QUANTUM MACHINE INTELLIGENCE

Intelligent Quantum Information Processing

Edited by

Siddhartha Bhattacharyya,
Iván Cruz-Aceves,
Arpan Deyasi,
Pampa Debnath, and
Rajarshi Mahapatra

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Intelligent Quantum Information Processing

The book discusses the foundations of intelligent quantum information processing applied to several real-life engineering problems, including intelligent quantum systems, intelligent quantum communication, intelligent process optimization, and intelligent quantum distributed networks.

This book:

- Showcases a detailed overview of different quantum machine learning algorithmic frameworks.
- Presents real-life case studies and applications.
- Provides an in-depth analysis of quantum mechanical principles.
- Provides a step-by-step guide in the build-up of quantum inspired/ quantum intelligent information processing systems.
- Provides a video demonstration on each chapter for better understanding.

It will serve as an ideal reference text for graduate students and academic researchers in fields such as electrical engineering, electronics and communication engineering, computer engineering, and information technology.

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Siddhartha Bhattacharyya would like to dedicate this volume to his loving wife, Rashni.

Iván Cruz-Aceves would like to dedicate this volume to his children, Ivan and Yusef, hoping that they keep their energy and curiosity!!!

Arpan Deyasi would like to dedicate this book to his guru, Swami Atmapriyananda Maharaj, who first introduced him to the world of Quantum Physics.

Pampa Debnath would like to dedicate this book to her respected father, Mr. Parimal Debnath; her mother, Mrs. Krishna Debnath; her beloved husband, Mr. Snehasis Roy; and her kid, Master Deeptanshu Roy.

Rajarshi Mahapatra would like to dedicate this volume to his wife, Sarmila.

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Preface

Quantum computer, as the name suggests, principally works on several quantum physical features. These could be used as an immense alternative to today's apposite computers since they possess faster processing capability (even exponentially) than classical computers. The term "quantum computing" is fundamentally a synergistic combination of thoughts from quantum physics, classical information theory, and computer science.

Quantum information processing entails the processing of information represented using qubits, which is the basic element of a quantum computer. Information processing in the quantum domain is centered on qubit encoding of the classical information, using the inherent properties of superposition and coherence followed by some quantum measurement operations to arrive at the classical outcome. In addition, the property of entanglement of the qubits helps in long-haul communication at an enhanced data transfer rate. This increased data transfer rate forms the basis for implementing distributed quantum networks in the near future. In addition, faster quantum communication is imminent due to rapid research on quantum information processing, the possible realization of quantum networks, and quantum internet services. Novel algorithms on quantum key distributions have been proposed to pave the way for a secured and robust communication system, thanks to the progress in research on single photon sources and detectors. Sequential single photon communication leads to quantum cryptography, which not only helps prevent eavesdropping but also forms the backbone for building quantum teleportation networks. Although entangled photon generation at the chip level still remains a challenging proposition, semiconductor-based quantum dot detectors and novel optical fibers can become effective for the practical implementation of encryption algorithms.

In addition to device-level research, scientists have invested their efforts to induce intelligence in quantum information processing in order to make the systems robust, fail-safe, and efficient. Utilization of the basic features of quantum computing in different machine learning algorithms has been explored over the decades, thereby evolving quantum-inspired/quantum computational intelligent algorithms. Starting from evolving quantum neural networks to emulating quantum fuzzy principles to evolving quantum metaheuristics, these have been the trends of research in recent years. The advent of these quantum algorithms has opened up a new era in the field of intelligent information processing, where the principles of quantum mechanics are conjoined successfully to enhance the real-time performance of the existing quantum information processing algorithms.

This volume aims to bring together recent advances and trends in the methodological approaches, theoretical studies, and mathematical and applied techniques related to intelligent quantum information processing and their applications to engineering problems. The scope of the book, in essence, is confined to but not bounded to introducing different novel hybrid quantum computational algorithms for addressing the limitations of the conventional information processing algorithms, including quantum machine learning, quantum key distribution, quantum information processing, quantum encryption algorithms, quantum networks, and quantum knowledge discovery in databases, to name a few. It is also aimed to emphasize the effectiveness of the proposed approaches over the state-of-the-art existing approaches by means of illustrative examples and real-life case studies.

This volume contains ten well-versed chapters, addressing different facets of intelligent quantum information processing.

The exponential rise in the demand for secured information processing requires an alternative approach from the conventional classical world, and the present scientific community believes that one of the most distinctive physical resources of the quantum world is quantum entanglement. It is a unique correlation between the components of quantum multipartite systems, which has never been observed in the classical macroscopic world. It is a tool that not only explains the effectiveness and fruitfulness of quantum information processing compared to its classical counterpart but also becomes significant from the security point of view when quantum communication is considered. Chapter 1 discusses the importance of quantum entanglement as regards to processing of information for secured data transmission. The most trusted and investigated resource to date is quantum entanglement, for the purpose of secured data communication. Similar to energy, quantum entanglement is a physical resource connected to the odd nonclassical connections that can occur between distant quantum systems. Using a pair of entangled quantum systems, it is feasible to carry out computing operations that are impractical for conventional systems. Quantum information theory is a broad study of the information processing capabilities of quantum systems.

At the most microscopic level, all physical systems are governed by the laws of quantum mechanics. Quantum information processing is the study of how information is gathered, transformed, and transmitted at the quantum level—in atoms, ions, photons, elementary particles, and microscopic solid-state systems, which obey fundamental quantum mechanical laws. Chapter 2 highlights the essential tenets of quantum information processing for the next-generation communication system design. Quantum computers, quantum communication channels, and quantum sensors are devices that can attain the ultimate limits of information processing. The laws of quantum mechanics give rise to counterintuitive effects. Quantum information processors use "quantum weirdness" to perform tasks that classical information processors cannot. Quantum computers are conceived to process information stored on atomic, optical, and solid-state systems. They aim to use counterintuitive effects including quantum superposition and entanglement to perform tasks such as quantum simulation, quantum search, and factoring/code-breaking to solve problems that are hard or impossible on conventional classical computers. Quantum communication systems transmit information encoded in individual photons: they exploit the fact that quantum measurement is inevitably stochastic and destructive to enact quantum-encrypted communication whose security is guaranteed by the laws of physics. Quantum sensors and measurement devices operate at the greatest possible sensitivity and precision allowed by physical law: from magnetometers to quantum clocks to advanced gravitational interferometers (e.g., LIGO), quantum metrology supplies the techniques required to push measurement to its ultimate limits.

Extracting and automatically classifying information elements (UIE) such as tables, figures, and equations from (scientific) documents is a challenge in the area of information retrieval. Convolutional neural networks (CNNs) are widely used models in image classification due to their good performance in pattern detection. However, CNNs present some problems in learning large tasks because they depend on having a considerable amount of data for optimal performance. On the contrary, Quantum Convolutional Neural Networks (QCNNs) have been increasingly used because they provide efficient solutions using the concept of quantum computing to improve the performance of a learning model. In Chapter 3, a Hybrid Quantum Convolutional Quantum Neural Network (HQCNN) is analyzed and compared with different state-of-the-art CNNs in the problem of classifying tables extracted from scientific documents. Given the limited access to specialized hardware, in this work, the simulations were carried out using the PennyLine platform and the Multiscale Entanglement Renormalization Ansatz (MERA) model. Results obtained in this work show that HQCNN results in superior performance than a traditional convolutional network compared to the literature.

Quantum computing, a branch of quantum physics, is seen as a promising solution to many of the world's problems. This dynamic research field has gained momentum over the past two decades, driven by the interaction between light and matter. Electromagnetic (EM) waves resonantly interacting with charged particles result in electrodynamics, as described by Maxwell's equations. Maxwell's equations are known for their form-invariance under arbitrary spatial coordinate transformations, enabling effects resulting from a coordinate transformation to be assimilated by the material properties that the EM waves pass through. Transformation optics (TO) applies a coordinate transformation-based approach to create a non-homogeneous and an anisotropic transformation medium, paving the way for unique electromagnetic and optical devices previously thought impossible. TO concepts can also be applied to the regions containing electromagnetic sources, known as source transformations. Chapter 4 delves into the theoretical and mathematical foundations of TO to help readers better understand the concepts behind it. Using this knowledge, this chapter discusses a phased array antenna with new pinwheel-shaped elements that incorporate structural and mechanical constraints using source transformations. Numerical simulations are used to demonstrate the radiation properties of the array, which has the potential to be integrated into conformal arrays for wireless communications, radars, and sensing. This chapter also discusses the future direction of TO-based device design, including the potential use of deep learning (DL), a subfield of machine learning (ML), and artificial intelligence (AI), to predict material properties and to determine design parameters for the desired performance.

The authors present an improved method for quantum machine learning, using a modified Levenberg-Marquardt (LM) method, in Chapter 5. The LM method is a powerful hybrid gradient-based reinforcement learning technique, ideally suited to quantum machine learning, as it only requires knowledge of the final measured output of the quantum computation, not intermediate quantum states, which are generally not accessible without collapsing the quantum state. With this method, the authors have been able to achieve true online training in a quantum system to do a quantum calculation, which has never been done before. The authors demonstrate this using a fundamentally non-classical calculation: estimating the entanglement of an unknown quantum state. Machine learning is applied to learn this algorithm and is demonstrated in simulation and hardware. Results are exhibited for two-, three-, four-, five-, six-, seven-, and eight-qubit systems, in Matlab simulations, and, more importantly, these run on the IBM Qiskit hardware interface as well. With this approach, the quantum system, in a sense, designs its own algorithm. Moreover, the approach enables scaleup, is potentially more efficient, and provides robustness to both noise and decoherence.

When an optimization problem needs to be solved, it is possible to use some classical methodology, such as the gradient-guided or exhaustive search technique. However, to be able to use any of them, it is necessary to have an extra knowledge of the problem. Evolutionary algorithms have been tested and applied to a wide variety of problems of this type, being a very good search strategy having the characteristic of not requiring extra information from the problems like those previously mentioned. One type of evolutionary computation is Genetic Algorithms (GAs), which are based on the mechanics of natural selection proposed by Charles Darwin. In a GA, a population of possible solutions is generated, and later, this is evolved through genetic operators (crossover, mutation, and selection) to generate a new one with better individuals (new possible solutions) that are close to the sought solution. Since 1996, a modification to GAs was presented by Narayanan and Moore, employing quantum mechanisms where the Schrödinger equation is essential to bring an initial state to a final state, the Quantum Genetic Algorithms (QGAs). Here, the concept of qubit arises, which aims to store the minimum unit of information of the quantum states, being $|0\rangle$ and $|1\rangle$. The advantage of this is that now it is also possible to have a state superposition of the two previous states $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, increasing the space of solutions. Similar to GAs, in QGAs, there are quantum crossover and quantum mutation (Q-gates), genetic operators that help to evolve the initial population toward the optimal value sought. In Chapter 6, a QGA is used to fit a curve on an image, the Major Temporal Arcade (MTA) vein in fundus images, which has been segmented previously. The aim is to determine the coefficients and the degree of the polynomials that, in linear superposition, fit the curve as best as possible, finally having a functional expression that can be manipulated in order to extract as much information as possible and help in the diagnosis and treatment of diseases related to the retina.

Quantum computing, which is the most famed topic in this era, a combination of quantum mechanics from the 1900s and computing point of view, takes a huge place in the quantum realm. Starting from the foundation of abacus from 2700 BC to 2300 BC, we humans always try to compute in different ways; the most modern ways of doing it come with the binary system. Bit is the smallest unit of a binary system and can be in two states: either 0 or 1. On the contrary, quantum computing deals with the "quantum bit" or "qubit"; possible outcomes from the qubits are neither 0 nor 1. It will always be a combination of 0 and 1, which is based on the superposition principle from quantum physics. In Chapter 7, the details of quantum logic gates are discussed from a circuit design perspective, which will be achievable for future realization of quantum computers. The architecture and the corresponding formation of basic quantum circuits are discussed, along with methods of quantum computing. How the technique differs from conventional approaches is also highlighted. The work may be directed toward future hardware realization of quantum information processing.

Quantum computing is a rapidly evolving industrial technology that employs quantum mechanics laws to address issues that traditional archaic computers find impossible to solve. It is a computation method that uses phenomena such as superposition, interference, and entanglement. It is one of the most effective theories of the twentieth century, contributing to the progressive growth of scientific investigations. In this modern-day world, there have been certain advancements in quantum computers that have encouraged researchers to opt for a number of algorithms. There are certain drawbacks in the architecture, mainly the presence of certain physical constraints that restrict the logical qubits from getting mapped and converted to physical qubits. Chapter 8 puts forward the modern-day trends in the field of quantum computing and focuses on the various restrictions faced in building a device following the principles of quantum computing.

Chapter 9 deals with fundamental concepts and corresponding algorithms related to quantum microwave propagation and its application in various sensing and communication networks. Propagation in both unbounded and bounded media is briefly mentioned with a detailed elaboration on qubits. The role of qubits as resonators is analyzed along with their physical representation. A few adopted algorithms are mentioned, which are nowadays essentially used for realizing quantum logic gates for sequential circuits. Both spin qubits and superconducting qubits are discussed at the end of this chapter to emphasize their future potential application areas.

Finally, Chapter 10 concludes the findings of the volume and future research directions.

This volume is meant for undergraduates and postgraduates of information science, computer science, electronics, and communication engineering for some part of their curriculum. The volume would also benefit aspiring and senior researchers to carry out further exploration of the application areas pertaining to this upcoming technology. The volume is also intended to benefit the faculty of relevant disciplines in premier institutes.

About the Editors

Siddhartha Bhattacharyya did his Bachelor in Physics, Bachelor in Optics and Optoelectronics, and Master in Optics and Optoelectronics from the University of Calcutta, India, in 1995, 1998, and 2000, respectively. He completed his PhD in Computer Science and Engineering from Jadavpur University, India, in 2008. He completed a habilitation thesis from VSB Technical University of Ostrava, Ostrava, Czech Republic, in 2023. He is the recipient of the University Gold Medal from the University of Calcutta for his Master. He is the recipient of several coveted awards, including the Distinguished HoD Award and Distinguished Professor Award conferred by the Computer Society of India, Mumbai Chapter, India, in 2017; the Honorary Doctorate Award (D. Litt.) from the University of South America; and the South East Asian Regional Computing Confederation (SEARCC) International Digital Award ICT Educator of the Year in 2017. He has been appointed as the ACM Distinguished Speaker for the tenure of 2018–2020. He was inducted into the People of ACM Hall of Fame by ACM, the USA, in 2020. He has been appointed as the IEEE Computer Society Distinguished Visitor for the tenure of 2021–2023. He has been elected as a full foreign member of the Russian Academy of Natural Sciences (RANS) and the Russian Academy of Engineering (REA). He has been elected a full fellow of the Royal Society for Arts, Manufacturers and Commerce (RSA), London, UK. He is currently serving as a Senior Researcher in the Faculty of Electrical Engineering and Computer Science of VSB Technical University of Ostrava, Czech Republic. He is also serving as the Scientific Advisor of Algebra University College, Zagreb, Croatia. Prior to this, he served as the Principal of Rajnagar Mahavidyalaya, Rajnagar, Birbhum. He served as a Professor in the Department of Computer Science and Engineering of Christ University, Bangalore. He was the Principal of RCC Institute of Information Technology, Kolkata, India, from 2017 to 2019. He has also served as a Senior Research Scientist in the Faculty of Electrical Engineering and Computer Science of VSB Technical University of Ostrava, Czech Republic (2018–2019). Prior to this, he was a Professor of Information Technology at RCC Institute of Information Technology, Kolkata, India. He served as the Head of the

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Iván Cruz-Aceves received an MS degree in Computer Science in 2009 from the Leon Institute of Technology and a PhD in Electrical Engineering from the University of Guanajuato with Summa Cum Laude distinction in 2014. He joined the Department of Computer Science at the Centre for Research in Mathematics (CIMAT) in 2014 as part of the program "Investigadores por México" at the National Council for Science and Technology (CONACYT). He is currently a full-time researcher of Computer Science, and he is the author of more than 30 international conference papers, 35 papers in journals (JCR), international book chapters, and 10 transfer technologies to the medical area, involving medical image processing and analysis. His areas of interest are Artificial Intelligence focused on stochasticity and Evolutionary Computation with applications to medical image and video processing and analysis.

Pampa Debnath is presently working as an Assistant Professor in the Department of Electronics and Communication Engineering at RCC Institute of Information Technology, Kolkata, India. She has more than 16 years of professional teaching experience in academics. Her research interest covers the area of microwave devices, high-frequency antennas, SIW, and RGW-based circuits. She has already served as the technical chair and session chair of several IEEE, Springer, and other international conferences and coordinated several faculty development programs, workshops, laboratory and industrial visits, seminars, and technical events under the banner of IEEE and the Institution of Engineers, Kolkata section, India. She is a reviewer of a few journals of repute and some IEEE, Springer, and other national and international conferences. She is a member of the Institute of Engineers (IE), the Institution of Electronics and Telecommunication Engineers (IETE), the Indian Society for Technical Education (ISTE), and the International Association for Engineers (IAENG).

Arpan Deyasi is presently working as an Associate Professor in the Department of Electronics and Communication Engineering in RCC Institute of Information Technology, Kolkata, India. He has more than 17 years of professional experience in academia and industry. His work spans around in the field of semiconductor nanostructure and semiconductor photonics. He has published more than 200 peer-reviewed research papers and edited 8 books. He is associated with different international and national conferences in various aspects and is also Guest Editor of a few renowned journals. He is a senior member of IEEE, Vice-Chair of IEEE Electron Device Society (Kolkata Chapter), and a member of IE(I), Optical Society of India, IETE, ISTE, ISVE, and so on.

Rajarshi Mahapatra received a PhD degree in electronics and electrical communication engineering from the Indian Institute of Technology Kharagpur, Kharagpur, India, and a postdoctoral degree from the CEA-LETI, Grenoble, France. In his postdoctoral research, he was engaged in FP7 Call4 BeFEMTO and Greentouch projects. He is presently serving as an Associate Professor with the Department of Electronics and Communication Engineering, Dr. SPM IIIT, Naya Raipur, Chhattisgarh, India. He also served as the Dean (Academics) of IIITNR. Earlier, he had worked for Collins Aerospace, Hyderabad, on software-defined radio and electronic warfare.

He has worked extensively in the domain of physical layer design and analysis of a wireless communication system. He worked in the fields of cognitive radio, 5G and 6G communication, heterogeneous wireless communication, molecular communication, and energy-efficient communication. His team designed and developed software-defined radio and direction-finding systems for EW applications in Collins Aerospace industry. He has about 18 years of teaching, research, and industry experience. He has guided PhD scholars in the area of wireless communication. He has published several research papers in various refereed journals and IEEE journals. He is a regular reviewer of premier IEEE Transactions and other peer-reviewed journals and IEEE conferences. He has been organizing many workshops on 5G in recent years. He has also developed several high-value research labs, including the 5G test bed. He has successfully completed and undertaken high-value sponsored projects in the field of communication systems.

He has been awarded a national scholarship, an MHRD scholarship for research, and an EU-FP7 fellowship for a European project. He is a senior member of IEEE and a member of the Communication Society. His research interests include 5G and beyond communication, machine learning for communication, molecular communication, intelligent reflecting surfaces, and optical access networks.

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