A giant leap for quantum science

Associate Professor Min-Hsiu Hsieh highlights some of the exciting opportunities quantum information science presents for society and how his work is helping to advance the field.

What first inspired you to pursue a career in quantum information science (QIS)?

When I was a graduate student, there had been two recent significant breakthroughs made in the field of QIS. These included the existence of an unconditionally secure quantum key distribution (QKD) protocol, which was invented in 1984 by Charles Bennett and Gilles Brassard, and an exponentially fast factoring algorithm known as Shor’s algorithm. I was fascinated by the thought of how many more advantages QIS could provide, and decided to dedicate my research career to it.

Can you provide some examples of scientific opportunities offered by QIS?

One excellent example is the emerging topic of quantum machine learning. Google and NASA announced the Google/NASA Quantum Artificial Intelligence Lab in 2013. Its goal is to pioneer research on how quantum computing might help with machine learning. Microsoft also created a research initiative called the Quantum Architectures and Computation Group focusing on this topic.

These actions signal two important messages. Firstly, classical learning machines have faced a significant limitation in the critical area of big data analysis and machine learning. Secondly, small-scale quantum computing devices have become a viable technology due to several theoretical and experimental breakthroughs. I am also hoping to see advances along these lines in the near future so that quantum learning machines become a viable technology.

What are quantum error-correcting codes (QECCs)? How have you furthered understanding in this area?

Error correction is ubiquitous in all of our electronic devices such as mobile phones and PCs. QECCs are a technique for correcting errors introduced by imperfect circuit operations or environmental disturbances. This issue of the appearance of errors is even more prominent in the quantum regime due to the delicacy of a quantum system. As a result, the existence of good QECCs is the first and the most important step towards a quantum computer. The original theory of QECCs was shown to be equivalent to a special class of classical error-correcting codes. This defies our general belief that a quantum theory normally encompasses the classical theory as a special case. In 2006, we showed that QECCs are indeed more general if the entanglement resource is available.

In 2013, you established a quantum rate distortion theory. Can you discuss the significance of this advancement to the wider field?

Typically, a substantial amount of data can be discarded before the information is sufficiently degraded to be noticeable. A data compression scheme is said to be ‘lossy’ when the decompressed data are not required to be identical to the original data, and the ability to recover a reasonably good approximation of the original data is considered to be sufficient. The theory of lossy data compression, which is also referred to as rate distortion theory, was developed by Claude Shannon in 1959. It deals with the trade-off between the rate of data compression and the allowed distortion.

It might be easier to talk about the significance of classical rate distortion theory, and consider the corresponding quantum rate distortion theory as a generalisation. The rate distortion theory is a fundamental theory behind which most compression techniques operate on data that will be perceived by human consumers, such as when listening to music, looking at pictures and watching videos.

In information theory, why is it important to distinguish one physical configuration from another?

This ability lies at the heart of information theory. When quantum systems are used for information transmission, messages are encoded into quantum states, and the processing of this information in a faithful manner requires the encoded states to be distinguishable from one another. Hence, a fundamental topic in quantum information is the problem of state discrimination, which investigates how well ensembles of quantum states can be distinguished under various physical conditions.

How has the thriving area of QKD resulted in currently available quantum technology? Can you offer some examples?

QKD can be implemented without utilising quantum entanglement, hence it is relatively easier to build. Experimental networks running QKD have been built in national laboratories and universities in a number of countries, including Australia, Canada, China, Japan, Switzerland, the UK and US. In fact, the technology has matured to a point that it is now commercially available. Companies, such as ID Quantique and MagiQ Technologies Inc, have started to sell QKD devices.
The science of information

By finding solutions to challenges that have hindered the advancement of quantum computing, a lab at the University of Technology, Sydney is paving the way for quantum systems to become more widely available.

THE INFORMATION REVOLUTION – which has given rise to the computers and telecommunications systems we use every day, including the internet – was made possible in large part by the science behind information theory. It provides the groundwork for remote communication over much longer distances than were possible in the past, as well as the ability to create more streamlined codes that allow increased data storage and compression, as seen in zip files, MP3s and JPGs that are ubiquitous today.

Quantum information science (QIS) expands on this line of study. Digital computers run on data that have been encoded into binary digits, or bits, which are in definite states of either 0 or 1. In contrast, quantum computation uses qubits – quantum bits – which can exist in a superposition of states. As a result, quantum computers would be able to carry out tasks much faster than traditional computers; however, the full potential of these systems has yet to be realised due to issues with reading out the computation outcomes.

For this reason, scientists such as Associate Professor Min-Hsiu Hsieh at the Quantum Computation Lab in the Centre for Quantum Computation and Intelligent Systems at the University of Technology, Sydney, Australia, are pursuing research in QIS to better understand the full scope of possibilities this field can offer. The lab focuses on mathematically intensive and interdisciplinary approaches to a wide range of subjects including quantum Shannon theory, computational complexity, quantum error correction, quantum simulation, quantum cryptography and quantum computing architectures.

AROUND THE WORLD
Hsieh has been working in QIS since 2004, with the long-term goal of uncovering the power of quantum information and computation. For over a decade he has been helping to advance the field in three core areas: quantum error-correcting codes, quantum Shannon theory and quantum state discrimination.

The contributions Hsieh has made to QIS are, in part, a result of the highly collaborative approach he takes to his work. His research has benefited from the contributions of leading experts in the fields of engineering, computer science, mathematics and physics across several continents, including North America, Asia, Europe and Australia. “These experiences have played a large part in my research career, and have contributed significantly to the scientific outcomes that I have produced so far. Through these involvements, I was able to stand on the shoulders of giants,” enthuses Hsieh.

Hsieh’s current work centres on two research projects, which he hopes will help to further advance the subject of QIS. “The first project aims to quantify a quantum channel’s capability for secure communications. This quantity will provide the ultimate limit to benchmark practical quantum key distribution protocols for their performance,” he explains. The second has the goal of developing a general framework for the theory of machine learning that can include hybrid classical-quantum and fully quantum learning environments. Moreover, the project aims to identify how advantages can be found solutions to challenges that have hindered the advancement of quantum computing, a lab at the University of Technology, Sydney is paving the way for quantum systems to become more widely available.

Hsieh’s achievements are part of a number of significant theoretical breakthroughs that are providing the momentum to achieve things that were not possible in the past.
ADVANCING QUANTUM INFORMATION SCIENCE

OBJECTIVE
To advance the subject of quantum information science by identifying problems where a quantum advantage exists. These outcomes will help to build next-generation quantum technologies, creating new market opportunities driven by powerful quantum computers. It will thus provide the whole nation with economic and social benefits.

KEY COLLABORATORS
Dr Andreas Winter, Universitat Autonoma de Barcelona, Spain
Dr Nilanjana Datta, University of Cambridge, UK
Dr Todd A Brun, University of Southern California, USA
Dr Mark M Wilde, Louisiana State University, USA
Dr Eric Chitambar, Southern Illinois University, USA
Dr François Le Gall, The University of Tokyo, Japan
Dr Steven T Flammia, The University of Sydney, Australia

FUNDING
Australian Research Council (ARC)

CONTACT
Associate Professor Min-Hsiu Hsieh
ARC Future Fellow and Associate Professor
Centre for Quantum Computation and Intelligent Systems,
Faculty of Engineering and Information Technology
University of Technology, Sydney
15 Broadway
Ultimo
New South Wales 2007
Australia

T +61 9514 4494
E min-hsiu.hsieh@uts.edu.au

www.uts.edu.au/staff/min-hsiu.hsieh
www.researchgate.net/profile/Min-Hsiu_Hsieh

MIN-HSIU HSIEH received his PhD in Electrical Engineering from the University of Southern California, Los Angeles, in 2008. He was a postdoctoral researcher with the ERATO-SORST Quantum Computation and Information Project, Japan Science and Technology Agency, Tokyo, Japan, from 2008-10, and with the Statistical Laboratory, the Centre for Mathematical Sciences, University of Cambridge, UK, from 2010-12. He joined the Centre for Quantum Computation & Intelligent Systems (QCIS), Faculty of Engineering and Information Technology (FEIT), University of Technology, Sydney (UTS) in 2012. He is now an ARC Future Fellow and Associate Professor. His scientific interests include quantum Shannon theory, entanglement theory and quantum coding theory.

DEALING WITH DISTORTION
One of the theoretical findings that Hsieh’s research has revealed expands upon rate-distortion theory (the theory of lossy data compression), which was developed by Claude Shannon in 1959. The theory aimed to identify the extent to which data could be compressed and still be stored and communicated reliably, without being significantly affected by distortion. By understanding this, communication can be made faster and less room is needed for storing information.

Hsieh and his collaborators have advanced this theory by revising the tools and operating structure used in the classical setting. He outlines the significance of his contribution in this respect: “We established a quantum rate-distortion theory that governs the optimal trade-offs between the compression rate of a quantum source and the given distortion. This result resolved one of the most important capacity theorems remaining in quantum information theory”.

TRIAL AND ERROR
One of the greatest challenges for progressing quantum computers and quantum communication protocols is their susceptibility to error from environmental noise. In fact, it was such a serious issue that until 1995 when quantum error-correcting codes (QECCs) were discovered, scientists did not believe it was possible to create quantum computers on a large scale due to the expected loss of information from a system to the environment. These codes can protect quantum information from losing coherence (quantum decoherence) and other errors caused by environmental noise, maintaining a pure quantum state.

For those who study QIS, QECCs are considered to be one of the most important discoveries in the field. Some issues remained, however, such as the fact that the connection between classical and quantum codes was not universal, and only a portion of classical codes that met specific criteria could be used to construct quantum codes. Hsieh and his colleagues have addressed this by developing a methodology that generalises the stabiliser codes. In a paper published in Science, they show that, with the assistance of prior shared entanglement, every classical linear code can be used to construct a corresponding quantum code, known as the entanglement-assisted quantum error-correcting code (EAQEC),” states Hsieh. This research significantly advances the theory of QECCs, justifying for the first time that quantum codes are more general and include classical error-correcting codes as a special case.

THE POWER OF PARTNERSHIP
Building on the success of Hsieh’s findings will require scientists to work together more closely and across subjects. At its heart, QIS is a highly cross-disciplinary subject that spans quantum physics, chemistry, mathematics, computer science and engineering, and its development will require input from researchers with a broad knowledge of these areas. “I believe that the future of QIS requires theorists and experimentalists to work more intimately,” Hsieh notes. “The first step will be to create powerful small-scale quantum devices that are useful for simulating complicated systems (a special-purpose computer). In my opinion, the ability to implement a general purpose quantum computer is still several decades away.”

Indeed, there is still a lot of progress to be made, but researchers working in the field of QIS have been moving from strength to strength in recent years. Hsieh’s achievements are part of a number of significant theoretical breakthroughs that are providing the momentum to achieve breakthroughs that were not possible in the past.

MIN-HSIU HSIEH received his PhD in Electrical Engineering from the University of Southern California, Los Angeles, in 2008. He was a postdoctoral researcher with the ERATO-SORST Quantum Computation and Information Project, Japan Science and Technology Agency, Tokyo, Japan, from 2008-10, and with the Statistical Laboratory, the Centre for Mathematical Sciences, University of Cambridge, UK, from 2010-12. He joined the Centre for Quantum Computation & Intelligent Systems (QCIS), Faculty of Engineering and Information Technology (FEIT), University of Technology, Sydney (UTS) in 2012. He is now an ARC Future Fellow and Associate Professor. His scientific interests include quantum Shannon theory, entanglement theory and quantum coding theory.