

# Structure and Interpretation of Quantum Mechanics — a Functional Framework

Jerzy Karczmarczuk  
Dept. of Computer Science, University of Caen  
Caen, France  
karczma@info.unicaen.fr

## ABSTRACT

We present a framework for representing quantum entities in Haskell. States and operators are functional objects, and their semantics is defined — as far as possible — independently of the base in the Hilbert space. We construct effectively the tensor states for composed systems, and we present a key model of quantum circuit calculus. We conclude that functional languages are right tools for formal computations in quantum physics. The paper focuses mainly on the representation, not on computational problems.

## Categories and Subject Descriptors

D.3.1 [Programming techniques]: Functional Programming

## General Terms

Theory

## Keywords

Haskell, Quantum physics, Vector spaces, Dual bases, Operators, Tensor products, Quantum gates, Multi-parametric clauses.

## 1. INTRODUCTION TO QUANTIZATION

### 1.1 How to model quantum objects?

Computer scientists became interested in quantum computing mainly because of the possibility to accelerate the solution of algorithmically hard problems, see e.g., [1, 2, 3], also [4] and many others. But — as Feynman [5] remarked in 1982, — perhaps the most promising direction of evolution of programmable quantum systems is not the “algorithmic”, but the simulation of other quantum structures. This is also advocated by Preskill [6], and worked upon by others [7, 8, 9, 10].

It is thus legitimate to ask how to represent properties of general quantum structures in a computer. As noted in [11], and elsewhere, we need a thorough abstraction layer upon physical details, in order to work on circuits and algorithms. There are attempts to introduce specific programming structures for the design of typical (computational) languages [12, 13], making it easier to code their

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transformations acting upon the quantum registers. Bird and Ma [11] discovered the applicability of functional languages for writing such codes in a particularly compact and elegant way, and propose to use functional compositions and monadic clauses to deal gracefully with the (non-deterministic) measures. Aude Salary [12] goes further, and develops in Haskell a more complete functional framework for the simulation of quantum processing units and the observation of results. He also points out some difficulties arising from the application of typical programming languages to a non-classical domain. For a review of other attempts to simulate quantum structures, mainly collections of qubits manipulated logically, see [13].

Typical representations of quantum entities are algebraic, in the classical sense. A quantum state is a vector belonging to a space, whose dimension is the number of discernible measurement results, e.g., a qubit which classically can be “up” or “down”, can be represented as a linear superposition of  $| \uparrow \rangle$  and  $| \downarrow \rangle$ . A multi-qubit is a Kronecker (tensorial) product of such matrices and needs compensated data structures. For a harmonic oscillator it is known that a measurement can yield its excitation level — an integer between 0 and  $\infty$ . Here we see that bare data structures might be useful. For the analysis of quantum algorithms qubits usually suffice, but some papers, e.g. [14], show that in order to assemble a physical multi-bit quantum gate, it is useful to couple the elements with quantum oscillators, objects beyond the qubit layer. In 1998 E. Knill observed [15] that a future quantum computer will certainly be a hybrid, with a classical part actively engaged in preparing and interpreting the quantum part (hardly a surprise for physicists performing experiments on quantum systems, but needing rewords as well...). These meta-operations will transcede the elementary qubit abstractions layer.

Thus, our ambition is to propose a general, not restricted to qubits, implementable, functional abstraction layer for quantum entities, which would be effective even in the (co)discrete sectors of any infinite-dimensional Hilbert space, and which would correspond formally and intuitively to the formalisms used in classical texts devoted to quantum physics, e.g., [16, 17]. Quantum states will be functions, and we shall use Haskell to code them. The title of the paper has been inspired by the book [20], whose authors underline the methodological usefulness of generic, functional structures for the computational representation of physical entities.<sup>1</sup>

Our framework achieves the following.

- We have a unified programming paradigm for different quantum systems.

<sup>1</sup>But the similarity to the title of the book of R.J.G. Hughes, *Structure and Interpretation of Quantum Mechanics*, Harvard University Press, is a pure coincidence. This book might be quite interesting for philosophically-oriented readers.

# Structure And Interpretation Of Quantum Mechanics

**Peter Mittelstaedt**

## **Structure And Interpretation Of Quantum Mechanics:**

The Structure and Interpretation of Quantum Mechanics R. I. G. Hughes, 1989 R I G Hughes offers the first detailed and accessible analysis of the Hilbert space models used in quantum theory and explains why they are so successful. He goes on to show how the very suitability of Hilbert spaces for modeling the quantum world gives rise to deep problems of interpretation and makes suggestions about how they can be overcome

### **Understanding Quantum Raffles**

Michael Janas, Michael E. Cuffaro, Michel Janssen, 2021-12-03 This book offers a thorough technical elaboration and philosophical defense of an objectivist informational interpretation of quantum mechanics according to which its novel content is located in its kinematical framework that is in how the theory describes systems independently of the specifics of their dynamics. It will be of interest to researchers and students in the philosophy of physics and in theoretical physics with an interest in the foundations of quantum mechanics. Additionally parts of the book may be used as the basis for courses introducing non-physics majors to quantum mechanics or for self study by those outside of the university with an interest in quantum mechanics. With a Foreword by Jeffrey Bub *Understanding Quantum Raffles* is a wonderful book for both the specialists and those with curious minds. The elegance and the simplicity with which the three Mikes explain some of the deepest aspects of quantum mechanics on the basis of probabilities and correlations are dazzling and delightful. The same elegance and simplicity also make the book ideal for any engaged reader who ever wondered what is so special about quantum mechanics. In our age of new quantum technologies this is something anyone should read. Guido Bacciagaluppi author of *Quantum Theory at the Crossroads* This book makes a sustained argument for an informational interpretation of quantum theory blending an elegant mathematical characterisation of quantum correlations with incisive historical and philosophical analysis. A must read for those interested in quantum foundations and also a fertile source of teaching inspiration for quantum theory.

Leah Henderson Department of Theoretical Philosophy University of Groningen This is one of the most fascinating and accessible presentations of the informational approach to quantum mechanics. What has so far been mostly restricted to the theoretical physics community is here masterfully explained for a broader audience even without a physics background. Scholars, students and laypeople alike will appreciate the clear, vivid and yet deep discussion of what raffle tickets and correlation ellipotes can tell us about the physics and philosophy of the quantum world.

Markus Müller Institute for Quantum Optics and Quantum Information Vienna

**Samson Abramsky on Logic and Structure in Computer Science and Beyond**

Alessandra Palmigiano, Mehrnoosh Sadrzadeh, 2023-08-01 Samson Abramsky's wide ranging contributions to logical and structural aspects of Computer Science have had a major influence on the field. This book is a rich collection of papers inspired by and extending Abramsky's work. It contains both survey material and new results organised around six major themes: domains and duality, game semantics, contextuality and quantum computation, comonads and descriptive complexity, categorical and logical semantics, and probabilistic computation. These relate to different stages and aspects of Abramsky's

work reflecting its exceptionally broad scope and his ability to illuminate and unify diverse topics Chapters in the volume include a review of his entire body of work spanning from philosophical aspects to logic programming language theory quantum theory economics and psychology and relating it to a theory of unification of sciences using dual adjunctions The section on game semantics shows how Abramsky's work has led to a powerful new paradigm for the semantics of computation The work on contextuality and categorical quantum mechanics has been highly influential and provides the foundation for increasingly widely used methods in quantum computing The work on comonads and descriptive complexity is building bridges between currently disjoint research areas in computer science relating Structure to Power The volume also includes a scientific autobiography and an overview of the contributions The outstanding set of contributors to this volume including both senior and early career academics serve as testament to Samson Abramsky's enduring influence It will provide an invaluable and unique resource for both students and established researchers

**The Philosophy Behind Physics** Thomas A. Brody, 2012-12-06 Thomas Brody had one of the most powerful and wide ranging intellects of his generation Although primarily a physicist who worked on statistical problems in nuclear physics on probability theory and on computational physics he had an extensive knowledge of the philosophy of science and of philosophy and was fluent in many languages He is well known among physicists for the Brody Moshinsky transformation but his extensive work on probability and on the philosophy of science remained almost unknown This was because the originality of his ideas entailed many lengthy battles with uncomprehending referees and he frequently published in Mexican journals of limited circulation In addition his strongly critical spirit inhibited his willingness to publish his ideas He was always most concerned by the very unsatisfactory situation in the philosophy of physics that is largely due to the generally poor knowledge that physicists and philosophers have of each other's disciplines Philosophers of science write at length about physics without any detailed first hand knowledge of how research is actually carried out Physicists for their part often implicitly assume naive or erroneous philosophical ideas and this often hinders their scientific work besides spreading further confusion if they try to give an account of what they are doing

**The Interpretation of Quantum Mechanics** Jeffrey Bub, 2012-12-06 This book is a contribution to a problem in foundational studies the problem of the interpretation of quantum mechanics in the sense of the theoretical significance of the transition from classical to quantum mechanics The obvious difference between classical and quantum mechanics is that quantum mechanics is statistical and classical mechanics isn't Moreover the statistical character of the quantum theory appears to be irreducible unlike classical statistical mechanics the probabilities are not generated by measures on a probability space i.e. by distributions over atomic events or classical states But how can a theory of mechanics be statistical and complete Answers to this question which originate with the Copenhagen interpretation of Bohr and Heisenberg appeal to the limited possibilities of measurement at the microlevel To put it crudely Those little electrons protons mesons etc are so tiny and our fingers so clumsy that when ever we poke an elementary particle to see which way it

will jump we disturb the system radically so radically in fact that a considerable amount of information derived from previous measurements is no longer applicable to the system We might replace our fingers by finer probes but the finest possible probes are the elementary particles them selves and it is argued that the difficulty really arises for these [RNA 3D Structure Analysis and Prediction](#) Neocles Leontis, Eric Westhof, 2012-06-05 With the dramatic increase in RNA 3D structure determination in recent years we now know that RNA molecules are highly structured Moreover knowledge of RNA 3D structures has proven crucial for understanding in atomic detail how they carry out their biological functions Because of the huge number of potentially important RNA molecules in biology many more than can be studied experimentally we need theoretical approaches for predicting 3D structures on the basis of sequences alone This volume provides a comprehensive overview of current progress in the field by leading practitioners employing a variety of methods to model RNA 3D structures by homology by fragment assembly and by *de novo* energy and knowledge based approaches [Structure Analysis by Electron Diffraction](#) B. K. Vainshtein, 2013-10-22 Structure Analysis by Electron Diffraction focuses on the theory and practice of studying the atomic structure of crystalline substances through electron diffraction The publication first offers information on diffraction methods in structure analysis and the geometrical theory of electron diffraction patterns Discussions focus on the fundamental concepts of the theory of scattering and structure analysis of crystals structure analysis by electron diffraction formation of spot electron diffraction patterns electron diffraction texture patterns and polycrystalline electron diffraction patterns The text then ponders on intensities of reflections including atomic scattering temperature factor structure amplitude experimental measurements of intensity and review of equations for intensities of reflections in electron diffraction patterns The manuscript examines the Fourier methods in electron diffraction and experimental electron diffraction structure investigations Topics include the determination of the structure of the hydrated chlorides of transition metals structures of carbides and nitrides of certain metals and semi conducting alloys electron diffraction investigation of clay minerals and possibilities inherent in structure analysis by electron diffraction The book is a helpful source of data for readers interested in structure analysis by electron diffraction [Empiricism and Philosophy of Physics](#) Lars-Göran Johansson, 2021-01-13 This book presents a thoroughly empiricist account of physics By providing an overview of the development of empiricism from Ockham to van Fraassen the book lays the foundation for its own version of empiricism Empiricism for the author consists of three ideas nominalism i e dismissing second order quantification as unnecessary epistemological naturalism and viewing classification of things in natural kinds as a human habit not in need for any justification The book offers views on the realism antirealism debate as well as on the individuation of theories as a thoroughly neglected aspect of underdetermination The book next discusses a broad range of topics including the predicates body spatial distance and time interval the ontology of electromagnetism propensities the measurement problem and other philosophical issues in quantum theory Discussions about the direction of time and about string theory make up the final part

of the book *Mathematical Methods for Protein Structure Analysis and Design* Concettina Guerra, Sorin Istrail, 2003-06-25

The papers collected in this volume reproduce contributions by leading scholars

arstoaninternational school and workshop which was organized and held with the goal of taking a snapshot of a discipline

undertumultuous growth Indeed the area of protein folding docking and alignment is developing in response to needs for a mix of heterogeneous expertise spanning biology chemistry mathematics computer science and statistics among others Some of the problems encountered in this area are not only important for the scientific challenges they pose but also for the opportunities they disclose in terms of medical and industrial exploitation Atypical example is offered by protein drug interaction docking a problem posing daunting computational problems at the crossroads of geometry physics and chemistry and at the same time a problem with unimaginable implications for the pharmacopoeia of the future The school focused on problems posed by the study of the mechanisms hind protein folding and explored different ways of attacking these problems under objective evaluations of the methods Together with a relatively small core of consolidated knowledge and tools important reactions were brought to this effort by studies in a multitude of directions and approaches It is obviously impossible to predict which if any among these techniques will prove completely successful but it is precisely the implicit dialectic among them that best conveys the current flavor of the field Such unique diversity and richness inspired the format of the meeting and also explains the slight departure of the present volume from the typical format in this series the exposition of the current sediment is complemented here by a selection of qualified specialized contributions

*An Introductory Guide to EC Competition Law and Practice* Valentine Korah, 1994 *Physics Briefs*, 1994 **Optics and Spectroscopy**, 2007 *The*

Modal Interpretation of Quantum Mechanics Dennis Dieks, Pieter E. Vermaas, 2012-12-06 According to the modal interpretation the standard mathematical framework of quantum mechanics specifies the physical magnitudes of a system which have definite values Probabilities are assigned to the possible values that these magnitudes may adopt The interpretation is thus concerned with physical properties rather than with measurement results it is a realistic interpretation in the sense of scientific realism One of the notable achievements of this interpretation is that it dissolves the notorious measurement problem The papers collected here together with the introduction and concluding critical appraisal explain the various forms of the modal interpretation survey its achievements and discuss those problems that have yet to be solved

Audience Philosophers of science theoretical physicists and graduate students in these disciplines *Progress of Theoretical Physics*, 1952 *Handbuch der Astrophysik: 1.-2. Hälfte. Grundlagen der Astrophysik. 3. teil. 1. Wärmestrahlung* Gustav

Eberhard, Arnold Kohlschütter, Hans Ludendorff, 1930 **Infra-red Analysis of Molecular Structure** Francis Ian Gregory

Rawlins, Alfred Maurice Taylor, 1929 *The Interpretation of Quantum Mechanics and the Measurement Process* Peter

Mittelstaedt, 2004-03-25 Monograph on the philosophy of quantum mechanics Education and Professional Employment in

the U. S. S. R. Nicholas De Witt, 1961 *Programme of the Courses of Instruction* Massachusetts Institute of

Technology,1922    The Philosophy of Quantum Mechanics Richard Healey,1989 One of the most important books on quantum mechanics to appear in recent years offers a dramatically new interpretation to resolve puzzles and paradoxes associated with the measurement problem and the behavior of coupled systems

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