第 1 部
特集1　#QuantumNative: Online Education and Research for the Next Generation AQUA (Advancing Quantum Architecture) Annual Report 2020

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Abstract

The AQUA (Advancing Quantum Architecture) working group continued research activities advancing quantum computing and communication, especially quantum networking and distributed quantum computing systems. Our research contributes to planning for the long-term evolution of the computing and networking industries as Moore's Law comes to an end. The MOOC created by WIDE members has reached over 8,000 people in 127 countries and territories, and helped establish the new IBM Q Network hub at Keio, where member companies will gather to develop quantum algorithms for production use in their business. We published four journal and peer-reviewed conference papers.

第 1 章　Introduction

WIDE, through the AQUA working group, is well positioned to participate in and help guide the field in the exciting area of quantum computing and quantum networking, particularly as it moves from theoretical papers and small laboratory technology demonstrations toward actual systems.

This report first discusses the massive open online course (MOOC) that attracted thousands of learners from around the world. We then turn to the IBM Q Network and to online experiments conducted by WIDE members and their students. This is followed by recent work in WIDE on quantum networks, then quantum error correction and quantum architecture. A brief summary of current work is followed by a description of WIDE's particiation in the quantum networking community. This report closes with a summary of major publications over the last two years. An introduction to the AQUA group and work areas is included as Appendix A. A brief introduction to the field of quantum information is included as Appendix B. Statistics on the MOOC are included in Appendix ??.

第 2 章　Quantum Networking

A quantum repeater's work consists of four tasks: (1) generation of base-level entanglement with its nearest neighbors, using fiber or free space links; (2) managing errors (via error detection or error correction); (3) coupling the singlehop entanglement into longer-distance entanglement, e.g. via a method known as entanglement swapping [9]; and (4) participating in management of the network. Experimental and theoretical physicists have worked hard on the physical layer mechanisms for generating entanglement, and theorists have studied means of managing errors while building entanglement along a chain of repeaters, but little energy has been invested so far in designing *networks* of quantum repeaters. A network diagram showing the elements of a network with Quantum Byzantine Agreement as an application is shown in Fig. 1.

Building on the work done over the last ten years, the work done by AQUA has completed our list of provisional technical proposals for almost every aspect of creating a true entanglement-based Quantum Internet above the physical layer.

2.1　Research Accomplishments

This year, AQUA had three major networking research accomplishments: we used a *quantum computer* to simulate a *quantum network*, much as a classical computer can be used to simulate a classical network; and design of a RuleSetbased connection architecture; and development of a simulator to support investigation of network protocol designs and emergent behavior. Furthermore, we expect to open-source the simulator early in 2020.

First, in a paper available in preprint, we used one of IBM's quantum computers to model *quantum network coding* [15, 19]. This represents an advance in our ability to model quantum networks. We found that quantum network coding can result in classical correlations that could potentially leak information even in cases when no unintended entanglement remains in the crossing-over entangled states that are the outcome of QNC.

Second, Takaaki Matsuo's master's thesis covers the key elements of the design of a RuleSetbased Quantum Internet. The fundamental service of an IP network is packet forwarding toward the endpoint, but in the quantum case the fundamental service is more subtle and complex. The goal is to create end-to-end services: Bell pairs are the most basic service, but data forwarding or creation of complex states such as W and GHZ states could also be fundamental. The actions necessary for all of these, including entanglement swapping, one or more types of purification, and quantum error correction, all can be derived from a set of rules created and distributed to the various nodes. It's important to recognize that a quantum connection is, in effect, a *distributed computation*.

Third, to support our analysis of that network design, we have created a Quantum Internet simulator, which will be released as open source in March 2020.

2.2 QuISP README

This subsection contains the README for the QuISP software package.

The Quantum Internet Simulation Package (QuISP) is an event-driven simulation of quantum repeater networks, which will be the ultimate foundation of the coming Quantum Internet. QuISP's goal is to simulate a full Quantum Internet consisting of up to 100 networks of up to 100 nodes each. Its focus is on protocol design and emergent behavior of complex, heterogeneous networks, while keeping the physical layer as realistic as possible.

QuISP is a product of the Advancing Quantum Architecture

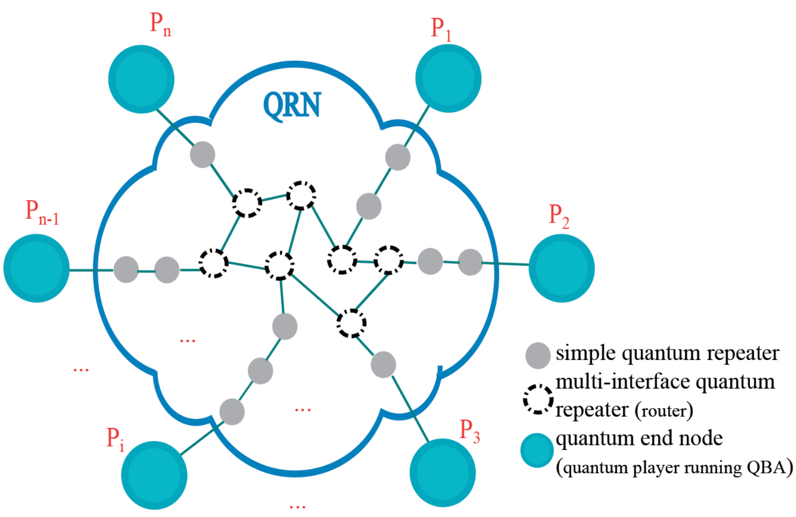

Fig 1 Required elements in Quantum Repeater Networks (QRN) for running scalable quantum distributed applications such as Quantum Byzantine Agreement. From [20].

(AQUA) research group headed by Prof. Rodney Van Meter, at Keio University's Shonan Fujisawa Campus, Fujisawa, Japan. `http://aqua.sfc.wide.ad.jp`

2.2.1 Research questions

A simulator is one or more of three things: a time machine, an X-ray machine, or a telescope.

Research questions we hope to answer:

- Emergent behavior
  - Classical networks exhibit *congestion collapse*; are quantum networks subject to the same thing?
  - Will the dynamics of large networks prevent us from making end-to-end connections under realistic scenarios, even when a naive model suggests it should be possible?
  - Are there other unexpected behaviors in large-scale networks?
- Protocol design
  - Testing of detailed protocol designs to validate correct operation.
  - Are there interactions between the classical and quantum portions of the network?
- Connection architecture and performance prediction
  - All three proposed network generations exhibit complex behavior that makes analytic prediction of performance difficult with realistic parameters; simulation, of course, will require the best effort we can make at validation, as well.

2.2.2 Simulation goals

We have a number of long-term goals for the simulator:

- Complex network topologies, including the notion of network boundaries and heterogeneity at the physical and logical levels
- support 1G, 2G and 3G quantum networks, utilizing either purify-and-swap (1G) or quantum error corrected (QEC) (2G and 3G) protocols for managing errors
- Distinct link architectures: memory-tomemory (MM), midpoint interference (MIM), and midpoint source (MSM)
- Internetworking protocols for connecting different types of networks
- Various applications running in complex traffic patterns

Because these protocols can result in hundreds of qubits in a

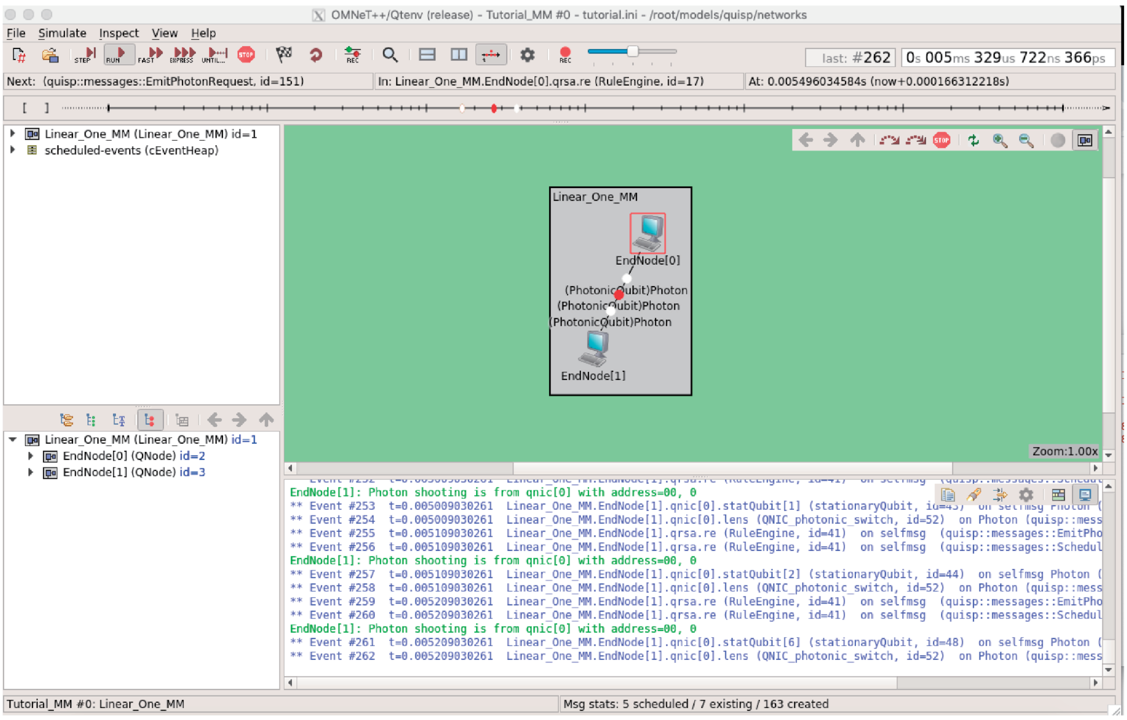

Fig 2 The Quantum Internet Simulator Package (QuISP) builds on OMNeT++.

single entangled state, and the entire system may consist of up to a million qubits, simulation at the physical Hamiltonian level or even just above that at the unitary (gate, e.g. CNOT) level is infeasible. We cannot calculate and store full density matrices for such states. Instead, like simulators for large-scale error correction, QuISP operates primarily in the *error basis*, in which we maintain a description of errors the states have incurred rather than the full state. However, unlike QEC simulators, QuISP supports non-Pauli errors, in a limited fashion.

QuISP is almost endlessly configurable; for example, it is possible to set not only different lengths for different links in the network, but also different gate error rates and memory lifetimes on individual qubits. Non-Pauli errors that are at least partially supported in the current release include qubit loss, relaxation to ground state, excitation to excited state, and complete mixing.

If you are unfamiliar with the research literature or the terminology above, see ”Learning more”, below.

2.2.3 Current status

Most of the *infrastructure* is up and running, though the sets of actual experiments (interesting simulations) you can do are fairly limited still.

Working infrastructure:

- All of the basic OMNeT++ functionality, such as events, visualization, logging, analysis, etc.
- Complex network topologies, defining per link parameters including length, channel error rates, numbers of qubit memories, gate error rates, etc. (You will see the included demonstration networks in the documentation linked below.)
- A complete internal model of the software architecture for a repeater, including a connection manager, the RuleSet execution engine, real-time tracking of quantum states, etc.

Besides the obvious joys of the endless network configurability, here are the key quantum protocols that are implemented:

- various purification protocols: Single round of X purification, alternating X/Z purification, etc. Extending these to test your own custom purification protocol is pretty straightforward.
- tomography: when the simulation boots, it assumes that the software at each end of each link knows *nothing* about the link, so it begins by performing tomography on the links. This is actually problematic, because it turns out to take a long time for tomography to converge, which means a lot of bootup time in the simulation before other interesting things start to happen. We are working on a way to pre-calculate this, so that you can choose to either include tomography or not; it sort of works, but may be a bit kludgy.

networking protocols:

- basics of RuleSet creation & distribution
- framework for a routing protocol

missing essential features:

- entanglement swapping (we hope to have this done before release)
- resource allocation & multiplexing (we need at least something crude here, or we can’t have multiple connections running that require access to the same links)
- some mechanism for establishing traffic patterns

2.2.4 Installation requirements

The full installation process is described in doc/INSTALL.md. The main software tools you will need are:

- QUISP requires OmNET++ `https://omnetpp.org/` and
- an external C++ library, Eigen `http://eigen.tuxfamily.org/`, to work.
- To contribute to QuISP development, you will also need to be familiar with at least the basics of git `https://git-scm.com/`.
- We recommend the use of `http://www.doxygen.nl/` for source code comments, but the Doxygen tools are not required unless you want to build the source code documentation.

Depending on your local setup and how you intend to use

QuISP, you may also need various tools (a C++ compiler, make, an X Windows server, Docker, etc.), documented in the installation notes.

2.2.5 Building and running

There are two main ways of working with QUISP. You can either use the Eclipselike graphical interface of OmNET++, for which you will find instructions in `doc/USAGE-omnetpp-gui.md`, or you can use the 'Makefile' and GNU make, by looking at instructions in `doc/USAGE-makefile.md`. Some operations are implemented in the Makefile and not explained for the graphical user interface.

2.2.6 Moving into useful work

Once you have gotten this far, you should be able to [run some of the most basic demos (doc/running-demos.md). Next, you'll want to learn how to create your own test networks, and how to extend the source code for your own uses.

2.2.7 Development tools

A few tools (mainly scripts) can be used to make development a bit easier. Look around in the 'bin' folder of this project.

2.2.8 Is QuISP right for me?

Fundamentally, the point of QuISP is that *networks are much more than point-to-point connections*.

If you want to know about the behavior of systems and networks, to study behavior of links that are too complex for simple analytic equations (esp. those with multiple qubits per link) or to contribute to the design of network protocols, QuISP is the simulator for you. If you're trying to adjust detector window timing v. entanglement fidelity, or figure out what Q factor your cavity needs to be, or understand dispersion in a fiber, it might not be.

2.2.9 Learning more

See the references `doc/References.md`.

2.2.10 License

We hope to release QuISP as open source QuISP on March 1, under a commercial-friendly (not copyleft) license. There are options for the license: MIT, Apache, Mozilla, BSD...most likely BSD. QuISP builds on OMNeT++. OMNeT++ itself is a custom license `https://omnetpp.org/intro/license,`

open source and free for academic use, but a license fee required for commercial organizations. QuISP also requires the linear algebra library Eigen, where license is MPL2, and so probably not an issue `http://eigen.tuxfamily.org/index.php?title=Main_Page#License.`

2.3 Community Participation

WIDE members participate actively in theWorkshop for Quantum Repeaters and Networks (WQRN). The second WQRN was held in Seefeld, Austria, in September 2017 [*1]. The next WQRN is scheduled for 2019, and WIDE member Rodney Van Meter will be the general chair of the conference. Attendance of around 100 researchers, from experimental physicists to classical networking experts, gather to exchange ideas and discuss the challenges in going from a simple channel to more complete networks.

In early 2018, several researchers including Rodney Van Meter are working to create an RG (research group) on quantum networking inside the IRTF. Meetings of QIRG (the Quantum Internet Research Group) are expected during calendar 2018.

2.4 Ongoing Research

Quantum network security: Work on understanding how to make quantum networks operationally robust against misbehavior (whether or not intentional) is needed as we begin to plan quantum repeater networks.

Impact of tomography on network operations: The tomography work and hijacking framework described

＊1 https://www.uibk.ac.at/congress/wqrn2/index.html.en.

above represent the first steps in understanding how the network is monitored in real time operation. A key concern is doing so in Internet-scale interconnected systems, where latencies are high and heterogeneity forces technology-independent data representations and communications.

Connection establishment methods: We now understand reasonably well how quantum connections want to use the network and at the abstract level how to select the resources to use. However, actually identifying and reserving the resources requires a good deal of engineering. A key concern is doing so in Internet-scale interconnected systems, where privacy and autonomy of operation are paramount.

Application analysis: Many more prospective applications of distributed quantum entanglement exist in the literature, but the operational demands they make of quantum networks is still poorly understood.

2.5 Prior Years

The results of 2017 and 2016 build on years of prior work quantum network and quantum internetwork architecture [24]. Almost every major network design issue has now been touched upon, though the design choices will evolve continually even after initial deployments. Our overall goal, therefore, is to build a future-proof, flexible architecture that allows indefinite innovation. A few key results are highlighted here.

Internetwork architecture: The Quantum Recursive Network Architecture (QRNA), building on the classical Recursive Network Architecture [22], will scale management of connections, work across heterogeneous networks, and retain autonomy and privacy of network operations [28].

Routing: A modified form of Dijkstra's algorithm will work for intermediate-sized networks [27].

Multiplexing: Assignment of resources to quantum network connections will likely follow circuit switching principles due to the need to continually execute distributed operations, but moment-by-moment allocation of entangled states may work acceptably even when performed in Internet-style best-effort, first-come, first-served fashion [2].

第3章 #QuantumNative: Online Education and Research for the Next Generation

For a number of years, the term *digital native* has been common:

> **digital native** (noun) a person born or brought up during the age of digital technology and so familiar with computers and the Internet from an early age.
> *Apple Dictionary 2.2.1, 2014*

Similarly, we can define a *quantum native:*

> **quantum native** (noun) a person born or brought up during the age of quantum technology and so familiar with quantum computers from an early age; a person whose first serious study of algorithms involved quantum algorithms, whether exclusively or in conjunction with classical algorithms.

We are using the hashtag `#QuantumNative` to describe such people. An important goal of the AQUA working group is to find and nurture quantum native talent; because the thought process for creating quantum algorithms is very different than that of classical algorithms, we believe it is important that potential quantum programmers are exposed to the concepts as early in their education as possible. For some years, WIDE member Rodney Van Meter has been teaching students as young as first-year bachelor's students, and in 2017 we extended our reach substantially.

3.1 Quantum Computing Workshop at WIDE Camp, Fall 2019

At the September WIDE Camp, we held a twoday hackathon, titled "Making New #Quantum- Natives", with three instructors and fifteen attendees, all complete beginners at quantum computing. The instructors were Rod Van Meter, Shin “parton” Nishio, and Makoto “dave” Nakai, all from SFC.

This workshop followed on from the successful workshop held at the September 2018 WIDE Camp, presented by Takaaki Matsuo and Clement Durand, which was not hands-on.

The curriculum for the workshop was entirely hands-on. Attendees first worked with the GUI for creating simple quantum circuits (quantum application algorithms are defined at the gate, or circuit, level), then progressed to working with Qiskit, the open-source, Python-based quantum programming toolkit created primarily by IBM.

The outline of the program is show in Figures 3 and 4. The discussion centered on seven key concepts:

1. Superposition
2. Interference
3. Entanglement
4. Unitary/Reversible Evolution
5. Measurement
6. No-Cloning Theorem
7. Decoherence

3.2 Graph Theory and Quantum Computing Workshop at WIDE Kenkyuukai, Fall 2019

At the December WIDE Kenkyuukai held in Nagoya, Rod Van Meter and Michal Hajdušek conducted a two-hour hands-on workshop on graph theory, covering the basics of classical graph theory and introducing how graph theory is applied in quantum computing and quantum networking.

Rod presented graph theory in the context of classical networks: how graph theory is important to routing, to spanning trees, etc. Basic notions such as adjacency matrices were presented.

Michal presented a mathematical approach to graph theory, putting a foundation underneath the applications and concepts presented earlier, then discussed the use of entangled graph states in quantum networks. Michal’s work covered mathematical definitions, subgraphs, transformation of graphs, then three key advanced notions: vertex deletion, local complementation, and pivot. With these tools, many graphs can be transformed into each other.

This was followed by hands-on work in Python on Dijkstra’s shortest path first algorithm (using the NetworkX library), triangle counting (a common, basic graph theory problem), and the Page Rank algorithm that was the original foundation for Google’s search algorithm. (By coincidence, Page Rank uses a “teleportation matrix”, which has nothing to do with quantum teleportation, but instead is just a matrix for a Markov chain that with a small probability takes you to a random place in the network, to reduce the influence of your starting position and of sinks with no outbound links in the graph.)

Out of all of the sub-fields of mathematics, in the current technology environment, studying graph theory may provide the biggest benefits for students across a range of applications, and we highly recommend it.

3.3 FutureLearn MOOC

In October 2017, WIDE members Rodney Van Meter and Takahiko Satoh, working with WIDE member Keiko Okawa, brought online a massive online open course (MOOC) titled, “Understanding Quantum Computers” (UQC). The course was presented online through the platform FutureLearn. Keio University has partnered with FutureLearn since 2016. UQC attracted more than 8,000 learners from 127 countries and territories A screenshot of the trailer is shown in Fig. 8.

Many MOOC platforms are ultimately passive, composed of little more than hour-long lectures by a professor or other expert, often recorded in a lecture hall and with no more attention to the clarity and attractiveness of visual aids than pointing a camera at a projection screen. FutureLearn, in contrast, emphasizes interactively for learners and high production values for audio and video. The Future- Learn

WIDE Camp Quantum Workshop 1909
Making New #QuantumNatives

rdv (Rod Van Meter), parton (Shin Nishio), dave (Makoto Nakai)

Tuesday

n.b.: Besides this drive, info can be shared using the WIDE Slack team, #1909ws-quantum channel

1300-1430 Basics

1. Create an IBM account
   https://quantum-computing.ibm.com/
2. Make a Bell pair in composer
3. Qiskit intro
4. Make Bell pair in Qiskit
   https://quantum-computing.ibm.com/jupyter/user/BellPair.ipynb
5. Seven key concepts:
   a. superposition
   b. interference
      i. Kiki's app: see wave_sample directory
      ii. Hideo's app: see 2D-interference-app directory
   c. unitary evolution
      i. Ch. 2 of Qiskit textbook
         https://community.qiskit.org/textbook/
   d. Measurement
      mooc
      https://www.futurelearn.com/courses/intro-to-quantum-computing/0/steps/31557
   e. entanglement
      i. Introduction to Quantum Circuits --> Entanglement and Bell
         ~~https://quantum-computing.ibm.com/support/guides/introduction-to-quantum-circuits?page=5cae705d35dafb4c01214bc5~~

         https://github.com/parton-quark/widecamp2019f/blob/master/CHSH_widecamp.ipynbW
   f. no-cloning theorem
      https://dojo.qulacs.org/ja/latest/notebooks/1.c_CHSH-inequality_etc.html
   g. decoherence (try the above on real devices!)

1500-1600 Teleportation in Qiskit

Fig 3 Outline of the WIDE Camp Quantum Workshop 1909: Making New #QuantumNatives (page 1) philosophy features three points: (1) tell stories; (2) provoke conversation; and (3) celebrate progress. Each learning Step is targeted at approximately ten minutes. Several types of materials can be presented; we used video; articles with text and graphics; quizzes; semi-moderated discussion boards, in which the educators and a team of assistants participated; and two types of external materials. Because the Futurelearn discussion boards do not allow learners to upload video or images, we linked to a separate site that allows this. We also included plans for 3-D printable objects for explaining some concepts.

3.4 Online Experiments

In addition to the MOOC, learners now have access through the web to several superconducting quantum computing systems of different architecture and capabilities.

IBM, with one of the world's leading industrial research efforts, has produced a fiftyqubit experimental system which remains proprietary (see the next section), a five-qubit system for which data has been published [21], and a sixteen-qubit system that is available to the public. These systems can be accessed via a web interface[*2]. A screen shot of the front end is shown in Fig. 9.

1. Sara's Jupyter notebook

   https://github.com/SaraM92/Quantum-Teleportation(click "Launch Binder")
2. https://community.qiskit.org/textbook/ch-algorithms/teleportation.html

1700-1900 Basic quantum algorithms in Qiskit
    https://community.qiskit.org/textbook/

2000-2400 Self-directed and group work (optional, along with Wine Time!)
- Translate key sections of textbook into Japanese?
- develop own Oracle for use in Grover
- work from the (very advanced) "algorithms for beginners" (link below)
- develop JS demos of key concepts

Wednesday

1240-1400 "future"

Additional Notes

Our MOOC, upcoming Oct. 1:
    https://www.futurelearn.com/courses/intro-to-quantum-computing

Advanced work:
    "Quantum Algorithm Implementations for Beginners"
    https://arxiv.org/abs/1804.03719

```
%matplotlib inline
# Importing standard Qiskit libraries and configuring account
from qiskit import QuantumCircuit, execute, Aer, IBMQ
from qiskit.compiler import transpile, assemble
from qiskit.tools.jupyter import *
from qiskit.visualization import *
# Loading your IBM Q account(s)
provider = IBMQ.load_account()
```

Fig 4 Outline of the WIDE Camp Quantum Workshop 1909: Making New #QuantumNatives (page 2)

*2 https://www.research.ibm.com/ibm-q/.

4.1　Quantum Software: IBM Q Network

In December 2017, IBM announced an organizational network of hubs around the world, where customers can gather to study quantum computing and develop algorithms suited to their own businesses. Members of the hubs have access to the fifty-qubit system and larger systems as they come online. Keio University is the only such hub in Asia, and WIDE Member Rodney Van Meter is the Vice Chair.

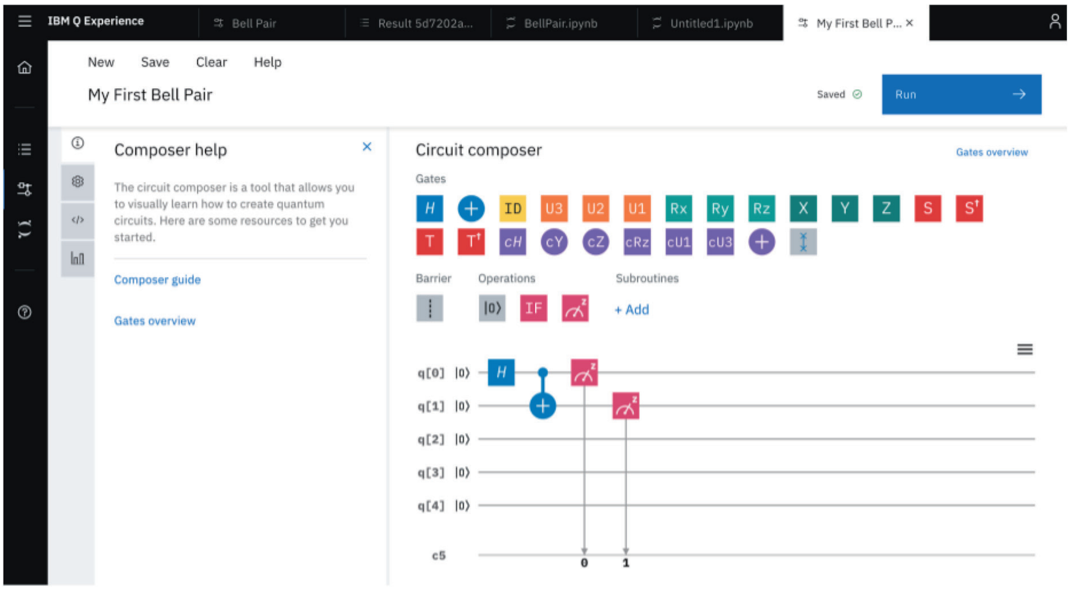

Fig 5　Making a Bell pair (an entangled quantum state) in the IBM GUI. Workshop participants executed this both using the simulator and using an real IBM quantum computer.

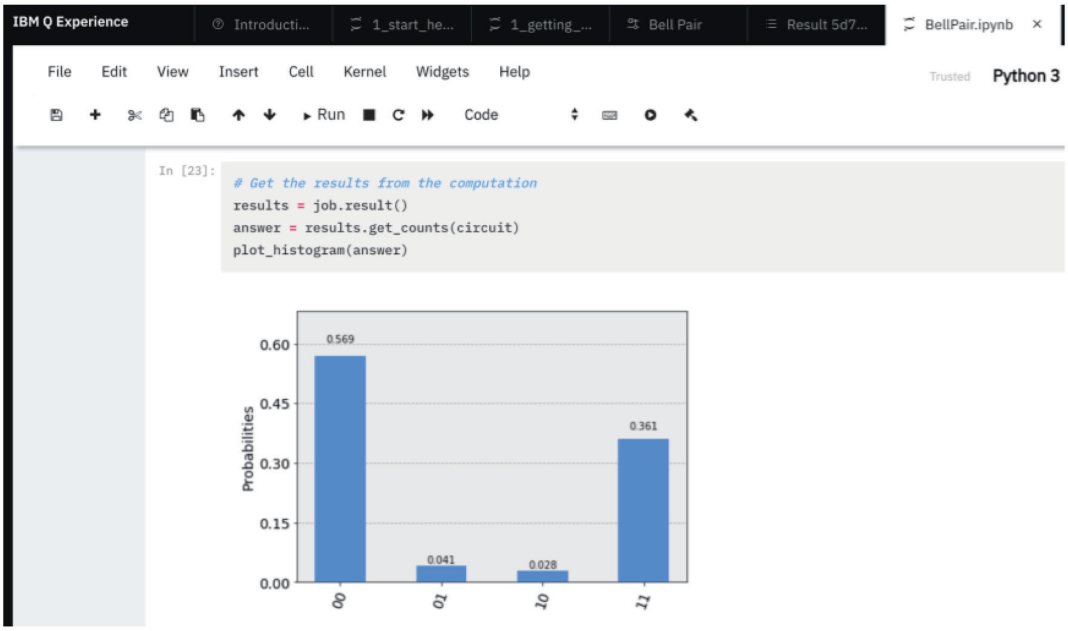

Fig 6　Results of making a Bell pair when created using an real IBM quantum computer.

In the short run, many researchers are focusing on the development of hybrid algorithms, using noisy, intermediate-scale quantum computers [16] to execute specific subroutines, and augmenting the quantum computation with significant amounts of classical computation. An important element in the success of such an approach is error mitigation, before complete quantum error correction becomes technically feasible [7].

4.2 Research Accomplishments

4.3 Quantum System Software

4.4 Quantum Error Correction and Quantum Computer Architecture Research

In addition to the work on quantum networks, AQUA members have conducted research on error correction for quantum computers and quantum computer architecture. In our opinion, as well as the opinion of a number of others, the *surface code* represents the most attractive method, encoding a logical qubit in the parity of chains of qubits on a surface [6, 17, 18].

4.5 Quantum Software: IBM Q Network

Hybrid algorithms: The current most important topic in the quantum computing community is how to combine noisy intermediate-scale quantum computers [16] with large-scale classical computers to solve problems more quickly than classical systems alone. These *hybrid algorithms* must take into account noise, and decompose larger problems into small sub-problems that can be effectively handled on existing and near-future quantum computers.

Error mitigation: The companion problem to developing hybrid algorithms is developing *error mitigation* techniques that will allow us to execute quantum algorithms effectively in the presence of noise, without the overhead and technical challenges of full-scale quantum error correction and fault tolerance.

第 5 章 Publications

5.1 2019

AQUA members had one journal paper published in 2019, several international conference poster presentations and invited oral presentations, and several additional submissions.

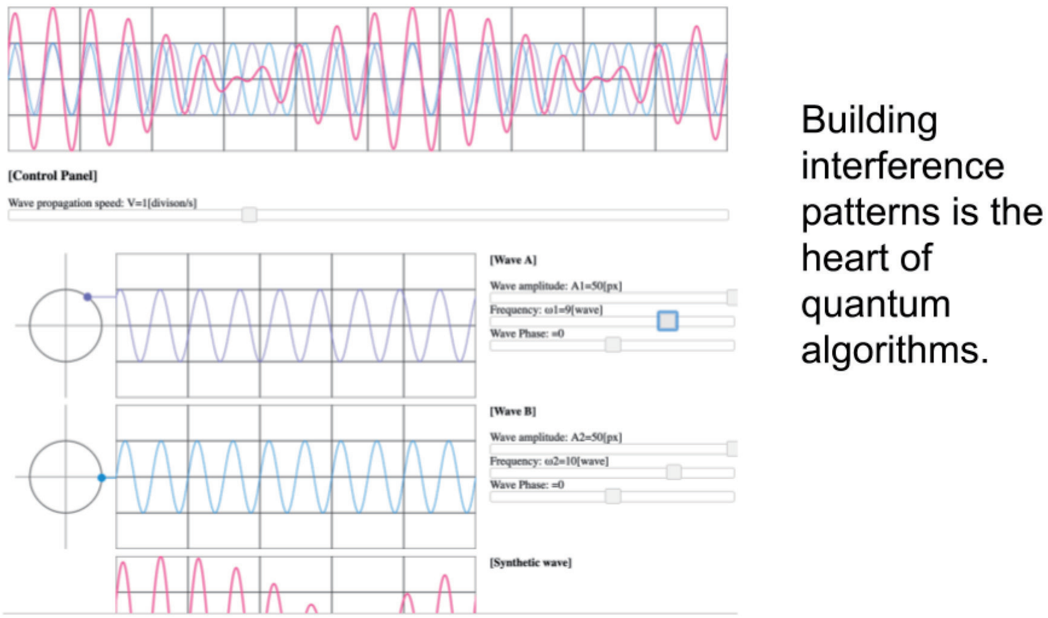

Fig 7 The JavaScript app used to demonstrate interference of two waves with slightly different frequencies.

The published, accepted and under review papers are:

1. T. Matsuo, Clement Durand, R. Van Meter, **Quantun link bootstrapping using a RuleSet-based communication protocol**, *Physical Review A*, 100, 052320, 2019.
2. Robert Wille, Rod Van Meter, Yehuda Naveh, **IBM's Qiskit Tool Chain: Working with and Developing for Real Quantum Computers**, *2019 Design, Automation & Test in Europe Conference & Exhibition (DATE)*
3. AS Cacciapuoti, M Caleffi, R Van Meter, L Hanzo, **When Entanglement meets Classical Communications: Quantum Teleportation for the Quantum Internet** arXiv preprint *arXiv:1907.06197*
4. S Nishio, Y Pan, T Satoh, H Amano, R Van Meter, **Extracting Success from IBM's 20-Qubit Machines Using Error- Aware Compilation,** *arXiv preprint arXiv:1903.10963*
5. P Pathumsoot, T Matsuo, T Satoh, M Hajdušek, S Suwanna, R Van Meter **Modeling of Measurement-based Quantum Network Coding on IBMQ Devices** *arXiv preprint arXiv:1910.00851*

In addition, one non-peer reviewed annotated bibliography was made available on the web:

1. R. Van Meter, **A #QuantumComputerArchitecture Tweetstorm,** *https://doi.org/10.5281/zenodo.3496597*

5.2 2018

AQUA members had two journal papers published in 2018, one peer-reviewed international conference talk, several international conference poster presentations, and several additional submissions. The published papers are:

1. T. Matsuo, T. Satoh, S. Nagayama, R. Van Meter, **Analysis of Measurementbased Quantum Network Coding over Repeater Networks under Noisy Conditions**, *Physical Review A*, 97, 062328, 2018.
2. T. Satoh, S. Nagayama, T. Oka, R. Van Meter, **The network impact of hijacking a quantum repeater**, *Quantum Science and Technology* 3 (3), 034008, 2018.
3. S Nishio, Y Pan, T Satoh, R Van Meter, **High Fidelity Qubit Mapping for IBM Q**, *Proc. 2nd International Workshop on Quantum Compilation,* 2018.

5.3 2017

AQUA members had three journal papers published or accepted for publication in 2017, one peer-reviewed international conference talk, several international conference poster presentations, and several additional submissions. The published and accepted papers are:

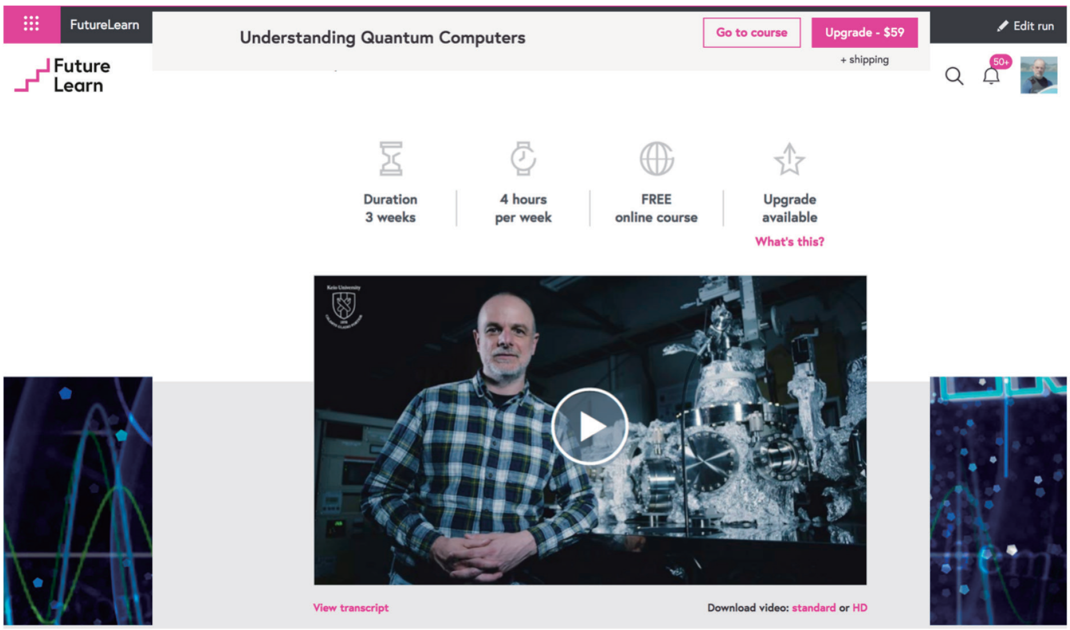

Fig 8 The trailer on the front page of the MOOC.

1. R. Van Meter, "Distributed quantum computing systems: Technology to quantum circuits," VLSI Symposium 2017 [25].
2. Shota Nagayama, Austin G. Fowler, Dominic Horsman, Simon J. Devitt and Rodney Van Meter, "Surface Code Error Correction on a Defective Lattice," *New Journal of Physics* 19(2), 023050, 2017 [12].
3. Shota Nagayama, Takahiko Satoh and Rodney Van Meter, "State Injection, Lattice Surgery and Dense Packing of the Defermation-Based Surface Code," *Physical Review A* 95(1), 012321, 2017 [13].
4. M. Amin Taherkhani, Keivan Navi, Rodney Van Meter, "Resource-aware architecture for implementation of quantum aided Byzantine agreement on quantum repeater networks," *Quantum Science and Technology* 3(1), 014011, 2018 [20].

Three additional papers are available as preprints or are under review at journals.

1. Takaaki Matsuo, Takahiko Satoh, Shota Nagayama and Rodney Van Meter, "Analysis of Measurement-based Quantum Network Coding over Repeater Networks under Noisy Conditions," preprint `arXiv:1710.04827`.
2. Takahiko Satoh, Shota Nagayama, and Rodney Van Meter, "The Network Impact of Hijacking a Quantum Repeater," preprint `arXiv:1701.04587`.
3. Rodney Van Meter, Takahiko Satoh, Shota Nagayama, Takaaki Matsuo and Shigeya Suzuki, "Optimizing Timing of High-Success-Probability Quantum Repeaters," preprint `arXiv:1701.04586`.

5.4 2016

AQUA members had five journal papers published in 2016 and one peer-reviewed workshop paper, and several international conference poster presentations. The published papers are:

1. Rodney Van Meter and Simon Devitt, "The Path to Scalable Distributed Quantum Computing," *IEEE Computer* 49(9), 31–42, Sept. 2016, [26].
2. Takahiko Satoh, Kaori Ishizaki, Shota Nagayama and Rodney Van Meter, "Analysis of quantum network coding for realistic repeater networks," *Physical Review A* 93(3), 032302, 2016, [19].
3. Shota Nagayama, Byung-Soo Choi, Simon Devitt, Shigeya Suzuki and Rodney Van Meter, "Interoperability in encoded quantum repeater networks," *Physical Review A* 93(4), 042338, 2016, [11].
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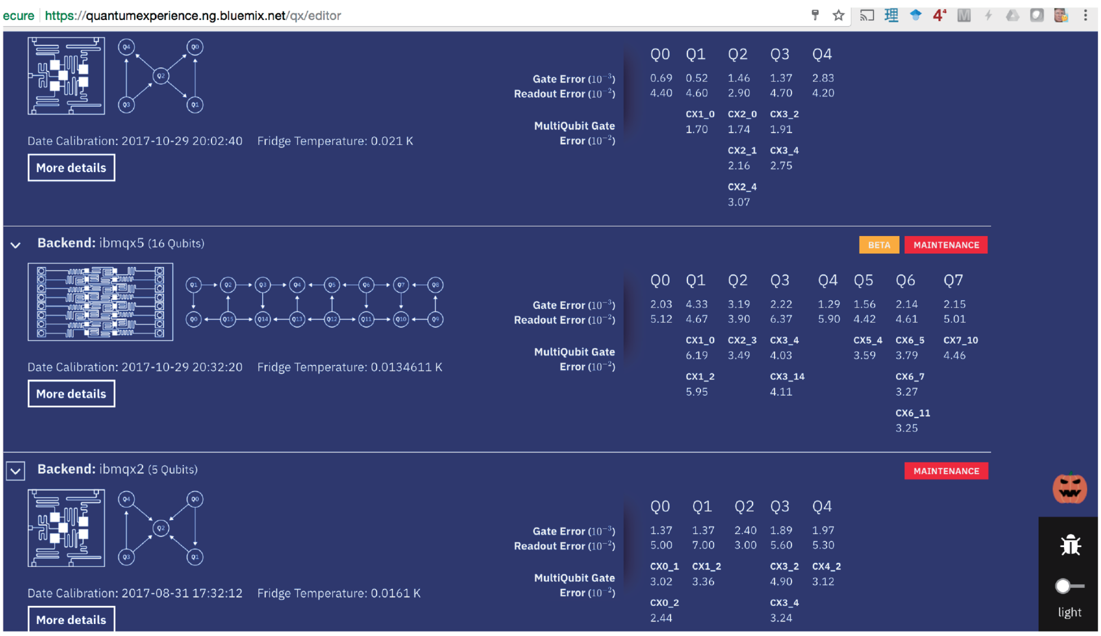

Fig 9 The GUI element showing the IBM quantum computers available for online use as of Oct. 30, 2017.

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Appendix A What is AQUA?

A.1 Goals

The primary goal of AQUA is to advance the deployment of quantum technologies in the real world, principally by applying known techniques from classical computer architecture, networking and distributed systems to the problems of scalability in quantum systems. This work will both bring new computational capabilities and help ensure that the progress of information technology does not end when the size of transistors can no longer be reduced.

The physical technology on which modern computing systems are built will change dramatically over the course of the next several decades. Beyond the research goals, AQUA also aims to expose the current generation of students to the principles that drive the evolution of computing technology, and the underlying physics of computation, preparing the students for forty-year careers in which they will work with applied physicists and electrical engineers to drive the coming technological revolutions.

A.2 Work Areas

AQUA works in five areas contributing to distributed quantum computing systems:

- Devices: In conjunction with researchers at Stanford University, RIKEN, and the University of Tokyo we are designing semiconductor-based chips using opticallycontrolled *quantum dots* and *superconducting flux qubits*.
- Workloads: Although AQUA does not focus on the creation of new quantum algorithms, we do work on how to implement known quantum algorithms efficiently on realizable architectures. We also perform the reverse analysis: to implement a given algorithm, how large and how accurate a quantum system is required?
- Tools: Proper analysis of new ideas in architecture and networks requires software tools for compiling programs and optimizing their mapping to particular systems, as well as physical simulation of quantum devices and effects.

- Principles: We are searching for new principles in quantum architecture and networking, as well as applications of known principles.
- Networks: Large systems must combine multiple devices into one system that can compute collaboratively, as well as share information; we are investigating both system-area and wide-area quantum networks.

Underlying all of these is the critical issue of error management in quantum systems; quantum data is far too fragile to store or compute upon without continuous, active correction. Our primary focus is on the promising surface code error correction, looking for ways to makes its implementation resource-friendly and robust in the face of various system constraints.

Appendix B Quantum Concepts

The following is a brief summary of the key aspects of quantum communication and computation that impact network and system architecture.

Qubits. Quantum information is most often discussed in terms of *qubits*. A qubit, like a classical bit, is something with two possible values that we can label zero and one. Unlike a classical bit, a qubit can occupy both values simultaneously, known as *superposition*.

Superposition and measurement. A qubit can represent multiple values in different proportions at the same time, e.g., two-thirds of a "one" and one-third of a "zero". This *superposition* determines the relative probability of finding each value when we *measure* the state. When we measure the qubit, we get only a single classical bit of information (the "one" or "zero") with 100% probability, and the superposition *collapses*.

Entanglement and Bell pairs. Some groups of qubits exhibit strong correlation between the qubits that cannot be explained by independent probabilities for individual qubits. Instead, the group must be considered as a whole, with interdependent probabilities. This phenomenon is known as *quantum entanglement*. A special entangled state known as a *Bell pair* or *EPR pair,* consisting of two quantum bits, figures prominently in quantum communication. Each qubit in the pair has a 50% probability of having a value of 1 and a 50% probability of having a value of 0 when we measure it. Although we cannot predict which will be found, when we measure one member of the pair, the value of the other is immediately determined. This happens independent of the distance between the two members of the Bell pair.

Interference. Quantum algorithms use some building blocks derived from classical concepts, such as adder designs, but the overall thrust of a quantum algorithm is very different from that of a classical algorithm. Rather than attempting to solve a problem and checking for the answer, a quantum algorithm's goal is to create *interference* between the elements of a superposition quantum state. The basic concept is shown in Figs. ?? and ?? in the main text, while in quantum computers the interference happens across a much larger space. Constructive interference reinforces desirable states, increasing the probability of finding a desirable outcome on measurement, while destructive interference reduces the probability.

No cloning. As mentioned above, a key restriction of quantum systems is that we cannot make *independent* copies of an unknown state [29]. This makes error correction exceedingly difficult.

Fidelity. The quality of a quantum state is described by its *fidelity*, which is, roughly, the probability that we correctly understand the state – if we ran the same experiment many times and measured the results, how close to our desired statistics would we be? Unfortunately, any physical operation results in a loss of fidelity, gradually degrading the state as we manipulate or even store it. We can counter this by using a form of error correction or detection.

Purification. The form of error detection historically favored in quantum repeater networks is *purification*, which uses minimal resources [4]. It sacrifices some quantum states to test the fidelity of others. There are various purification mechanisms, with different purification algorithms and different methods for determining which states are sacrificed, each with particular tradeoffs.

Quantum error correction (QEC). QEC may be based on classical codes or purely quantum concepts. The primary difficulties are extraction of errors without damaging quantum state, avoiding error propagation, and the increased resources required. (See references contained in [23], [10] and [8].)

Teleportation. Teleportation destroys the state of a qubit at the sender and recreates that state at the destination, teleporting information rather than matter, as explained in Figure 10 [3]. The process uses a Bell pair's long-distance correlation, followed by transmission of a pair of classical bits.

With these basic concepts, we can begin to construct networks. Bell pairs are consumed by teleportation, so one way to organize a network is to create a continuous stream of Bell pairs between source and destination – as long as we identify those sources and destinations, choose paths to get there, and manage the resources along the way.

1. Alice begins with a qubit to teleport, and she and the receiver Bob share an entangled Bell pair.
2. Alice performs local operations to entangle her two qubits.

3. Alice measures both qubits, obtaining two classical bits & destroying all entanglement.
4. Alice sends the classical bits to Bob.

5. Bob receives Alice's classical bits.
6. Bob combines the classical bits with his formerly entangled qubit to recreate Alice's original qubit.

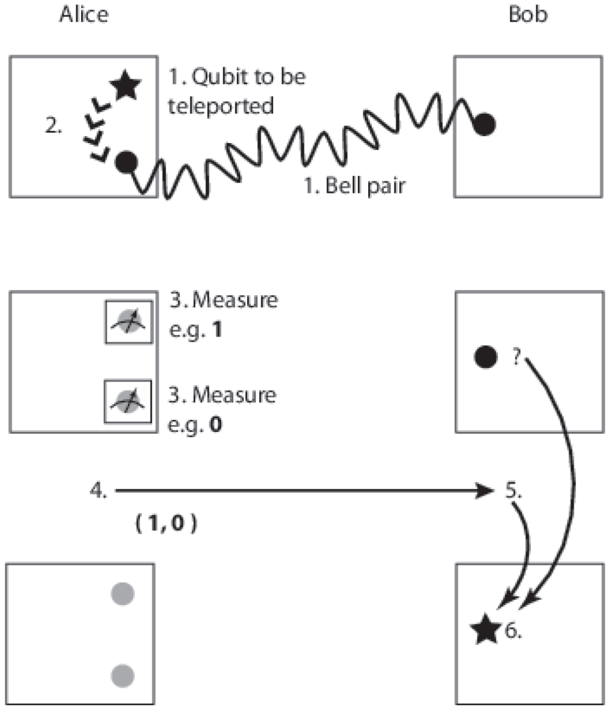

Fig 10 Operations in teleporting a qubit from Alice to Bob.