Preface: Misha Rabinovich and Nonlinear Dynamics in the Last Half-Century

ПОЗНАНИЕ
Узлами скручены спирали,
А между ними судеб путь.
Скопленья звезд спираль порвали,
Хотя б вполглаза мне взглянуть,
Потрогать грань меж Раем - Адом,
Порядок в хаосе понять,
Услышать рев галактик рядом
И... Богом все это назвать.

Михаил Рабинович

COGNITION
Spirals are wrung into knots.
Between them lies the way of the Fates.
Star clusters once tore the spirals.
Oh, if I could glimpse even half of this,
Touch the thin between Heaven and Hell,
Perceive Order in Chaos,
Hear the roar of galaxies next door,
And – to call it God: all of it.

Mikhail Rabinovich
(English translation by Olga Livshin)

This book is comprised of contributions by just a few of a very large cohort of friends, colleagues, and former students of Misha Rabinovich or, as he is often affectionally called after his initials, MIR.[1] In the last half-century, Misha

[1]The word *mir* means both *peace* and *world* in Russian.

Rabinovich has been at the forefront of most major developments in nonlinear dynamics, starting from the development of asymptotic methods for the analysis of nonlinear waves in non-equilibrium media to the present days when he is using nonlinear dynamics to advance the theory of cognition. In these brief introductory notes, we will attempt to sketch Misha's portrait both as a scientist and as a human being and connect it with the contents of this book.

Mikhail Izrailevich Rabinovich was born on April 20, 1941, in Nizhny Novgorod (then Gorky) in the family of Israel Rabinovich, a professor of chemistry at Gorky State University. In his teenage years, Misha was an avid cross-country skier and only got serious about science toward the second half of his university studies. But in science, just as earlier in sports, he was very fast and not only quickly caught up with his peers but left them far behind.

MIR got his first taste of doing research around 1960 during his sophomore university year in the field which now is called robotics. His first scientific mentor Tyoma Alekseev suggested to him a student project to improve the efficiency of a conveyor at Gorky Automobile Plant (GAZ). Before long, Misha developed an automation algorithm and implemented it at one of the plant conveyors. That work not only led to increased efficiency of the conveyor operation and caused some layoffs, but it also became his first published paper. However, MIR decided not to pursue his scientific career in robotics and switched to the nonlinear dynamics and theoretical physics. Nevertheless, this short stint at GAZ possibly played a big role in his future scientific development.[2] While MIR has always been a theorist, he is also known for deep understanding of experiment, often suggesting original ideas to his experimental colleagues.

He was only 26 when in 1967 he defended his candidate of physical and mathematical sciences' dissertation (an analog of Ph.D. thesis in the West), and at 33 he already obtained the doctor of science degree (an analog of habilitation in Germany, exceptionally early by Soviet standards). In 1991, he was elected the corresponding member of the Russian Academy of Sciences. The general direction of his scientific studies from those very early days has remained the theory of nonlinear oscillations and waves. This was quite natural for him, perhaps even unavoidable, because he belongs to the illustrious school of nonlinear dynamicists established by Leonid Mandelshtam and his students Alexander Andronov, Gabriel Gorelik, and Mikhail Leontovich, followed among others by Misha's Ph.D. adviser Andrey Gaponov-Grekhov. This scientific dynasty is widely known not only for their fundamental discoveries in physics of oscillations and waves but also for applying them in practice, ranging from clocks to powerful generators of electromagnetic or acoustic radiation.

One of Misha Rabinovich's first significant contributions to nonlinear dynamics was the theoretical discovery of stable stationary waves in active nonlinear media in the late 1960s. The first experimental studies were performed with the chains of

[2]This early phase of MIR's scientific career is not well documented, and our account of it is mostly based on our many friendly evening conversations.

coupled electronic self-sustained oscillators [6]. These stable nonlinear structures were later found in plasma physics and fluid dynamics and were used in lasers and networks of radio frequency oscillators. At about the same time, he with his Ph.D. student Alexander Rosenblum (who was 15 years older than MIR) proposed an asymptotic method for theoretical analysis of self-sustained oscillations which was a nontrivial extension of the classical Krylov-Bogolyubov asymptotic method to the distributed nonlinear systems [16].

Perhaps it is Misha's extremely active persona that always attracted him to non-equilibrium systems and nonlinear dynamics. In 1972, he discovered a novel phenomenon of explosive instability in the nonlinear interaction of waves in non-equilibrium media. In this situation the amplitudes of all three ways grow super-exponentially and become infinite in a finite time unless higher-order nonlinearities limit their growth [15]. When the new Institute of Applied Physics of the Soviet Academy of Sciences opened its doors in 1977, MIR became the head of the Laboratory for Nonlinear Dynamics and Chaos which quickly became one of the centers of nonlinear dynamics in the Soviet Union. Many of his students and junior collaborators (including editors and a large fraction of authors of this volume) worked in this laboratory and benefited from daily interactions with MIR. However, his role in grooming generations of "nonlinear dynamicists" is even greater. Misha has always been a wonderful teacher and mentor. As a professor of the Gorky State University, he established a yearlong lecture course on the theory of oscillations and waves and taught it himself every year for 30 years. This class was the highlight of our own years at the radiophysics department of the Gorky State University in the 1970s. This nonlinear dynamics course laid the foundation of the popular textbook written by him in collaboration with Dmitry Trubetskov [18]. His another crown achievement was establishing and running famous "Schools on Nonlinear Oscillations and Waves" that were held biannually in a beautiful countryside some 200 km from Gorky. These 2-week-long springtime gatherings brought together famous physicists and mathematicians (V.I. Arnold, B.B. Kadomtsev, Ya.I. Sinai, Ya.B. Zeldovich, and many others) and hundreds of young researchers in a very informal and stimulating atmosphere. This tradition survived even the demise of the Soviet Union and continues to this day; the next school is planned for 2018.

In the 1970–1980s, Misha Rabinovich turned his attention to deterministic chaos and pattern formation. They were nascent fields at the time, and Misha was one of the early pioneers. In his 1979 paper with his former student Anatoly Fabrikant [13], they demonstrated the emergence of low-dimensional deterministic chaos in a spatiotemporal system describing modulational instability of nonlinear waves in dissipative media. They reduced this infinite-dimensional problem to a set of three ordinary differential equations now known as "Rabinovich-Fabrikant equations." In 1980, MIR with Sergey Kiyashko and one of us demonstrated deterministic chaos in a simple electronic circuit [7]. His influential 1978 review in "Soviet

Physics-Uspekhi" called "Stochastic Self-Oscillations and Turbulence" [10][3] and two chapters on chaos and turbulence written for the classic Landau-Lifshitz textbook series on theoretical physics [8] opened up this field and set the agenda for generations of Soviet physicists. One of the most important discoveries made in that field was *synchronization of chaos*. Misha and his group were the first to experimentally observe this new phenomenon by coupling two electronic chaotic oscillators [2]. This early work heralded the beginning of a new rich field with thousands of scientific publications to date. Other significant scientific achievements of that time were the discoveries of stable particle-like localized solutions of nonlinear field equations [4] and the spatiotemporal chaos in the Ginzburg-Landau equation [3]. Very deep studies of turbulence and pattern formation (see his review article [17] and book [12]) followed.

By the mid-1980s, Misha Rabinovich became well known in the West, but only by name and by his influential papers. Soviet authorities never allowed him to leave the country, not even to the "brotherly" socialist countries of the Soviet bloc. The Institute of Applied Physics and the whole city of Gorky were off limits for foreigners as well. However, as soon as the Iron Curtain began to rust, crack, and crumble during the perestroika years, Misha was able to finally meet his Western colleagues in person. It was during this time that Misha established a long-term collaboration with the Institute for Nonlinear Science at UCSD that in a few years became his new scientific home.

At about the same time as MIR made UCSD his home base, he became interested in neuroscience. Early on he sensed that this field and the biology as a whole were becoming new frontiers for applications of nonlinear dynamics. He quickly realized that deterministic chaos must play a major role in complexity and plasticity of neural systems. His pioneering work on deterministic chaos in stomatogastric ganglia of lobsters in collaboration with Henry Abarbanel, Allen Selverston, and others [11] produced not only fresh new insights into the role of nonlinearity in neuroscience but also tasty leftovers that were enthusiastically consumed at INLS parties.

Observing very complex but often reproducible patterns of neural activity, Misha came to the realization that this complexity must have somewhat different origins from by-now-familiar deterministic chaos. Using a simple Lotka-Volterra system as the paradigmatic model, he introduced a new dynamic concept that governs such complex but stable transient phenomenon which is now known as *winnerless competition* [1]. The geometrical image of such dynamics is the so-called *stable heteroclinic channel* which connects a unique sequence of saddle fixed points in the phase space of the corresponding dynamical system [5]. While the original motivation for this work was the olfactory system in locust, Misha and his collaborators uncovered evidence that this principle governs visual and spatial memory, as well as many other neural systems. In the last several years, Misha has been thinking about the role of nonlinear dynamics in cognition [14]. He is

[3]At that time, the word *stochastic* was commonly used in Soviet scientific literature to describe deterministic chaos as opposed to noise that was labeled by the word *random*.

not deterred by the enormous complexity of human brain. Misha's main idea is that different modalities of brain function also represent the saddle points of the global phase space, and brain activity from this vantage point can be represented as sequential switching from one modality to the next, akin to winnerless competition in smaller neural circuits.

Our portrait of Misha would be grossly incomplete if we did not mention his love of poetry. Although he wrote poems since a young age, it became a real passion in the last 15–20 years. He published seven books of poetry to date (December 2016), and by the time this book is in print, this number could well be greater. His poems are often reflections on the philosophy of science and the creative process in general; in his worldview, the creativity does not know the boundaries between exact and ephemeral and science and art.

We already mentioned that Misha's unique personality makes him contagious, in the good sense of the word. Many of his ideas fertilized scores of his junior colleagues which followed his lead into new fields. In this book, we assembled papers of Misha's former students and his past and present colleagues.

Misha Rabinovich's best scientific insights were borne of his physical intuition and experience, but then he often recruits mathematicians to help put his ideas on firm theoretical foundation. On the other hand, his deep insight into the nonlinear phenomena inspired many experimental physicists and biologists. Therefore, in this book, the reader will find quite a broad coverage of modern topics in nonlinear theory of complex systems, from mathematics to experiments. We have organized the contributions into four parts, highlighting also the main milestones in the scientific life of Misha Rabinovich.

Part I "Chaos and Dynamics" is devoted to the field where Misha Rabinovich made seminal contributions. In one of his now classical works published in 1978, he introduced a low-dimensional model for three parametrically coupled waves that exhibited chaotic behavior, now called the Rabinovich system [9]. Two chapters, by Kuznetsov and by Pusuluri et al., report on recent progress in studies of this simple model. Pusuluri with collaborators describe the global organization of the chaotic attractor of that system using a combination of novel analytical and computational techniques. Kuznetsov addresses possible experimental implementation of the Rabinovich system; he demonstrates that this three-wave system can be implemented as a simple electrical circuit. He further shows that this circuit indeed generates chaotic trajectories described by a Lorenz-type quasi-hyperbolic attractor. Three other chapters in this part are devoted to the dynamics on the border of chaos and regularity. The contribution by Pesin et al. introduces a new class of scaled Lyapunov exponents, suitable for quantitative characterization of systems with sub-exponential separation of trajectories. These exponents are used in the chapter by Afraimovich and Neiman for the description of weak transient chaos in the switching dynamics. Another example of dynamics between order and chaos is presented in a chapter by Zaks and Nepomnyashchy, where anomalously slow dynamically generated diffusion is described.

Part II "Synchronization and Networks" reflects Misha's long-term interest in spatially organized models such as coupled map lattices and in synchronization phenomena. It opens with the contribution by Anishchenko et al. devoted to complex states, including chimera-like configurations, in networks of nonlocally coupled chaotic maps. Two chapters deal with phase oscillator networks. V. Belykh et al. consider star networks of phase oscillators and describe regular and chaotic transitions to synchrony. The chapter by Bick describes possible Lotka-Volterra-type dynamics in phase oscillator networks. Effect of symmetry in the network on the appearance of synchronous clusters is analyzed in the contribution by Pecora et al. The chapter by Bunimovich and Webb describes the stability analysis of networks with time delays. Finally, Reimayev and collaborators analyze synchronous states in coupled bursting neurons. This contribution makes a bridge to the following Part III.

The opening chapter of the Part III "Brain" deals with the subject of large-scale brain dynamics, which is the focus of Misha's current interest that has emerged from his previous work on neural dynamics. It is written by Karl Friston, his collaborator and co-editor of the recent book *Principles of Brain Dynamics: Global State Interactions* [14]. In this chapter, Friston proposes a variational principle that casts motor and sensory activity of the brain as an optimization strategy to minimize a particular free energy functional. Chapters by Mangin and Courbage and Rubchinsky et al. deal with synchronization of electrical activity in various biological neural networks. In related contributions, Komarov et al. and Nowotny and Szyszka describe coding of odors in neural activity of olfactory systems.

The final part of the book, "Waves," is devoted to the topic with which MIR started his scientific career. Krinsky and collaborators in their chapter describe how vortices of electrical activity in cardiac tissues can be controlled. Two other chapters deal with conservative problems. Pelinovsky and Shurgalina demonstrate that complexity can emerge even in integrable systems by analyzing statistical properties of a gas of solitons in the classical Korteweg-de Vries (KdV) equation. Stepanyants describes complex patterns emerging in the two-dimensional generalization of the KdV equation, the Kadomtsev-Petviashvili model. This final chapter of the book also contains some personal remarks based on the long-term friendship between the author and Misha Rabinovich.

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University Park, PA, USA — Igor S. Aranson
Potsdam, Germany — Arkady Pikovsky
La Jolla, CA, USA — Nikolai F. Rulkov
La Jolla, CA, USA — Lev S. Tsimring
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