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Preface: Introduction to special issue: In memory of Ludwig Faddeev

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Ludwig Faddeev made fundamental contributions to the development of a number of areas of mathematical physics. There are several major topics in mathematical physics that originated with work by Faddeev or were revolutionized by his and his school's results. Notable examples are mathematical scattering theory which includes inverse scattering theory for 1D and 3D Schrödinger operators, trace formulae, and the solution of the quantum 3 body problem; quantization of the Yang-Mills field; spectral theory of automorphic functions; pioneering works on the inverse scattering method in soliton theory; the quantum inverse scattering method and quantum groups. Faddeev also was a visionary who had a unique understanding of the discipline as a whole, with all its profound theoretical physics and pure mathematical connections. For a detailed exposition of Faddeev's outstanding achievements, see the recent survey.[40]

Mathematical physics is a very vibrant, diverse, and dynamical discipline. It started with setting solid mathematical foundations for quantum mechanics and statistical physics. The mathematical foundations of quantum mechanics are where the earlier studies of Faddeev produced several major breakthroughs. In the 1960's, quantum field theory became a subject in mathematical physics of primary importance. The 1967 work of Faddeev and Popov where they introduced the famous "Faddeev-Popov ghosts" made a fundamental contribution to quantizing gauge fields. A striking aspect of this discovery was expanding the "tool box" of mathematical physics from analytic to geometric.

Starting from the 1970's, an increasingly important role in mathematical physics has been played by classical and quantum integrable systems. The theory of integrable systems has become one of the principal sources of new analytic, geometric, and algebraic ideas in many directions of modern mathematics and theoretical physics. This is where the work of Faddeev and his school again became pivotal. Among the areas which have been recently energized and revolutionized by the developments in integrable systems, we want to single out such important fields as the theory of stochastic processes, random matrices, and universalities.

This Special Issue is intended to be broad in scope. It would not, however, be possible to cover all the branches of modern mathematical physics. Therefore, we decided to focus on the topics related to classical and quantum integrability, statistical mechanics, and random matrices and processes. We believe this is a good way to pay tribute to the memory of Ludwig Faddeev.

We have asked several experts working in the above-mentioned fields to contribute a paper for this Special Issue of JMP. The very positive response to our request has resulted in the present collection of papers of which we now give a brief overview.

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The theory of classical integrable systems and its several important ramifications are considered in the paper[2] of Ablowitz, Luo, and Cole, in the paper[34] of Matveev and Smirnov, in the paper[20] of Fokas and van der Weele, in the paper[14] of Dubrovin and Skrypnik, in the paper[22] of Harnad and Lee, in the paper[31] of Lisovyy, Nagoya, and Roussillon, in the paper[6] of Biswas and Hurtubise, in the paper[30] of Korotkin and Zograf, in the paper[4] of Babich and Slavyanov, and in the paper[8] of Bobenko and Tsarev.

The paper of Ablowitz, Luo, and Cole deals with the Cauchy problem for the KdV equation with step boundary conditions. There is a vast literature devoted to this subject. The specific situation studied by Ablowitz, Luo, and Cole corresponds to the presence, in addition to the step, of the delta-function, or box, or soliton/$sech^2$ profiles in initial data. Using the inverse scattering technique, the authors have discovered a new very interesting physical phenomenon. It turns out that if the initial profile is of a sufficient size, then it can propagate through the step. If, however, the original amplitude is too small, then the soliton becomes eventually trapped inside the rarefaction ramp (for the step up initial condition), or inside the dispersive shock waves (for the step down case). The paper also shows that the trapped case corresponds to the appearance of the so-called pseudo-embedded eigenvalue of the Schrödinger operator associated, in the framework of the Inverse Scattering Transform (IST) method, to the KdV equation.

The paper of Matveev and Smirnov is concerned with the various classes of rational solutions of the nonlinear Schrödinger (NLS)-type integrable partial differential equations (PDEs). The paper further develops the approach which was earlier suggested by the first co-author and which combines the rational version of the Krichever and the Darboux-Matveev methods. The particular focus of the paper is on the so-called rogue waves and (first described for the focusing NLS in Ref. 13) multi-rogue waves which is a fascinating topic and which now attracts great attention in the applied mathematical community. In the paper, the previous NLS result of Ref. 13 is extended to the full NLS hierarchy.

The problem of integrability in multidimensions is discussed in the paper of Fokas and van der Weele. Specifically, the 4 + 2 and 3 + 1 integrable generalizations of the Kadomtsev-Petviashvili (KP) and Davey-Stewartson (DS) equations are studied. The relevant non-local d-bar formalism for solving the initial value problem for the DS equation is developed (similar formalism for the 4 + 2 KP equation has been developed earlier in the paper[19] of the first author). It should be pointed out that the analysis of the multidimensional inverse scattering problems takes its origin in the seminal paper[16] of Faddeev on the inverse scattering problem for 1D and 3D Schrödinger operators.

The paper of Dubrovin and Skrypnyk addresses the important question of the construction of the canonical coordinates that separate the variables in the Hamilton-Jacobi equations corresponding to the algebraically integrable Hamiltonian systems. The paper considers the case of $gl(n)$ -valued Lax pairs and uses the classical r-matrix formalism in the description of the corresponding Poisson structure. The authors present the comprehensive solution of the following problem: describe the classical r-matrices for which separating functions (constructed via the standard, spectral-curve based algebro-geometric recipe) produce canonical variables for the corresponding linear Poisson structure. As an important example, a complete set of separated variables for the generalized Gaudin models, with or without an external magnetic field, is obtained. It should be noted that the concept of the classical r-matrix, one of the fundamental ingredients of modern theory of integrable systems, together with its quantum analog, was born in the works of the Faddeev school[37,38,18] (for a detailed history—see monographs Refs. 17 and 25).

In addition to the notion of r-matrix, modern theory of integrable systems gave rise to several other new mathematical concepts. One of these concepts is the concept of the tau function, which was introduced in the theory of systems of linear differential equations by Jimbo, Miwa, and Ueno in 1980[24] and which since then has been playing an increasingly important role in the theory of integrable systems and its numerous applications. Correlation functions of various exactly solvable quantum mechanical and statistical models are tau functions associated with special examples of linear systems. Partition functions of matrix models and 2D quantum gravity and the generating functions in the intersection theory of moduli spaces of algebraic curves are again special examples of tau functions. And, more examples arise in the study of Hurwitz spaces and quantum cohomology.

In this volume, we have three papers which are concerned with tau functions. The paper of Harnad and Lee is one of them and it uses a branch of the theory of tau functions which is associated with Grassmanians and symmetric functions. Specifically, the paper studies the Grassmanian of n-dimensional subspaces in the Hardy space and establishes a set of generalized Jacobi-Trudi identities for symmetric polynomials. These identities are then used in a number of applications for tau functions of soliton equations, and for tau functions related to classical group character expansions, matrix model partition functions, and generators for random processes.

The second paper dealing with the tau functions is the work by Lisovyy, Nagoya, and Roussillon. This is a continuation of a series of papers originated in 2012 work[21] of Gamayun, Iorgov, and Lisovyy where a remarkable link between the Painlevé tau functions and c = 1 Virasoro conformal blocks was discovered. This discovery has finally allowed one to address a long-standing problem of evaluation of the constant terms in the asymptotics of tau-functions near the relevant critical points and at generic values of monodromy data. The work of Gamayun, Iorgov, and Lisovyy, where the "constant problem" was solved for the sixth Painlevé equation, yielded a surge of activity in the area that, in particular, lead to establishing (Gavrylenko and Lisovyy) of new and very efficient determinant formulae for the Painlevé tau-functions. These determinant formulae, in particular, justify the original conformal black constructions of Ref. 21 which are essentially heuristic. In the current paper, both techniques–the determinant formulae approach and the conformal block technique are used to derive the complete combinatorial series expansions near 0 and $i\infty$ and the corresponding connection formulae for the Painlevé V tau function. Important novelty is the handling of the expansions corresponding to the essential singularity at $i\infty$.

The paper of Korotkin and Zograf is the third paper in this volume devoted to the theory of tau functions. This paper addresses the algebraic- geometric aspects of the theory. Specifically, the authors consider the generalization of the isomonodromic Jimbo-Miwa tau function to the module spaces of holomorphic abelian differentials earlier introduced by Kokotov and the first author.[28] In their previous work,[29] the authors used this tau function, which is also a natural generalization of the Dedekind eta-function to higher genus, to compute the class of degenerate abelian and n-differentials in the Picard group. The present paper extends this construction to the moduli space of Hitchin's spectral covers, which play a central role in the celebrated Hitchin's integrable systems. The authors express the class of the universal Hitchin's discriminant in terms of standard generators of the Picard group.

An important branch of modern theory of integrable systems are the integrable multi body dynamical systems of the Claogero-Moser type. These systems are considered in the paper of Biswas and Hurtubise where the authors address the algebra-geometrical aspects of the Calogero-Moser theory. Specifically, the paper builds on the work of the second author and Nevins[23] where a duality of Calogero-Moser systems reflecting the Langlands duality was previously studied. In the present paper, the authors explore this duality through the Fourier-Mukai transform. The authors use this transform to map the Higgs bundles introduced by Hurtubise and Nevins to geometric objects on a complex of curves in the dual variety. The results of the paper give an important geometric structure that sheds light on the nature of dualities of Calogero-Moser for general root systems.

The paper of Babich and Slavyanov reflects on different ways to relate the 2×2 system of linear ordinary differential equations and the sixth (nonlinear) Painlevé equation. Specifically, the authors are comparing the traditional way to relate the sixth Painlevé equation to the 2×2 Fuchsian system via the context of isomonodromic deformation and the "antiquatization" approach to the issue. The latter is based on the quite remarkable fact observed by the second author in 1996[36] that the second order Fuchsian linear differential equation with four singular points, i.e. the Heun equation, is just the quantization of the classical PVI Hamiltonian. In addition, the authors explain how one can use the invariant language of the Lie-Poisson-Kirillov-Kostant symplectic form in producing the relevant Darboux coordinates which transform the original Schlesinger Hamiltonian exactly to the Hamiltonian of the Painlevé VI equation.

In recent years, an increasingly important role in the theory and applications of integrable systems is played by the discrete integrable systems. One very interesting application of the discrete integrable systems is in geometry. In fact, most recently, interactions between discrete integrable systems and geometry led to the emergence of a new field—Discrete Diferential Geometry (see Ref. 7). This field is represented in the volume by the paper of Bobenko and Tsarev. In this paper, the authors study local and global approximations of smooth nets of curvature lines and smooth conjugate nets by discrete nets. Both smooth and discrete geometries are described by integrable systems, and it is shown that one can obtain a uniformly close approximation globally with points of the discrete nets on the smooth surface.

The quantum integrable systems are featured in the volume in the paper[5] of Belliard and Eynard, in the paper[26] of Kozlowski, in the paper[33] of Maillet and Niccoli, and in the paper[39] of Spohn.

The work of Belliard and Eynard deals with the interplay (through the Alday-Gaiotto-Tachikawa (AGT) correspondence) between the conformal field and integrable system theories; specifically, Toda systems theory. The authors consider $\mathcal{W}(\hat{g}_d)$-symmetric Toda conformal field theory in topological regimes for a generic value of the background charge. Using a generalization of the topological recursion (a notion introduced earlier by the second author) to non-commutative, or quantum, spectral curves, they attempt to obtain a refined genius expansion of the corresponding partition function. They show that with the help of the topological recursion on a quantum spectral curve, the associated Ward identities for chiral conformal blocks with current insertions can be solved perturbatively in topological regimes.

One of the most intriguing questions in the theory of the exactly solvable quantum field and statistical mechanics models is the question of the asymptotic analysis of the correlation functions in the non-free fermionic models, such as XXZ spin 1/2 chain. In spite of a considerable number of very impressive results in this area, it remains one of the most challenging problems in mathematical physics. In the volume, the non-free fermion models are considered in two papers. One of them is Kozlowski's paper which is concerned with the XXZ spin model. The paper produces a well-defined, viz., free of any divergencies, form factor series expansion for dynamical two-point functions of the XXZ spin 1/2 chain in the massless regime and in the thermodynamic limit. These series expansions are expected to allow one, by solely relying on saddle-point techniques, to access the asymptotic regimes of the two-point functions. It should be noticed that this is also the first result incorporating the bound state contribution into the asymptotic analysis of the correlation functions.

The second "non-free fermionic" paper is the paper of Maillet and Niccoli, and it is devoted to the question of quantum separation of variables. Although based on the quantum inverse scattering method, the authors' approach offers a new way to formulate the quantum separation of variables which allows them to construct a complete base of separated states and to obtain a complete characterization of the spectrum in the rather general quantum integrable lattice model. For the particular case of the model associated with $Y(gl_2)$ R-matrix, the author's scheme reproduces the well-known Sklyanin's construction of quantum separate variable, and, simultaneously, covers the general $Y(gl_n)$ case.

The paper by Spohn addresses a very general question of the distinction between interacting and noninteracting quantum integrable systems. The author argues that this distinction is characterized by the Onsager matrix: it being zero is the defining property of a noninteracting integrable system. The main focus is on the spin chain systems. The authors' point of view is illustrated by various statistical and quantum integrable chains. Principal examples are *XY* and *XYZ* spin 1/2 Heisenberg models. This paper is less the theorem-proof variety and more a paper that proposes a broader view that is backed up by specific examples.

Statistical mechanics is represented in this volume by the paper[35] of Moon and Nachtergaele, by the paper[10] of Bleher, Elwood, and Petrović, by the paper[3] of Borodin, and by the paper[32] of Lyberg *et al.*

The paper of Moon and Nachtergaele studies the stability of the spectral gaps of one-dimensional quantum lattice systems under weak perturbations. The paper extends the existing results to Hamiltonians with open boundary conditions. The authors, in particular, obtain the explicit bounds on the spectral gaps in the spectrum of perturbed spin and even fermion chains with one or more frustration free ground states that satisfy a local topological order condition.

Next in popularity among the exactly solvable statistical mechanics models, after the Ising model, is the dimer model. It is the subject of the paper of Bleher, Elwood, and Petrović. The authors give a complete rigorous proof of the full asymptotic expansion of the partition function of the dimer model on a square lattice on a torus for general weights. The answer is given in terms of such jewels of the theory of special functions as Dedekind eta function, Kronecker double series, and Jacobi theta functions.

There are two papers in the volume which are concerned with the another important statistical mechanics model—the six vertex model. The paper of Lyberg *et al.*, presents numerical results for the six-vertex model with a variety of boundary conditions. Adapting an algorithm proposed by Allison and Reshetikhin for domain wall boundary conditions, the authors examine some other choices of boundary conditions; specifically, they study the partial domain wall, reflecting, and half-turn boundary conditions. The authors' results support a natural universality conjecture which states that the oscillations near the boundary do not depend on details of the interaction and that the profile should be given by Airy functions.

The second "six vertex paper" is the paper by Borodin. It deals with the stochastic version of the model. The author proves an identity that relates the q-Laplace transform of the height function of a (higher spin inhomogeneous) stochastic six vertex model in a quadrant on one side, and a multiplicative functional of a Macdonald measure on the other. The identity is used to prove the GUE Tracy-Widom asymptotics for two instances of the stochastic six vertex model via asymptotics analysis of the corresponding Schur measures. From a general methodological point of view, the paper gives a relation between two recent general developments in the theory of what has become known as integrable probability, MacDonald processes on the one hand and stochastic higher spin vertex models on the other.

Stochastic processes, random matrices, and their applications are considered in the paper[1] by Adler and Van Moerbeke, in the paper[27] by Keating and Sridhar, in the two papers[41,42] by Tracy and Widom, in the paper[11] by Bothner *et al.*, and in the paper[9] of Basor, Ge, and Rubinstein.

Starting from the pioneering paper[15] on the domino tiling of the "Aztec diamond," different random tiling problems have become one of the most favorite topics in the modern theory of random processes. This area is also marked by the increasing use of the integrable techniques. Random tilings is the subject of the two papers in the Special Issue. The first paper is the paper by Adler and Van Moerbeke where the lozenge (domino) tilings of non-convex polygon regions is considered. The authors show that the non-convexities (cuts) lead to the appearance of new universal correlation kernels which describe the new statistics for the tilings fluctuations near the lines between the cuts. The main result of the paper is an explicit formulae for the probability distributions for these fluctuations.

The second paper devoted to the tilings is the paper by Keating and Sridhar where the authors present the results of computer simulation of models of certain random tilings and a six-vertex model. The main result of this paper is a code that allows one to generate random tilings and random configurations in a very efficient way.

One of the principal stochastic models in nonequilibrium statistical physics and interacting particle systems is the asymmetric simple exclusion process (ASEP) on the integer lattice $\mathbb{Z}$. This process is intimately related to the XXZ spin model and can be thought of as a bridge between the integrable quantum systems and integrable probabilistic systems. In our volume, we have two papers, both written by Tracy and Widom that are concerned with the ASEP. These papers continue the authors' previous studies of the ASEP model which have already made a very significant impact on the development of the field of stochastic and growing models. The specific question which is addressed in the current papers of Tracy and Widom is the explicit evaluation and the asymptotic analysis of the ASEP blocks and gaps distribution functions. In the first work, the authors obtained formulas for the probability that at time t a particle is at site x and is the beginning of a block of L consecutive particles. In the second paper, the authors consider asymptotics. Specifically, for the KPZ regime with a step initial condition, they determine the conditional probability (asymptotically as $t \to \infty$) that a particle is the beginning of an L-block, given that it is at site x at time t.

The paper of Bothner *et al.* is a review of a series of recent works[12] by the authors devoted to the asymptotic analysis of the sine determinant process. This process is described by the sine-kernel Fredholm determinant, which is one of the principal objects in random matrix theory. This determinant also appears in the theory of Dyson's one-dimensional log-gas model with a variable external field.

The paper provides a detailed description of all the different asymptotic regimes depending on the rate of growth of the external potential. The main result is a complete description of the transition between the Gaussian and the linear exponential behaviors of the sine-kernel determinant, which constitutes a solution of a long-standing problem in the theory of random processes. This result is obtained by a Riemann-Hilbert problem analysis of the double-scaling limit of the sine-kernel determinant near its critical spectral value.

The paper of Basor, Ge, and Rubinstein belong to a very interesting and relatively new direction in the number theory which relates the number theoretical objects associated with the Riemann zeta function to the similar objects in the random matrix theory. The area goes back to the famous Montgomery-Odlyzhko conjecture describing the spacing distribution of the nontrival zeros of zeta function in terms of the spacing distribution of the Gaussian Orthogonal Ensemble (GOE) ensemble, i.e., in the terms of above mentioned sine-kernel determinant. The Montgomery-Odlyshko conjecture had been followed by the Keating-Snaith conjecture which, this time, relates the moments of the zeta function to the moments of the characteristic polynomials of random matrices. Since then, the different aspects of the Keating-Snaith conjecture and its generalization have been extensively discussed in the literature. The paper of Basor, Ge, and Rubinstein belongs to this area. They consider the asymptotics of the mean square of sums of the kth divisor function over short interval. Arcording to the Keating, Rodgers, Roditty-Gershon, and Rudnick (KRRR) conjecture, the leading term of this asymptotics is described by a certain multiple integral which also appears in the asymptotic analysis of secular coefficients of the characteristic polynomials of random unitary matrices. The authors show that this multiple integral is, in fact, the inverse Fourier transform of a Hankel determinant that satisfes a Painlevé V equation.

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