# Decision Making and Modelling in Cognitive Science

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Sisir Roy
National Institute of Advanced Studies, IISc
Campus
Bengaluru, Karnataka
India

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# Foreword

Decision making is a hot topic in the cognitive neurosciences, with several applications in the practical human sciences. If humans is not the rational agent assumed by the classics of the science of economics, is he then an irrational one, as some authors have recently claimed?

The answer could be stated in this manner: it may be the case that we are not irrational, but follow a quantum-probabilistic kind of rule. In this book, Sisir Roy deeply investigates the logic of human decision making, arguing that the probability calculus, which is similar to the formalism of quantum theory, better describes and simulates human decision making. Classical logic and probability theory would not account for how human beings really make decisions in everyday life.

If human rationality is to be conceived according to quantum theory, which interpretation of the theory should be selected? There are so many interpretations that, depending on a particular one, this may not be a good choice. The book overcomes this problem by going beyond a purely epistemological view—as in the case of the Copenhagen interpretations–towards an encompassing theory of reality based on quantum theory, i.e., "quantum ontology".

The theoretical path followed by Sisir Roy contains an excursion through quantum probability theory, non-Boolean logic, context dependence, and possible relationships between modern neuroscience and quantum logic. Besides his expertise in formal sciences, he has also collaborated with reputed neuroscientists such as Rudolf Llinás and Gustav Bernroider. This background affords concreteness to the arguments developed in the book, all of them well grounded in contemporary scientific achievements.

As long as the ontology expresses itself in the minds of human beings, there may be cultural patterns that fit the corresponding rules. This seems to be the case for Buddhism, a way of thinking and living that is discussed in the final chapters.

This book is a formidable interdisciplinary investigation into the logic of human behavior that advances our understanding of decision-making processes. It will satisfy the most rigorous specialists while offering a wealth of information to the general reader.

Alfredo Pereira, Jr.
Adjunct Professor
São Paulo State University (UNESP)
São Paulo, Brazil

# Preface

*Hence, in order to have anything like a complete theory of human rationality, we have to understand what role emotion plays in it.*

—Herbert Simon (*Reason in Human Affair*, 1983)

One of the fundamental requirements in the cognitive processes of human beings is to decide with precision. Therefore, it is necessary to understand how human decision makers, in actual situations, i.e., in complex real-world settings, make decisions as well as to learn how to these processes are supported. Though, taking it as a well-established fact, we can describe the main themes of naturalistic decision making as classical decision theory, we should keep in mind some of limitations of that theory. It has been already been recognized that an axiomatic, as well as other kinds of rigorous models of the cognitive decision making, are very much in need. The recent empirical findings in cognitive domain clearly suggest the necessity of changing the paradigm from classical Bayesian probability theory to quantum probability to construct the model of decision making in a consistent manner. Some of these empirical findings are based on gambling. For many centuries across various cultures, gambling has been treated as a form of entertainment. The studies on decision making during gambling, raise much interest regarding the role of interaction between cognition and emotion. The necessity of a theoretical model and its computational aspect are very much thought to answer the question "*how do emotions affect the cognitive function of a decision maker?"* One of the challenging aspects of artificial intelligence (AI) is to model the "human characteristics" like emotions, behavior, etc. in a comprehensive manner. Some attempts have been made to build up theoretical models of emotions in decision making and judgments using multidimensional logic. In this book, the author emphasizes the use of quantum probability, i.e., an extension of quantum logic, to model the decision-making process in the cognitive domain. Now, quantum logic can be shown to be a kind of paraconsistent logic that incorporates the contradictions arising from the simultaneous existence of two mutually exclusive events in a logical way rather than discarding them. This gives rise to a new possibility to model the various degrees of contradictions involved in emotions, as well as to quantify the effect of emotions on judgments and decision making.

The book is planned according to the following scheme: In Chap. 1, various aspects of decision making in the cognitive domain are critically discussed. The role of emotions and logic play very important roles in decision making. They are discussed in the latter half of this chapter.

Various approaches to decision making are discussed in Chap. 2. Two main categories of decision theories, i.e., descriptive and normative theories, are elaborated here. The axiomatic approach deals with deterministic axioms that cannot comply with the uncertainty involved during the decision-making process. In such a situation, the Bayesian framework provides readily applicable statistical procedures where typical inference questions are addressed. Here, the Bayesian probabilistic approach is more appropriate to handle empirical data. Then the importance of the Dumpster-Shafer theory (basically, the extended framework of Bayesian probability theory) is also discussed in handling empirical data. However, this approach is not yet fully developed.

In Chap. 3, decision making and functioning of the brain are discussed from a neuroscience perspective. One of the most challenging aspects of understanding the brain is to understand its predictability. The brain needs to tackle the uncertain situation associated with neuronal dynamics for any kind of decision making. This uncertainty is due to the existence of various types of noise or unwanted variations associated with neuronal functioning. To handle such uncertainties, the Bayesian approach is discussed.

New empirical findings for decision making in the cognitive domain are classified into different categories. We critically analyze this evidence in Chap. 4. The data clearly indicate that classical probability cannot explain the results consistently. Many authors suggested that the concept of quantum probability is needed to explain the data. Of course, this framework of quantum probability is an abstract framework devoid of any material content. Here, the quantum formalism as such is not considered as applicable to the neurophysiology of the brain or in the cognitive domain.

To understand quantum probability, it is required to have some mathematical knowledge of vector spaces, scalar products, operators, Hilbert spaces, etc. These mathematical concepts are described in Chap. 5.

Niels Bohr introduced the concept of the complementary principle in understanding the mutually exclusive aspects of an entity in microscopic domains. For example, the particle and wave aspects of a microscopic entity like the electron are two mutually exclusive aspects, i.e., they cannot be measured simultaneously with infinite precision. This concept of complementarity is very important in the context of the total probability sum rule. Along with a collaborator, I have proposed a generalized complementary principle in the cognitive domain. This is discussed in Chap. 6.

Quantum probability is an extension of quantum logic. This is different from Boolean logic. In Boolean logic, there exist two truth values, ‘yes or no’ (1 or 0).

On the other hand, in quantum mechanics, the intermediate situation due to the superposition rule poses contradictions within the purview of Boolean logic. There is a long debate over whether one can think of logic as separate from cognition or psychology. In the Bayesian framework, probability is considered to be an extension of logic. The classical Bayesian probability is used to handle the uncertain situation for decision making in the cognitive domain. Here, since the concept of quantum probability is used to explain the data, we discuss the structure of quantum logic in Chap. 7.

Quantum ontology has been discussed by many authors, since the very inception of quantum theory. Recently, quantum ontology and quantum probability have been defined in an abstract manner, i.e., defined in such a manner that they can be applied to any branch of knowledge like social sciences, biology, etc. But the main challenge is how to contextualize these. For example, to apply them to cognition, one needs to contextualize them in the context of neuroscience. Quantum ontology and its contextualization are discussed in Chap. 8.

In Chap. 9, we discuss quantum logic in the context of modern neuroscience.

Finally, we make some remarks regarding emotions, affective computing, and quantum logic. Quantum logic and decision making raise important epistemological issues, and similar questions are found in ancient Indian texts. These are discussed in Chap. 10.

The framework of quantum probability and quantum logic help us make a detailed analysis of mental functions and their modeling. This will open up new vistas to understand the man-machine interface and affective computing from a more realistic perspective.

The writing of this book would have been impossible without help from my wife, Dr. Malabika Roy, who read the entire manuscript and provided critical suggestions. Some portions of the book were written during my stay at the Indian Statistical Institute, Kolkata, and the rest at the National Institute of Advanced Studies, Bengaluru. The representatives of Springer are greatly acknowledged for their very constructive suggestions from time to time, which ultimately produced the present, final form of this manuscript.

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Sisir Roy

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# About the Author

**Sisir Roy** is T.V.Raman Pai Chair Visiting Professor at the National Institute of Advanced Studies, Indian Institute of Science Campus, Bengaluru, India. He was previously professor at the Physics and Applied Mathematics Unit, Indian Statistical Institute, Kolkata, and was associated with that institute for over 30 years. He is a quantum physicist, and his interests include the foundations of quantum theory, cosmology, brain-function modelling, and higher-order cognitive activities. He has published more than 150 papers in peer-reviewed international journals and 12 research monographs/edited volumes with Kluwer Academic Publishers, World Scientific, etc. He has been a visiting professor at George Mason University and the University of Arkansas, and at the Henri Poincare Institute in Paris. His present focus of research is to pursue interdisciplinary research on quantum probability and cognitive science, information theory in living organisms, and neuroscience and consciousness. His forthcoming monographs are on quantum effects in biology and the role of noise in living organisms.