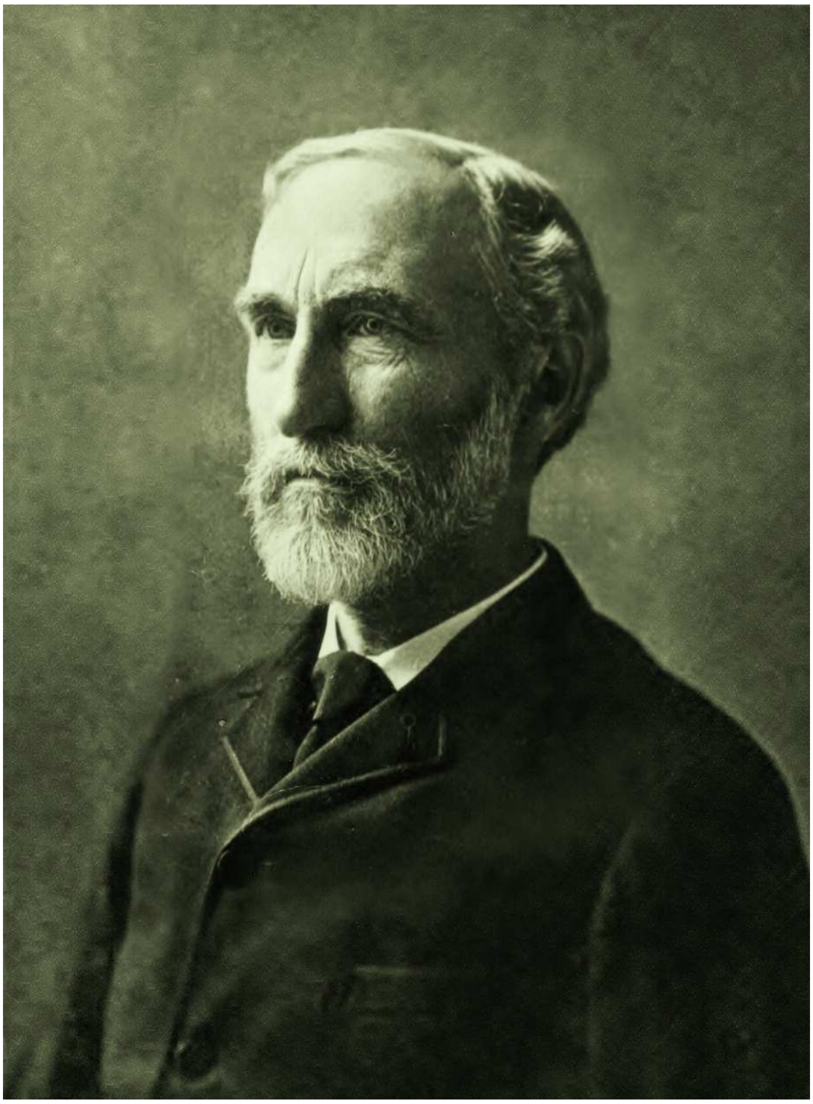
International Association of Mathematical Physics

# News Bulletin

## April 2012



# International Association of Mathematical Physics News Bulletin, April 2012

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*Cover photo:* Josiah Willard Gibbs (February 11, 1839 – April 28, 1903), professor of mathematical physics at Yale in 1871, founding father of Statistical Mechanics, made seminal theoretical contributions to physics, chemistry, and mathematics. In this issue see the Aernout van Enter article about a non-Gibbsian Statistical Mechanics.

# Before the Congress

by Antti Kupiainen (IAMP President)

A much awaited part of the International Congress of Mathematical Physics has in recent years been the prize ceremony taking place during the opening day of the Congress. In that ceremony are awarded the IAMP prizes, which are the Henri Poincaré Prize and the IAMP Early Career Award and also the International Union of Pure and Applied Physics prizes for young scientists. The Henri Poincaré Prize is sometimes called the Nobel prize of IAMP, "recognizing outstanding contributions in mathematical physics" whereas the ECA could be viewed as the analogue of the Fields Medal, being reserved for scientists whose age is less than 35. To qualify to the IUPAP prize one has to have at most eight years of research experience following the PhD.

The Henri Poincaré Prize was instituted in 1997 and funds for it are generously provided by the Daniel Iagolnizer Foundation. The Early Career Award and the IUPAP prizes are much more recent: this year is the second time they are given. The ECA is funded by IAMP, i.e. by our membership dues.

During their relatively short time in existence these prizes have come to occupy an important role in the mathematical physics community. They of course provide us an opportunity to show our appreciation of the best work done in our field, but they also serve as windows through which to portray IAMP to the external world. For these reasons it is important that we devote proper attention to the prize selection process. For the IAMP prizes this process is started every three years by the appointment by the IAMP Executive Committee of a special Prize Committee (or rather two committees for the two categories of prizes). The prize committee will then seek nominations for the prizes from our members and upon reaching a decision presents the proposal for winners to the EC, which upon vote gives the final endorsement.

The EC's have during the past years made every effort to appoint to the prize committees prominent members of our community that are representative of the various fields it contains. I think this has so far worked very well and our prize committees have done an excellent job. However, an equally important part of the process is that of nominations. After all the best expertise on what is happening in our field is to be found among our members. It is unreasonable to expect the prize committee to do the selection process without outside input. This would place too much burden on their time and subject the final choice to the bias that necessarily is in any finite size committee. This is why we call for nominations and indeed by and large there has been good participation by our members. However, unfortunately there is a lot to improve in the care with which the nominations have been done so far. To reach the best results the prize committees need good letters emphasizing the key contributions of the nominees, and a list of experts who could be contacted for more information. This will save their time for the real work they are best qualified to do, namely the comparison of the candidates. Submitting a name, even a well known one, is definitely not enough to be called a nomination letter. However, the typical nomination seems to be more like this than what the committees really would need.

The reason for this state of affairs is of course partly in us, the EC, for not providing more instructions to the nomination process. To remedy this we are going to draft for the next round of nominations directions of what a nomination letter is supposed to contain. Although a proper nomination requires more work on part of the proposer I hope it does not diminish the desire by our members to make proposals.

Let me finish this note by a small bit of reminiscence. The first time I took part in ICMP was 33 years ago in the Lausanne meeting right after finishing my PhD. I still remember vividly how terrified I was when I was entering the podium to give my first conference talk ever. I also remember the excitement of participating in this great gathering of my community. There are nowadays of course many more meetings than in those times, but large congresses providing a panorama of a whole field are still not that common. Mathematical physics is a bigger field than in those days and nobody masters more than a small corner of it, but nevertheless we have a community with enough common language to be able to follow at least all the plenary talks of the ICMP. Thus send your students and postdocs to Aalborg this August to provide them that excitement and to keep our community thriving!

# Stochastic integrability and the KPZ equation

by Herbert Spohn (Munich, Germany)

*Herbert Spohn received his Ph.D. in physics at the Ludwig-Maximilians-Universität, München. He is now professor for Mathematical Physics at the Zentrum Mathematik, Technical University Munich, with joint appointment in the Physics Department. His main research focus is nonequilibrium statistical mechanics. He has published "Large Scale Dynamics of Interacting Particles" with Springer-Verlag and "Dynamics of Charged Particles and Their Radiation Field" with Cambridge University Press.*

*Spohn was awarded the 2011 Dannie Heineman Prize for Mathematical Physics, the 2011 Leonard Eisenbud Prize for Mathematics and Physics, the 2011 Caterina Tomassoni Prize, and a Ph.D. honoris causa of Université Paris-Dauphine. He served in the IAMP executive committee 1997–1999 and as president 2000–2002.*

As a common experience from basic courses in Classical Mechanics, for some mechanical systems the equations of motion can be solved up to quadratures, while others persist to deny such access. This experience can be formalized and leads to the notion of an integrable system. For a Hamiltonian system with $n$ degrees of freedom, one requires to have at least $n$ functions on phase space, $H_j$, $j = 1, \dots, n$, which are in involution, meaning that the Poisson brackets $\{H_i, H_j\} = 0$ for $i, j = 1, \dots, n$, see [1] for details. $H_1$, say, is the system's Hamiltonian. Then the manifold $\{H_j = c_j, j = 1, \dots, n\}$ has the structure of an $n$-torus and the motion is characterized by at most $n$ frequencies. Hence, up to deformation, the motion looks like the well-known Lissajous figures.

The text book example is the motion of a particle subject to a central potential. More spectacular is the observation that integrability persists for particular systems with a large number of degrees of freedom, which first surfaced indirectly through the discovery of solitary wave solutions by N.J. Zabusky and M.D. Kruskal [2] for the Korteweg-de-Vries equation in one dimension and for a chain of nonlinear coupled oscillators by M. Toda [3]. A very rich field ensued. In the following my focus will be on the aspect of many interacting components.

Naturally one may wonder how integrability survives under quantization. A Hamiltonian operator, $H$, allows for many commuting operators. Thus a simple minded extension from the classical case will not do and there seems to be no generally agreed upon definition of quantum integrability. On the other side there are clear signatures to identify a quantum integrable system (once it is found), to name only a few: the Bethe ansatz, the Yang-Baxter equation, and a factorized $S$-matrix.

From the perspective of statistical mechanics it is also a natural issue to understand whether and how integrability extends to stochastic systems. To have one distinction very clear, many systems of 2D equilibrium statistical mechanics are integrable, the correspondence being related to the fact that the transfer matrix has a structure akin to a quantum integrable system. In contrast, here I discuss stochastic time evolutions modeled as a Markov process, either diffusion or jump. As a linear operator, the generator, $L$, of the Markov process has possibly some structural similarity to $-H$, hence it seems reasonable to expect a corresponding version of integrability. On the other side, $\mathrm{e}^{Lt}$ is already the normalized transition probability; there are no probability amplitudes, the partition function equals 1, and the largest real part of the eigenvalues is 0.

With R. Dobrushin the Russian probability school pioneered the many component aspect. Integrability is usually first associated with R. Glauber's exact solution of the one-dimensional stochastic Ising model [4]. This solution is based on what is now called duality, a concept introduced and generalized to other systems by F. Spitzer in the very influential article [5]. The dual description is here in terms of evolution equations for the time-dependent correlation functions, which decouple for integrable systems. An example is the symmetric simple exclusion process on the one-dimensional lattice $\mathbb{Z}$. In this model there is at most one particle per site and, under this restriction, particles perform independently nearest neighbor symmetric random walks. The generator $L$ equals $-H$ with $H$ the Hamiltonian of the ferromagnetic Heisenberg chain. (In this case, duality holds in arbitrary dimension and also for longer-range symmetric jumps.)

On the level of duality, none of the signatures known for quantum integrability make their appearance. This situation changes drastically as we turn to the asymmetric version of the simple exclusion process, ASEP (now 1D and n.n. do matter). A particle at site $j$ jumps to site $j+1$ with rate $p$ and to site $j-1$ with rate $q$, $q+p=1$, provided the destination site happens to be empty. The symmetric case corresponds to $q=p=\frac{1}{2}$. The generator can be written in the notation of quantum spin chains. If $\sigma_j^z = 1$ means site $j$ is occupied by a particle, then

$$L = \frac{1}{4}\sum_{j\in\mathbb{Z}} \big(\vec{\sigma}_j \cdot \vec{\sigma}_{j+1} - 1 + 2i(p-q)(\sigma_j^x\sigma_{j+1}^y - \sigma_j^y\sigma_{j+1}^x)\big)\,. \tag{1}$$

Note that $L$ is not symmetric. All eigenvalues are in the open left hand plane except for 0. On a ring with a fixed number of particles, the unique invariant measure is the uniform distribution. The other eigenvectors are determined through the Bethe ansatz [6]. Much more powerful is the Bethe ansatz inspired expression for the transition probability $\mathrm{e}^{Lt}$ discovered by C. Tracy an H. Widom [7]. Their expression is still extremely complicated and to simplify further one has to specify some initial conditions. A widely studied choice is the initial step, for which the half lattice $\{j\leq 0\}$ is empty and $\{j\geq 1\}$ is occupied. For $q>p$ Tracy and Widom write a Fredholm determinant for the probability distribution of $x_j(t)$, the position of the $j$-th particle at time $t$. Much earlier K. Johansson [8] found a distinct Fredholm determinant for a related quantity in the totally asymmetric limit $q=1$ (TASEP). Both results serve as the stepping stone for an intricate asymptotic analysis eventually arriving at objects familiar from random matrix theory.

Very recently one accomplished to cross the border from discrete jump processes to a particular stochastic PDE, which reads

$$\frac{\partial}{\partial t}h = \frac{1}{2}\big(\frac{\partial}{\partial x}h\big)^2 + \frac{1}{2}\frac{\partial^2}{\partial x^2}h + W\,, \quad x\in\mathbb{R}\,,\, t\geq 0\,, \tag{2}$$

and is the 1D version of the equation first proposed by Kardar, Parisi, and Zhang [9] as a model for growing interfaces. Here $h(x,t)$ is viewed as a height function and $W(x,t)$ is white noise in space-time. Integrability is seen most explicitly for the sharp wedge initial condition,

$$h(x,0) = -\frac{1}{\delta}|x| \quad \text{with } \delta \to 0\,, \tag{3}$$

which, at $\delta = 1$, should be understood as the analogue of the once integrated initial step. (2) together with (3) looks very singular, and it is. For smooth initial data the solution is constructed by L. Bertini and G. Giacomin [10] and for the sharp wedge in [11].

The KPZ equation turns linear through the Cole-Hopf transformation

$$Z = \mathrm{e}^{h}\,. \tag{4}$$

Then

$$\frac{\partial}{\partial t} Z = \frac{1}{2}\frac{\partial^2}{\partial x^2} Z + WZ\,, \quad Z(x,0) = \delta(x)\,, \tag{5}$$

from which one concludes that the exponential moments of $h$ are linked to the attractive $\delta$-Bose gas in one dimension, which is a quantum integrable system solvable through the Bethe ansatz. For example, for (2) together with (3),

$$\mathbb{E}(Z(0,t)^n) = \langle 0|\mathrm{e}^{-tH_n}|0\rangle \tag{6}$$

with $H_n$ the $n$ particle attractive Lieb-Liniger hamiltonian,

$$H_n = -\frac{1}{2}\sum_{j=1}^{n}\frac{\partial^2}{\partial x_j^2} - \frac{1}{2}\sum_{i\neq j=1}^{n}\delta(x_i - x_j)\,, \tag{7}$$

and $|0\rangle$ the state where all $n$ quantum particles are at 0. Unfortunately, the moments in (6) increase as $\exp(n^3)$, which makes a rigorous control difficult. But replica schemes have been employed and yield fascinating results [12, 13, 14, 15, 16].

Currently the integrability of the KPZ equation can be deduced only indirectly by taking a continuum limit of the asymmetric simple exclusion process, where the lattice spacing is $\varepsilon$, the time scale $\varepsilon^{-2}$, and the asymmetry $q - p = \sqrt{\varepsilon}$ with $\varepsilon \ll 1$. To give an impression, I record the generating function for the height at the origin at time $t$,

$$\mathbb{E}\big(\exp\big[-\mathrm{e}^{-s}\mathrm{e}^{h(t)+(t/24)}\big]\big) = \det(1 - P_0 K_{s,t} P_0)\,. \tag{8}$$

Here the determinant is in $L^2(\mathbb{R})$, $P_0$ projects onto $[0,\infty)$, and $K_{s,t}$ is an operator with integral kernel

$$K_{s,t}(x,y) = \int_{\mathbb{R}} \big(1 + \mathrm{e}^{-(t/2)^{1/3}\lambda + s}\big)^{-1} \mathrm{Ai}(x+\lambda)\mathrm{Ai}(y+\lambda)\mathrm{d}\lambda \tag{9}$$

with Ai the Airy function. $P_0 K_{s,t} P_0$ is of trace-class. For large $t$, $h(t) \cong -t/24 + (t/2)^{1/3}\xi$, where the random amplitude $\xi$ is Tracy-Widom distributed, just as is the largest eigenvalue of a GUE random matrix in the large $N$ limit. (8) together with (9) was obtained independently in [11, 17, 18]. In this context the introductory review [19] is highly recommended, with some complementary information provided in [20].

The integrability of the KPZ equation triggered further advances. One interesting direction is to consider discretized versions of the stochastic heat equation (5). Somewhat unexpectedly, the completely asymmetric discretization turns out to be more tractable and one starts from the equations of motion

$$\frac{d}{dt}Z_j(t) = Z_{j-1}(t) - Z_j(t) + \big(\tfrac{d}{dt}b_j(t)\big)Z_j(t)\,, \quad Z_j(0) = \delta_{j0}\,,\ j \in \mathbb{Z}\,, \tag{10}$$

where $\{b_j(t), j \in \mathbb{Z}\}$ is a collection of independent, standard Brownian motions. N. O'Connell [21] established a close connection between $\log Z_n(t)$ and the last particle in the open quantum Toda chain of $n$ sites. Very recently A. Borodin and I. Corwin [22] explain how Macdonald functions enter the picture. They are the eigenfunctions of the commuting set of Macdonald operators. In the future, for sure, the interface between stochastic and quantum integrability will be further elucidated.

While we emphasized the notion of integrability, let me add as a fairly extended footnote that the predictions based on the exact solutions have been confirmed recently in spectacular experiments [23], see also the expository article [24]. Of course, physical systems are much more complex than simple models like the TASEP. But on a large space-time scale microscopic details hardly matter, except for generic properties, like the condition of a sufficiently local update rule. In fact, such universal behavior can be proved for the integrable models discussed, but it should hold at much greater generality, including physical systems. In the experiment [23] one studies droplet growth in a thin film of turbulent liquid crystal. The film thickness is 12 $\mu$m, while the droplet grows laterally to a size of several mm. The droplet consists of the stable DSM2 phase and is embedded in the metastable DSM1 phase. Hence the interface is a line and it advances through nucleation events where the stable phase is created out of the metastable one. On average, the solution to the KPZ equation with sharp wedge initial data has a parabolic profile which self-similarly widens linearly in $t$ and thus models one section of the droplet. By the physical conditions, the droplet growth is isotropic, guaranteeing that the non-universal coefficients do not depend on the direction of growth, which is the basis for high precision sampling of entire probability density functions. In fact, the GUE Tracy-Widom distribution for the height fluctuations is confirmed with accuracy. It is also observed that for flat initial conditions, $h(x, 0) = 0$, the height fluctuations switch from GUE to GOE statistics, implying that some features of the initial conditions are still visible in the large scale universal limit.

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# Negligible numbers

by Olaf Teschke (Zentralblatt MATH / FIZ Karlsruhe, Germany)

*This article first appeared in the EMS Newsletter 82, December 2011. Reprinted with permission.*

The question "Who is the top author in mathematics?" may appear to be a less sensible one, but some weeks ago, Microsoft[1] was bold enough to answer this: it's Claude Shannon with more than 11,000 citations, followed by Warren Weaver and Barry Simon. The Top Ten were completed by Ingrid Daubechies, Elias M. Stein, Sir Michael Atiyah, William Feller, Scott Kirkpatrick, Mario P. Vecchi and C.D. Gelatt - making up a list one would expect from such an attempt: objective, transparent, and meaning nothing.[2]

Actually, less transparent, after looking into the details. Having such a ranking, one might ask what might be the origin of the most blatant failures for inclusion and omission. In general, mistakes of the first type are more obvious, and can be usually traced back to some systematic misconceptions of the criteria (or even, as in the case of several recent events pertaining ISI rankings, active enhancement of the data). In the list above, Kirkpatrick, Vecchi and Gelatt reached their position due to their single *Science* publication on simulated annealing. The main contribution to the citation count comes from outside mathematics, so the completely different citation behaviour in another discipline is sufficient to push a single borderline article.

On the other hand, knowing the vast citations in physics, one might wonder why e.g. Witten didn't made it to the top: the simple answer is that he is just not considered by Microsoft as a mathematician, so his more than 31,000 citations didn't help. Merely a standard remark is that people from outside the American System are typically mistreated by such measures: No comparable citation achievements for Kolmogorov or Gelfand. A funny footnote is that both Bernhard Riemann the German-writing guy (36) and Bernhard Riemann the English-writing guy (26) belong to the very bottom. (I won't go into the often discussed details for journal rankings - it might be sufficient to say that the *Annals* don't make it into the top 20 of the Microsoft Math ranking).

The example illustrates, in a nutshell, some of the problems inherent to bibliometric computations:

Systems, classification, and data quality may influence the outcome heavily. There are many possible error sources, and the dependence on the input is not stable: A misassigned single publication may completely change the results. (Which, by the way, also contradicts one of the main assumptions of bibliometrics: that it is sufficient to evaluate a small fraction of "core data" to obtain comprehensive results). Nice interfaces and

[1] http://academic.research.microsoft.com/?SearchDomain=15

[2] Now, a few weeks later, the site has switched to another bibliometric ranking criterion as a standard, the H-index. This result is a quite different top list, where Shannon goes to math oblivion, while Simon, Atiyah, Lions, Yau and Fan are in the top).

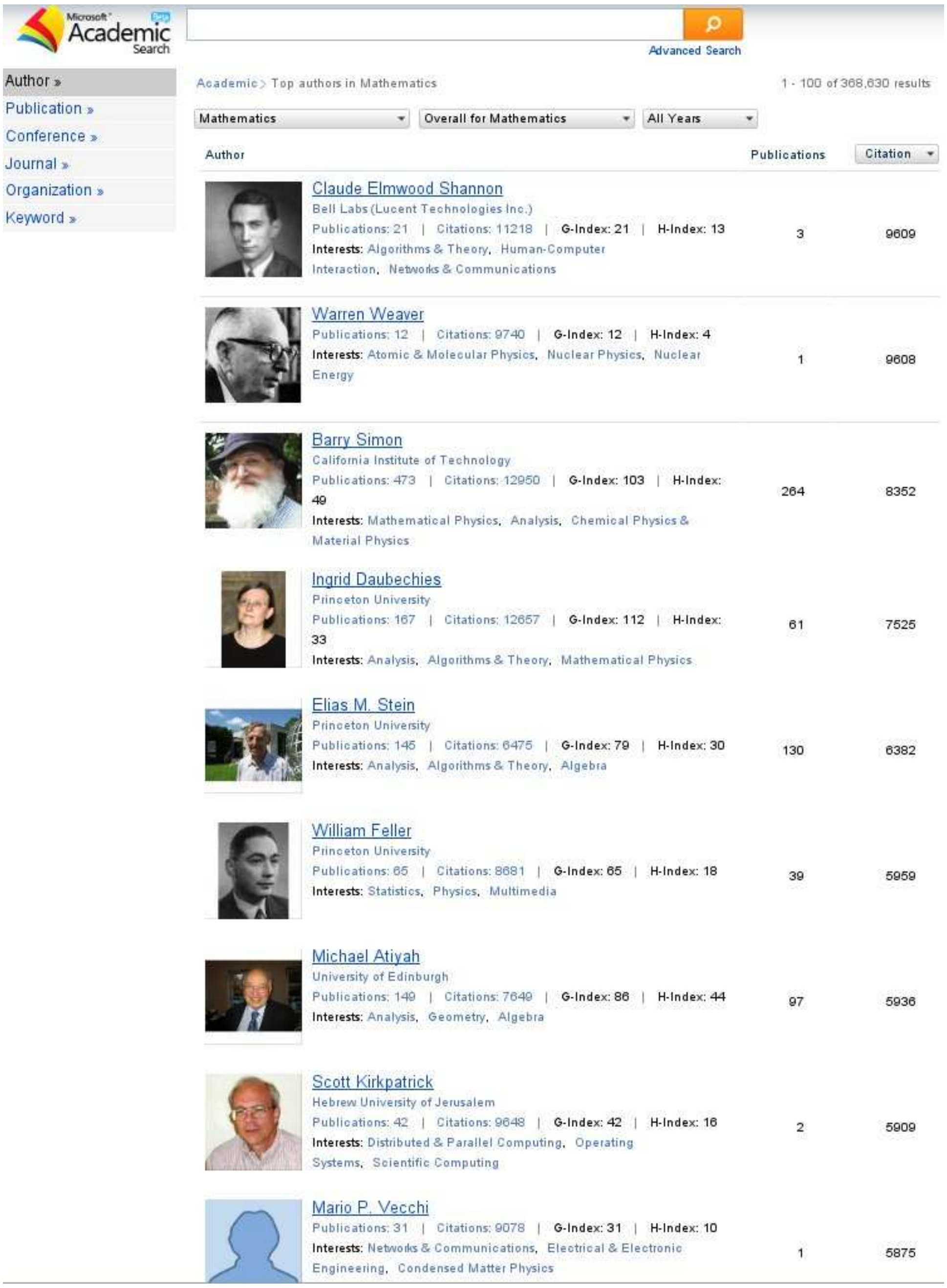


Figure 1: Top mathematicians, according to a certain citation count.

features may be tempting for the user, but are no good replacement for contents; indeed, the generation of pseudo-knowledge may often be more dangerous than no information at all.

With a continuing demand for citation-related measures, however, it was at least worth a try to investigate what might be the outcome on a corpus like the Zentralblatt MATH database, which is both more homogeneous and far more complete in its area compared to the example above (Microsoft considers about 1 Mio. articles as mathematics which include a lot of descriptive statistics and computer science compared to $> 3$ Mio. in Zentralblatt MATH). With the addition of a considerable amount of references during the last two years, one might at least hope to have a critical mass; and there might be the hope that some intrinsic knowledge of the data originating from mathematics may help to avoid common pitfalls.

The starting point were about $7,000,000$ (raw) reference data in Zentralblatt MATH, which contain about $5,000,000$ in display-ready format and about $4,000,000$ reliably identified (a necessary basis for statistics). One immediately realizes that this means only a small fraction of the 3 Mio. articles have such reference lists — indeed, the number is about $200,000$ (or less than 10%). The main difficulty is, indeed, getting reliable data — the scale of the figures is indeed similar to those in MathSciNet (ca. $5,500,000$ identified references for about $300,000$ articles of 2.7 Mio.) or ISI ($< 100$ journals both in the lists of pure and applied mathematics compared to $> 2000$ currently existing). The exclusion of most journals (like e.g. Chaos, Solitons & Fractals or International Journal of Nonlinear Sciences and Numerical Simulation whose citation enhancement has been the topic of recent discussions) from the reference list helps to avoid some distortions but implicitly acknowledges that citation statistics are no suitable objective measure (indeed, an exclusion decision will always be a subjective one, however well-founded).

The possible influence of the uncertainties of the author identification has been already a subject of several articles in this column[3]. By now, the progress is sufficiently substantial to expect only minor errors from this source compared to the influence of the lack of reference data for most articles.

Taking this ambiguity into account, the different samples indicated nevertheless several tendencies. First, in the short scale articles and authors from mathematical physics completely dominated the top lists. Article from the very border of mathematics (like of Albert and Barabási on Statistical mechanics of complex networks) could easily collect enough citations from mathematical physics to make it to every short-term tops. The situation becomes slightly different when enlarging the timescale — to give an impression, we list the 20 top-referenced authors for the overall database: Louis Nirenberg, Barry Simon, Pál Erdős, Theodore E. Simos, Elias M. Stein, Stanley Osher, Shing-Tung Yau, Sir Michael Atiyah, Hans Grauert, Saharon Shelah, Haïm Brézis, Edward Witten, Peter D. Lax, Olvi L. Mangasarian, Jürgen Moser, Michio Jimbo, Isadore M. Singer, Elliott H. Lieb, Chi-Wang Shu, Pierre-Louis Lions. Though this is certainly no longer fully physics-dominated, several heavy biases become visible: at best, one may describe the list as mixed, with citations in some cases collected in a rather short period and thanks to intense citation behaviour in the field, other through decades. The complete absence of several fields of mathematics is especially striking (this continues when going down to the top 50). Obviously, even within pure mathematics, different fields cite differently, so one cannot expect to find anything from a comparison without completely dissolving the unity of mathematics (including the splitting of authors who work in different fields).

[3]See, e.g., EMS Newsletter 79 (March 2011)

On the journal level, it may hence not come as a surprise that (slightly depending on the timescale) mathematical physics perform quite well: their impact factors (for Zentralblatt MATH data) puts e.g. *Archive for Rational Mechanics and Analysis* or *Communications in Mathematical Physics* just behind *Acta Mathematica*, *Annals*, *Inventiones* or *Communications on Pure and Applied Mathematics*, and in front of many others. A good illustration is a correlation display like the one of D. Arnold and K. Fowler for journals in applied mathematics[4]. While they used the four Australian categories for math journals, we performed a similar test for a sample of journals w.r.t. the internal Zentralblatt MATH categories (which serve primarily to decide workflow schedules, but are naturally influenced by their mathematical content):

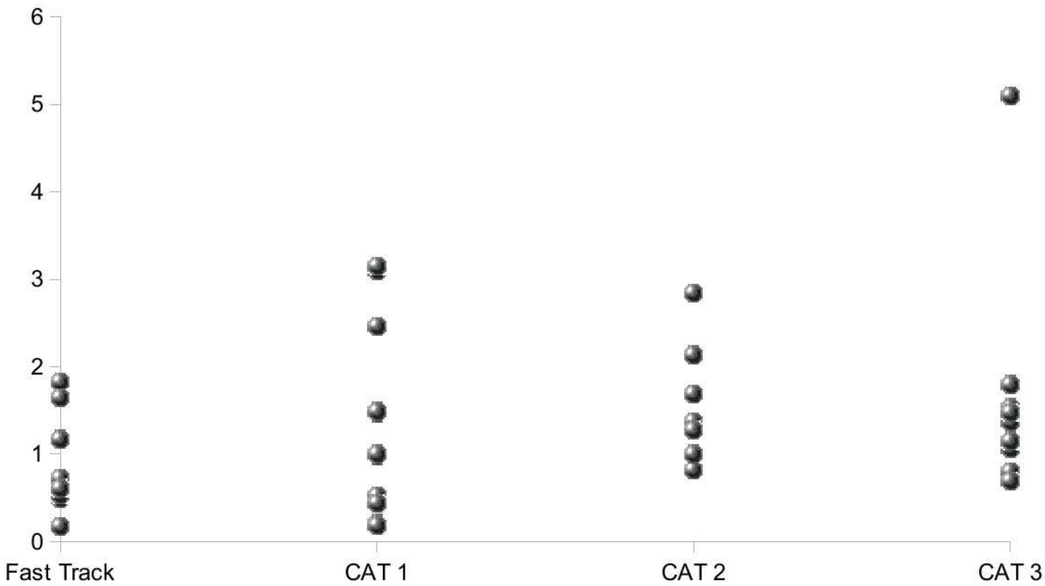


Figure 2: Correlation between impact factor and journal categories

The results are striking - there is even less correlation than in the Arnold/Fowler example. Some patterns can be identified, but only for negative correlation: Fast Track journals with very low impact factors are often high-quality Russian, low category journals with high impact factors belong to the class which has been recently under the suspicion of enhancing citations. As mentioned, the correlation with the field appears to be much higher than with the category.

Finally, there was some hope that one could resolve the effects at least partially by evaluating review citations instead of references. They are much less numerous, and are the result of an additional intellectual analysis. Even more important, they are expected to be much more homogeneous throughout the database. Unfortunately, these expectations are only fulfilled partially. Several negative effects mentioned above can be excluded, but it turns out that reviewers in different fields cite still different within their

[4]Nefarious numbers, EMS Newsletter 80 (June 2011)

reviews. As an example, the top list would now look like Pál Erdős, H. M. Srivastava, Israel M. Gelfand, Sergio Albeverio, Noga Alon, Haïm Brézis, Vladimir G. Mazya, Jean Bourgain, Béla Bollobás and again one would miss some very well-known names.

From a certain viewpoint, the most satisfying results were produced when asking for a huge difference between the publication and the citation: when requiring a mathematical viability of several decades (the Jahrbuch data contribute heavily to such a statistic), one ends up with probably agreeable collections containing Riemann, Poincaré, Hilbert, Hardy, Ramanujan, Banach, Weyl, Kolmogorov, Gödel, von Neumann (all of them, by the way, outdone by their younger colleagues when using other counts). Fortunately, we do not need citation statistics to generate this; unfortunately, it may be hard to convince politicians that such long-term evaluation measures may be best suited for mathematics.

# On the prevalence of non-Gibbsian states in mathematical physics

by Aernout C.D. van Enter (Groningen, The Netherlands)

*Aernout van Enter received his PhD in theoretical physics in 1981 at the University of Groningen (supervisors N.M. Hugenholtz and M. Winnink). After a number of temporary positions at Heidelberg University, the Technion (Haifa) and the University of Texas at Austin, alternating between mathematics and physics departments, he returned to Groningen where he is now an honorary professor in the Johann Bernoulli Institute of Mathematics and Computer Science of Groningen University. He has mainly worked on lattice models in statistical mechanics, both ordered and disordered ones. The theory of Gibbs states and the occurrence of non-Gibbsian states has been one of his main research interests for a number of years.*

Gibbs measures are the main object of study in equilibrium statistical mechanics, and are used in many other contexts, including dynamical systems and ergodic theory, and spatial statistics. However, in a large number of natural instances one encounters measures that are not of Gibbsian form. We present here a number of examples of such non-Gibbsian measures, and discuss some of the underlying mathematical and physical issues to which they gave rise.

## Introduction

### Gibbs measures according to DLR

Gibbs (or DLR) measures, or Gibbs states, are the main objects in classical equilibrium statistical mechanics. They were introduced in the sixties by Dobrushin, Lanford and Ruelle, as probability measures on systems of infinitely many particles (or spins) in infinite volume, satisfying a set of consistent conditional probabilities for configurations in finite volumes, conditioned on external configurations. This is expressed by the so-called DLR equations. These conditional probabilities are of the Gibbsian form $Cst \ \exp -\beta H$, where the Hamiltonian $H$ describes the interactions between particles both inside the volume and between the volume and the outside. In particular for classical lattice models, the theory of infinite-volume statistical mechanics has developed in substantial detail, see e.g. [18]. Gibbs measures also play a role in various other domains, such as Dynamical Systems, non-equilibrium theory, Interacting Particle Systems, Euclidean Quantum Field Theory, ergodic theory, spatial statistics and pattern recognition.

For finite-range interactions, Gibbs measures satisfy a spatial Markov property, for regular infinite-range potentials a weak form thereof, which goes by the names of the " almost Markov" or "quasilocality" property. For discrete bounded-spin models this property is equivalent with the conditional probabilities being continuous functions of the boundary conditions, in the product topology.

It is a nontrivial result that in fact equivalence holds: any measure whose conditional probabilities are quasilocal is a Gibbs measure for a regular interaction, once it satisfies a natural nonnullness condition.

### Effective descriptions and the Gibbs-non-Gibbs question

In many parts of statistical physics use is made of effective interparticle Hamiltonians. That is, one tries to describe a system in which one forgets about small-scale details, but that still can be described by a Hamiltonian, which contains only properties of larger-scale entities. (E.g. an effective molecular Hamiltonian does not include properties of the constituent atoms, electrons or quarks, but only -effective- forces between molecules). To make this notion mathematically precise, that is, to decide if such an effective Hamiltonian exists, the quasilocality property mentioned above needs to be checked for an appropriate measure (in the example above, that would be the measure restricted to all the molecular degrees of freedom). However, it has turned out, initially rather surprisingly, that in many natural examples this quasilocality property is violated, and no regular interaction can be found: the measure is *non-Gibbsian*. Often, the Gibbsian or non-Gibbsian character of a measure depends on certain parameters of the problem under consideration, such as temperature, magnetic field, time, or rescaling parameters, in an a priori non-obvious way.

Examples of such contexts that occur in statistical mechanics are renormalisation group theory, the theory of disordered systems and the theory of stochastic dynamics (interacting particle systems).

In renormalisation group theory, a renormalisation group map is a kind of coarse-graining map. One considers only a subset of coarse-grained or "renormalised" objects (spins, fields), and then considers the restriction or projection of Gibbs states on those. In physical terms, one integrates out some short-range degrees of freedom. In probabilistic terms, one takes the marginal of a probability measure on a subset of random variables, often called the set of "block spins". This renormalised measure then is supposed to be describable by a renormalised Hamiltonian. The philosophy of renormalisation group theory is based on studying the properties of this map from original to renormalised Hamiltonians in some appropriate space. The ultimate goal is to determine the fixed points of this map, together with their stability properties, and to relate them to the critical behaviour inside corresponding "universality classes", which are classes of physical systems with the same critical exponents. In this way, critical behaviour is expected to follow from the properties of certain renormalisation group maps. This paradigm is based on the assumption that such a map exists, in other words, that the renormalised measure *is* in fact a Gibbs measure.

It is precisely this step which has turned out to be doubtful in a variety of circumstances. The first clear indication that defining a well-behaved renormalisation group map might be problematical was found by Griffiths and Pearce [19] and the nature of the problem was identified shortly after by Israel [20]. A first extensive analysis appeared in

[6]. We will see the mechanism in the particularly simple example of the decimation transformation later on. Although in a majority of cases the predictions of the renormalisation group approach about the nature of phase transitions and critical properties are not affected, in some cases, especially in the theory of first-order transitions, non-Gibbsianness results restricted and even excluded renormalisation group descriptions which had been proposed in the physics literature.

Follow-up studies identified a variety of other occurrences of non-Gibbsian measures. A direct generalisation of the above treatment of block-spin maps often works in considering single-site renormalisations, including dicretisations, the so-called "fuzzy" or "amalgamation" maps [2, 9, 34].

Another example is provided by low-temperature Gibbs measures, subjected to a high-temperature or infinite-temperature Glauber (stochastic spin-flip) dynamics. This is an example from the area of interacting particle systems [28], which models a fast heating procedure. The initial Gibbs measure after some finite time can become non-Gibbsian. So instead of raising the temperature [31], one may altogether lose the notion of effective temperature [7]. The proofs of such non-Gibbsianness results are quite similar to the ones in a renormalisation group context, but with the distinction that one may consider now the marginal of a two-time (initial time and end time) system which is of a Gibbsian form. One can in fact go into more detail, and perform a path-space analysis in which the whole dynamics is included [8].

Yet another family of occurrences of non-Gibbsian measures is in the theory of disordered spin systems [1]. In such systems the Hamiltonians contains, next to the spin variables, disorder variables, e.g. occupation numbers or random fields. When a "quenched" disordered measure is non-Gibbsian, that means that one cannot write it as an "annealed" measure, that is a Gibbs measure for an effective Hamiltonian. Physically, in a quenched, fast cooled, system the disorder is frozen, while the spins equilibrate; in other words, the disorder variables are slow and the spins fast. In annealed, slowly cooled, systems the disorder variables equilibrate with the spins, and there is only one timescale, and there are no fast or slow variables. Probabilistically, for a quenched measure the disorder variables are independent, identically distributed; conditioned on the disorder variables the spins are distributed according to a Gibbs measure. Annealed measures are Gibbs measures on a product space of spin and disorder variables. The impossibility of writing a quenched measure as an annealed measure is in contrast to what has been proposed in the physics literature as the Morita approach [11, 23, 25] where one aims to compute a "grand potential", an effective interaction for a quenched measure, viewed as a Gibbs measure (an annealed one).

## Gibbs measures and non-Gibbsian measures

### Notation and Definitions

We will consider lattice spin systems with a single-spin space $\Omega_0$, on a lattice $Z^d$, and a configuration space $\Omega = {\Omega_0}^{Z^D}$. We will, for simplicity, mainly consider Ising models, for which $\Omega_0 = \{-1, +1\}$. We will indicate the spin variables at site $i$ by $\sigma_i$, $\omega_i$, $\eta_i$, and similarly spin configurations in a volume $\Lambda$ by $\sigma_\Lambda$, $\omega_\Lambda$, $\eta_\Lambda$.

We will consider Gibbs measures, which are defined for absolutely summable interactions $\Phi$ via the DLR equations. An interaction $\Phi$ is a (translation-invariant) collection of functions $\Phi_X(\sigma_X)$. Each $\Phi_X$ describes an energy contribution in a finite subset $X$ of the lattice. Absolute summability means that $\sum_{0 \in X} ||\Phi_X|| < \infty$. This implies that any finite change in an infinite-volume configuration only comes with a finite energy cost (or gain), uniformly in the external configuration. Such interactions form an interaction (Banach) space. The DLR equations say that given an external configuration $\eta_{\Lambda^c}$, the probability (density) of configurations in a volume $\Lambda$ is given by the Gibbs expression

$$\mu_\Lambda^{\eta_{\Lambda^c}}(\sigma_\Lambda) = \frac{\exp -\beta H_\Lambda^\Phi(\sigma_\Lambda \eta_{\Lambda^c})}{Z_\Lambda^{\eta_{\Lambda^c}}},$$

where

$$H_\Lambda^\Phi = \sum_{A;\ A \cap \Lambda \neq \emptyset} \Phi_A(\sigma_\Lambda \eta_{\Lambda^c}).$$

This should hold for all volumes $\Lambda$, internal configurations $\sigma_\Lambda$ and external configurations $\eta_{\Lambda^c}$. The conditional probabilities given above have a continuous (in the product topology) version due to the summability of the interaction. This means that the conditional expectation of any local observable cannot change much between two configurations which are identical in a sufficiently large environment, and are different only far away, whatever the configuration in this finite environment is. Each such configuration is thus a point of continuity for each conditional expectation.

It also turns out to be true that a measure having a continuous version of its conditional probabilities, and satisfying a nonnullness (or "finite-energy") condition, is a Gibbs measure for a reasonable interaction. The finite-energy condition for Gibbs measures follows immediately from the absolute summability. See e.g. [6, 15, 18] for further background.

In the standard nearest-neighbour Ising model we have

$$-H_\Lambda = \sum_{<i,j> \in \Lambda} \sigma_i \sigma_j + \sum_{<i \in \Lambda, j \in \Lambda^c>} \sigma_i \eta_j.$$

**Decimating the Ising model, a paradigmatic example**

Decimation, in which one considers just a subset of the spins, is a conceptually easy example of a renormalisation group map. Let us consider the even decimation of the two-dimensional Ising model, in which $\sigma'_{i,j} = \sigma_{2i,2j}$. Thus we consider only a quarter of the spins, namely those on sites with both coordinates even. Those primed spins will be our renormalised or "visible" spins. If the original Gibbs measure is at low enough temperature, the primed measure defined by taking the marginal of this measure on the primed spins is non-Gibbsian. Indeed, let us fix all primed spins in a large box in an alternating configuration. Then the other, "invisible" spins in the box don't feel any influence from them, due to cancellation effects. Thus the conditioned system of the invisible spins, forms a spin system on a lattice with periodic holes, a "decorated" lattice.

Any configuration of the visible (renormalised) spins acts as a condition in a conditional probability of the invisible-spin system, conditioned on it. But it is the alternating configuration which will be the one that we will show to be responsible for non-Gibbsian behaviour.

If in an annulus outside the box all visible spins are plus (that is, they are pointing upwards), we have a plus-like boundary condition, for *any* condition of the invisible spins outside the annulus. Now let us unfix the visible spin at the origin. Then this spin has a positive expectation, larger than some constant, uniformly in the size of the box. Making the visible spins minus outside the box produces a negative expectation. Thus the visible spin at the origin, conditioned on a large surrounding alternating configuration of visible spins has a large change in expectation, when one changes the configuration far away.

Notice that the phase transition in the system of invisible spins gets translated in a nonlocal influence –action at a distance– between the visible spins, violating the quasilocality condition for the measure on the visible spins. This renormalised measure thus is non-Gibbsian. The alternating configuration is a point of discontinuity of the spin at the origin, conditioned on (considered as a function of) the visible spins. This argument works if the temperature is low enough, as the decorated lattice has a strictly lower transition temperature than the original Ising model.

Although there are other choices possible than the alternating configuration, we expect that in fact for most choices of the primed-spin configuration continuity holds.

It can be shown that renormalising different Gibbs measures for the same interaction results in the renormalised measures being either all Gibbsian or all non-Gibbsian.

By similar arguments other decimated measures become non-Gibbsian. This includes a finite number of decimations applied to Ising models in dimension at least two in a weak field at low temperatures, or (arbitrarily often) repeated decimations in zero field at low temperatures. In the zero-field case the alternating configuration is neutral, in that it does not favour either the plus or the minus phase. The Ising model with a small plus field, does not exhibit multiple phases, but conditioning on a configuration which is predominantly minus can induce a phase transition. Thus the presence of a phase transition in the original system is neither necessary, nor sufficient, for the transformed measure to be non-Gibbsian.

On the other hand, at high temperatures, and also for decimation in strong fields, the transformed measures are Gibbsian. Thus, as Griffiths and Pearce [19] already noticed, one can define renormalisation group maps where one does not really need it, away from phase transitions (and even then not always). For mathematical details, see [6]. But even then, the renormalisation group map on the space of summable interactions has unexpected spectral properties, indicating that this space, although giving rise to proper Gibbs measures, is already too large to properly implement renormalisation group ideas in (see [35]).

### Extensions I: Renormalisation, stochastic dynamics, discretisations

The occurrence of non-Gibbsian measures is actually quite widespread. Indeed, in a topological sense, they occur generically, for a residual set (that is, a countable intersection of dense open sets) in the set of probability measures [21].

Similar results as proven above for decimation can be proven for a variety of renormalisation group transformations. For example, one can prove non-Gibbsianness for Ising models subjected to majority-rule transformations (in which a renormalised spin equals the sign of the majority of the spins in a block) at low temperatures in any external field, various random versions thereof (the Kadanoff transformations), etc.

Beyond renormalisation group transformations, similar results hold also for evolved Ising systems, under a high-temperature Glauber (stochastic spin-flip) dynamics. Starting from a low-temperature Gibbs measure in the phase-transition regime, for a short time the evolved measure is Gibbsian, but at larger times it becomes non-Gibbsian, and then it stays so for any finite time in this transient, nonstationary, regime. This is true although the measure converges exponentially fast to a very well-behaved high-temperature Gibbs measure. Other sources of non-Gibbsian measures are single-site coarse-grainings. In the dynamical case the visible spins are evolved spins, and the invisible ones the initial spins. For single-site coarse-graining (fuzzy [34] or amalgamation [2]) maps, fine details become invisible, and one can only observe coarser details, the fuzzy, or amalgamated, spins.

In all these examples, the presence of a transition in the invisible spins, conditioned on some special configuration of the visible spins, gets translated into the fact that this special configuration is a point of discontinuity (a "bad point"). If for no possible conditioning a phase transition occurs, the transformed or evolved measure is a Gibbs measure. This typically happens if the transformation is close to unity. Examples of Gibbsian regimes are very-short-time evolutions, or very fine discretisations for initial systems that are at not too low temperatures.

Let me emphasize that the absence or presence of these transitions is for conditioned systems, and *not* for the original, untransformed system, which may or may not be in a phase transition regime.

### Extensions II: Trees and Mean-Field theory. Path approach

Related results can be proven in a mean-field setting, in this case, the (dis)continuity to be investigated of, for example, a spin expectation, is not any more of that of a function of the external configurations in the product topology. Rather, the conditional expectation value of a spin is seen as a function of some order parameter, such as a magnetisation. This approach has especially been pioneered by C. Külske, see e.g. [26, 30].

In the above context, the "bad points" are exceptional, that is they have measure zero. In other situations, in particular in the random field Ising model, and also for evolved unstable Gibbs measures on trees, it can even happen that *almost all* or *all* configurations become bad [5, 24]. Gibbs measures on trees differ from those on lattices in that, due to the large boundary terms, at low temperatures one can have metastable and even unstable homogeneous Gibbs measures, corresponding to different types of solutions of a self-consistency equation. In this sense they violate the variational principle that says that all Gibbs measures minimise a free energy density. Due to this, the Gibbsian and non-Gibbsian properties of the evolved measures can be very different for different initial

Gibbs measures for the same initial interaction.

Recently, in the dynamical Gibbs-non-Gibbs transitions a more refined analysis has led to the identification of bad objects (bad points or bad measures) as points or measures which can have different, competing, histories. A large-deviation analysis on the level of trajectories in a space of paths then becomes required. The corresponding rate functions are sums of an initial rate function, and a dynamical rate function, which can be computed as a particular Lagrangian by the methods developed in [14]. For these developments we refer to [8, 13, 33, 17]. A bad value of the magnetisation then would be one which can have two quite different origins, starting from either a positive or a negative value, for example.

**Further generalizations. Other sources of non-Gibbsianness.**

The above description has been mostly about discrete-spin models, but extensions to continuous, possibly unbounded, spin systems also exist. In the bounded-spin case of vector models, the case which has in particular been studied is that of stochastic time evolutions, see e.g. [10]. Continuous-spin systems have been studied either be subjected to single-site or weakly interacting diffusions, or (as mentioned before) to discretisation. In the unbounded-spin case, the notion of what is a Gibbs measure for a "decent" interaction becomes a bit more arbitrary. For some of the literature on this issue, see [3, 27, 32]. In the case of discretisation of vector spins one determines the angle of an XY (vector) spin up to finite precision, obtaining a "visible" clock-spin measure, which in the Gibbsian situation has a summable clock-spin interaction, but at very low temperatures becomes non-Gibbsian [9].

Other examples of non-Gibbsian measures abound, including random-cluster (Fortuin-Kasteleyn) measures, invariant measures for stochastic evolutions, g-measures, which satisfy a one-sided version of the continuity (Gibbs) property of their conditional probabilities, lower-dimensional projections of Gibbs measures, sign-fields of massless Gaussians.... See e.g. [16] and for earlier results [15, 6] or the special Vol 10(3) of the journal "Markov Processes and Related Fields". Next to a violation of the quasilocality property, another way of proving non-Gibbsianness which works in some of the above cases, is showing either anomalous large-deviation properties, or a violation of the non-nullness (or finite-energy) condition.

Another, as yet unexplored, direction is about quantum statistical mechanical systems. In this case one is still looking for a characterisation of Gibbs or KMS states which can actually be checked in examples. Conditional probabilities have no analogue in a quantum context, which makes the above classical analysis not applicable.

## Conclusions

Although a variety of examples of non-Gibbsian measures have by now been discovered, the significance of this fact still appears somewhat controversial.

Mathematically, the phenomenon seems quite widespread, and we have developed a fairly systematic approach to handle a lot of examples, many of which are measures showing up in natural circumstances.

One response has been to try to make non-Gibbsian measures " as Gibbsian as possible", by weakening the definition of what a Gibbs measure is. This approach, which was suggested by R.L. Dobrushin, has led to the notions of almost, weak and intuitively weak Gibbs measures [29, 4, 12]. As a warning, it should be noted that the quenched random field Ising measure, which can be shown to be weakly Gibbsian, (that is, one can define a Hamiltonian which is defined almost everywhere with respect to this measure), violates the variational principle [24]. This implies that measures from these classes can be substantially less well-behaved than regular Gibbs measures.

Physically, non-Gibbsianness reflects the presence of some nonlocal correlations, describable by interactions that have an extremely long range. They are not even summable and represent some "actions at a distance". In the theory of the renormalisation group, as applied to critical phenomena, the appearance of long-range interactions often leads to these interactions belonging to a different universality class, even if they are summable. Hence there is serious cause for concern if terms appear which are even worse. Ideally, a renormalisation group map would act on a subspace of interactions within the same universality class.

The fact that a proposed algorithm is mathematically ill-defined may or may not invalidate results which are obtained by approximate methods. However, for a mathematical physicist to develop a systematic understanding when and when not to trust renormalisation-group folklore remains a big challenge. Similar questions arise if one tries to introduce effective temperatures, or effective potentials of the Morita (quenched-as-annealed) type.

If one can prove the Gibbsianness of a measure, one can in principle trust numerical approximations, and hopefully obtain some proper error bounds. However, even that appears to be a much harder problem than one would a priori expect [22].

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# News from the IAMP Executive Committee

## Call for bids for the ICMP 2015

*The executive committee (EC) invites bids for the organization of the ICMP 2015.*

The site of the next ICMP conference will be decided by the EC after non-binding consultation of the general assembly. The site of ICMP 2015 will be decided at the EC meeting in Aalborg in August 2012, following a meeting of the general assembly.

According to IAMP rules, the bid to organize the $(n+1)^{\mathrm{st}}$ ICMP has to be made no later than one month before the $n^{\mathrm{th}}$ ICMP. A letter of application should be sent to the Secretary, preferably in electronic form, no later than July 6, 2012. It should contain a description of the proposed dates and facilities as well as a sketch of the congress budget, in particular, the expected cost per participant.

Bidders are welcome to present their bids at the EC meeting as well as at the General Assembly meeting in Aalborg (on August 5 and 6, 2012). The IAMP cannot cover expenses of the bidders.

It is IAMP continuing policy to avoid any form of discrimination and the EC is committed to ensuring this in the bidding process.

For more details see also http://www.iamp.org/page.php?page=page_congress.

The IAMP officers are happy to answer any questions the potential bidders may have to prepare their bid.

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http://www.crm.cat/Activitats/Activitats/2011-2012/OTAMP/web-otamp/
This conference is partly funded by the IAMP.

*Mechanics: classical, statistical and quantum*
Conference in Honour of the 70$^{\text{th}}$ Birthday of Giovanni Gallavotti
July 2 - 5, 2012, Rome, Italy
http://ricerca.mat.uniroma3.it/ipparco/convegno70/index.html
This conference is partly funded by the IAMP.

3$^{\text{rd}}$ *Feza Gürsey International Summer School in Mathematical Physics*
June 20 - July 6, 2012, Feza Gürsey Institute Kandilli, Istanbul, Turkey
http://www.fezagurseysummerschool.com

*Spectral Theory and Differential Equations*
International Conference dedicated to the 90th birthday of Vladimir A. Marchenko
August 20  24, 2012, Kharkiv, Ukraine
http://www.ilt.kharkov.ua/marchenko2012

*Complex patterns in wave functions – drums, graphs, and disorder*
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## Open positions

### Faculty position at KU Leuven

KU Leuven invites applications for a mathematical physicist in the Department of Physics and Astronomy, working in the area of mesoscopic phenomena and condensed matter physics, to start in October 2013. Please contact Christian.Maes@fys.kuleuven.be for more information. The electronic application can start from http://www.kuleuven.be/personeel/jobsite/vacatures/science.html#2013_2014 under number 22/2012 where the official announcement and further information are posted. The candidates have an excellent track record in the research of complex systems as from problems in statistical mechanics and have interest in collaborating with other theoretical and/or experimental scientists in their field of research. The candidates are also dedicated to education in mathematics or physics at university level.

The deadline for application is September 30, 2012.

## Post-doctoral positions

1. A two - year postdoc position is available, funded by NWO, to work on the topic of *Hidden symmetries, new and dual models of interacting particle systems.* The project has as targeted starting date before September 1, 2012.

   The postdoc will spend one year at TU Delft and one year at Rijksuniversiteit Groningen and will work with the main investigators F. Redig and A.C.D. van Enter. Besides he will have the opportunity to collaborate within an international network related to this and comparable projects, situated in Modena ( C. Giardina, G. Carinci) and Warwick ( S. Grosskinsky).

   More information and details about the project and the position can be obtained from F. Redig (http://dutiosb.twi.tudelft.nl/~redig) and A.C.D. van Enter (http://www.math.rug.nl/dsmp/People/AernoutvanEnter).

   Interested candidates are asked to send a letter of motivation and CV to F. Redig (f.h.j.redig@tudelft.nl) and A.C.D. van Enter (avanenter@gmail.com)

   Deadline for applications: April 30, 2012.

2. A 2-years postdoc position in mathematical physics within the ERC project CoMBoS (Collective Phenomena in Classical and Quantum Many Body Systems; PI: Alessandro Giuliani) is now open. The position will be based in the Mathematics Department of the University of Roma Tre and will start in January, 2013. For more informations about the position and details about how to apply, please visit http://www.mat.uniroma3.it/users/giuliani/public_html/erc/index.html

   Deadline for applications: June 3, 2012.

## PhD student positions

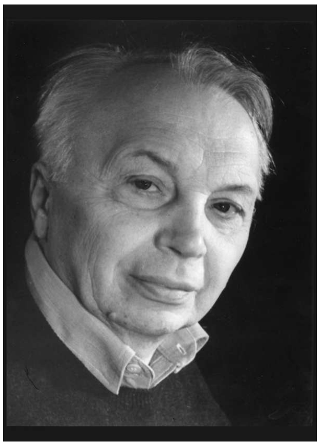
The Dept. of Mathematics, Stockholm university, Sweden, is looking for good candidates for two PhD student projects in analysis and mathematical physics. Possible research projects are devoted to spectral theory of singular differential equations and to quantum graphs. The candidates should have a strong background in operator theory, differential equations and spectral analysis, as well as in quantum mechanics.

Duration: 4 years (5 years if 20 % teaching included). Starting: Fall 2012. Salary: approx. 2 500 Euro/month. More information is available at the web-page: http://www2.math.su.se/~pak/PhD.html. Before you apply send an e-mail to pak@math.su.se (Pavel Kurasov) or luger@math.su.se (Annemarie Luger) . How to apply see: http://www.math.su.se.

Deadline for applications: May 2, 2012.

**Manfred Salmhofer** (IAMP Secretary)

# Vladimir Savelievich Buslaev



Vladimir Savelievich Buslaev, an outstanding Russian mathematician and one of the leaders of the modern Saint-Petersburg mathematical school, died suddenly on March 14th, 2012, aged 74.

Since his early years as a student, Buslaev was associated with the Department of Mathematics and Mathematical Physics of Saint-Petersburg State University. His scientific advisors were O.A. Ladyzhenskaya and L.D. Faddeev. V. S. Buslaev was a member of the faculty of Physics for fifty years, and Head of Department for the last 12 years.

Buslaev's area of interests and the variety of his results were remarkably wide. His works on the mathematical theory of diffraction and wave propagation, scattering theory, nonlinear equations, quasi-classical and adiabatic asymptotic methods, as well as the theory of difference equations with periodic coefficients have been highly recognized by the mathematical community world wide.

Buslaev's most important result in diffraction theory was the rigorous justification of the high-frequency asymptotics of waves scattered by a two-dimensional convex obstacle. Speaking about this problem, one should mention a short but extremely elegant paper in which he presented a heuristic derivation of these asymptotics by means of the Wiener integral.

Buslaev's works on long-range scattering and on many-particle scattering are widely known. Together with V.B. Matveev, Buslaev introduced the notion of modified wave operators for the case of potentials decaying slower than the Coulomb potential. He was responsible for several profound results within the analytic theory of many-particle scattering. Together with S.P. Mercuriev, he derived the trace formulas, described the singularities of the scattering matrix and found the asymptotics of eigenfunctions for many-particle quantum systems.

V.S. Buslaev was co-author of the famous Buslaev-Faddeev trace formulas. Later on, having developed very involved analytic technique, he generalized this result to the multi-dimensional case. These trace formulas became an important tool in the proof of integrability.

V.S. Buslaev did pioneering work in the theory of nonlinear equations, notably concerning the question of the large time behavior of solutions of integrable nonlinear equations. Together with V.V. Sukhanov, he carried out a rigorous analysis in the case of the Korteweg-de Vries equation. Soon after that, in collaboration with L.D. Faddeev and L.A. Takhtajan, he worked out the Hamiltonian interpretation of the scattering theory for this equation. Furthermore, together with G.S. Perelman, he obtained a series of results on the nonlinear scattering and the asymptotic stability of solitons for general nonlinear wave equations.

V.S. Buslaev wrote a number of well-known papers on asymptotic analysis. In particular, he developed an original approach to the study of the asymptotics of solutions of periodic Schrödinger equations with adiabatic perturbations. Using this approach, he obtained results concerning the spectral properties of Bloch electrons in external fields and the asymptotics of Stark-Wannier resonances (with L.A. Dmitrieva and with A. Grigis). Together with A.A. Fedotov, he developed a version of the complex WKB method for difference equations in the complex plane, which was applied to study quasi-classical properties of the spectrum of Harper equation. In collaboration with A.M. Budylin, V.S. Buslaev obtained a series of results on the quasi-classical analysis of pseudo-differential operators with symbols discontinuous with respect to both dual variables. These results were then applied to a number of problems in the asymptotic analysis of integrable differential equations and to problems of quantum statistical physics and hydro- and aero-dynamics. One should also mention Buslaev's paper concerning a new invariant approach to the canonical Maslov operator.

Several times during his mathematical carrier V.S. Buslaev turned his attention to the problems of diffraction and wave propagation. He devoted many papers to the study of sound propagation in the ocean. His best known results in this field are the four-ray formulas for the sound field near the surface of a deep sea and the description of the scattering of high-frequency sound waves by synoptic rings (adiabatically inhomogeneous structures) in the ocean (in collaboration with A.A. Fedotov).

Over a long period V.S. Buslaev, together with A.A. Fedotov, studied difference equations with periodic coefficients on the real line and in the complex plane. He considered the monodromization method – a renormalization method which was developed in the course of this work – and the related results as being among the most important of his achievements.

The papers of Vladimir Savelievich Buslaev, his ideas and methods became starting points for various new research directions in modern mathematical physics.

Many of Buslaev's students have now become well-known mathematicians. He taught his young colleagues to focus on non-trivial concrete problems, to search for the key analytic features of these problems and to consider the work with formulas as central. From his point of view this way of thinking was a principal characteristic of the St. Petersburg mathematical school.

Vladimir Savelievech Buslaev was an extraordinary personality. His ideas and results will be treasured by the mathematical community for many years to come, and his pupils and colleagues will always remember him as a brilliant scientist and a wonderful man.

**Ludvig Faddeev, Alexander Fedotov, Alexander Its, Ari Laptev,**
**Alexander Sobolev, Tatyana Suslina, Vitali Tarasov, Dimitri Yafaev**