Preface

The aim of this book is to introduce a theoretical/conceptual principle (based on *quantum information theory* and *non-Kolmogorov probability theory*) to understand information processing phenomena in biology as a whole—the *information biology* —a new research field, which is based on the application of open quantum systems (and, more generally, *adaptive dynamics* [173, 26, 175]) outside of physics as a powerful tool. Thus this book is about information processing performed by bio-systems. Since quantum information theory generalizes classical information theory and presents the most general mathematical formalism for the representation of information flows, we use this formalism. In short, this book is about *quantum bio-information*. However, it is not about quantum physical processes in bio-systems. We apply the mathematical formalism of quantum information as an operational formalism to bio-systems at all scales: from genomes, cells, and proteins to cognitive and even social systems.

F. Crick proposed a central dogma in molecular biology to understand the genetic coding problem in biology in 1970 [62]. So far researchers in biological sciences have elucidated individual molecular mechanisms of any information processing phenomena in biology, such as signal transduction, differentiation, cognition and even evolution. However, we do not have basic/unified principles underlying such information flows in biology from genes to proteins, to cells, to organisms, to ecological systems and even to human social systems. It seems that we are now at the brink of the crisis (catastrophe) of the integrity of our earth system including human societies. We are longing for any possible tools to predict our state in the future.

Nowadays, quantum information theory is widely applied for microscopic physical carriers of information such as photons and ions. This is definitely one of the most rapidly developing domains of physics. Classical information theory is based on a special model of probability theory, namely the model proposed by A.N. Kolmogorov in 1933 [148]. Quantum information theory is based on the quantum probability model—the calculus of complex probability amplitudes. The latter was elaborated by the founders of quantum mechanics, first of all, by M. Born and J. von Neumann. Quantum probabilities exhibit many unusual (even exotic and mystical) features. In particular, they violate the main laws of classical *Kolmogorovian probability*. As was emphasized by R. Feynman (one of the physical genies of the twentieth century), the quantum interference phenomenon demonstrated in the two slit experiment (where a quantum particle interferes with itself) can be probabilistically interpreted as *violation of the formula of total probability*. The latter is one of the most fundamental laws of classical probability theory, the heart of *Bayesian analysis* with corresponding applications to the game theory and decision making. Thus quantum physics has demonstrated that the classical probability model (as any mathematical model) has a restricted domain of application. In particular, it can be used in classical statistical mechanics, but not in quantum mechanics.

The situation in probability theory is similar to the situation in geometry. During two thousand years Euclidean geometry was considered as the only possible mathematical model of physical space. (We recall that E. Kant even claimed that this geometry was one of the basic elements of reality.) However, the discovery of N. Lobachevsky showed that other consistent mathematical geometric models were possible as well. Later, Riemann by inventing geometric models known nowadays as Riemann manifolds opened the doors to a variety of geometric worlds. Finally, the genial mind of A. Einstein coupled these mathematical models of geometry to the physical reality by developing the theory of general relativity. (And Lobachesvky's geometry has applications in special relativity).

Physics was one of the first scientific disciplines that were mathematically formalized. Plenty of mathematical theories, which were born in physical studies, have later found applications in other domains of science. The best example is the differential calculus originally developed by Newton for purely physical applications, but nowadays is applied everywhere, from biology to finances. A natural question arises: *Can quantum and, more generally, non-Kolmogorov probability be applied anywhere besides quantum physics?* In this book we shall demonstrate that the answer is positive and that biology is a novel and extended field for such applications. We noticed that biological phenomena, from molecular biology to cognition, often violate classical total probability conservation law [26]. There is plenty of corresponding experimental statistical data.[1] Therefore, it is natural to apply non-Kolmogorovian probability to biology (in the same way as non-Euclidean geometric models are applied in physics). Since the quantum probabilistic model is the most elaborated among non-Kolmogorovian models, it is natural to start with quantum probabilistic modelling of biological phenomena. However, since biological phenomena have their own distinguishing features, one can expect that the standard quantum formalism need not match completely with biological applications. Novel generalizations of this formalism may be required. And this is really the case, see Chap. 4.

[1] A lot of data has been collected in cognitive science and psychology; unfortunately, in molecular biology we have just a few experimental data collections which can be used for comparison of classical and nonclassical probabilistic models. We hope that the present book will stimulate corresponding experimental research in molecular biology.

In this book we show that quantum theory considered as an *operational formalism* can be applied to any biological scale by representing statistical experimental data by means of quantum probability and information. In the last years a general model representing all basic information flows in biology (from molecular biology to cognitive science and psychology and to evolution) on the basis of quantum information theory has been elaborated. In this book the general scheme of embedding of biological information processing into the quantum information formalism is presented and the foundational issues related to usage of quantum representation for macroscopic bio-systems, such as genome, protein,…, cognitive system,…, bio-population are discussed in detail and clarified.

Since a biological system is *fundamentally open*, i.e. it cannot survive without contact with an environment, it is natural to apply the powerful and well-developed apparatus of *theory of open quantum systems* and more generally *adaptive dynamics* to the description of biological information flows. For those who have some preliminary knowledge of quantum mechanics, we say that it seems that Schrödinger's dynamics (describing the evolution of isolated systems in quantum physics) seems to be not so much useful for biological applications. One has to use quantum master equation and its generalizations (see again Chap. 4).

The "constructive know-how" of our quantum bio-information is the procedure of reconstruction of quantum(-like) operators on the basis of the experimental statistical data. *Such an operational representation can be used to predict probabilistic results of new experiments.* Thus quantum bio-information is not only a powerful descriptive formalism unifying the variety of biological processes, but it also has *predictive power*.

Quantum bio-information has already been applied to such basic phenomena as cell differentiation, diauxie (two phase) growth of *Escherichia coli* in glucose and lactose mixed medium, irrational behaviour in games of the Prisoner's Dilemma type, non-Bayesian probability updating in cognitive psychology and evolution theory (unifying Darwinism and Lamarckism and supporting recent theoretical studies in epigenetic). On this basis, we believe that quantum bio-information is the most predictive tool to know our future state on earth. We expect that this quantum operator formalism is a kind of a brave trial to unify our social and natural sciences. We now ask many researchers to recognize the usefulness of this formalism to understand any information processing in biology from micro- to macro-scale and to make benefit for human beings and society on earth.

This approach raises the deep foundational problem: application of information laws of quantum mechanics to *macro bio-systems.* We hope that our book may generate a foundational debate on the approach of experts from physics and biology (in the latter, in a very general sense: from molecular biology to social science). Our approach to biology also raises deep philosophic questions about the role of information in living and physical systems, see Chap. 1.

This book does not present a complete quantum-information account of biological phenomena. Nevertheless, some important examples of applications are given, see Chaps. 5, 6 and 8.

This book is intended for diverse groups of readers: biologists (molecular biology, especially genetics and epigenetics), experts in cognitive science, decision making, and sociology, psychologists, physicists and mathematicians working on problems of quantum probability and information, experts in quantum foundations (physicists and philosophers).

We start the book with an introduction followed by two chapters devoted to fundamentals: Chapter 2 on classical and quantum probability (it also contains a brief introduction to quantum formalism) and Chap. 3 on information approach to molecular biology, genetics and epigenetics. The latter is basic for proceeding to applications of quantum(-like) theory to molecular biology, see Chap. 5. On the other hand, Chap. 3 might be difficult for experts in physics, mathematics, cognition and psychology. Therefore, those who are not interested in applications of quantum methods to molecular biology can jump directly to Chap. 6. However, a part of the biological fundamentals presented in Chap. 3 is used in Chap. 8, which is about the application of open quantum systems to epigenetic evolution.

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