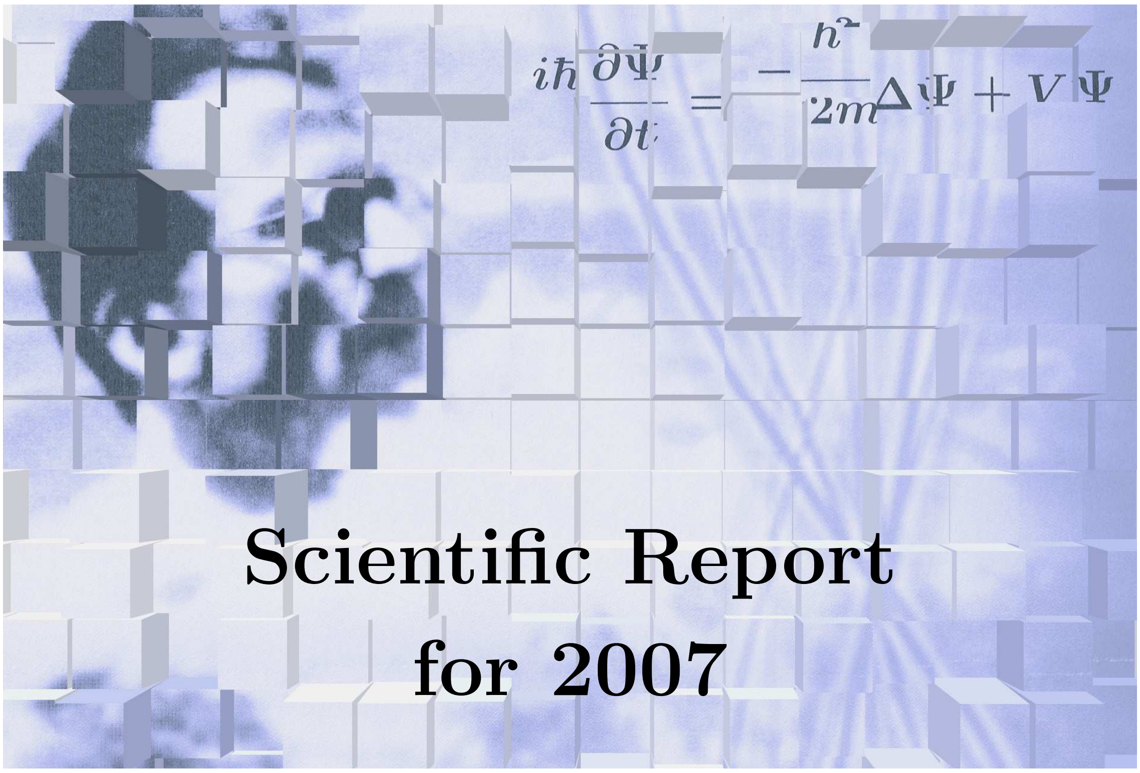

Scientific Report for 2007

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Contents

Preface

The scientific activities of the ESI in 2007 covered a wide range of topics, with major thematic programmes on *Mathematical and Physical Aspects of Perturbative Approaches to Quantum Field Theory* (R. Brunetti, K. Fredenhagen, D. Kreimer and J. Yngvason), *Amenability* (A. Erschler, V. Kaimanovich and K. Schmidt), *Poisson Sigma Models, Lie Algebroids, Deformations, and Higher Analogues* (H. Bursztyn, H. Grosse and T. Strobl) and *Applications of the Renormalization group* (H. Grosse, G. Gentile, G. Huisken, and V. Mastropietro). These programmes were accompanied and complemented by a host of smaller workshops and conferences on *Renormalization Theory*, *Automorphic Forms*, *Lieb-Robinson Bounds*, *Deterministic and Stochastic Dynamics*, *Arithmetic Groups*, *Spectral Theory* and many other topics.

The *ESI Junior Research Fellows Programme* (JRF-Programme) had officially come to an end in 2006 after three years of very successful operation. The total amount of funding for that programme was €450.000, of which about €50.000 were actually spent on Junior Research Fellowships ending during the first half of 2007. Although the extension of this programme for another three years (2007 – 2009) was confirmed only towards the end of 2007, the ESI decided to continue the JRF-Programme at full strength during 2007 in order to avoid uncertainty among potential applicants for Fellowships. Again the number and quality of applications was excellent, and many highly qualified applicants regretfully had to be turned down.

During 2007 the ESI-JRF Programme was augmented by several *instructional workshops* partly funded by outside sources (ESF, EU-Marie Curie Programmes and the Central European Joint Programme on Doctoral Studies in Theoretical Physics). The topics of these workshops included Amenability Beyond Groups (March 2007), *Algebraic, Geometric and Probabilistic Aspects of Amenability* (June-July 2007) and *Operator Algebras and Ergodic Theory* (December 2007), as well as two series of lectures by H. Grosse and J. Yngvason on *Quantum Field Theory* for the Central European Joint Programme on Doctoral Studies in Theoretical Physics.

As in previous years, the Junior Research Fellows Programme was complemented by the *Senior Research Fellows* (SRF) Programme of the Institute which is funded jointly by the Austrian Ministry for Science and Research and the University of Vienna and has the purpose of inviting senior scientists for extended periods of time to offer advanced lecture courses and longer-term scientific interaction with graduate students, post-docs, the local scientific community and the Institute's scientific programmes. The SRF programme is organized by Joachim Schwermer and is described in detail on p. 42ff.

There was an addition to the *International Scientific Advisory Committee* of the ESI in 2007: John Cardy (Oxford) kindly agreed to join the board from 2008.

There was also a change in the administration of the ESI in 2007. Irene Alozie left the ESI administration at the end of 2007, and the vacant position will be filled in early 2008. As has become tradition, I would like to thank the administrative staff — currently reduced to Isabella Miedl and Maria Windhager — for their friendly and efficient work and their good humour towards the visitors, research fellows and scientific staff of the Institute.

Klaus Schmidt February, 2008
President

General remarks

Management of the Institute

Honorary President: Walter Thirring
President: Klaus Schmidt
Directors: Joachim Schwermer and Jakob Yngvason
Administration: Isabella Miedl, Maria Windhager, Irene Alozie
Computers: Andreas Čap, Gerald Teschl, Hermann Schichl

International Scientific Advisory Committee

John Cardy (Oxford)
Edward Frenkel (Berkeley)
Harald Grosse (Vienna)
Giovanni Gallavotti (Roma)
Nigel Hitchin (Oxford)
Gerhard Huisken (Potsdam)
Antti Kupiainen (Helsinki)
Michael Struwe (ETH Zürich)

Budget and visitors: The budget of ESI for 2007 was € 845.000,– from the Austrian Federal Ministry of Science and Research (incl. € 100.000,– for the Senior Research Fellows Programme, € 55.000,– for the Junior Research Fellows Programme 2006) and € 22.000,– from the University of Vienna for the Senior Research Fellows Programme. € 554.614,59 were spent on scientific activities and € 384.480,54 on administration and infrastructure.

The number of scientists visiting the Erwin Schrödinger Institute in 2007 was 586, and the number of preprints was 101.

Scientific Reports

Main Research Programmes

Langlands Duality and Physics

Organizers: E. Frenkel (Berkeley), N. Hitchin (Oxford), J. Schwermer (Vienna), K. Vilonen (Northwestern University, Illinois)

Dates: January 9 – 20, 2007

Budget: ESI €12.240,78, DARPA: National Science Foundation, USA €2.805,–

Report on the programme

In January 2007, the Erwin-Schrödinger Institute hosted a program entitled "Langlands Duality and Physics", organized by Edward Frenkel (UC Berkeley, U.S.A.), Nigel Hitchin (U Oxford, UK), Joachim Schwermer (U Vienna, Austria), and Kari Vilonen (Northwestern U, U.S.A.). The workshop brought together leading experts in mathematics and physics as well as post-doctoral fellows from various countries. The main emphasis was put on some of the major developments of the past years in the relation between the geometric Langlands program (or correspondence) and conformal field theory.

It is one of the pillars of what is now known as the Langlands program that there exists a correspondence between the n-dimensional representations (i.e., into $GL_n(\mathbb{C})$) of the absolute Galois group $\mathcal{G}_k$ of a global field k and the automorphic representations of the general linear group $GL_n(\mathbb{A}_k)$ over the ring of adeles of k which preserves the L-functions attached to each of these objects. More generally, Langlands formulated in 1968 a correspondence between certain Galois representations and automorphic representations for any connected reductive algebraic group G. On the automorphic side one replaces $GL_n(\mathbb{A}_k)$ by $G(\mathbb{A}_k)$. On the Galois side, in view of the classification of representations of algebraic tori he had obtained, Langlands introduced his idea of a dual group, now known as the Langlands dual group or the L-group and to be denoted ${}^LG$, to play the role of $GL_n(\mathbb{C})$.

More precisely, given a reductive group G there is the complex dual group ${}^LG$, and the conjectures by Langlands predict natural correspondences between admissible homomorphisms of the Weil group W_k (a generalization of the absolute Galois group) into the dual group and automorphic representations of $G(\mathbb{A})$ and compatible local correspondences between admissible homomorphisms of W_{k_v} into the dual group and admissible representations of $G(k_v)$ where k_v denotes the local field associated to a place v of the field k. One can view this as an arithmetic parametrization of automorphic representations.

The principle of functoriality is interwoven with the Langlands program. This principle is associated to what is called an L-group homomorphism $\mu : {}^LH \to {}^LG$ between the L-groups attached to given reductive groups G and H. Whenever one has such a homomorphism, one should expect a strong relationship between automorphic representations of the two groups. This transfer of automorphic representations is encoded in the Langlands correspondence and mediated by an equality of Artin L-functions.

Already in 1988, Witten had observed that there is an analogy between some aspects of conformal field theory and the theory of automorphic representations. In particular, there should be a close relation between Langlands duality and S-duality in quantum field theory. As suggested it is based on a reduction of four-dimensional gauge theory to two dimensions and the analysis of D-branes under this reduction. Remarkably, the Langlands dual group appears in this physical context as the group introduced by P. Goddard et al. in the realm of gauge theories in 1977.

Based on Drinfeld's geometric approach to the Langlands program for GL_2 over a function field, that is, the field of functions on an algebraic curve over a finite field, Laumon among others suggested a geometric formulation for the Langlands correspondence for curves defined over an arbitrary field. It is this reformulation, to be called geometric Langlands program, which permits to make the connections to quantum field theory more precise.

Given a complex reductive Lie group G, coming along with its L-group ${}^LG$, the geometric Langlands correspondence relates Hecke eigensheaves on the moduli stack of G-bundles on a smooth projective algebraic curve X and holomorphic ${}^LG$-bundles with connection on X. When the connection has no singularities, that is, is unramified, this correspondence is quite well understood. Thus, the case where the connection has singularities at finitely many points of X formed a focal point for the workshop. Again, as in the unramified case, using D-modules which naturally appear in two-dimensional conformal field theory, one might be able to give an explicit construction of Hecke eigensheaves in this case as well.

One of the most exciting developments in this area in the last few years has been the works of E. Witten *et al* unifying the Langlands Program with the dualities in quantum field theory and string theory. Specifically, they have related the so-called S-duality of the four-dimensional gauge theory (discovered by the physicists P. Goddard, J. Nuyts and D. Olive in the 70's) to the geometric Langlands correspondence via the dimensional reduction from four to two dimensions.

More concretely, let X be a smooth projective curve over $\mathbb{C}$, and G a reductive Lie group over $\mathbb{C}$. Hitchin has defined the moduli space $\mathcal{M}_G = \mathcal{M}_G(X)$ of (stable) *Higgs bundles* on X. By definition, a Higgs bundle is a pair consisting of a principal G-bundle $\mathcal{P}$ on X and a one-form $\eta \in H^0(X, \mathfrak{g}_\mathcal{P} \otimes \Omega_X)$, where $\mathfrak{g}_\mathcal{P} = \mathcal{P} \underset{G}{\times} \mathfrak{g}$. The moduli space $\mathcal{M}_G$ actually has a Hyperkähler structure, and in a different complex structure it appears to be the moduli space of G-local systems on X. The key point of the work of Witten *et al* is the fact that $\mathcal{M}_G$ and $\mathcal{M}_{{}^LG}$ are *mirror dual* manifolds; that is, they are related by mirror symmetry. In fact, both moduli spaces fiber over the same vector space $\mathcal{H}$, and the generic fibers are dual tori (so these two fibrations give us an example of what physicists call "T-duality"):

$$\begin{array}{ccc} \mathcal{M}_{{}^LG} & & \mathcal{M}_G \\ & \searrow \quad \swarrow & \\ & \mathcal{H} & \end{array}$$

Mirror symmetry predicts that the category of "B-branes" on one mirror dual manifold (which we will choose to be $\mathcal{M}_{{}^LG}$) is equivalent to the category of "A-branes" on the other one (which will be $\mathcal{M}_G$ in our case). A B-brane on $\mathcal{M}_{{}^LG}$ is essentially a coherent sheaf on $\mathcal{M}_{{}^LG}$. Let us take, for example, the skyscraper sheaf supported at a point of $\mathcal{M}_{{}^LG}$, which we interpret as a ${}^LG$-local system E on X. This B-brane turns out to be an "eigenbrane" of the so-called Wilson operators. The dual A-brane A_E to this skyscraper sheaf should therefore be an eigenbrane of the so-called 't Hooft operators. Next, Witten *et al* give a recipe how to assign to this A-brane A_E a $\mathcal{D}$-module on $orthonormalBun_G$, the moduli space of G-bundles on X. Then the claim is that this $\mathcal{D}$-module will be the Hecke eigensheaf with "eigenvalue" E, whose existence is predicted by the geometric Langlands correspondence. This gives us an interpretation of the Langlands duality in terms of the mirror symmetry (or T-duality) of the Hitchin moduli spaces.

The goal of the programme was to discuss this new approach to the Langlands correspondence and related topics, from the perspective of both physics and mathematics.

The programme comprised the following three-lecture series:

Edward Frenkel: *Geometric Langlands programme and ramifications*

Oliver Biquard: *Non-abelian Hodge theory with ramifications*

Andrei Losev: *Gaussian model, T-duality and D-branes - elementary introduction for mathematicians*

Nigel Hitchin: *Moduli of Higgs bundles*

Anton Kapustin: *Gauge theory, mirror symmetry and the geometric Langlands programme*

Sergei Gukov: *Gauge theory, Langlands duality and ramifications*

There were many fruitful discussions across boundaries, and these led to some additional lectures of a more specialized nature. In particular, R. Bezrukanikov discussed some recent results regarding local questions in the geometric Langlands programme whereas Graeme Segal gave a talk in the realm of supersymmetry. David Ben-Zvi gave an introductory lecture in which he explained to a general audience the circle of problems the geometric Langlands programme addresses.

Invited scientists: Aliaa Barakat, David Ben-Zvi, Roman Bezrukavnikov, Olivier Biquard, Philip Boalch, Edward Frenkel, Harald Grosse, Sergei Gukov, Nigel Hitchin, Anton Kapustin, Maximilian Kreuzer, Andrei Losev, Ivan Mirkovic, Takuro Mochizuki, David Nadler, Thomas Nevins, Tony Pantev, Karl-Georg Schlesinger, Joachim Schwermer, Graeme Segal, Matthew Szczesny, Constantin Teleman, Michael Thaddeus, Kari Vilonen

Automorphic Forms, Geometry and Arithmetic

Organizers: S.S. Kudla (Toronto), M. Rapoport (Bonn), J. Schwermer (Vienna)

Dates: February 11 – 24, 2007

Budget: ESI €19,487.29

Preprints contributed: [1863], [1864], [1891], [1892], [1894], [1928], [1937], [1970], [2014]

Report on the programme

The programme "Automorphic Forms, Geometry and Arithmetic" was organized by S. S. Kudla (Toronto), M. Rapoport (Bonn), and J. Schwermer (Vienna). It was a reunion or follow up programme to the programme "Arithmetic Algebraic Geometry" held at the ESI from 2 January to 18 February of 2006, with an intensive workshop from 23–27 January.

The main emphasis in the original programme was put on the relation between algebraic cycles on Shimura varieties, automorphic forms and special values of L-functions, and p-adic methods. More specifically, the main scientific themes of the activity in 2006, were the following.

1. Generating series and special cycles on Shimura varieties. This lies at the intersection of automorphic forms and arithmetic geometry.

2. Langlands functoriality and L-functions. The main themes here were recent progress on Langlands functoriality conjecture, the local Langlands conjecture, and relations to Galois representations.

3. Interaction with p-adic methods. The main themes here were the p-adic Langlands correspondence, p-adic L-functions, p-adic Heegner points and Euler systems.

4. Residues of Eisenstein series. The main themes were the relation of residues of Eisenstein series to poles of L-functions, Eisenstein cohomology, CAP representations and CAP cohomology.

5. Trace formula and analytic approaches. The main themes here were the relative trace formula, periods of cusp forms and mass equidistribution.

6. Arakelov geometry. The main topic here was Hermitian bundles on arithmetic varieties. This brings us full circle since Arakelov geometry plays an important role in the work of Kudla and Rapoport on special cycles on Shimura varieties.

Besides the primary scientific aim of the original 2006 programme, one of the intents was to bring together in one location for an extended period of time researchers in arithmetic geometry and automorphic forms in the hopes of fostering communication if not collaboration. It would give the automorphic forms community the opportunity to explain to the arithmetic geometers the types of tools they have to offer as well as give the arithmetic geometers the opportunity to explain to the automorphic forms crowd the types of results they would like to have. Of course this created a certain creative tension and on the whole it was quite successful. There were extended conversations between mathematicians of different temperament and interests, that had never met each other in person, and these interactions have continued since the meeting. The reunion meeting in 2007 was much shorter, a mere two weeks, and it seems the two weeks were more homogeneous in terms of topics. This was probably more an indication of who could get free to come rather than any overt action on the part of the organizers. However, the themes listed above served as thematic guidelines for this workshop.

In the first week the emphasis was more on arithmetic geometric topics: an explicit construction of cycles on Shimura varieties of unitary type (work of Kudla and Rapoport), mod-p and p-adic questions, Galois representations. The speakers on these topics were Rapoport, Nekovar, and Wedhorn. Colmez presented his most recent results on the p-adic local Langlands correspondence for $GL(2, \mathbb{Q}_p)$, and Wintenberger surveyed his approach (jointly with Khare) to Serre's modularity conjecture.

The automorphic forms representation was also quite arithmetic with contributions by Henniart and Carayol, with more traditional topics related to Siegel modular varieties by Luo and Schmidt. The survey talk by Carayol on the recent work by Taylor, Harris among others on the Sato-Tate conjecture was a highlight of the workshop. Several talks were progress reports on projects reported on in the original meeting in 2006. The second week was mainly automorphic forms, with contributions by Badeleacu, Rohlfs, Harris, Raghuram, Wee-Teck Gan, Ullmo, Grbac, Harder, and Shahidi.

The programme itself was what one would hope for for such a meeting. There were progress reports on results that were described as "work in progress" at the 2006 meeting, which included the talks of Luo, Raghuram, and Shahidi. There were reports on new developments since the 2006 meeting; these included the two lectures on the proof and extension of the Sato-Tate conjecture by Carayol and Harris and the announcement by Rohlfs of a major new result on the unitary structure on the Hecke eigenspaces in the cohomology of arithmetically defined locally symmetric spaces. There were talks on results that seem to have grown out of the atmosphere of the last meeting, such as Harder's talk on p-ordinary cohomology of arithmetic groups. Finally there were some young participants that were not part of the original meeting but whose presence was welcome and whose talks were quite interesting. For example, Grbac reported on his results in describing the residual spectrum of Hermitian quaternionic classical groups. In addition to the quality of the talks, the participants were very pleased with the organization of the programme. Of course, all participants did not speak, but all took part in the general scientific discussions. There were an average of two lectures per day, both held in the afternoon. This left the mornings free for working with collaborators, discussions that grew out of the talks (and there were quite a few of these), and just general free floating discussions. Such discussions, particularly those related to the talks, can sometimes be a casualty of a more intense workshop.

Invited Scientists: Ioan Badulescu, Jean-Benoit Bost, Henri Carayol, James Cogdell, Pierre Colmez, Alberto Minguez Espallargas, Wee Teck Gan, Gerald Gotsbacher, Neven Grbac, Günter Harder, Michael Harris, Guy Henniart, Stephen S. Kudla, Klaus Künnemann, Erez Lapid, Wenzhi Luo, Goran Muic, Werner Müller, Jan Nekovar, Anantharam Raghuram, Michael Rapoport, Jürgen Rohlfs, Ralf Schmidt, Joachim Schwermer, Freydoon Shahidi, Ulrich Stuhler, Emmanuel Ullmo, Ognjen Vukadin, Christoph Waldner, Torsten Wedhorn, Jean-Pierre Wintenberger, Chia-Fu Yu.

Amenability

Organizers: A. Erschler (Lille), V. Kaimanovich (Bremen), K. Schmidt (Vienna)

Dates: February 26 – July 31, 2007

Budget: ESI €36,565.70, EU €49,432.18

Preprints contributed: [1915], [1920], [1924], [1930], [1931], [1940], [1968], [1978], [1986]

Report on the programme

The notion of *amenability* is a natural generalization of finiteness or compactness. It was introduced in 1929 by J. von Neumann (under the straightforward German name *Messbarkeit* later changed to the more appropriate *Mittelbarkeit*, cf. the French *moyennabilité*; in 1955 M. M. Day first called it amenability). *Amenable groups* are those which admit an *invariant mean* (rather than an invariant probability measure, which is the case for finite or compact groups).

Actually, the history of the subject goes back to H. Lebesgue who asked in 1904 whether or not a positive, finitely (but not countably!) additive, translation-invariant locally finite measure different from the standard Lebesgue measure exists on the real line. Later, a fundamental question of F. Hausdorff led to a general study of isometry invariant measures and the well-known Banach–Tarski–Hausdorff paradox. J. von Neumann showed that the dichotomy in this paradox resides in the different properties of the corresponding isometry groups.

Nowadays there are numerous (equivalent) characterizations of amenable groups. The constructive *Reiter condition* (existence of approximately invariant sequences of probability measures on the group) is often used for verifying amenability (for instance, for the group of integers such a sequence is provided by the usual Cesaro averages). On the other hand, the most important application of amenability comes from its characterization by the *fixed point property* for affine actions of amenable groups on compact spaces (once again, for the integers this amounts to the Bogolyubov–Kryloff theorem on existence of invariant measures for homeomorphisms of compact sets). Other definitions of amenability can be given in isoperimetric terms (Følner sets), in terms of the representation theory (the weak containment property), in spectral terms (Kesten's spectral gap theorem), etc., etc.

The classical notion of an amenable group has been generalized in many directions and currently plays an important (and sometimes crucial) role in many areas, such as dynamical systems, von Neumann and C^*-algebras, operator K-theory, geometric group theory, rigidity theory, random walks, etc.

For instance, R. Zimmer was the first to notice that certain actions of non-amenable groups behave as if these groups were amenable, which in the late 70's led him to the notion of amenability for group actions, equivalence relations and foliations. Simultaneously R. Bowen and A. Vershik came up with the first examples of hyperfinite orbit equivalence relations for actions of non-amenable groups. Following Zimmer's work, A. Connes, J. Feldman and B. Weiss proved the equivalence of amenability and hyperfiniteness for discrete equivalence relations. Actually, groups, group actions, equivalence relations and foliations can all be treated in a unified way by using the notion of an *amenable groupoid* introduced by J. Renault.

Amenable groupoids (in particular, those associated with boundary actions) have been at the center of the recent developments in the theory of operator algebras. For example, if a locally compact group admits an amenable action on a compact space, then its reduced C^*-algebra is exact. The question of whether or not every locally compact group admits such an action was settled negatively with a counterexample by M. Gromov. A recent theorem of N. Higson and G. Kasparov for groups, and its generalization to groupoids by J. L. Tu, show that amenable groups and groupoids satisfy the Baum–Connes conjecture, which led to a proof by N. Higson of the Novikov conjecture for any locally compact group (more generally, any locally compact groupoid) that admits an amenable action on a compact space.

These developments were the subject of several monographs (let alone numerous survey articles) on various aspects of amenability: F. P. Greenleaf, *Invariant means on topological groups and their applications* (1969), J.-P. Pier, *Amenable locally compact groups* (1984), A. L. T. Paterson, *Amenability* (1988), C. Anantharaman-Delaroche and J. Renault, *Amenable groupoids* (2000), V. Runde, *Lectures on amenability* (2002).

However, certain very basic questions about amenability are still very much open, one of the well-known examples being the question about the amenability of the Thompson group.

It would be impossible to cover all the subjects connected with the notion of amenability within the framework of a single programme. Instead, the organizers concentrated on several interconnected research areas at the crossroads of Analysis, Algebra, Geometry and Probability:

- amenability of self-similar groups; relation with conformal dynamics for iterated monodromy groups of rational maps; non-elementary amenable groups (Bartholdi, Grigorchuk, Nekrashevych, Virag, Zuk);
- graphed equivalence relations and amenability; cost of equivalence relations; L^2 cohomology (Gaboriau, Kechris, Furman);
- amenable groupoids; topological amenability of boundary actions; amenability at infinity; Baum–Connes and Novikov conjectures (Higson, Kasparov, Roe);
- amenability and rigidity; bounded cohomology (Burger, Monod, Shalom);
- quasi-isometric classification of amenable groups, in particular, of nilpotent and solvable ones; geometricity of various group properties (Eskin, Farb, Mosher, Shalom);
- Dixmier's conjecture on characterization of amenability in terms of unitarizable representations (Pisier);
- generalizations of amenability: A-T-menabilty (property of Haagerup); groups without free subgroups; superamenability (Olshansky, Pestov, Sapir);
- quantitative invariants of amenable groups: growth, isoperimetry, return probability, asymptotic entropy of random walks, etc. (Grigorchuk, Saloff-Coste, Pittet, Vershik, Ledrappier);
- characterization of amenable groups and graphs in terms of percolation (Benjamini, Nagnibeda, Pak, Schramm).

During the programme there were two periods of special activity: *Amenability beyond groups*, February 26 – March 17, 2007 and *Algebraic, geometric and probabilistic aspects of amenability*, June 18 – July 14, 2007.

Amenability beyond groups

During this period of activity the following 5 mini-courses (5 hours each) were held.

Vadim Kaimanovich (Bremen): *Amenability of algebraic structures from groups to groupoids.*

This introductory course was aimed at giving general background concerning the notion of amenability. It began with the classic definition of amenable groups due to von Neumann followed by a discussion of equivalent definitions (fixed point property, Følner sets, Reiter condition) as well as their generalizations to other algebraic structures (group actions, equivalence relations, pseudogroups and, finally, groupoids).

Gabor Elek (Budapest): *Amenability in ring theory.*

Amenability of algebras over a given field can be defined in the same fashion as amenability of discrete groups (M. Gromov, *Topological Invariants of Dynamical Systems and Spaces of Holomorphic Maps, I,* Math. Phys. Anal. Geom. **2** (1999) 323-415). These lectures reviewed the basic definitions and surveyed some recent results regarding amenable affine algebras, amenable skewfields, amenable group algebras, the rank function as well as von Neumann's continuous rank algebras and their applications.

Alain Valette (Neuchâtel): *Affine isometric actions on Hilbert spaces and amenability.*

These lectures were centered around the notion of affine isometric actions on Hilbert spaces (together with the relevant mild cohomological formalism) and discussed several results in amenability

Claire Anantharaman-Delaroche (Orléans): *Amenability and exactness for group actions and operator algebras.*

In these lectures the operator algebras associated with groups and group actions were introduced. The interactions between amenability properties of groups and group actions and amenability properties of the corresponding operator algebras were also discussed. The focus was on boundary amenability and exactness.

Masaki Izumi (Kyoto): *Non-commutative Poisson boundaries.*

It is well-known that the structure of the Poisson boundary of a group is very much related to amenability (or non-amenability) of the group. In recent works, a non-commutative version of the Poisson boundary, defined for von Neumann algebras, turned out to be very useful in operator algebras. A survey of this development was given.

It is planned to publish the lecture notes of these mini-courses in the ESI lecture notes series.

Algebraic, geometric and probabilistic aspects of amenability

During this period of activity there were 4 mini-courses (5 hours each):

Alekos Kechris (Caltech): *Extreme amenability: some new interactions between combinatorics, logic and topological dynamics.*

This minicourse provided an introduction to the property of extreme amenability (or fixed point on compacta property) of topological groups, which arises in the context of topological dynamics and is related to asymptotic geometric analysis, especially concentration of measure phenomena, and described its connections with ideas from finite combinatorics, particularly Ramsey theory, and logic.

Nicolas Monod (Geneva): *Some topics on amenable actions.*

In this series of lectures some aspects of the classical question of the existence of invariant means on a set under a group action were studied. Monod restricted himself to the “naked” setting where no topology or measure-theory is involved. On the one hand Mondod addressed classical results, giving for instance a short proof of Tarski’s theorem on paradoxical decompositions. On the other hand, he presented a few new aspects that have been historically overlooked, regarding e.g. amenable actions of non-amenable groups. He also presented a few problems that are simple to formulate but appear to be unsolved.

Dave Witte Morris (Lethbridge): *Some discrete groups that cannot act on 1-dimensional manifolds.*

It is easy to give an algebraic characterization of the amenable groups that have a nontrivial action on the real line. The course discussed relations between amenability, the Furstenberg boundary, and actions of lattices on 1-dimensional manifolds (or other spaces).

Volodymir Nekrashevych (Texas A&M): *Contracting self-similar groups.*

Contracting self-similar groups appear naturally as iterated monodromy groups of expanding self-coverings of orbispaces. They include many examples of non-elementary amenable groups. An open question is if they all are amenable. The speaker discussed relations of contracting groups to dynamical systems and their properties related to amenability (growth, absence of free subgroups, amenability of the associated groupoids of germs, etc.).

Invited scientists: Jon Aaronson, Samy Abbes, Aurelien Alvarez, Claire Anantharaman-Delaroche, Gastao Bettencourt, Andrzej Bis, Dietmar Bisch, Theo Bühler, Dariusz Buraczewski, Jan Cameron, Michel Coornaert, Ewa Damek, Emilie David-Guillou, Pierre de la Harpe, Gabor Elek, Anna Erschler, Alex Eskin, Jacob Feldman, Thierry Giordano, Mikhail Gordin, Evgeny Goryachko, Rostislav Grigorchuk, Yves Guivarch, Uli Haböck, Andrzej Hulanicki, Wilfried Huss, Masaki Izumi, Pierre Julg, Vadim Kaimanovich, Alexander Kechris, Iva Kozakova, Fabrice Krieger, Bernhard Krön, Maria Kuhn, Olga Kulikova, Yves Lacroix, Francois Ledrappier, Franz Lehner, Malgorzata Letachowicz, Douglas Lind, Andrei Lodkin, Keivan Mallahi-Karai, Andrey Malyutin, Maria Milentyeva, Mariusz Mirek, Michail Monastyrsky, Nicolas Monod, Soyoung Moon, Sebastien Moriceau, Dave Morris, Hitoshi Nakada, Volodymir Nekrashevych, Piotr Nowak, Denis Osin, Athanase Papadopoulos, Dmitry Pavlov, Rodrigo Perez, Mattia Perrone, Gilles Pisier, Christophe Pittet, Olga Pochinka, Mark Pollicott, Gerhard Racher, Jean Renault, Mark Sapir, Ecaterina Sava, Gregory Shapiro, Richard Sharp, Tatiana Smirnova-Nagnibeda, Florian Sobieczky, Piotr Soltan, Elmar Teufl, George Tomanov, Todor Tsankov, Roman Urban, Alain Valette, Evgeny Verbitskiy, Anatoly Vershik, Dan-Virgil Voiculescu, Benjamin Weiss, Rufus Willett, George Willis, Wolfgang Woess, Taoyang Wu, Phillip Yam, Andrzej Zuk

Mathematical and Physical Aspects of Perturbative Approaches to Quantum Field Theory

Organizers: R. Brunetti (Trento), K. Fredenhagen (Hamburg), D. Kreimer (Paris), J. Yngvason (Vienna)

Dates: March 1 – April 30, 2007

Budget: ESI €38.754,53

Preprints contributed: [1902], [1903], [1907], [1923], [1936]

Report on the programme

Quantum Field Theory aims at a unifying description of nature on the basis of the principles of quantum physics and field theory. Its main success is the development of a standard model for the theory of elementary particles which describes physics between the atomic scale and the highest energies which can be reached in present experiments. It has, however, turned out to be also very important in other branches of physics, in particular for solid state physics. Its mathematical complexity is enormous and has induced many new developments in pure mathematics. In its original formulation it was plagued by divergences whose removal by renormalization lead to fantastically precise predictions which could be verified experimentally.

A full construction of quantum field theories was possible up to now only for unphysical models. For realistic models one still has to rely on uncontrollable approximations among which perturbation theory, which constructs the models as formal power series in the coupling constants, is the most important one.

Perturbation theory in quantum field theory has been developed as a rigorous mathematical framework in the fifties-sixties thanks to the work of Hepp, Lehmann, Symanzik, Zimmermann, Steinmann, Epstein, Glaser, Bogoliubov, Stückelberg and several others. These authors found a mathematically consistent method to construct the perturbation series of quantum field theory at all orders, thereby making mathematical sense of the recipes for renormalizations suggested before.

More recently, there has been renewed interest in the foundations of perturbation theory. Two independent directions were traced. The first took place around 1996, due to Brunetti and Fredenhagen, and was centered around the problem of constructing quantum field theories on curved spacetimes, and the other started around the end of the nineties and is due to Connes and Kreimer and deals with structural insights into the combinatorics of Feynman graphs via Hopf algebras. In both cases there arise direct connections to the application of quantum field theory to physics problems. The two settings gave a lot of striking results and applications that were unforeseen before. In particular, new aspects of the renormalization group were uncovered.

The programme was designed to bring together the most important experts of the field. In particular it was a crucial motivation to emphasize the connection between the groups working in different directions, as in the Epstein-Glaser and in the Hopf-algebraic cases. In the following these topics are briefly reviewed.

A peak of the activities was reached during the workshop "New Development in Perturbative Quantum Field Theory," March 26-30, the full program of which is available on the web page

http://www.thp.univie.ac.at/ESI/workshop_schedule.html

The main topics discussed during the programme were

- Hopf algebras and renormalization.

- Epstein-Glaser perturbative approach.
- Renormalization group approaches.

In the following we resume the highlights of the various topics:

1. **Hopf algebras and renormalization**

   An important progress in the connection to mathematics has been obtained recently by Connes and Kreimer. Their idea of using Hopf algebras in perturbation theory has led to a mathematical understanding of the forest formula in momentum space. Kreimer's original insight originated from a study of number-theoretic properties of Feynman integrals and related the amplitudes term by term in the perturbative expansion to polylogarithms and motivic theory as well as, ultimately, to arithmetic geometry.

   It turns out that Feynman graphs carry a pre-Lie algebra structure in a natural manner. Antisymmetrizing this pre-Lie algebra delivers a Lie algebra, which provides a universal enveloping algebra whose dual is a graded commutative Hopf algebra. It has a recursive coproduct which agrees with the Bogoliubov recursion in renormalization theory. This provides a mathematical framework for perturbation theory involving Feynman integrals in momentum space and also suggests to incorporate some notions of perturbative quantum field theory into mathematics.

   Indeed, very similar Hopf algebras have emerged in mathematics in the study of motivic theory and the polylogarithm through the works of Spencer Bloch, Pierre Deligne, Sasha Goncharov and Don Zagier. The hope is that a link can be established between number theory and quantum field theory in studying the relevant Hopf algebras and their relation in detail.

   A major problem here is the understanding of the quantum equations of motion, which are governed by the closed Hochschild one-cocycles of the Hopf algebra.

   This Hochschild cohomology of perturbation theory illuminates the role of locality in momentum and coordinate space approaches. At the same time, it provides a crucial input into the function theory of the polylog, and certainly into a yet to be developed function theory of quantum field theory amplitudes. Extensions of these ideas to gauge theories are under active investigation and the connection to motivic theory have been considered by Kreimer and Spencer Bloch. At the same time, Connes and Marcolli have incorporated the techniques of arithmetic geometry into quantum field theories, which utilize again the underlying Hopf structure in the context of Tannakian categories, intimately connected again to the theory of the polylogarithm.

   During the programme several talks were delivered by many of the best researchers of this field, ranging from introductions to the main structures to rather advanced mathematical connections to motives.

2. **Epstein-Glaser perturbative approach**.

   Another important direction of recent research has been put forward by Brunetti and Fredenhagen and refined by Hollands and Wald in a series of papers. The local point of view is emphasized and allows a description of perturbation theory on any background spacetime. Basic to this approach is the connection with the field of microlocal analysis pioneered by Radzikowski. These methods allowed the cited authors to prove for the first time, that up to possible additional invariant terms of the metric, the classification of renormalization in a general spacetime follows the same rules as that on Minkowski spacetime. Actually the theory suggests further possibilities, the most important of which is a conceptually new approach to quantum gravity, at least in the perturbative sense. Another direction is that taken by Dütsch and Rehren for perturbation theory on AdS and connections with the quantum field theory perspectives on holography.

Also in this field many researchers joined the programme including the pioneer of the approach, Prof. Henri Epstein.

3. **Renormalization group approaches**

   Renormalization group ideas seem to be crucial in both approaches. Other groups have pioneered different ideas, for instance by making rigorous the work of Polchinski and Wilson. However, a connection between all these seemingly different perspectives is lacking and an important issue would be a comparison and attempt to find a possible unification. A first step in this direction was done by T. Krajewski and collaborators. He showed how to use tree-like expansions and the universal Hopf algebra of rooted trees to reformulate the Wilson-Polchinski approach. In the local approach this connection has been investigated by Brunetti, Dütsch and Fredenhagen.

   Many participants from different sides of the field were present, among them Salmhofer and Müller on the side of Polchinski's Flow Equation, and Falco on the methods that were pioneered by Gallavotti.

A large number of discussion rounds and seminars complemented the activities. We may safely say that the programme was quite successful and we wish to express our gratitude to the staff of ESI for the precious collaboration.

Invited Scientists: Christoph Bergbauer, Hans-Jürgen Borchers, David Broadhurst, Francis Brown, Jacques Bros, Romeo Brunetti, Claudio D'Antoni, Michael Duetsch, Kurusch Ebrahimi-Fard, Henry Epstein, Bertfried Fauser, Christopher Fewster, Klaus Fredenhagen, Herbert Gangl, Hanno Gottschalk, John Gracey, Dan Grigore, Riccardo Guida, Fumio Hiroshima, Stefan Hollands, Diana Kaminski, Christoph Kopper, Dirk Kreimer, Gregor Leiler, Martin Lippl, Pjotr Marecky, Gerardo Morsella, Volkhard Müller, Heiner Olbermann, Gherardo Piacitelli, Nicola Pinamonti, Karl-Henning Rehren, Abhijnan Fej, John Roberts, Giuseppe Ruzzi, Manfred Salmhofer, Günther Scharf, Klaus Sibold, Stanislav Stepin, Adrian Tanasa, Ivan Todorov, Walter van Suijlekom, Rainer Verch, Fabien Vignes-Tourneret, Stefan Weinzierl, Eberhard Zeidler

Poisson Sigma Models, Lie Algebroids, Deformations and Higher Analogues

Organizers: H. Bursztyn (Rio de Janeiro), H. Grosse (Vienna), T. Strobl (Lyon)

Dates: August 1 – September 20, 2007

Budget: ESI € 75.632,65, ESF/MISGAM € 5.000,–

Preprints contributed: [1944], [1954], [1955], [1956], [1957], [1958], [1962], [1972], [1973], [1975], [1976], [2003], [2005], [2008]

Report on the programme

There are two major mathematical results related to the Poisson sigma model (PSM): On the one hand, Kontsevich's famous explicit formula for the deformation quantization of Poisson manifolds was obtained by a perturbative path integral quantization of the PSM, as made transparent thereafter by Cattaneo-Felder. On the other hand, the reduced classical phase space of the model is closely related to the integration problem of Lie algebroids to Lie groupoids, solved in the fundamental work of Crainic-Fernandes.

The PSM has also been used in the context of theoretical physics. In fact, this sigma model was introduced by Ikeda and Schaller-Strobl in order to recast several two-dimensional (super)gravity Yang-Mills theories into a common concise framework. It is also a generalization of several 2d topological string theories. It has led to many generalizations, including to higher dimensions, resulting in new topological sigma models, as well as attempts for generalizations of physical Yang-Mills theories to the world of algebroids and nonabelian gerbes.

A recent variation of the ideas in Poisson geometry known as "generalized geometry", also treated in the programme, unifies mathematical and physical ideas in a similar way. Just as Dirac geometry places Poisson and presymplectic structures into a common setting, Hitchin's generalized complex geometry unifies symplectic and complex geometries. On top of opening many new possibilities of generalizations of results known in one of the two corners of this new field, it also relates to theoretical physics and sigma models; in fact, as first noted by Lindstrom-Minasian-Tomasiello-Zabzine and elaborated in several subsequent papers, having a second supersymmetry in 2d sigma models requires geometrical data that become most transparent in the language of generalized geometry. Under some conditions the existence of the second supersymmetry is equivalent to a generalized complex structure in the target.

The programme brought together leading experts in mathematics and theoretical physics on the interface of the above topics. Following a tradition of ESI, a particular emphasis was put on supporting researchers from Eastern European countries. In addition, the programme also attracted a large amount of younger researchers.

Special minicourses helped to structure the programme into different subtopics, permitting participants with different backgrounds to get acquainted with the latest status of a particular subject. Additional specialized "extended lectures" served a similar purpose; standard one hour talks completed an important part of the daily interaction at the institute, which often led to lively discussions on the many blackboards available. The minicourses also attracted several local people. One of the programs highlights was the workshop "Poisson geometry and sigma models", coorganized with A. Alekseev and partially supported by MISGAM and Bank Austria. It took place after about the first half of the programme and regularly filled ESIs main lecture hall to more than the available number of seats.

In what follows, we list the main topics of the programme, all of which were introduced in the minicourses, describing their content in some more detail thereafter (for some complementary information cf. also http://w3.impa.br/∼ henrique/esi.html):

1. BV-, AKSZ-, super formalism
2. Deformation theory
3. Lie (n-)algebroids, Lie (n-)groupoids, and Poisson geometry
4. Low dimensional and supersymmetric topological sigma models
5. Generalized complex geometry

ad 1. and 2. M. Henneaux's minicourse gave an introduction to the physical aspect of the BV formalism. On the classical level it is tailored to encode the gauge symmetry and the related redundancy of field equations of a general Lagrangian theory. It is the formalism that is needed for a path integral quantization if the theory has open algebra symmetries (i.e. if there are no representatives of symmetry generators which are non-vanishing on the space of solutions and which form a Lie algebra already by themselves). It is also a concise framework for studying possible deformations of known gauge theories to retrieve more intricate new ones: non-trivial deformations up to field redefintions as well as obstructions in deformations are related to BV-cohomology in the space of local functionals at ghost number zero and one, respectively.

This aspect of deformation of action functionals was illustrated e.g. by talks of N. Ikeda, showing how this leads to the Courant sigma model starting from Chern-Simons and BF theories in three dimensions, and by S.-O. Saliu, who constructed in this way a generalization of the Freedman-Townsend model in four dimensions.

The AKSZ-formalism derives a BV formulation of topological sigma models without the need of undergoing the usual procedure of analysis of gauge symmetries. In the simplest, lowest dimensional case, it produces the Poisson sigma model, as recalled e.g. in the minicourse of M. Zabzine. Using this formalism, D. Roytenberg showed how to obtain the Courant sigma model directly from an appropriate superformulation of Courant algebroids, namely as degree two symplectic Q-manifolds (a Q-manifold is a graded or super manifold with a homological degree one vector field). In this sense, the Courant sigma model represents the first "higher analogue" of the Poisson sigma model.

L. Lyakhovich and A. Sharapov, on the other hand, adapted the standard BV formalism, on the quantum as well as on the classical level, so as to incorporate gauge theories that are *not* governed by a Lagrangian. The first step in this context is to permit a different number of gauge symmetries and dependencies of the field equations. Although this formalism includes non-Lagrangian, non-topological theories in any dimension d, they permit an AKSZ-type action functional in $d+1$ dimensions. In another talk they provided characteristic classes of Q-manifolds. Related talks in this context were the one of P. Bressler, describing a generalization of the Pontryagin class as well as the one of A. Kotov, who talked about characteristic classes associated to Q-bundles. In this context, Pontryagin or Chern classes arise as particular cases, and the general AKSZ-topological model is found to be a transgression of the construction for QP-bundles with symplectic Q-fibers. Kotov illustrated this in particular for the Poisson sigma model, which corresponds to a deRham 3-form class obstructing some lift to a covering bundle of a given Q-bundle with symplectic fiber of degree one.

J.S. Park gave an extended lecture on more mathematical aspects of the BV formalism. He provided a set of algebraic axioms on an algebra over a formal parameter $\hbar$, from which one retrieves the usual classical BV formalism in an appropriate $\hbar \to 0$ limit. He showed how the standard gauge fixed BRST formulation is related to this formulation and pinpointed the obstructions for extending all classical observables to quantum ones. He finally showed that in the absence of obstructions the problem of defining an algebra structure for the quantum BV observables suggests naturally a deformation of the quantum action in directions related to operator products.

Further related talks on BV were given by G. Barnich, K. Bering, M. Grigoriev and F. Schaetz, proposing modifications and relating the formalism in several ways to mathematical or physical problems; this included the deformation problem of coisotropic submanifolds of Poisson manifolds, the quantization of higher spin gauge theories, and the thermodynamics of black hole dyons.

ad 2. There were also other complementary activities focusing on deformation than those mentioned already above, in particular in the context of deformation quantization.

S. Merkulov's minicourse used operads to provide an alternative formulation of the problem of deformation quantization. Although there is still a missing step in reobtaining Kontsevich's result in this alternative systematic manner, there are also applications, like the quantization of Lie bialgebras, where the formalism has been successfully applied. An important observation made possible by the programme was that many of the mathematical results of Merkulov in that context have a clear counterpart in the more physically oriented work of Lyakhovich and Sharapov.

Other related talks extended ideas of deformation quantization to the case of orbifolds (talks by G. Halbout and X. Tang)—relating it to ideas from noncommuative geometry—or other singular symplectic quotients (H.-C. Herbig) and to the world of quasi-Poisson geometry (G. Halbout). N. Neumeier presented a generalization of the Fedosov star product of cotangent bundles to the case of fiber-linear Poisson brackets defined on a vector bundle, as they correspond to a general Lie algebroid. E. Hawkins related deformation quantization to the question of choices of a polarization as it usually appears in the context of the geometric quantization scheme. Quantization formulas in the context of Lie algebras were applied to the problem of quantizing Wilson loops in WZW sigma models by S. Monnier. B. Tsygan, finally, discussed notions of module in deformation quantization and presented ideas that could lead to a "microlocal" approach to the Fukaya category.

ad 3. In his minicourse R. Fernandes recalled the notions of Lie groupoids and their relation to Lie algebroids, with important examples coming e.g. from Poisson manifolds, where in the integrable case the respective groupoids are symplectic. He stressed the notion of proper groupoids, where the source and target maps are required to be proper, as the "correct" generalization of compactness to which it reduces in the special case of Lie groups. In this case one can prove e.g. triviality of groupoid cohomology, or, assuming connectedness of source fibers, stability of fixed points. Fernandes also showed that symplectic groupoids are an important tool in the study of group actions on Poisson manifolds. A group action by Poisson diffeomorphisms on an integrable Poisson manifold can be lifted to its symplectic groupoid, and this lifted action carries a canonical moment map, which allows to prove that "integration commutes with reduction"; this result includes singular reductions in the context of stratified spaces.

Related to the above, M. Crainic presented a cohomological criterion for the stability of (compact) symplectic leaves in Poisson manifolds. The criterion (the vanishing of a certain degree-2 cohomology group) is closely tied with other classical stability results in geometry, including the stability of leaves in regular foliations and of orbits of group actions. This stability result is believed to be a key step towards a *geometric* proof of Connes' linearization theorems, which is one of the outstanding open problems in the field.

Higher analogues of Lie groupoids and algebroids were discussed e.g. by J. Baez, U. Schreiber, A. Kotov, and D. Roytenberg, relating them in part to the issue of constructing gauge theories for higher form degree gauge fields. In the latter context one considers a generalization of gauge theory that describes the parallel transport not just of particles, but also strings or higher-dimensional branes. Using categorification of mathematical structures (Baez, Schreiber), this leads to the notions of "principal 2-bundles" with a given "structure 2-group", for example. A complementary useful tool in the description and construction of "higher gauge theories" and corresponding structures are Q-manifolds and Q-bundles (Kotov, cf. also issue 1 above). D. Roytenberg analysed weak Lie 2-algebras to some depth in this context, exploring their connections with other structures "up to homotopy" and putting the established connection between Courant algebroids and $L_\infty-$algebras in a broader framework.

A. Vaintrob stressed the usefulness of the concept of Q-manifolds in the context of Lie/Courant algebroid and Dirac geometry. T. Voronov demonstrated that double Lie algebroids, as they were defined by Mackenzie, also have a much simpler description using this language, here with two commuting Q-structures, using a bi-grading coming from a double vector bundle.

A. Morozov showed how A-infinity structures on simplicial complexes can be reconciled with locality, as mandatory for some physical applications. B. Uribe and M. Zambon discussed group actions and reduction for exact Courant algebroids. Also in this case the superlanguage seemed a promising alternative, the corresponding reformulation of which is work in progress.

ad 4. and 5. C. Lazaroiu gave several talks surveying the status of topological open/closed string theories, leading to a set of axioms of a particular modular functor. The topological A and B models appear as particular examples of this construction. M. Zabzine gave a minicourse focusing more on the construction of low dimensional topological sigma models. He showed that the

Hamiltonian formulation is particularly well suited for some generic features of such models. In this context he explained the relation of symmetry algebras of two-dimensional sigma models to Courant algebroids living over the target manifold and how the choice of a Dirac structure therein leads to the A-, the B-, or the Poisson sigma model. Supersymmetrization of the Hamiltonian considerations relate supersymmetric sigma models to generalized complex structures (cf. also below). He then shows that for the Poisson sigma model the space of quantum observables does not seem to agree with the one of classical ones—an agreement usually assumed in the context of BV-quantization. Zabzine pointed out, moreover, that the non-perturbative quantization of the Poisson sigma model on a sphere forces the target Poisson manifold to be unimodular, a condition absent in Kontsevich's deformation quantization (following a perturbative treatment of the PSM), but related to the geometric (pre)quantization of the target.

G. Calvacanti recalled in his course on generalized complex geometry several equivalent notions and stressed in particular the usefulness of the one via pure spinors. He also showed how bi-Hermitian geometry, as introduced long before in the context of supersymmetric sigma models, fits into generalized Kähler. This presentation was nicely complemented on the sigma model side by a minicourse of U. Lindstrom and a lecture of M. Rocek. R. von Unge addressed the problem of finding a function (the generalized Kähler potential) encapsulating all the data about the metric and antisymmetric B-field defining a generalized Kähler structure.

Different topological sigma models relating to generalized complex structures were presented by N. Ikeda, V. Pestun and R. Zucchini. Ikeda related the dimensional reduction of the Courant sigma model to generalized complex geometry. Using the AKSZ-formalism, Pestun presented a generalization of the A- and B-model defined for any generalized complex structure. In fact, ideas of topological sigma models and deformations described by them suggest how to further generalize "generalized geometry", something that was then taken up and discussed during the workshop by A. Gerasimov, V. Pestun and V. Roubtsov. Zucchini provided several action functionals, one of which related also to the reduction of Courant algebroids mentioned above.

Possible applications of Courant sigma models were discussed by A. Cattaneo, including the integration of bialgebroids and the construction of double symplectic groupoids. The quantization of bialgebras from this perspective leads to an interesting proposal on the relation between deformation quantization and quantum groups, to be further explored. A potentially promising direction for further applications to topological field theories was provided by P. Mnev, who introduced a discrete BF-theory on manifolds of various dimensions, where the set of data of a continuous topological field theory are reduced to a combinatorial one in a first step.

A. Kotov gave a useful description of Dirac structures using an auxiliary metric. He then defined a topological sigma model for any given Dirac structure, which generalizes the Poisson sigma model and the completely gauged WZW model. K. Gawedzki addressed the issue of defining such models for unoriented worldsheet manifolds. Studying the problem for WZW models, one is led to consider gerbes in the case of non simply connected target group manifolds. An interesting direction to be pursued concerns the extension of this discussion to the context of Dirac sigma models with nontrivial Severa class.

On the purely mathematical side, M. Gualtieri focused on generalized complex geometry in dimension four. He discussed a surgery procedure which leads to the construction of a 4-manifold admitting neither symplectic nor complex structures but yet a generalized complex one. F. Wit spoke about generalized G2-manifolds, generalizing Riemannian manifolds with G2-holonomy group in a direction motivated by mathematical physics that parallels Hitchin's generalized geometry in this setting.

Many new collaborations and projects were initiated at the ESI programme, only partially finished ones brought into a final state (cf. also the above list of preprints), and presented work that had been completed already before was discussed from various new perspectives. People from different areas were brought together, which complemented one another in a positive sense, as may become transparent also from links between the different subjects mentioned in the short description above. All this would not have been possible without the program, which we believe found a very positive echo in the community.

Invited Scientists: Anton Alekseev, Sergey Arkhipov, Paolo Aschieri, John Baez, Glenn Barnich, Laurent Banlieu, Klaus Bering, Constantin Bizdadea, Christian Blohmann, Martin Bojowald, Francesco Bonechi, Martin Bordemann, Nicolas Bovetto, Friedemann Brandt, Paul Bressler, Henrique Bursztyn, Alberto Cattaneo, Gil Cavalcanti, Eugene Cioroianu, Marius Crainic, Joel Ekstrand, Fernando Falceto, Rui Loja Fernandes, Andrea Ferrario, Krysztof Gawedzki, Anton Gerasimov, Pascal Grange, Janusz Grabowski, Johan Granaker, Maxim Grigoriev, Harald Grosse, Daniel Grumiller, Marco Gualtieri, Simone Gutt, Sebastian Guttenberg, Markus Hansen, Gilles Halbout, Eli Hawkins, Marc Henneaux, Chris Hull, David Iglesias-Ponte, Noriaki Ikeda, Sergey Ketov, Takashi Kimura, Ctirad Klimcik, Yvette Kosmann-Schwarzbach, Peggy Kao, Alexei Kotov, Olga Kravchenko, Libor Krizka, Svatopluk Krysl, Calin Lazaroiu, Peter Lee, Ulf Lindstrom, Simon Lyakhovich, Franco Magri, Fedor Malikov, Sergei Merkulov, Christoph Maier, Rene Meyer, Peter Michor, Jouko Mickelsson, Eva Miranda, Pavel Mnev, Samuel Monnier, Alexei Morozov, Ryszard Nest, Nikolai Neumaier, Mikhail Olshanetsky, Dmitry Orlov, Valentin Ovsienko, Anna Paolucci, Jae-Suk Park, Serge Parmentier, Vasily Pestun, Norbert Poncin, Romaric Pujol, Ronald Reid-Edwards, Antonio Ricco, Martin Rocek, Dmitry Roytenberg, Volodya Rubtsov, Solange Sararu, Olof Ohlsson Sax, Florian Schätz, Karl-Georg Schlesinger, Martin Schlichenmeier, Urs Schreiber, Peter Schupp, Alexei Sharapov, Martin Sikora, Petr Somberg, Vladimir Soucek, Vid Stojevic, Thomas Strobl, Henrik Strohmayer, Rafal Suszek, Xiang Tang, Boris Tsygan, Bernardo Uribe-Jongbloed, Arkady Vaintrob, Izu Vaisman, Dmitri Vassilevich, Richard von Unge, Theodore Voronov, Aissa Wade, Stefan Waldmann, Frederik Witt, Maxim Zabzine, Anastasia Zakharova, Marco Zambon, Chenchang Zhu, Roberto Zucchini

Applications of the Renormalization Group

Organizer: G. Gentile (Rome), H. Grosse (Vienna), G. Huisken (Potsdam), V. Mastropietro (Rome)

Dates: October 15 – November 23, 2007

Budget: ESI €34.118, 75

Preprints contributed: [1900], [1953], [1979], [1981], [1982], [1984], [1985], [1991], [1998], [2009]

Report on the programme

In the last half century, Renormalization Group (RG) Theory based on multiscale analysis has become a central topic both in theoretical and mathematical physics. This method represents not only a powerful technical tool, but it has also deeply changed our view of many physical phenomena: it has provided a unifying language for many apparently unrelated fields, which have been shown to exhibit unexpected similarities in their underlying mathematical structure. An example, widely discussed during the programme, is the link between the theory of Ricci or mean curvature flow with the RG flow equations of the non-linear sigma model. Other examples, also discussed in the programme, are the emergence of a RG structure in problems such as the stability of KAM tori or the quantum diffusion in a random potential. It is likely that further advances both in physics and in mathematics will require a better understanding of the emergence of such common mathematical structures.

Several qualified researchers, with different interests and working in different and apparently unrelated areas (quantum field theory, statistical physics, condensed matter, dynamical systems, PDE theory, probability, Fourier theory, etc.), but all using RG ideas and methods met during this programme; the interaction between researchers belonging to different groups was rather strong, and many deep insights were reached.

The main topics of the programme were

(1) Ricci flows and renormalization.

(2) Renormalization in dynamical systems.

(3) Renormalization and condensed matter.

(4) Commutative and non-commutative QFT.

(5) Nonlinear sigma models, supersymmetry and quantum diffusion.

Ricci Flow and renormalization

A series of lectures (G. Huisken, M. Carfora, A. Grigor'yan, R. McCann, B. Wilking) on the theory of Ricci and mean curvature flow, and lectures by V. Schomerus and Ch. Kopper made evident the striking relation between the second order beta function equation of the nonlinear sigma model and the Ricci or mean curvature flow equations. A number of discussions and extended talks followed in order to explore the reasons and implications of this remarkable universality, and to get insights in possible extensions.

Renormalization in Dynamical systems

Since its emergence at the end of the fifties, KAM theory has become a basic topic in the theory of dynamical systems, and many new results, applications and extensions have been obtained and widely studied until today. Recently, new approaches to KAM theory, explicitly based on RG, have been proposed. At least two of them have been extensively discussed in the programme. The first one aims at making rigorous the so-called dynamical RG, introduced by Kadanoff, Schenker and MacKay. The lectures by S. Kocic and J. Lopes Dias illustrated how the analysis near the trivial fixed point (KAM tori) can extend to any Diophantine or even Bryuno rotation vector (so overcoming a limitation of the first implementations of the method, where only special vectors were considered), either by using a multidimensional continued fraction algorithm or by avoiding at all any continued fraction expansion. On the contrary, the RG analysis of the break up of the invariant tori (critical tori) is still far from a full mathematical understanding: a clear exposition of the state of the art was provided by H. Jauslin. The second approach uses multiscale techniques typical of QFT, also applied to the condensed matter problems mentioned below: some applications, both to the stability of the solutions of the Hill equation (J. Barata) and to the existence of periodic solutions for the NLS equation in higher dimension (M. Procesi), have been discussed during the program. RG ideas are implicit also in the more standard KAM approach, which has been applied also to the problem of existence and stability of quasi-periodic solutions for the NLS equation (H. Eliasson), to the problem of reducibility of some classes of cocycles (J. You), and to the problem of quasi-periodic breathers in Hamiltonian networks (Y. Yi): here, small divisor problems arise and can be dealt with by using KAM techniques. Another RG method was also illustrated by P. Moussa in his talk, devoted to the interval exchange maps, which arise when considering the first return map of flows on compact Riemann surfaces of arbitrary genus.

Finally we mention the lectures by M. Bartuccelli on the application of the so-called energy and ladder methods to some classes of dissipative partial differential equations, in order to obtain estimates on the well-posedness and asymptotics of the solutions, and by V. Rom-Kedar on the problem of non-ergodicity of the smoothed Boltzmann gas (which concerns billiards, where the elastic collisions with the boundaries are replaced by the action of a smooth external potential).

Besides the lectures officially announced on the program, several more informal discussions were organized on the following topics: comparison of results on quasi-periodic solutions for PDE problems in higher dimension (chaired by G. Gentile), study of the break-up of invariant tori (chaired by H. Jauslin), and almost everywhere reducibility for skew product systems (chaired by H. Eliasson).

Renormalization and Condensed Matter

The experimental discoveries of non-Fermi-liquid behaviour, high-temperature superconductivity and other unexpected properties had an enormous impact on solid state physics, and the study of these phenomena has shown the limitations of many of the standard theoretical techniques. Renormalization Group is one of the more powerful and sophisticated tool to understand such phenomena, and several results were presented in talks and discussions by several experts present in the workshop. The application of renormalization approach to the study of 2d interacting Fermi systems from a physical point of view was presented by A. Ferraz in a talk, in which an anomalous behaviour was found. Such results were naturally linked to some results presented by E. Langmann on the bosonization of the 2d Hubbard model, and, as was stressed in subsequent discussions, a bridge between the two methods which will hopefully overcome some of their limitations is surely provided by the use of Ward Identities in a RG contexts. The talk of Ch. Kopper on the renormalization of QFT with real time seems to suggest new perspectives to the problems discussed by P. Kopietz in his talk, regarding the dynamic structure factor of Luttinger liquids with long-range. On a more mathematical side, the recent and quite complex mathematical proof of Fermi liquid behavior in the 2d Hubbard model (G. Benfatto, A. Giuliani, A. Pedra, M. Salmhofer) was extensively discussed and compared. A rigorous justification of the functional integral approach given for granted by physicists in the analysis of Bose condensation was presented by H. Knoerrer in a talk. Periodic striped ground states of a two-dimensional system of discrete dipoles were presented in a talk by A. Giuliani.

Commutative and non-Commutative QFT

Recently rigorous Renormalization Group methods have been applied to the analysis of non-commutative quantum field theory, providing examples of truly renormalizable QFT models, like the Grosse-Wulkenhaar model. A key result is the vanishing of the beta function for that model; this was first proven by Grosse and Wulkenhaar by a one-loop calculation and then proven to all orders, so opening up the way to a non-commutative ϕ^4 theory with no Landau pole. The proof to all orders has been presented in a talk by J. Magnen, and the possibility of getting a fully non-perturbative proof, using also the methods discussed in the talk by V. Mastropietro for a similar problem in commutative QFT, was extensively discussed. Regarding commutative QFT, a nonperturbative approach to field renormalization in the context of operator algebras was discussed by H. Bostelmann, and applied to the Schwinger model; subsequent discussions regarded a comparison between this approach and the constructive one. G. Benfatto proved a rigorous version of Coleman bosonization, which stimulated discussions on its relation with the heuristic one used by physicists. Ch. Kopper presented a version of perturbative renormalization in real time, and Yigarashi presented the exact RG approach for treating Ward Identities. V. Bach and A. Pizzo applied renormalization group methods to nonrelativistic QED directly at the level of spectral theory.

Nonlinear sigma models, supersymmetry and quantum diffusion

While the proof of localization for large disorder in 3d was established since long time, one of the most important problems of contemporary mathematical physics is to prove diffusion in the

Schrödinger equation at weak disorder. L. Erdős presented a rigorous derivation of a diffusion equation as a long time scaling limit of a random Schrödinger equation in a weak, uncorrelated disorder potential. This talk initiated a number of discussions, focusing mainly on the role of a possible multiscale analysis. A different approach was presented by M. Disertori, reporting on the supersymmetric approach of Spencer and Zirnbauer. The problem is reduced to the analysis of a supersymmetric non-linear sigma model, for which quantum diffusion can be established. Non-linear sigma models were discussed by Schomerus, mainly from the renormalization point of view, and the relation between the beta function truncated at the second order and the Ricci flow evolution was presented and extensively analyzed in subsequent discussions. Symmetry breaking of nonlinear sigma models were discussed by E. Seiler, and a constructive result on a supersymmetric model by P. Mitter.

Invited Scientists: Volker Bach, Joao Carlos Alves Barata, Michele Bartucelli, Giosi Benfatto, Henning Bostelmann, Mauro Carfora, Claudio D'Antoni, Walter de Siqueira Pedra, Margherita Disertori, Hakan Eliasson, Laszlo Erdős, Alvaro Ferraz, Guido Gentile, Alessandro Giuliani, Alexander Grigor'yan, Harald Grosse, Thanassis Hatzista-Vrakidis, Gerhard Huisken, Yuji Igarashi, Hans Rudolph Jauslin, Horst Knörrer, Sasa Kocic, Peter Kopietz, Christoph Kopper, Dirk Kreimer, Thomas Krajewski, Joao Lopes Dias, Joszef Lörinczi, Jacques Magnen, Vieri Mastropietro, Robert McCann, Mukadas Missarov, Pronob Mitter, Gerardo Morsella, Pierre Moussa, Ileana Naish-Guzman, Alessandro Pizzo, Michela Procesi, Vered Rom-Kedar, Manfred Salmhofer, Volker Schomerus, Erhard Seiler, Burkhard Wilking, Yingfei Yi, Jiangong You, George Zoupanos

Workshops Organized Outside the Main Programmes

Winter School in Geometry and Physics, Srni (Czech Republic)

Organizers: P. Michor (University of Vienna), J. Slovak (Masaryk University), V. Souček (Charles University)

Dates: January 13 – 20, 2007

Budget: Budget contribution by the ESI € 1.000,–

Report on the programme

This traditional conference has taken place each January since 1980 for one week in a picturesque village in the Czech part of the Bohemian mountains. Since 1994 it has been a joint enterprise of the Czech Society of Mathematicians and Physicists and the Erwin Schrödinger International Institute for Mathematical Physics. The meeting this year centered around questions in Lie theory proper and relations with geometry and harmonic analysis.

Lieb-Robinson Bounds and Applications

Organizers: F. Verstraete (Vienna), J. Yngvason (Vienna)

Dates: February 20 – 24, 2007

Budget: ESI € 5,072.05

Preprints contributed: [1932], [1933], [1934]

Report on the programme

The goal of the workshop was to bring together people working in the field of strongly correlated quantum many-body systems to discuss the recent applications of so-called Lieb-Robinson bounds. Such bounds for the group velocity in quantum lattice systems were first proven by Lieb and Robinson in 1972 and give estimates on the spatial decay of correlations. Recent work of M. Hastings has lead to a revival of interest in the Lieb-Robinson bounds. Hastings, Nachtergaele and Sims recently generalized this work and showed that it can be used to solve long-standing open problems in the field of mathematical physics and quantum information theory. The workshop brought together the key players in this new interdisciplinary field.

During the workshop Nachtergaele described the proof of the *Lieb-Schultz-Mattis Theorem*. Hastings gave a detailed exposition of the new derivations of Lieb-Robinson bounds, and discussed applications such as the proof of exponential decay of correlations and the existence of a strict *area law* in gapped quantum spin systems. There were further lectures by M. Plenio *(Entanglement and Area)*, F. Benatti *(Entropies and algorithmic Complexities in Quantum Spin Chains)*, J. Eisert *(Unitary networks, Flows and Renormalization)* and T. Osborne *(Approximate Locality for Quantum Systems on Graphs)*.

The workshop was not limited to discussions about Lieb-Robinson bounds and encompassed work done in different communities of mathematical physics, theoretical condensed matter physics and quantum information theory. The interdisciplinarity of the participants made the workshop very stimulating. New ideas that originated from the discussions were e.g. the construction of quantum expander graphs (generalizing the ubiquitous concept of expander graphs in computer science) and a proof of area laws for classical and quantum spin systems in thermal equilibrium.

Invited scientists: Fabio Benatti, Oliver Buerschaper, Jens Eisert, Aram Harrow, Matthew Hastings, Bruno Nachtergaele, Heide Narnhofer, Tobias Osborne, Martin Plenio, Norbert Schuch, Robert Seiringer, Robert Sims, Barbara Terhal, Frank Verstraete, Reinhard Werner, Michael Wolf

Deterministic Dynamics meets Stochastic Dynamics

Organizer: C. Dellago (Vienna), P. Hänggi (Augsburg), H. Kauffmann (Vienna)

Dates: April 18 – 20, 2007

Budget: ESF €16.430,–

Preprints contributed: [1898]

Report on the programme

The workshop *Nonlinear Dynamics Meets Stochastic Dynamics*, funded by the European Science Foundation and hosted by the Erwin Schrödinger Institute for Mathematical Physics (ESI), took place in Vienna from April 18-20, 2007. More than 30 researchers from 10 countries working in the field of statistical physics participated in this workshop in a very active and lively way such that for all participants the workshop was a very fruitful and stimulating event.

To provide information on the theme of the workshop, the format of the workshop and the meeting place the organizers set up a webpage that is still available to the public at http://comp-phys.univie.ac.at/destodyn.

Most participants came to Vienna upon invitation by the organizers. A few additional participants were admitted after they had applied to the organizers. All workshop participants were offered to bring along students and young collaborators such that they can get in touch with the international community. However, only a few colleagues made use of this possibility.

The goal of the meeting was to bring together researchers that address the physics of systems far from equilibrium in two different ways. One approach is to consider the deterministic time evolution of systems driven away from equilibrium by external perturbations. Often in this case thermostats are used to stabilize the system in non-equilibrium steady states. Such deterministic thermostats were the topic of several talks and discussion of this workshop. In this context, configurational thermostats emerged as a particularly interesting new possibility to generate stationary states in an efficient way. The alternative way to describe non-equilibrium steady states and transport is to replace the heat bath by a random stochastic force that satisfies the fluctuation-dissipation theorem. A number of speakers reported on their work on the stochastic dynamics of various systems ranging from proteins to ion channels. Both areas have been strongly stimulated by the discovery of so called fluctuation theorems. These exciting and very general new results yield quantitative and exact descriptions of the fluctuations occurring in non-equilibrium processes and have consequences that can be tested in experiments. A whole session of the workshop was dedicated to these non-equilibrium fluctuation theorems and their application to various systems. The discussions about this topic continued at the conference dinner that took place at a traditional Viennese Heurigen.

Although the deterministic and stochastic communities have much in common, there is surprisingly little overlap between them. The organizers hope that at this workshop some ties have been established between the two groups for the benefit of non-equilibrium statistical mechanics.

Invited scientists: Francisco Cao, Christoph Dellago, Carl Dettmann, Christian Drobniewski, Werner Egger, Denis Evans, Christina Forster, Luca Forte, Giovanni Gallavotti, Pierre Gaspard, Peter Hänggi, Robin Hirschl, Carol Hoover, William G. Hoover, Gerhard Kahl, Harald Kauffmann, Yossi Klafter, Roberto Livi, L. Milanovic, Manuel Morillo-Buzon, David Mukamel, Shaul Mukamel, Heide Narnhofer, Markus Niemann, Martin Neumann, H. Oberhofer, Harald Posch, Günter Radons, Miguel Rubi, Stefano Ruffo, Lutz Schimansky-Geier, Gerhard Schmid, Elisabeth Schöll-Paschinger, Peter Talkner, Walter Thirring, Stefan Thurner, Andreas Tröster, Jacobus van Meel, Angelo Vulpiani

ThirringFest

Organizers: W.L. Reiter (Vienna), K. Schmidt (Vienna), J. Schwermer (Vienna), J. Yngvason (Vienna)

Date: May 15, 2007

Budget: ESI € 7.282,93

Report on the programme

On the occasion of the 80th birthday of Professor Walter Thirring the ESI organized in cooperation with the Faculty of Physics of the University of Vienna a colloquium with distinguished speakers on topics that were chosen with special regard to Walter Thirring's wide range of interests.

Wolfgang Rindler, University of Texas at Dallas, gave a lecture on "Vienna's Tradition in Relativity Theory", Julius Wess, University of Munich, on "Deformed Theory of Gravity", and Elliott Lieb, Princeton University, on "Remarks on Density Functional Theory".

In a sequel to the lecture of Wolfgang Rindler, Barry Muhlfelder, Stanford University presented the first results of satellite measurements by the "Gravity Probe B" of the Lense-Thirring effect. He also gave a lecture on this subject at the Faculty of Physics on May 16th. The Lense-Thirring effect, that concerns the dragging of gravitational fields by rotating bodies, was predicted theoretically by Walter Thirring's father Hans Thirring and Josef Lense in 1918. Precision measurements of this effect, that require long duration satellite observations, offer a sensitive test of General Relatvity.

On the evening of May 15th a "Kleine Hausmusik" with chamber music by Walter Thirring took place in the Beethovensaal in Heiligenstadt, followed by a Heuriger.

Invited scientists: Gianfausto Dell'Antonio, Jan Fischer, Nevena Ilieva, Elliott Lieb, Andre Martin, Barry Muhlfelder, Wolfgang Rindler, Robert Seiringer, Geoffrey Sewell, Domokos Szasz, Armin Uhlmann, James Woods, Evelyn Weimar-Woods, Julius Wess

Theory meets Industry

Organizers: J. Hafner (Vienna), Ryoji Asahi (Toyota Central Research and Development Laboratory), Risto Nieminen (Helsinki Technical University), Herve Toulhoat (Institut Français du Pétrole), Erich Wimmer (Materials Design Inc.), Chris Wolverton (Ford Motor and Northwestern University)

Dates: June 11 – 14, 2007

Budget: ESI € 3.942,00

Report on the programme

The development of modern materials science has led to a growing need to understand the phenomena determining the properties of materials on an atomistic level. Density-functional theory (DFT) represents a decisive step forwards to develop tools for ab-initio atomistic simulations of complex materials, preparing the way towards computational materials design. Accurate, efficient and stable software packages for ab-initio simulations are now available and DFT-based techniques are routinely used in many industrial laboratories worldwide.

The workshop "Theory meets Industry" held at ESI June 12–14 2007 was the second one in Vienna devoted to this subject, the first having been organized at the Technical University in 1998. The workshop was sponsored by the University of Vienna through the VASP (Vienna ab-initio simulation program) project, the Center for Computational Materials Science Wien, the ESI, and the European Science Foundation programme "Towards Computational Materials Design". The 35 invited talks presented at the meeting were divided equally between researchers from academia and from industry. The contributions from academia concentrated on a wide range of new developments in DFT and post-DFT simulations (with contributions from the developers of the leading software-packages for ab-initio simulations), as well as on applications in front-line materials research.

Despite fast progress during the last decade several fundamental challenges to theory remain: more accurate total energies, application to larger and even more complex systems, and access to new materials properties. Possible responses to these challenges, including hybrid functionals for solids, dynamical mean field theory (DMFT), many-body perturbation theory (GW), quantum Monte-Carlo, and multi-scale simulations strategies, were presented and discussed at the meeting.

Proceedings of the Workshop have appeared as a Special Issue of *Journal of Physics: Condensed Matter*, Vol. **20**, no.6, 2008.

Invited Scientists: Rajeev Ahuja, Emilio Artacho, Ryoji Asahi, Thomas Bligaard, Tomas Bucko, Hansong Cheng, Betty Coussens, Christophe Domain, Martin Friak, Clint Geller, Miguel A. Gosalvez, Jürgen Hafner, Louis Hector Jr, Karsten Held, Tilmann Hickel, Berit Hinnemann, Michal Jahnatek, Georg Kresse, Robert Laskowski, Wolfgang Mannstadt, Martijn Marsman, Oleg N. Mryasov, Richard Needs, Lars Nordström, Fumiyasu Oba, Artem Oganov, Pär Olsson, Susanne Opalka, Pascal Raybaud, Jutta Rogal, Paul Saxe, Nicola Seriani, Sadasivan Shankar, Donald Siegel, Lucie Sihelnikova, Chris-Kriton Skylaris, Petrie Steynberg, Kurt Stokbro, Alessandro Stroppa, Joost van de Vondele, Chris van de Walle, Werner Janse van Rensburg, Matthieu Verstraete, Erich Wimmer, Walter Wolf, Chris Wolverton, Jan Wröbel, Yasunari Zempo, Filippo Zuliani

Central European Joint Programme of Doctoral Studies in Theoretical Physics

Organizers: H. Grosse (Vienna), H. Hüffel (Vienna), J. Yngvason (Vienna)

Dates: September 24 – 2007

Budget: ESI €1.515,42

Report on the programme

The Central European Joint Programme of Doctoral Studies in Theoretical Physics is a joint effort of nine Central European universities and institutions to strengthen and develop their PhD programs with particular emphasis on particle physics, gravity and cosmology. Within the frame of this program two intensive courses of 15 lectures each for graduate students and PostDocs were held at ESI September 24 – 28 2007. The courses were designed as an introduction to the subject of the "4th Vienna Central European Seminar on Particle Physics and Quantum Field Theory", November 30 to December 2, 2007.

Harald Grosse: *Quantum Field Theory and Noncommutative Geometry*

Aim and contents of the Course: The course gave an introduction to quantum field theory over noncommutative space-times including the construction of some renormalizable models and a discussion of noncommutative gauge fields.

Topics: Differential calculi on algebras, projective modules, formulation of field theories over noncommutative algebras, regularization of models, Infrared/Ultraviolet mixing problem, renormalization.

Jakob Yngvason: *Local Quantum Field Theory*

Aim and contents of the course: This compact course was conceived as an introduction to the basic principles of relativistic quantum field theory (QFT) in the algebraic formulation together with some important applications.

Topics: Observables and Fields, Superselection sectors, the PCT theorem and the modular structure of QFT, scattering theory.

Spectra of arithmetic groups

Organizers: J. Schwermer (Vienna)

Dates: October 7 – 13, 2007

Budget: ESI € 4.583,31

Report on the programme

The spectral theory of the Laplace-Beltrami operator on Γ-invariant functions on the upper half plane is an analytic problem in its own right for any discrete subgroup Γ of the special linear group $SL_2(\mathbb{R})$ whose fundamental domain has finite volume with respect to the hyperbolic metric. If the quotient H/Γ is compact the spectrum is discrete but otherwise there is a continuous spectrum built up by Eisenstein series. The construction of the eigenfunctions for the continuous spectrum via an analytic continuation of a given series attached to a cusp was given by Roelcke for congruence subgroups whereas the general case was treated by Selberg in1956 but without a complete proof at that time. However, beyond the spectral theory, Selberg outlined an argument for establishing a trace formula for a non-compact quotient when the underlying real Lie group has real rank one, for example, in the case of the isometry group of hyperbolic n-space. In the sixties the interest turned to the general case of a given reductive group G defined over some number field k and an arithmetic subgroup Γ. On one hand, Selberg emphasized the importance of a trace formula in general, and of applying it to Hecke operators. On the other hand, there was the need to describe the decomposition of the regular representation of G on the space $L^2(G/\Gamma)$ into a direct integral of irreducible representations. A decisive step in these investigations of groups of higher rank was the notion of cusp forms as introduced by Gelfand. The regular representation restricted to the subspace of cusp forms in $L^2(G/\Gamma)$ decomposes as a discrete sum of irreducible representations of G. In 1963 Langlands carried out the spectral decomposition and the theory of Eisenstein series in full generality. He constructed within the discrete spectrum a complement to the space of cusp forms by means of residues of Eisenstein series and gave a description of the continuous spectrum by means of the discrete spectrum attached to Levi subgroups of G. This study was meant and turned out to be a fundamental pillar in developing a trace formula.

In October 2007, the Erwin-Schrödinger Institute hosted a programme entitled "Spectra of Arithmetic Groups", organized by Joachim Schwermer (U Vienna, Austria). The workshop brought together leading experts in the theory of automorphic forms and related local and global questions in the representation theory of Lie groups and algebraic groups. The main emphasis was put on some of the major developments of the past years in the study of the internal structure of the automorphic spectrum, the use of the trace formula and various applications of the investigations to the existence of cohomology classes for arithmetic groups.

Generalizing a previous construction of Piatetski-Shapiro and Rallis, Muic discussed his results on residual automorphic representations for split classical groups by analyzing certain degenerate Eisenstein series. The analysis of local normalized intertwining operators played a decisive role in this study. He interpreted his work in the framework of the conjectures of Arthur regarding the structure of the automorphic spectrum.

Grbac presented his recent results on the residual spectra of Hermitian quaternionic classical groups and the general linear group over a division algebra. His approach uses, besides Langlands spectral theory, in the case of the general linear group the description of the whole discrete spectrum by Badulescu which is obtained via Arthur's trace formula. The required normalization by L–functions of the standard local intertwining operators at non–quasi–split places is beyond the scope of the Langlands–Shahidi method. Hence, Grbac had to develop a new technique based on the comparison of the Plancherel measures obtained by a global argument firstly used by G. Muić and G. Savin. It turns out that in some cases the normalization is not of the same form as the Langlands–Shahidi normalization at split places which gives interesting local conditions in the description of the residual spectra.

The cohomology of an arithmetic subgroup of a reductive algebraic group G defined over some number field k can be interpreted in terms of its automorphic spectrum. Various techniques have been used, on the one hand, to detect the internal automorphic structure of certain analytically defined subspaces of the cohomology (cuspidal, Eisenstein) and to establish the actual existence of specific types of automorphic representations in the automorphic spectrum, on the other. Rohlfs reported on the use of Lefschetz numbers in the actual determination of multiplicities with which non-discrete series representations might occur in the cuspidal automorphic spectrum. He derived a formula for the trace of a twisted Hecke operator on the cohomology of an arithmetic group in terms of twisted orbital integrals. Various previous versions of such a formula are due to Harder, Franke, Goresky-MacPherson, and Rohlfs. A similar approach to non-vanishing results of this type has been used by Borel-Labesse and Schwermer via Arthur's trace formula. Grobner discussed the specific case of the cohomology of congruence subgroups of a $\mathbb{Q}$-rank 2 form of the group $Sp(2,2)$. In the case of a regular coefficient system he gave a complete description of the Eisenstein cohomology. Recent results of Grbac allow him to obtain partial results in the case of an arbitrary coefficient system as well. Waldner discussed the geometric construction of cohomology classes for arithmetic groups as initiated by Millson-Raghunathan for classical groups in the case of the exceptional group G_2. His results imply non-vanishing results for the cohomology of these groups and, in turn, non-vanishing results for the occurrence of specific representations in the automorphic spectrum.

Mahnkopf constructed p-adic families of automorphic forms on GL(2) as predicted by the Mazur - Gouvea conjecture. In the ordinary case he obtained the full conjecture, in the non-ordinary case his result is weaker than the M-G-conjecture. The M-G-conjecture has been proven in the ordinary case by Hida and in general using completely different (geometric) methods by Coleman. Mahnkopf's construction, which again is completely different, is based on a comparison of trace formulas, a technique which he adopted from the Langlands programme. Unlike in applications to functoriality there is no need to use a Fundamental Lemma as it is called and which is in its conjectural form one of the main difficulties occurring in the Langlands programme. On the other hand

- since he constructs families of automorphic forms he has to "compare infinitely many trace formulas"
- he has to compare trace formulas modulo powers of p, i.e., he is partly working in characteristic $\neq 0$.

Unitary representations of reductive groups occurring in the automorphic spectrum form via its local components an important source for irreducible unitary representations of classical groups over local fields. In this realm Tadic presented some recent classification results, in particular, of the unitary dual of GL(n) over non-archimedean division algebras (Badulescu and Renard, together with Secherre), and of the unramified unitary dual of non-archimedean split classical groups: orthogonal and symplectic ones. He stressed the point of view that the automorphic forms approach serves as an unifying element between archimedean and non-archimedean classifications.

There were many fruitful discussions across boundaries, and these led to some additional lectures of a different but closely related nature. In particular, Hanzer discussed her recent results regarding Bernstein's conjecture which states that the Aubert involution preserves unitarity of smooth irreducible representations of reductive groups. Stuhler lectured on buildings of Kac-Moody groups and representations.

Invited Scientists: Neven Grbac, Harald Grobner, Marcela Hanzer, Joachim Mahnkopf, Goran Muic, Jürgen Rohlfs, Johannes Schoissengeier, Joachim Schwermer, Ulrich Stuhler, Marko Tadic, Ognjen Vukadin, Christoph Waldner,

ESF Workshop on Noncommutative Quantum Field Theory

Organizers: H. Grosse (Vienna)

Dates: November 26 – 30, 2007

Budget: ESF €12.320,–

Report on the programme

The subject of noncommutative quantum field theory has been developed within the last 15 years with the aim to cure the diseases of quantum field theory and include in addition certain quantum gravity effects. First the formulations were given and it was realized that the deformed spaces act as interesting regularizations. At the turn of the century the connection to string theory was realized and the subject expanded rapidly. Afterward the question of renormalizability became of interests and the IR/UV mixing problem was identified. A way to treat it for matter fields was found. Of course, in the meantime developments in various directions set in.

This workshop consisted of four days of seminars and discussions and saw an impressive review of this lively expanding subject: The Fuzzy physics was dealt with from various point of views. The deformed quantum field theories were discussed as well as deformed gravity. This subject is still not settled and a number of discussions set in. The Euclidean models were treated at length, these are the main focus of the Paris-Münster-Vienna groups and a number of colleagues. The question of quantum group deformations was discussed too. The difficult problems connected to a Minkowski space formulation complemented the set of subjects. A very interesting discussion session led to lively exchange of ideas.
There were two special lecture courses given during the two weeks before the workshop:
John Barrett (Nottingham): *Quantum Gravity*

and
Richard Szabo (Edinburgh): *Two-dimensional Noncommutative Gauge Theory*

Barrett started from the Ponzano-Regge Model, explained the connection to 6-j symbols and gave a simple introduction to spin networks. Next, topological quantum field theory models and quantum groups were treated, and the way from quantum gravity ideas to Feynman diagrams explained. A lively discussion on the categorical approach set in.
Szabo formulated noncommutative gauge models, explained Wilson loop operators in that framework and treated in details the Eguchi-Kawai model. The two dimensional noncommutative gauge model can be treated almost explicitly. He explained in a very nice way the equivariant localization approach.

Description of the scientific content

Fuzzy geometries lead to matrix models. They can be treated by various techniques, which allow to obtain detailed information on the phase structure (contributions by Denjoy O'Connor and Wolfgang Bietenholz). These partly numerical simulations give impressive information on striped phases respectively phase transitions.
A generalization to relativistic fuzzy models was pointed out by Peter Presnajder in his presentation on fuzzy twistors. This line of research may lead to new directions.
Deformed, respectively twisted field theories were formulated recently and depending on the approach different formulations were given. Aiyalam Balachandran opened up this discussion, Laurent Freidel connected gravity models to models defined on the κ- deformed space and discussed the question of Lorentz invariance breaking. This issue was furthermore discussed by Patricia Vitale, who reported on the common work with Fedele Lizzi on deformed classical field equations. The lecture on noncommutative instantons by Richard Szabo continued an impressive series of lectures, which he gave the week before the workshop as an introduction to noncommutative field theory and to the Eguchi-Kawai model.
Deformed gravity was nicely reviewed by Peter Schupp. The formulation of deformed gravity with euclidean metric is by now well-known, the fine details like the formulation of an action principle and solutions to the equation of motion have been discussed too and led to interesting Fuzzy solutions hopefully suitable for black hole physics.
Of course, such fuzzy models are closely related to spin foam models of quantum gravity although the point of view is put a little bit differently. The gravity models were reviewed by John Barrett, starting from the Ponzano Regge model, mentioning topological invariants up to the recent categorical and field theoretical developments, which continued again a series of lectures which was given two weeks before the workshop at ESI.
The subject of renormalization of deformed models following the work of Raimar Wulkenhaar and Harald Grosse was dealt with by a number of researchers: The three groups from Münster, Paris-Sud Orsay and from Vienna presented recent developments. Michael Wohlgenannt explained the heat kernel expansion for external gauge fields interacting with scalars on the noncommutative space, Adrian Tanasa showed the way to obtain parameter representations for a set of Feynman graphs and Razvan Gurau presented representations for Feynman graphs, which allow to use dimensional regularization methods.
The somewhat more complicated formulation of Fermions on deformed spaces was explained by Raimar Wulkenhaar. Through the use of an eight dimensional Clifford algebra he obtained (in common work with Grosse) a spectral triple and the coupled gauge Higgs field model shows an interesting new symmetry breaking effect. The vacuum structure is now under investigation.
Jean-Christophe Wallet explained the Münster-Paris work on deformed gauge models and obtained results in agreement with the results of Grosse and Wulkenhaar.
The quite difficult task of renormalization of models over deformed Minkowski space-time was

the subject of the seminar be Dorothea Bahns. Her method allows to handle a subset of graphs, which do not show the infrared-ultraviolet mixing.
John Madore explained the attempts to obtain solutions of deformed gravity and Bruno Iochum the construction of spectral triples for the quantum group deformed space. The absolute highlight was the beautiful review by Vincent Rivasseau, who gave an overview on the developments of renormalization of deformed models and explaining in particular the taming of the Landau ghost, a property, which will (hopefully) allow to construct the first nontrivial model of a (deformed) quantum field theory.
As mentioned, the discussion session by Fedele Lizzi led to an interesting exchange of ideas.

Invited Scientists: Dorothea Bahns, Aiyalam Balachandran, Glenn Barnick, John Barrett, Wolfgang Bietenholz, Maja Buric, Marija Dimitrijevic, Bryan Dolan, Gaetano Fiore, Laurent Freidel, Axel de Goursac, Harald Grosse, Razvan Gurau, Bruno Iochum, Larisa Jonke, Daniela Klammer, Seckin Kurkcuoglu, Edwin Langmann, Gandalf Lechner, Fedele Lizzi, Thomas Ludwig, John Madore, Harald Markum, Max Meinhart, Albert Much, Denjoe O'Connor, Gerhard Petrakovits, Roger Picken, Peter Presnajder, Vincent Rivasseau, Oliver Rosten, Karl-Georg Schlesinger, Paul Schreivogl, Peter Schupp, Rene Sedmik, Harold Steinacker, Richard Szabo, Adrian Tanasa, Josip Trampetic, Fabien Vignes-Tourneret, Patrizia Vitale, Jean-Christophe Wallet, Satoshi Watamura, Raimar Wulkenhaar, Gheorge Zet

4th Vienna Central European Seminar on Particle Physics and Quantum Field Theory

Organizer: H. Hüffel (University of Vienna). Advisory Board: K. Fredenhagen (Hamburg), H. Grosse (Vienna), W. Majerotto (Vienna), P. Presnajder (Bratislava), J. Yngvason (Vienna).

Dates: November 30 – December 02, 2007

Budget: ESI €2.400,–. Also supported by the Austrian Federal Ministry for Science and Research, by the Institute for High Energy Physics of the Austrian Academy of Sciences, by the Faculty of Physics (University of Vienna) and by the Vienna Convention Bureau

Preprints contributed: [1992]

Report on the programme

The "Vienna Central European Seminar on Particle Physics and Quantum Field Theory" is a unique forum for coordinating conferences, schools and doctoral courses in the Central European Region and particularly intended to be a platform for junior scientists.

This year the chosen subject was *Commutative and Noncommutative Quantum Fields.* Recent developments and new phenomena in relativistic quantum field theory were discussed within the framework of local quantum physics in its algebraic formulation as well as by deforming space time. Aspects of renormalization were dealt with.

Invited Scientists: D. Bahns, A.P. Balachandran, W. Bietenholz, D. Blaschke, G. Bregar, D. Buchholz, A. Chatzistavrakidis, C. Dehne, M. Dimitrijevic, S. Doplicher, W. Dybalski, K. Fredenhagen, A. Glück, A. de Goursac, H. Grosse, H. Hüffel, M. Kladiva, D. Klammer, T. Krajewski, M. Kreuzer, S. Kürkcüoglu, A. Lavagno, G. Lechner, C. Levy, J. Lukerski, W. Majerotto, P. Martinetti, T. Miller, N. Nikolov, M. Pardy, P. Presnajder, V. Rivasseau, P. Roche, Peter Schupp, H. Steinacker, R. Szabo, A. Tanasa, J. Trampetic, A. Tureanu, J.-C. Wallet, S. Weiß, J. Yngvason, L. Zhifeng

Miniworkshop on Ergodic Theory and von Neumann Algebras

Organizers: K. Schmidt (Vienna)

Dates: December 3 – 14, 2007

Budget: ESI €3.188,13, EU Network €3.814,50

The first semester of the EU-NCG Network in Noncommutative Geometry from July 1, 2007 – December 31, 2007, was based at the ESI (cf. `http://www.cf.ac.uk/maths/opalg/qsng.html`). This workshop formed part of the activities at the ESI linked to this network and was largely funded by the EU-Network.

Report on the programme

This workshop was built around four expository lecture courses on connections between ergodic theory, dynamical systems and operator algebras. In spite of their expository nature these courses presented active areas of current research. The courses were complemented by five research seminars. There were 17 external participants (lecturers and a small number of young mathematicians from the EU-NCG network), as well as some local mathematicians and physicists.

Christopher Deninger (University of Münster, Germany): *Entropy of algebraic actions by amenable groups and determinants on Neumann algebras* (4 lectures, December 11 – 13)

Contents: This lecture course discussed expansiveness and entropy for actions of amenable groups in measurable and topological dynamics. After a general introduction it focused on a very interesting and explicit class of such dynamical systems called 'algebraic' which are constructed using ideals in group rings of amenable groups. Expansiveness and entropy of these algebraic systems can be characterized in terms of the L^1 group algebra and the von Neumann algebra of the amenable group. In particular the entropy is given by the logarithm of a suitable Fuglede-Kadison determinant. In the abelian case where the group is $\mathbf{Z}^d$ this formula expresses entropy as a Mahler measure. The lecturer then explained how to calculate Fuglede-Kadison determinants explicitly in some non-commutative cases. The course ended with a p-adic analogue of the theory, relations to number theory and a relation to the theory of orthogonal polynomials on the unit circle.

Sergey Neshveyev (University of Oslo, Norway): *Bost-Connes type systems, ergodic theory and equidistribution* (5 lectures, December 3 – 7)

Contents: In 1995 Bost and Connes constructed a remarkable C^*-dynamical system with the Galois group of the maximal abelian extension of $\mathbf{Q}$ as the symmetry group and with phase transition related to properties of the Riemann zeta-function. Since then similar systems have been constructed for arbitrary number fields and for higher dimensions. The analysis of phase transition of these systems leads to study of actions of groups on adelic spaces. The uniqueness of a phase for large temperatures is related to ergodicity of certain actions and to equidistribution results in number theory. The goal of the lectures was to survey these developments.

Ian Putnam (University of Victoria, Canada): *C^*-algebras and topological dynamics* (5 lectures, December 3 – 7)

Contents: The course began with a general introduction about the construction of C^*-algebras from various types of dynamical systems: group actions, equivalence relations and topological groupoids. After a discussion of basic properties of these C^*-algebras the course turned to orbit equivalence for minimal systems on Cantor sets, hyperbolic dynamical systems and aperiodic tilings.

Erling Størmer (University of Oslo, Norway): *Dynamical entropy in operator algebras* (5 lectures, December 6 – 7 and 10 – 12)

Contents: The course started by reformulating the definition of classical entropy and then showing how this reformulation extends to a definition of noncommutative dynamical entropy. After describing its basic properties the lecturer considered the generalization of topological entropy to C^*-algebras and showed how the two kinds of noncommutative entropy (metric and topological) behave under crossed products, the variational principle and binary shifts.

These courses were complemented by various research lectures on related topics.

Invited Scientists: Stephen Barreto, Alan Carey, Christopher Deninger, David Evans, Emmanuel Germain, Vadim Kaimanovich, Anselm Knebusch, Magnus Landstad, Julia Magnusson, Sergey Neshveyev, Denes Petz, Ian Putnam, Erling Størmer

Spectral Theory and Schrödinger Operators

Organizers: T. Hoffmann-Ostenhof (Vienna), A. Laptev (Stockholm)

Dates: December 10 – 21, 2007

Budget: ESI €14.539,43

Preprints contributed: [1926], [1927], [2011]

Report on the programme

This was the last workshop within the scientific program SPECT that started in 2002 and which was supported by the European Science foundation, ESF (http://www.esf.org). ESI supported the visitors by per diems and the ESF paid the travel costs.

The workshop consisted of 25 talks. All talks had a connection to spectral theory and PDE and gave an instructive survey of some recent developments in those fields of Mathematics and Mathematical Physics.

The main topics that were presented in talks and discussed were:

Hardy-inequalities, including relativistic problems (M. Esteban, J. Dolbeault, R. Bosi)
Hardy-Sobolev inequalities (M. Loss, A. Laptev).
Relativistic Scott corrections (J.P. Solovej, H. Siedentop)
Schrödinger operators with magnetic fields (A. Sobolev, R. Frank)
Spectral theory for certain models from physics and geometry: liquid crystals (B. Helffer)
Non-linear variational membrane problems (S. Terracini)
Superconductivity (V. Bonnaillie Noel), *Rotating Bose gases* (J. Yngvason),
BCS hamiltonians (C. Hainzl)
Special membranes (P. Freitas), *Fourier coefficients, Dirichlet and Neumann problems* (M. Levitin), *Fourth order membrane problems* (A. Dall'Acqua)
Fundamental aspects of the time-dependent Schrödinger equation (G. Friesecke)
Relation to Classical Mechanics (A. Pushnitski)
Heat equation (M. van den Berg).

Logarithmic Lieb Thirring inequalities (T. Weidl).
One dimensional problems: Inverse problems (E. Korotyaev), *Steepest descent* (G. Teschl)
Regularity of Coulombic wavefunctions (T. Østergaard Sørensen)
Random Schrödinger operators (J.M. Combes).

Invited Scientists: Virginie Bonnaillie-Noel, Roberta Bosi, Jean-Michel Combes, Anna Dall'Acqua, Jean Dolbeault, Andreas Enblom, Maria Esteban, Pavel Exner, Rupert Frank, Gero Friesecke, Pedro Freitas, Christian Hainzl, Bernard Helffer, Rainer Hempel, Horst Knörrer, Evgeny Korotyaev, Ari Laptev, Michael Levitin, Michael Loss, Annemarie Luger, Carole Mabrouk, Sergey Morozov, Alexander Puhsnitski, Heinz Siedentop, Alex Sobolev, Jan Philip Solovej, Thomas Sorensen, Susanna Terracini, Michiel van den Berg, Timo Weidl

Ergodic Theory, Limit Theorems and Dimensions

Organizers: F. Hofbauer (Vienna), R. Zweimüller (Vienna)

Dates: December 17 – 21, 2007

Budget: ESI € 1.213,19, University of Vienna € 7.000,–

Preprints contributed: [1999]

Report on the programme

The study of statistical features of (chaotic) dynamical systems has become a very active field of mathematical research. Based on (and interwoven with) ergodic theory, the aim of this specialized branch of probability theory is to enable rigorous quantitative predictions about the long-term behaviour of deterministic systems whose irregular behaviour rules out detailed predictions for individual trajectories. The analysis of features responsible for the emergence of stochastic behaviour in models based on deterministic systems is intimately related to that of other (analytical and geometrical, like dimension theory) aspects of the dynamics, and the thermodynamic formalism provides a common framework for a variety of questions.

The aim of this workshop was to bring together a group of scientists working on closely related topics in these fields, and on their interrelations. Accordingly, the two main aspects of this workshop were the visitor's talks, presenting most recent results as well as ongoing work to a specialist audience, and the continuation of several individual research projects. The participants unanimously described this week at the ESI as a very productive and inspiring one, and emphasized their interest in further events of this type. We thank the ESI for its financial and (excellent) administrative support.

The invited scientists contributed 19 research talks, devoted to three main topics (but with an emphasis on overlaps and connections between them):

Probabilistic limit theorems for dynamical systems. While analogues of several basic classical probabilistic results are well established for measure-preserving transformations with good mixing properties, dynamical systems with weaker (or harder to capture) mixing properties, or infinite invariant measures, remain a challenge. (Dually, so do questions about observables with heavy-tailed distributions.) Work approaching such questions, and others devoted to refinements of classical topics, or taking up recent developments in mainstream probability like concentration of measure phenomena, has been discussed in the following talks.

Jon Aaronson: Limit theorems à la Darling-Kac

Jean-Baptiste Bardet: A local limit theorem for coupled interval maps

Zoltan Buczolich: The bilinear Hardy-Littlewood function for the tail

Jean-René Chazottes: Moment and concentration inequalities and applications

Mark Holland: Extreme value theory in Dynamical Systems

Benoît Saussol: Quantitative recurrence in two-dimensional extended processes

Marta Tyran-Kaminska: Ergodic properties and limit theorems for some stochastic processes

Dalibor Volný: Central limit theorems via martingale approximation - Choice of filtration

Foundations of the ergodic theory for systems with some hyperbolicity. As precise stochastic results for dynamical systems depend on a thorough understanding of their ergodic properties, the study of certain invariant measures is the natural starting point if one attempts to extend the above theory to new classes of systems. Strong results can be obtained in situations with enough hyperbolicity, and it is crucial, for wider applicability of the theory, to develop techniques enabling an analysis of systems which only exhibit weaker forms (non-uniform, partial, piecewise, etc) of hyperbolicity. Several talks were devoted to questions about existence and basic properties of distinct (absolutely continuous, physical, maximal entropy) invariant measures in such situations, and to peculiarities of certain (apparently) weak hyperbolicity conditions.

Jerome Buzzi: Hyperbolicity from Entropies

Yves Coudene: The mixing property for hyperbolic systems

Sébastien Gouëzel: Physical measures for piecewise hyperbolic maps

Jörg Schmeling: The miracle of Anosov-Baire rigidity - Nonuniform hyperbolicity everywhere implies uniform hyperbolicity

Serge Troubetzkoy: Random iterations of planar isometries

Sandro Vaienti: On some properties of randomly perturbed dynamical systems

Thermodynamical formalism and dimensions. Topological pressure was introduced to the theory of dynamical systems in order to study equilibrium states and their phase transitions (which correspond to nondifferentiability of the pressure functions). More recently, applications to dimension theory were found. It is possible to determine the Hausdorff dimension of certain invariant sets as zeroes of pressure functions, and multifractal spectra of local quantities (pointwise dimension, Lyapunov exponent, local entropy) can be characterized by Legendre transforms of pressure functions. This is well understood for hyperbolic dynamical systems. Several talks discussed these questions for certain dynamical systems with weaker hyperbolicity properties, and used this thermodynamic formalism to investigate the dimension of the set of non-differentiability for certain distribution functions.

Henk Bruin: Equilibrium states for non-Collet-Eckmann multimodal maps

Katrin Gelfert: On the Lyapunov spectrum of parabolic maps

Thomas Jordan: The dimension of non-differentiability of topological conjugacies

Marc Keßeböhmer: Hölder-differentiability of Gibbs distribution functions

Bernd Stratmann: Non-differentiability of slippery devil's staircases

The workshop was also meant to serve as an opportunity to continue ongoing cooperations between the participants, and to initiate further joint work. Specific research projects (working titles) pursued during this meeting include:

Eigenvalues of cocycles (Aaronson & Volný)

Limit theory for positive mixing stationary sequences (Aaronson & Zweimüller)

Large and moderate deviations for Poisson suspensions (Bardet & Zweimüller)

Hölder irregularity of conjugacy maps (Jordan & Keßeböhmer & Stratmann)

The Hausdorff dimension of the set of dissipative points for a Cantor-like model set of singly cusped parabolic dynamics (Schmeling & Stratmann)

Conditional limit theorems in infinite ergodic theory (Thaler & Zweimüller)

According to participants' comments, the motivating atmosphere of the workshop, and the stimulating environment at the ESI provided excellent conditions for fruitful discussions, and, despite limited time, enabled significant progress on some of these projects. In fact, the above project by Schmeling and Stratmann was completed during the meeting, and has already been submitted as an ESI-preprint.

Invited Scientists: Jon Aaronson, Jean-Baptiste Bardet, Henk Bruin, Zoltan Buczolich, Jerome Buzzi, Yves Coudene, Jean-René Chazottes, Katrin Gelfert, Sebastien Gouëzel, Thomas Jordan, Franz Hofbauer, Mark Holland, Marc Keßeböhmer, Benoît Saussol, Jörg Schmeling, Bernd Stratmann, Maximilian Thaler, Serge Troubetskoy, Marta Tyran-Kaminska, Sandro Vaienti, Dalibor Volny, Roland Zweimüller

Junior Research Fellows Programme

Established in 2004 and funded by the Austrian government, the Junior Research Fellows Programme provides support for PhD students and young post-docs to participate in the scientific activities of the Institute and to collaborate with its visitors and members of the local scientific community.

Due to its international reputation and to its membership in the European Post-Doc Institute the ESI received many applications from highly qualified post-docs for funding of extended visits (ranging from two to six months) only some of which could be covered by the Junior Fellows Programme. In view of the close and well-established links between the ESI and many leading Eastern European academic institutions this programme was particularly beneficial to young researchers from Eastern Europe and Russia. The presence of the Junior Research Fellows contributed significantly to the positive and dynamic atmosphere at the ESI.

In 2007 the JRF Programme was supported by three instructional workshops funded from other sources: *Amenability beyond groups* (February 26 – March 17, see p. 13), *Algebraic, geometric and probabilistic aspects of amenability* (June 18 – July 14, see p. 13) and a *Miniworkshop on Ergodic Theory and von Neumann algebras* (December 3 – 17, see p. 35). The second and third of these workshops were partially funded by EU-Networks.

The figures for the two regular rounds of applications were as follows:

1st deadline: 30.04.2007
Number of applications: 37
Number of accepted applicants: 9
Number of months granted: 19 for 2007, 16 for 2008

2nd deadline: 10.11.2007
Number of applications: 41
Number of accepted applicants: 15
Number of months granted: 57 for 2008

Junior Research Fellowships in 2007

Name	Gender	Duration	Nationality
Stuart Armstrong	male	09/01 – 01/07	Canada
Christoph Bergbauer	male	01/03 – 30/04	Germany
Olivier Bernardi	male	01/08 – 27/09	France
Henning Bostelmann	male	01/03 – 30/06	Germany
Pierluigi Falco	male	01/03 – 30/04	Italy
Josh Garretson	male	30/07 – 30/09	USA
Gerald Gotsbacher	male	01/01 – 30/06	Austria
Peggy Kao	female	30/07 – 30/09	Taiwan
Aleksey Kostenko	male	04/05 – 30/06	Ukraine
Gandalf Lechner	male	01/01 – 30/06	Germany
Christian Lübbe	male	01/09 – 31/12	Germany
Sean Murray	male	01/08 – 30/09	Ireland
Tomasz Paterek	male	01/01 – 31/01	Poland
Tomasz Paterek	male	01/03 – 31/03	Poland
Pietro Polesello	male	01/08 – 30/09	Italy
Julia Reffy	female	01/10 – 31/12	Hungary
Florian Schätz	male	01/08 – 30/09	Austria
Evelina Shamarova	female	01/01 – 28/02	Russia
Wonmin Son	male	02/05 – 30/06	Korea
Mihaly Weiner	male	01/03 – 31/03	Hungary
Mihaly Weiner	male	07/05 – 07/08	Hungary
Michael Wohlgenannt	male	01/07 – 31/12	Austria

Preprints contributed: [1895], [1896], [1900], [1902], [1908], [1909], [1910], [1953], [1971], [1984], [1985], [1987], [2004]

Senior Research Fellows Programme

To stimulate the interaction with the local scientific community the ESI offers lecture courses on an advanced graduate level. These courses are taught by Senior Research Fellows of the ESI whose stays in Vienna are financed by the Austrian Ministry of Education, Science and Culture and the University of Vienna. The coordinator of this programme was Joachim Schwermer.

This year's programme concentrated on the following lecture courses:

Vadim Kaimanovich (Internationale Universität Bremen), Summer 2007: *Boundaries of groups: geometric and probabilistic aspects*

Miroslav Englis (Academy of Sciences, Prague), Summer 2007: *Analysis on Complex Symmetric Spaces*

Thomas Mohaupt (University of Liverpool), Summer 2007: *Black holes, supersymmetry and strings (Part II)*

Christos N. Likos (Universität Düsseldorf), Winter 2007: *Introduction to Theoretical Soft Matter Physics*

Radoslav Rashkov (Sofia University), Winter 2007: *Dualities between gauge theories and strings*

Vadim Kaimanovich: Boundaries of groups: geometric and probabilistic aspects

Course: The course was devoted to a discussion of the boundary theory as a powerful tool for understanding big groups, i.e., the ones which admit a sufficiently rich behaviour at infinity (as, for instance, word hyperbolic groups or lattices in semi-simple Lie groups). I discussed interrelation between the geometrical and probabilistic approaches to the boundary theory and the ensuing applications to rigidity, geometric group theory and functional analysis. I covered the following subjects:

- Basic notions from measure theory, Lebesgue spaces, measurable partitions;
- Measure-theoretical boundaries of Markov chains;
- Entropy of random walks;
- The Poisson boundary of groups; criteria of triviality and maximality;
- Relation with ergodic properties of geodesic and horocycle flows;
- Amenability of groups and actions;
- Compactifications of groups (ends, visibility and hyperbolic compactifications);
- Boundary properties of semi-simple Lie groups, their discrete subgroups and symmetric spaces, relation with the Lyapunov exponents;
- Boundary properties of the mapping class group and Teichmüller space.

I have to point out a very useful interaction between the course and the periods of activity of the *"Amenability"* program at ESI, during which the lectures were also attended by the participants of the program. Otherwise the audience was about 5-6 on average.

Research: My research during the time of the fellowship was mainly connected with the *"Amenability"* program concurrently run at the ESI, of which I was one of the organizers. I was able to profit from visits of many of my collaborators to ESI, both as my personal visitors in the framework of the fellowship and as invited scientists in the framework of the "Amenability" program. More precisely:

- I completed my work on the paper *Amenability of automata groups* (joint with L. Bartholdi, V. Nekrashevych and B. Virág). In this work we show that the group of bounded automatic automorphisms of a rooted tree is amenable, which implies amenability of numerous classes of groups determined by finite automata. The proof is based on reducing the problem to showing amenability just of a certain explicit family of groups ("Mother groups") which is done by analyzing the asymptotic properties of random walks on these groups.

- I completed my work on the paper *Ergodic properties of boundary actions and Nielsen's method* (joint with R. Grigorchuk and T. Nagnibeda). In this paper we study ergodicity and conservativity of the action of a subgroup H of a free group F on the boundary ∂F with respect to the uniform measure. The ergodicity of the action is equivalent to the Liouville property of the quotient graph. We give a combinatorial description of the conservative part of the boundary and give a necessary and sufficient condition for it to be of full measure in terms of growth of the quotient graph. We construct several examples illustrating the connections between various related notions, in particular, the first examples of actions with both conservative and dissipative parts of positive measure.

- In the course of my work on the aforementioned joint paper with R. Grigorchuk and T. Nagnibeda I came across a number of very natural questions related to the notions of conservativity and dissipativity for general measure class preserving actions of countable groups. It resulted in a short note entitled *Hopf decomposition and horospheric limit sets.* By looking at the relationship between the recurrence properties of a countable group action with a quasi-invariant measure and the structure of its ergodic components I establish a simple general description of the Hopf decomposition of the action into the conservative and the dissipative parts in terms of the Radon–Nikodym derivatives of the action. As an application I prove that the conservative part of the boundary action of a discrete group of isometries of a Gromov hyperbolic space with respect to any invariant quasi-conformal stream coincides (mod 0) with the big horospheric limit set of the group.

- In discussions with Florian Sobieczky (Technical University, Graz) we have basically completed (still to be written up though) a study of asymptotic properties of *Horospheric products of random trees* (including the issues of amenability and boundary behavior of simple random walks on them). The main tool in our analysis is the theory of graphed measured (in this particular case "treeed") equivalence relation and the new notion of "conformal" random trees (based, in particular, on an analysis of the growth properties of random Galton–Watson trees).

- The previous work has naturally prompted the question about the *Structure of treed equivalence relations with an invariant measure* in general. I have discussed this problem with Michail Gordin (Steklov Institute, St. Petersburg), but this work is still at a rather preliminary stage.

- Another project in progress started during my stay at ESI and related to the theory of equivalence relation is the work with Ekaterina Sava (Technical University, Graz) on the *Quantitative invariants of random walks on groupoids* (in particular, the asymptotic entropy). This is a very general model which generalizes random walks on groups, their various extensions (like random walks in random environment, with internal degrees of freedom, with random transition probabilities, etc.) and random walks on equivalence relations within the framework of a single theory.

- Several other projects discussed during my stay at ESI and prone to a further development are: *Self-similar pseudo-groups and groupoids* (with Andrzej Bis, University of Lódz), *Applications of amenability in algebraic geometry* (with Boris Shoikhet, University of Luxemburg), *Random knots, braid groups and their applications in theoretical physics* (with Mikhail Monastyrsky, ITEP, Moscow)

I would like to use this opportunity and to thank the Erwin Schrödinger Institute once again for awarding me its Senior Research Fellowship and for excellent and very stimulating working conditions.

Miroslav Englis: Analysis on Complex Symmetric Spaces

Course: The lectures consisted of two parts. The first part, delivered in January 2007, was of introductory nature, concentrating on prerequisites on reproducing kernel Hilbert spaces, several complex variables, and group representations, and culminating in the thorough discussion of the Fock (Segal-Bargmann) space and associated Toeplitz (anti-Wick), Hankel, and Weyl operator calculi.

The second part resumed in the beginning of March and continued to the end of April. It began by a detailed treatment of the simplest non-Euclidean situation, the Poincare disc, which already captures a lot of the phenomena that occur in the general case. In particular, the topics discussed included the various spaces of holomorphic functions, invariant measures and operators, basic ideas of non-Euclidean harmonic analysis, and Toeplitz and Hankel type operators in this context. Finally the most general case of bounded symmetric domains was treated, with the generalizations of the various objects to this context and their applications in mathematical physics, related questions from operator theory, and the like. Possible extensions of the whole theory beyond the symmetric setting, i.e. to general pseudoconvex domains in $\mathbb{C}^n$, were mentioned very briefly.

The course was attended mostly by graduate students from the NuHAG group of the University of Vienna, but also by some ESI junior fellows and visitors. Especially for the benefit of the former, I paid a special attention throughout the lectures to connections with time-frequency analysis and related areas. I also took part in two NuHAG seminars, and had a number of fruitful discussions with several students and NuHAG members. My other, thought less intensive, contact was with the prof. Haslinger, including a talk on his complex analysis seminar.

An expanded version of the lecture notes from the course is being prepared for possible publication in the ESI Lecture Notes series; these are progressing at a slower pace then I would wish, but I hope to have a first draft available in 2008.

Research: The wonderfully peaceful and stimulating ambiance of ESI gave me the opportunity to produce three papers related to the area of my lectures, which would probably not come into being otherwise or would at least appear much later; I am adding these to the ESI preprint collection. Beside them, I have also developed ideas for another paper, which is now being finished jointly with R. Rochberg. Yet one more paper may possibly result in future, based on discussions with Prof. Gröchenig.

Preprints contributed: [2000], [2001], [2002]

Thomas Mohaupt: Black holes, supersymmetry and strings (Part II)

Course: The idea of the course was to bridge the gap between a first introduction to general relativity and the description of black holes in string theory, including recent developments. For organizational reasons I had to to split my stay at the ESI into two blocks of four weeks each (November 2006 and May/June 2007). During each block there were nine lectures, supplemented by seminars dedicated to problems posed during the lectures.

The first two lectures reviewed the Schwarzschild and Kerr solutions of Einstein gravity and introduced the concept of black hole event horizons, both from the local and global point of view (gravitational redshift, surface gravity, Killing horizons, geometry of null hypersurfaces, conformal diagrams). In the next two lectures we went through the proofs of the zeroth and first law of black hole mechanics, using the approach pioneered by R. Wald and his coworkers, which applies to any gravitational theory based on an action invariant under diffeomorphisms. We saw why in the presence of higher curvature terms the naive area law needs to be replaced by a more complicated expression involving integrals of functional derivatives of the action over the horizon.

The next lecture introduced Einstein-Maxwell theory, electric-magnetic duality, and the Reissner-Nordstrom solution. We gave a detailed account of the special properties of the extreme Reissner-Nordstrom solution and its multi-centered extension (Majumdar-Papapetrou solution), motivating the subsequent study of $N = 2$ supergravity, which is the supersymmetric extension of Einstein-Maxwell theory. The final four lectures of the first block were devoted to black hole solutions in supergravity. After a brief outline of the representation theory of the $N = 2$ supersymmetry algebra, the construction of matter coupled $N = 2$ supergravity was described in considerable detail. We choose the approach based on the superconformal calculus, which allows to perform the construction off-shell, and to include a class of higher curvature terms appearing in string theory. The so-called special geometry of the scalar fields (affine and projective special Kähler manifolds) was explained in detail. In the final lecture we introduced the concept of BPS solitons, encountered the black hole attractor mechanism, and presented the general class of stationary solutions with four Killing spinors. These solutions contain corrections coming from an infinite series of higher derivative terms in the action, which are encoded in the so-called Weyl multiplet.

The first lecture of the second block started with a detailed overview of the four laws of black hole mechanics, covering both classical and quantum aspects, and discussing their tentative thermodynamical interpretation. In the second part of the lecture we reviewed how gravity is described in string theory, putting emphasis on the complementary perspectives of the microscopic worldsheet description and the macroscopic space-time effective field theory. This naturally lead to a discussion of the heuristic string-black hole correspondence introduced by L. Susskind in 1993. The main goal of the second block of lectures was to develop the quantitative, supersymmetric version of this correspondence, which has been formulated recently. Black hole microstate counting was explained in detail using the simplest example provided by toroidal compactification of the heterotic string. One lecture was devoted to a review of the heterotic string and the derivation of its massless and BPS spectrum in toroidal compactification. In the next lecture we derived the partition function and, subsequently, an integral representation for the BPS states (short representations of the $N = 4$ supersymmetry algebra), and reviewed modular forms. The problem of finding the asymptotic degeneracy of BPS states, which are the tentative microstates of a black hole carrying the same quantum numbers, turned out to be related to the classical problem of counting partitions of an integer, already studied by Hardy and Ramanujan. While the saddle point evaluation of the state degeneracy was left to the students as an exercise, the exact evaluation (Rademacher expansion) was presented in the next lecture. Following R. Dijkgraaf et al, we used the Poincaré series and the 'Farey Tail Transform', rather than Rademacher's

'Kreisbogenmethode'.

In order to corroborate the conjecture that the states just counted are indeed the black hole microstates, we needed to construct the corresponding black hole solutions and to compute their entropy. We started by reviewing the four-dimensional effective field theory of the toroidally compactified heterotic string, which is matter coupled $N = 4$ supergravity, and explained how this theory can be described using the $N = 2$ formalism introduced in the first block. In the following lecture we presented the solutions for the near horizon geometry and black hole entropy, emphasizing the corrections due to higher derivative terms in the effective action. The observed matching between black hole entropy and string state counting is subtle, because it requires to take into account both the explicit modification of the horizon area by higher derivative corrections and the deviation from the naive area law implied by Wald's derivation of the first law of black hole mechanics.

The final three lectures covered subleading corrections to both entropy and state counting, and further developments. In the seventh lecture we introduced a variational principle for extremal black holes and defined black hole partition functions. Then we gave a critical discussion of a conjecture put forward by H. Ooguri, A. Strominger and C. Vafa ('OSV conjecture'), which relates black hole partition functions to string partition functions. The eighth lecture reviewed the successful test of the conjecture for so-called large black holes, corresponding to intermediate rather than short representations of the $N = 4$ supersymmetry algebra. In this case the microscopic description involves five-branes rather than strings. The derivation of the state counting formula of Dijkgraaf, Verlinde and Verlinde was sketched, which can be viewed as a generalisation of the work of Hardy and Ramanujan to Siegel modular forms. Using the variational principle we could show that the OSV conjecture predicts the state degeneracy correctly, including an infinite series of instanton corrections and so-called non-holomorphic corrections. In the final lecture tests of the OSV conjecture for so-called small black holes (short representations of the $N = 4$ supersymmetry algebra) were discussed, leading to an overview of open problems.

Seminars: Throughout the lectures it was suggested to the students to carry out parts and details of calculations which could not be presented in the lectures for lack of time. During the first block these problems were mainly concerned with the geometry of Killing horizons and the laws of black hole mechanics. In the second block we suggested a mini-project on microstate counting, which culminated in the saddle point evaluation of the state degeneracy.

Research: During the two stays at ESI, I was visited by my coworkers Bernard de Wit (U. Utrecht), Gabriel Lopes Cardoso (LMU Munich) and Ulrich Theis (U. Jena). We investigated problems closely related to the topics of my lectures, i.p., further tests and refinements of the OSV conjecture and the relation between black holes and instantons. I also found time to revise and substantially extend my overview article on special geometry, which will appear in the 'Handbook of Pseudo-Riemannian Geometry and Supersymmetry'. The proceedings contribution for the 'International Workshop on High Energy Theory' at IIT Roorkee (India) was written during my second stay, and the style of the presentation was inspired by the lectures given at the ESI. I also found time to construct a new class of instanton solutions in Euclidean $N = 2$ supergravity, which will be published in a joined article with V. Cortés (U. Hamburg).

Acknowledgment: I would like to thank the ESI for the opportunity to give this lecture series, and for providing a very pleasant environment during my visit. The lively and active participation of the groups of Prof. Kreuzer and Prof. Grosse contributed much to the success of the lectures.

Preprints contributed: [1990]

Christos N. Likos: Introduction to Theoretical Soft Matter Physics

Course: In this course, we first presented a general introduction to the systems that are broadly classified under the term "Soft Matter". These encompass colloids of various shapes, polymers of a very large variety of architectures, micelles, rods, membranes, polyelectrolytes etc. We emphasized that the common characteristic of all these lies in the occurrence of *mesoscopic structural length scales* in the problem, associated with the fact that soft matter consists of mesoscopic entities dissolved in a microscopic solvent.

To deal with the complicated statistical-mechanical problem, we rigorously derived the strategy of *coarse-graining*, introducing thereby the concept of effective interactions. We showed how spontaneous, correlated dipole-dipole fluctuations lead to the ubiquitous van der Waals, or dispersion, attractions between colloids. Thereby, we introduced charge- and steric stabilization as means to overcome the attractions.

We further discussed in some details some basic notions from polymer physics, starting from the random walk and proceeding to its self-avoiding version, which model the statistics of real chains in a good solvent. Afterward, we went into quite some detail into the theory of structure and thermodynamics of classical liquids and liquid mixtures, including the theory of liquid-gas phase transition and of crystallization.

At the last part of the course, we discussed in depth the principles and applications of Density Functional Theory (DFT), which allows for a unified treatment of the properties of both homogeneous and inhomogeneous fluids and their mixtures. After spending a few lectures to thoroughly understand the mathematical uniqueness and minimization theorems of the free energy functional, we derived specific, accurate functionals to analyze: demixing transitions; the calculation of the free interfaces; and wetting. In a specific application, we also applied DFT to understand various scenarios of cluster formation that are in soft matter systems. We also briefly discussed computer simulation techniques.

The course was attended throughout the semester by 6 to 15 participants, most of them being Graduate students at the University of Vienna or the Vienna University of Technology. Each student submitted a short research report in lieu of regular exercises, which would have been rather inappropriate for a research-oriented course.

Research: My main research partner in Vienna has been Prof. Dr. Gerhard Kahl from the TU Wien, with whom we have carried on our collaboration on a number of topics. Mainly, we focused on the further development and application of genetic algorithms, which resulted in one paper already accepted for publication (submitted in the preprint server), as well as one more coming up. We have carried out extended and detailed research on work to-date on GAs, with the goals of (a) writing together a review article (in preparation) and refining the technique to meet the needs of soft matter research. In addition, we put the finishing touches on work that preceded my stat at ESI, and which has just appeared in print [Physical Review Letters 100, 028301 (2008).] Further contacts were established with Prof. Dr. Christoph Dellago from the University of Vienna, pertaining to the study of nucleation in cluster-forming systems.

I continued and completed work on the effective forces between polyelectrolyte-grafted colloids, in collaboration with Prof. Dr. Friedrich Kremer (Leipzig), submitted as preprint at the ESI-server and being currently under consideration in Physical Review Letters.

Visitors from my group in Düsseldorf and external collaborators: Dr. Federica Lo Verso contributed both to work on genetic algorithms and to independent work on end-functionalized polymers (ESI-preprint). Tobias Tückmantel established important contacts with the Kahl-group and will be visiting them in May, 2008. Sven van Teeffelen and Oliver Jansen had some very fruitful exchanges with the Dellago group. Dr. Emanuela Zaccarelli and Dr. Christian Mayer visited to complete work on glassy soft mixtures (ESI preprint) and established contacts with the Kahl group. Finally, Dr. Ronald Blaak, Dr. Aaron Wynveen and Sebastian Huißmann, all members of the Düsseldorf group, visited the ESI to keep up on common work.

Preprints contributed: [1994], [1995], [1996], [1997]

Radoslav Rashkov: Dualities between gauge theories and strings

First I would like to thank ESI for the appointment as an Senior Research Fellow (October 01-January 31), which gave me the opportunity to do productive research enhancing my expertise and in the same time to enjoy the unique atmosphere of the city of Vienna.

Course:

The idea about the correspondence (duality) between the large N limit of gauge theories and string theory has been developed over the years in many directions. Recently the research in this area became topical in view of expected new experimental results from LHC (CERN). The lectures were based on recent advances on both, the string and the gauge theory sides of the conjectured duality. The aim was to describe the physical ideas and provide mathematical tools to attack the challenges arising in this fascinating area.

The course was divided in four parts. In the first part of the lectures I gave a brief review of (super) string theory. This included the notion of worldsheet symmetries and 2d (super) conformal field theories. Here I recalled basic facts about vertex operators and representations of infinite dimensional algebras.

The next part of the lectures contained the notion of supersymmetry algebra, $\mathcal{N} = 4$ superconformal algebra in four dimensions and their representations. In this part I discussed the properties of $\mathcal{N} = 4$ Supersymmetric Yang-Mills (SYM) theory as well as its derivation from $\mathcal{N} =$ SYM in 10d.

Part III of the lectures dealt with the low-energy limit of string theory and its effective target space action. In this part I discussed in some length D-branes and their dynamics as well as dualities between various string theories. Based on the properties of the branes and the effective geometries accounting for the backreaction, I formulated and discussed the Maldacena conjecture and elaborated on examples demonstrating how the conjectured duality works.

The last part of the lectures dealt with the most recent developments in the area. Many papers have indicated that type IIB string theory on $AdS_5 \times S^5$ and $\mathcal{N} = 4$ super-Yang-Mills (SYM) theory in four dimensions may be integrable in the planar limit (and maybe beyond). The techniques of integrable systems have thus become useful in studying the AdS/CFT correspondence in details. In this part I gave examples of various reductions of the string theory to integrable models. I discussed the integrability of the theory from various points of view using different techniques: reduction to Neumann (Neumann-Rosochatius) model, Pohlmeyer reduction, approximation with certain spin chain models, how one can solve these models by making use of Bethe ansatz. The subsequent discussion of the application of Backlund transformations/dressing method, local and non-local currents/charges etc. was based on the most recent developments in the area.

Although intensive and covering wide range of problems, I enjoyed very much giving this course.

Research:

During my stay at ESI I attended several activities related, or pretty close, to my research interests. The discussions with the participants will certainly have an impact on my future research. These are: ESI workshop “Noncommutative Quantum Field Theory”, EU Network in Noncommutative Geometry, Workshop “Renormalization group flow and Ricci flow”. My stay at ESI was particularly valuable giving me the opportunity to start new projects and continue my collaboration with Prof. M. Kreuzer and his group. Moreover, I enjoyed the fruitful discussions with Prof. Harald Grosse.

I published my research results at ESI in the following preprints: "A Note on the Near Flat Limit for Strings in the Maldacena-Nunez Background", ESI-1983 (with M. Kreuzer and C. Mayrhofer); "Non-Topological Non-Commutativity in String Theory", ESI-1992 (with Sebastian Guttenberg, Manfred Herbst and Maximilian Kreuzer); "On the Anatomy of Multi-Spin Magnon and Single Spike String Solutions", ESI-1993.

The new projects I started at ESI are: on integrable structures of superstring theory in diverse backgrounds and their relations to gauge theories; integrable limits of string theory in non-trivial backgrounds; phenomenological consequences of marginally deformed gauge theories and their string duals; Seiberg-Witten map and effective actions for non-constant B-field.

I highly appreciate the grant provided by the Senior Fellowship Programme to invite visiting researchers in support of on-going and future research projects. The scientists I had invited for this period are Dr. Manfred Herbst, Dr. Hristo Dimov and Prof. Ralph Blumenhagen.

The ESI: This was my first visit to ESI and I would say that it is a perfect place to work (my conclusion should not be a big surprise for those who know the Institute). I want to thank Professor Joachim Schwermer for the invitation and the staff for very warm reception. I benefited from friendly discussions with Prof. Klaus Schmidt, Prof. Joachim Schwermer and Prof. Jakob Yngvason.

Preprints contributed: [1983], [1992], [1993]

Seminars and colloquia outside of conferences

2007 01 09, D. Ben-Zvi: “Introduction to the Geometric Langlands Program”
2007 01 10, O. Biquard: “Non-abelian Hodge theory with Ramifications”
2007 01 18, I. Mirkovic: “Langlands Duality and positive characteristic”
2007 01 19, D. Ben-Zvi: “Geometric Langlands program and real groups”
2007 02 13, G. Henniart: “On mod p Representations of Reductive p-adic Groups”
2007 02 13, W. Luo: “Equidistribution Problems on Siegel Modular Varieties”
2007 02 14, J. Nekovar: “Some Questions about Hilbert Modular Varieties”
2007 02 14, M. Rapoport: “Special Cycles on Shimura Varieties of Unitary Type”
2007 02 14, R. Schmidt: “Local Newforms for GSp(4)”
2007 02 15, P. Colmez: “On the p-adic Local Langlands Correspondence for $GL(2, \mathbb{Q}_p)$”
2007 02 15, T. Wedhorn: “Classification of mod p Reductions of Crystalline Representations”
2007 02 16, G. Muic: “Analytic Continuation of Local Intertwining Operators”
2007 02 16, H. Carayol: “On the Sato - Tate Conjecture”
2007 02 16, J. Wintenberger: “On Serre’s Modularity Conjecture”
2007 02 19, I. Badulescu: “Global discrete series for inner forms of GL(n)”
2007 02 19, J. Rohlfs: “On the cohomology of locally symmetric adele spaces as a module over the Hecke algebra”
2007 02 20, A. Raghuram: “Some period relations for cusp forms on GL(n)”
2007 02 20, B. Nachtergaele: “Lieb-Robinson bounds and the Lieb-Schultz-Mattis Theorem”
2007 02 20, M. Harris: “Potential modularity of odd-dimensional symmetric powers of elliptic curves”
2007 02 20, M. Plenio: “Entanglement and area”
2007 02 20, W. Gan: “Regularized Siegel-Weil formula: a second term identity”
2007 02 21, E. Ullmo: “Around the André-Oort conjecture”
2007 02 21, F. Benatti: “Entropies and algorithmic complexities in quantum spin chains”
2007 02 21, M. Hastings: “Entropy and Entaglement in Quantum Ground States”
2007 02 21, N. Grbac: “On the residual spectrum of Hermitian quaternionic classical groups”
2007 02 22, B. Terhal:”Stochastic Hamiltonians and Their Properties”
2007 02 22, G. Harder: “On the p-ordinary cohomology of arithmetic groups”
2007 02 22, J. Eisert: “Unitary networks, flow and renormalization”
2007 02 23, F. Shahidi: “On Orthogonal and Symplectic Representations of GL(n)”
2007 02 23, T. Osborne: “Approximate locality for quantum systems on graphs”
2007 03 06, T. Büehler: “Some homological characterizations of amenability”
2007 03 08, H. Gottschalk: “AdS/CFT correspondence: lessons from Constructive quantum field theory”
2007 03 08, K. Mallahi-Karai: “Free semi-groups in discrete solvable groups”
2007 03 14, J. Cameron: “Hochschild cohomology of factors with Cartan MASAs”
2007 03 14, M. Weiner: “Local nets of observables and vertex algebras, or: chiral QFT from two

different points of view"
2007 03 16, G. Lechner: "Towards the construction of the O(N)-Sigma models"
2007 03 21, H. Bostelmann: "Renormalization from an abstract point of view"
2007 03 22, M. Belolipetsky: "Counting maximal arithmetic subgroups"
2007 03 22, P. Falco: "Constructive approach to massive and massless Thirring's Quantum Field Model"
2007 03 23, G. Huisken: "The isoperimetric inequality and the mass in General Relativity"
2007 03 29, M. Belolipetsky: "Finiteness theorems for arithmetic reflection groups"
2007 04 04, W. van Suijlekom: "Renormalization of a gauge theory"
2007 04 05, F. Brown: "Multiple Zeta Values, Moduli spaces and periods"
2007 04 05, S. Hollands: "Quantum gauge invariance"
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2007 04 26, I. Todorov: "Building globally conformal invariant quantum field theory models"
2007 04 27, J. Roberts: "Net Bundles"
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2007 06 14, R. Zweimüller: "Measure preserving transformations similar to Markov shifts"
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EKS = Amenability
GHM = Applications of the Renormalization group
HNF = Langlands Duality and Physics
HOL = Spectral Theory and Schrödinger Operators
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