Title	Control theory to harness quanta : a beacon for the realization of quantum computers : forging new fields which merge mathematical engineering with quantum mechanics
Sub Title	
Author	平塚, 裕子(Hiratsuka, Yūko)
Publisher	Faculty of Science and Technology, Keio University
Publication year	2019
Jtitle	New Kyurizukai No.29 (2019. 1) ,p.2- 3
JaLC DOI	
Abstract	
Notes	The Research
Genre	Article
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO50001003-00000029-0002

Our latest column features Associate Professor Naoki Yamamoto who is driving research on quantum computing from theoretical perspectives.

Control theory to harness quanta: a beacon for the realization of quantum computers

Forging new fields which merge mathematical engineering with quantum mechanics

A quantum is an extremely minute substance or energy unit, and can include atoms, molecules, electrons and elementary particles. In the submicroscopic world of under one billionth of a meter, quanta dance a mysterious dance: a phenomenon which differs from any which we encounter in daily life. Efforts are now at full steam to make practical high-speed computers a reality by exploiting the characteristics of quanta. These attempts involved the challenging task of how to further quantify, understand, and subsequently control quanta. Professor Yamamoto is a quantum theorist whose research has grappled with this challenge for over twenty years.

A control theory and mathematical engineering approach at the dawn of quantum computers

Even though the idea for quantum computers has existed for over 30 years, harnessing quanta, the very observation of which is problematic, and creating actual measurement devices was a by-no-means-easy task. According to Yamamoto, "The chance that 'we could really make a quantum computer' increased," around 1998 when a "quantum teleportation experiment" by Akira Furusawa, then a researcher at the California Institute of Technology (Caltech), succeeded in conveying information instantaneously to a remote location.

Inspired by news of this success, Yamamoto began to dip his toes in the waters of quantum mechanics — in spite of the fact he had never actually specialized in this area. During this period, Yamamoto learned extensively on applied mathematics courses as a student at the Department of Mathematical Engineering and Information Physics at the University of Tokyo. He was highly influenced by Dr. Shun'ichi Amari's "Methods of Information Geometry" in particular. He would study neural nets, an AI tool, as part of his graduation research, and control theory and information geometry during his master's.

"Professor Amari gave me the bird's-eye-view on mathematical engineering from the perspective of "geometry," including statistics, control, and optimization. "Methods of Information Geometry" deals with domains such as neurons and neuroscience, and even at this early stage included a chapter on quantum information." The spirit espoused by this volume, of attempting to achieve a handle on diverse methodologies by numerical means, was taken on board by Yamamoto in his own approach to research and still guides him today.

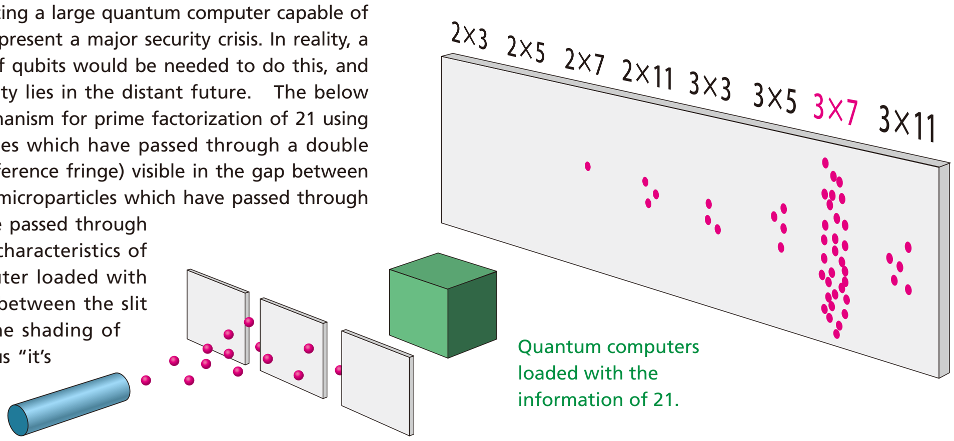
Yamamoto aspired to forging new fields which tied together mathematical engineering with quantum mechanics—including the control and optimization theory with which he had been engaged up until that point, and he wrote his thesis from his own new and distinctive perspective. After getting his master's degree, he honed in on "quantum control," undertaking a postdoc at the California Institute of Technology which was then at the top of this field and turning its hand to quantum texts on feedback theory in control engineering (controlling objects based on observations of their state.)

20 years which shook the quantum world

"Control" infers that a particular state is manipulated to change this into another state. However, for this to happen one must first observe and understand the state of the object in question. For example, a robot will most likely be unable to hold a cup properly unless it can calculate both its position and dimensions. Regular computers process by distinguishing bits of 1 and 0 (1s and 0s.) However, rather than processing distinct 1s and 0s, quantum computers are concerned with states

Fig.1 : Quantum computer mechanism

The quantum algorithm for prime factorization unveiled by Peter Shor in 1994 is one of the major sources of perturbation in the development of quantum computers. This is because constructing a large quantum computer capable of defeating RSA encryption would represent a major security crisis. In reality, a quantum computer of thousands of qubits would be needed to do this, and it is still assumed that this possibility lies in the distant future. The below figure is a visualization of the mechanism for prime factorization of 21 using a quantum computer. Microparticles which have passed through a double slit create a stripped pattern (interference fringe) visible in the gap between screens. This happens because the microparticles which have passed through the right slit and those which have passed through the left slit overlap to reveal the characteristics of the waves. If the quantum computer loaded with the information of 21 is inserted between the slit and the screen, gaps appear in the shading of the interference fringe. These tell us "it's around here" from amidst the various solutions which are encoded on the screen.



in which 1s and 0s (quantum bits/qubits) overlap. According to quantum mechanics this state is one which cannot be seen (observed.) This is because this "superposition state" of 1s and 0s will have dissipated into distinct 1s and 0s the instant at which it is observed.

The act of "observing" is achieved by exposing an "object" to light and measuring the reflected light. However, when these objects are of quantum size, exposing them to light changes their state. That is to say we cannot observe them by exposing them to light. This is the conventional wisdom of quantum mechanics.

"We need to control something that you must not observe (laughter.) This is the profound, inherent conundrum," says Yamamoto. In the famous thought experiment of Schrödinger's Cat, the cat is in a superposition state of wakefulness and sleep. But you cannot observe the cat by exposing it to normal light. This question of how one could observe the cat without being seen by the cat perplexed researchers. However, a method has already been developed to generate a unique, weak light which offers a solution to this conundrum. This gave us the means to observe Schrödinger's Cat. Following this, a further understanding of the means of unrestricted feedback control on the cat's state was also achieved.

The series of studies on quantum control stemming from this culminate in the Collège de France's Serge Haroche and David J. Wineland of the National Institute of Standards and Technology receiving the Nobel Prize in Physics "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems," in 2012.

The systems to enable effective feedback have gradually come into existence since development of the technologies to allow observation of quantum systems began in the latter half of the 1990s. While this field had a negligible profile in mathematics when Professor Yamamoto made his way to Caltech, a number of happy coincidences made him a global forerunner in acquiring the attendant theory. His subsequent journey by way of the Australian National University brought him to where he is today.

Yamamoto's papers were favorably received, including being verified by an experimental team at the University of California, Berkeley. He breaks a smile when recalling that: "This was an extremely happy event for a theoretician." Yamamoto-sensei explains that "Developments of theories on how to freely control overlapping states received recognition in the form of the Novel Prize, for example, which has radically transformed the domain of quantum physics in the last twenty years." He is now engaged with the quantization of feedback control for electronic circuits at the limits of integration by applying quantum control theory. There are expectations that this will be indispensable to the next-generation of computers and is being pursued as part of a Japan Science and Technology Agency (JST) project.

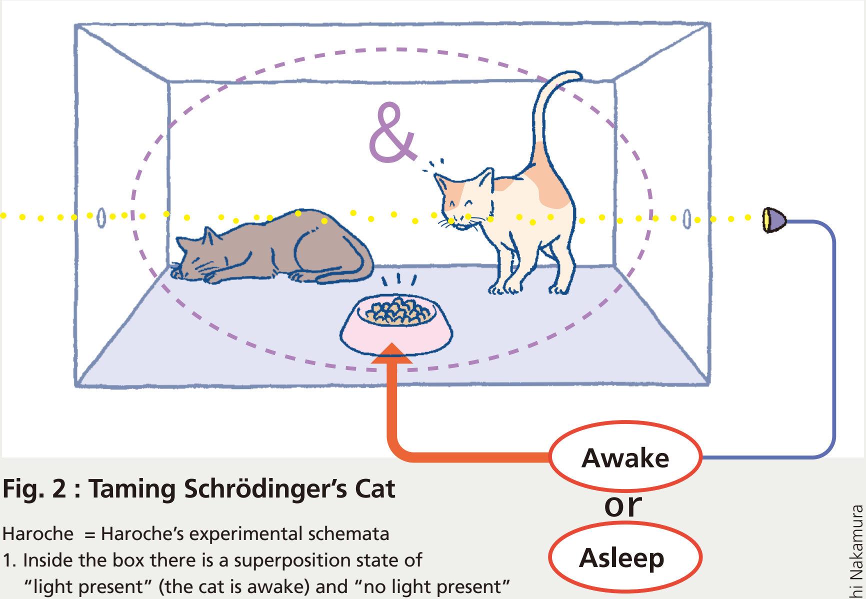


Fig. 2 : Taming Schrödinger's Cat

Haroche = Haroche's experimental schemata
1. Inside the box there is a superposition state of "light present" (the cat is awake) and "no light present" (the cat is sleeping).
2. The objective is to create "A stable state of light present."
3. The box is exposed to ions (sufficiently weak as not to change the light status.)
4. The ions emitted from the box inform us of the light status.
5. If information indicates that there is "no light," the light will be increased (give the cat food and wake it.)

illustration : Satoshi Nakamura

Quantum computer research sets the world alight

With anticipation on their practical implementation growing, all eyes are now on the development of quantum computers. "Corporate giants are investing massive sums of capital in quantum computer development. There is also a huge increase in start-ups and venture companies in this area in the United States, so Japan really can't afford to lose out," says Yamamoto-san. In addition to the hardware development, research on the algorithms set to be used in machine learning is thriving.

At Keio University, we launched the Quantum Computing Center and established the IBM Q Network Hub[*1] in May 2018, where we are now busying ourselves with quantum algorithm research using actual quantum computers of 20 quantum bits (qubits.)[*2] Yamamoto-sensei, as the Director of the Quantum Computing Center, is heading up research on this program, which links up with corporate entities with a view to creating future business.

Specifically, research is being conducted on a high-speed Monte Carlo method for rapid stock market appraisals and on quantum machine learning to enhance AI by making effective use of limited data. "This links back with the fields I covered both as an undergraduate and during my master's studies, which is certainly a stroke of good fortune. We are also aggressively engaging with various challenges of mathematical engineering. I would like to see an integration of the narratives of control and optimization, with which I was previously engaged, in the further development of mathematical engineering aspects of quantum computers," says Yamamoto. Yamamoto's battle continues as to how we can build on the original foundations laid by computational engineering amidst the constant evolutions in the domain of quantum computers.

(Interview and text : Yuko Hiratsuka)

[*1] IBM Q Network Hub
This is a mechanism launched by IBM Corporation in 2017 to construct an all-purpose quantum computing system with potential applications in business and science. Hub locations include Oak Ridge National Laboratory in the United States, University of Oxford in the United Kingdom, and Australia's University of Melbourne, with Keio University serving as the Japan hub. A 5 qubit quantum computer can be freely accessed and used on a cloud server at the following website.
IBM Q Experience
https://quantumexperience.ng.bluemix.net/qx/experience

[*2] 20 qubits
As one qubit can simultaneously represent superposition states of 1s and 0s, a 20 qubit quantum computer allows superposition of 2 to the power of twenty; in other words, approximately 1 million such states. Calculation speeds are thus exponentially greater as qubits increase.