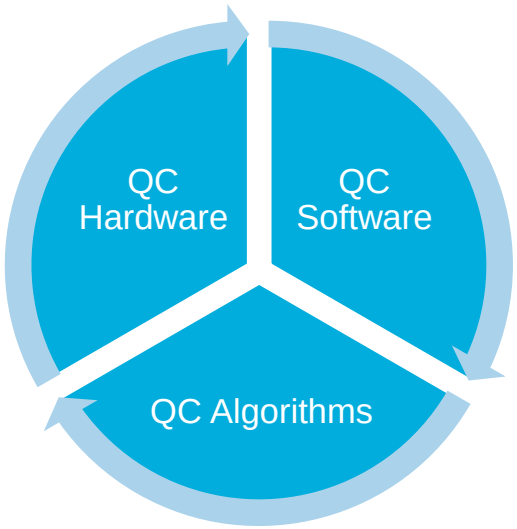
The Quantum Computing Program At Hyperion Research

Bob Sorensen, Earl Joseph, Steve Conway, and Alex Norton

Outline of Hyperion's New Program on Quantum Computing

- **Hyperion Research is expanding its advanced computing coverage to include all aspects of the quantum computing ecosystem, in a formalized program**



- This effort arises out of dozens of requests from members of the global HPC community that Hyperion Research starts a new practice area focused on quantum computing research
- This will be an addition to our 25-year history of closely tracking developments in the worldwide HPC community and market place

This Effort is an Amplification of Long-Term Coverage of QC by Hyperion Research

IDC

IDC TECHNOLOGY SPOTLIGHT

Quantum Computing in the Real World

April 2016

Sponsored by D-Wave Systems, Inc.

IDC Opinion

HYPERION RESEARCH

Technology Assessment

IBM Announces the Next Step in Its Plans to Develop a Universal Quantum Computing Ecosystem

Robert Sorensen, Steve Conway, Earl C. Joseph, Ph.D., Kevin Monroe

April 2017

EXECUTIVE SUMMARY

IBM recently announced an addition of important new capabilities in its continual effort to make its universal quantum computer prototype freely available to the global research community as part of its vision to encourage a broad range of potential innovators to explore and develop new quantum applications. Specifically, in March of 2017, IBM continued to demonstrate its commitment to developing a universal quantum computer with the release of two additional upgrades to its Quantum Experience:

- A new application program interface that enables developers and programmers to begin building interfaces between its existing five quantum bit (qubit) cloud-based quantum computer prototype and classical computers, without needing a deep background in quantum physics.
- An upgraded simulator on the IBM Quantum Experience that can model circuits with up to 20 qubits. In the first half of 2017, IBM plans to release a full software development kit on the IBM Quantum Experience for users to build simple quantum applications and software programs.

The IBM-developed five qubit quantum prototype system, along with a wide range of algorithmic and software development tools, is accessible through an IBM cloud software development environment specifically designed to facilitate such innovation and expand the potential pool of scientists experimenting with the prototype quantum system.

- Giving access to early leading-edge IBM prototypes of advanced quantum systems is a critical step forward in garnering support for the quantum field not only for IBM but for the global quantum computing research community as well.
- The ultimate success of IBM's initiative will be judged primarily by its ability to build a broad base of scientific interest that leads to the creation of a portfolio of quantum computing use cases and a robust quantum computing application development community.

Although the vision of a quantum computer has been around for almost 40 years, it has been only recently that the ability to build and operate a quantum computer has become more feasible. Today, the field is rich with various experimental designs for QC hardware and quantum systems.

Hyperion Research, LLC April 2017 #HR04282017

HYPERION RESEARCH

Quick Take

Chinese Plans to Build World's Biggest Quantum Research Facility

Alex Norton, Bob Sorensen, Earl Joseph, and Steve Conway

November 2017

HIGHLIGHTS

China recently announced its intentions to develop and build the world's largest quantum research facility, the National Laboratory for Quantum Information Science, slated to open in 2020. The facility, with a planned construction budget of 76 billion Yuan ($11.46 billion), initially will have two major research interests: advances in quantum metrology and general-purpose quantum computing design. Both efforts would support military and national defense efforts as well civilian innovations. The planned location is a 37-hectare (91-acre) plot of land in Hefei, Anhui Province, and the new facility will be under the control of the Chinese Academy of Science.

According to press reports, Chinese planners believe that building a large facility with centralized resources could accelerate Chinese progress in quantum computing development by pulling together the talents of scientists from all over the nation with knowledge and experience in multiple scientific disciplines to overcome a wide range of technical and engineering hurdles. Pan Jianwei, one of China's leading quantum scientists, told [illegible] military purposes.

November 2017, Hyperion Research #HR[illegible]

Welcome To The 50th HPC User Forum Meeting September 2013

Agenda: Day Two Afternoon

12:45pm Afternoon Session Chair: Rupak Biswas
Disruptive Technologies Panel: Panelists will briefly present potentially disruptive technologies that could change the HPC market
Panel Moderator: Earl Joseph
- System vendors: Inspur, HP, IBM, Cray, SGI
- New processor directions: Intel, Nvidia
- Software providers: Altair, VMware
- Storage vendors: Xyratex, EMC, NetApp

1:45pm Technology Focus Area: Quantum Computing
- Brief Introduction – Rupak Biswas, NASA
- Quantum Information Science and Technology, Isaac Chuang (MIT)
- The Quantum Artificial Intelligence Lab, Hartmut Neven, Google
- Break at 2:30pm to 3:00pm
- A New Computer for Quantum Computing, Geordie Rose, D-Wave Systems
- Quantum Computing Research at Microsoft, Dave Wecker, Microsoft
- Quantum Computing Research at IBM, Jay Gambetta, IBM Watson Research Center
- Discussion and Q&A on Quantum Computing

5:00pm Meeting Wrap-Up, Jim Kasdorf, Rupak Biswas, Earl Joseph and Steve Conway

Hyperion's Quantum Computing Program

- **Global Coverage of R&D Efforts**
  - Government, academic, commercial
  - US, China, EU, others
  - Crypto, HPC-accelerator, Quantum Supremacy
- **Highlights of Major Commercial Efforts**
  - DWave, Google, IBM, Rigetti, Microsoft, ATOS/Bull, etc.
  - Characterization analysis of competing QC development/product/commercialization models
- **QC Market Description and Analysis:**
  - Size, QC product categories, Regions, Sectors, Trends, Opportunities and Challenges
- **Insights on the QC sector as a Market Space**
  - Hardware & software ecosystem development, algorithm development trends, standards, collaborations, open source efforts, etc.
- **Impact on HPC sector writ large**
  - The role of QC in near-term and post Moore's law HPC environment
    - AI/ML/DL
    - Modelling/Simulation
    - Others

Hyperion's Research Approach

1. **Identify the QC experts around the world**
   - Invite them to be on a QC Experts panel
2. **Collect as many real-world use case examples as possible**
   - With a focus on where and how its used
   - Including plans for the future

     → *Publish as case studies*
3. **Collect many technology examples and vendor approaches**
   - Software, hardware, services, new discoveries, new innovations

     → *Publish as research reports*
4. **Then create taxonomies of the different technologies and where its used**
   - Both from a usage perspective and a technology perspective
   - We work to separate out one-off examples from main stream examples

     → *Publish as our base taxonomy (market definitions)*
5. **Then we can size the market and create 5-year forecasts**

   → *Publish "the numbers" and trends*

Current and Upcoming Activities

The QC Experts Panel:

- **We are contacting thought leaders throughout the global QC community to join the panel**
  - Invitations have been sent across the QC ecosystem including HW researchers, algorithm developers, QC solutions providers, and the growing QC user base
  - Positive returns are coming in almost daily
  - If interested in participating, let us know
- **The panel will be used for developing and testing technology definitions, market use cases, etc.**
  - And for probing and exploring all different types of questions about QC and its future evolution

First Survey for Experts Panel

We are seeking to establish the big picture for QC:

- **Which organizations (government, academic, corporate) are conducting some of the most advanced QC activities today?**
- **What are some of the key QC technology developments currently underway at these locations?**
  - Address any/all of the following QC subcategories:
  - QC hardware, simulators, architectures, and algorithms
- **What are some of the key technical challenges/roadblocks facing QC developers today?**
- **What are some of the most compelling quantum computing applications currently under development?**
- **What kind of schedule do you see for the roll out of key quantum computing systems or application?**

Planned QC Program Deliverables

We are trying a new approach:

- **The primary deliverable will be the ability to ask questions that we will ask the "Experts Panel", and that we will research**
  - To provide these results quickly, many reports will be in the form of PowerPoint slide decks and Excel spreadsheets
  - Clients get to set the general question areas and topics
- **The research reports will include:**
  - Definitions/taxonomies for different QC products, different types of QC, and different areas were QC is and could be used
  - Then initial sizing of these different areas
  - Reports will be driven by the questions and topics requested by clients
- **In addition, we will be holding a number of QC meetings/conferences**

Planned QC Program Deliverables

Example of the market sizing and forecasts:

Hyperion Research Quantum Computing Market Sizing

1/25/2018

Table 1: Examples of Tracking the QC Market Areas

											CAGR
QC Market Area	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2017-2025**
QC hardware systems											
QC spending to access QC hardware in the cloud											
QC simulators											
QC software											
QC processor chips											
...											
Total QC Market											

Source: Hyperion 2018

Upcoming Hyperon User Forum Tucson AZ, US April 16-18 2018

Range of Talks/Discussions from QC experts

8:45am	**Session: HPC and Quantum Computing. Chair: Bob Sorensen, Hyperion Research** • John Martinis, Google • T.R. Govindan, NASA • Jim Held, Intel
10:15am	Networking Break
10:30am	**Session: HPC and Quantum Computing (continued)** • Jay Gambetta, IBM

1:00pm	**Session: HPC and Quantum Computing (continued)** • Matthias Troyer, Microsoft • Chad Rigetti, Rigetti Computing • Carl Williams, NIST • Will Oliver or Jaime Kerman, MIT Lincoln Laboratory • Final speaker (awaiting confirmation)
3:30pm	Networking Break
3:45pm	**Panel: HPC and Quantum Computing. Chair: Bob Sorensen, Hyperion Research**

- There is still time to register at: www.hpcuserforum.com

What Makes Quantum Computers Different?

In theory Qubits can outperform classical computer bits thanks to two uniquely quantum effects:

Superposition:

- Superposition allows a qubit to have a value of not just 0 or 1, but both states at the same time, enabling simultaneous computation

Entanglement:

- Entanglement enables one qubit to share its state with others separated in space, creating a sort of super-superposition, whereby processing capability doubles with every qubit

The Catch: Quantum superpositions and entangled states are extremely fragile. They can be destroyed by slight perturbations from the environment -- or by attempts to measure them.

These Quantum Phenomena Drive Unique QC Capabilities

Three QC use cases are currently being explored:

1. **QC-based applications that are intractable on traditional von-Neumann systems**
   - Shors Algorithm
   - Quantum Supremacy
2. **Traditional HPC-based applications running on a QC with significant speed-up**
3. **Hybrid applications (combing QC and HPC)**
   - Quantum Accelerators (a subroutine call)
   - QC-assisted HPC algorithms

Many Hardware Options are in the Works to Address These Issues

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

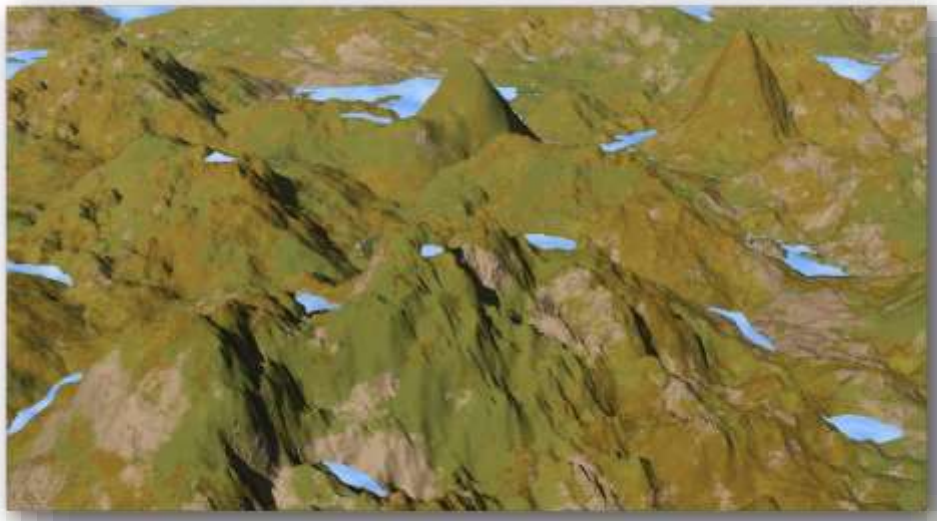
CREDITS: (GRAPHIC) C. BICKEL/*SCIENCE*; (DATA) GABRIEL POPKIN

Many Developers, Many Approaches

- Dwave
- IBM
- Google
- Quantum Circuits
- ionQ
- Intel
- Rigetti
- Microsoft
- Quantum Diamond Technologies
- ATOS/Bull
- More….

DWave: Rebel With A Cause

- Shipping QC hardware for multiple years to multiple sites
- Founded in 1999
- World's first quantum computing company
- Public customers: Lockheed Martin/USC, Google/NASA Ames/USRA, Los Alamos National Laboratory, Temporal Defense Systems, Oak Ridge National Laboratory
- ~150 U.S. patents



IBM: Racing to Build A QC

IBM established a landmark in computing in November 2017, announcing a quantum computer that handles 50 qubits

- The company is also making a 20-qubit system available through its cloud computing platform
- IBM offers a full QC software stack as well

According to IBM:
In last 18 month 60,000 users from
- *1,500 universities,*
- *300 high schools*
- *300 private institutions*

have registered for accounts on the IBM Q experience

Collectively they have run 1.7 million experiments

IBM: The Race to Build *Useful* QCs

Research Hubs

- The planned locations are at **IBM Research**, **Keio University** in Japan, **Oak Ridge National Lab** in the United States, **Oxford University** in the United Kingdom and the **University of Melbourne** in Australia.
- The IBM Q Network is exploring practical applications of quantum computing for science with Keio University, Oak Ridge National Lab, Oxford University and University of Melbourne.

IBM Q Network Members

- **Barclays, Hitachi Metals, Honda and Nagase** will build their knowledge of general approaches to quantum computing and begin to investigate potential use cases for their industries of finance, materials, automotive and chemistry respectively.

Direct IBM Partnerships

- **JPMorgan Chase**: use cases for quantum computing applicable to the financial industry including trading strategies, portfolio optimization, asset pricing and risk analysis.
- **Daimler AG**: use cases of quantum computing for the automotive and transportation industry. Some areas of research include finding and developing new materials for automotive application through quantum chemistry, complex optimization problems such as for manufacturing processes or vehicle routing for fleet logistics or autonomous/self-driving cars, and the intersection of quantum and machine learning to enhance the capabilities of artificial intelligence.
- **Samsung** of use cases where quantum computing may impact the future of the semiconductor and electronics industry.
- **JSR Corporation**, use cases for material improvements for electronics, environmental and energy applications

Google: Seeking to Demonstrate Quantum Supremacy

- In September 2014, Google announced that it was expanding its research around quantum computing and that it had hired UC Santa Barbara's (UCSB) John Martinis and his team to work on new quantum processors based on superconducting electronics
- Google has been working together with NASA and the Universities Space Research Association (USRA) to operate DWave system processor at the NASA Ames Research

Characterizing Quantum Supremacy in Near-Term Devices

Sergio Boixo,[1] Sergei V. Isakov,[2] Vadim N. Smelyanskiy,[1] Ryan Babbush,[1] Nan Ding,[1] Zhang Jiang,[1,3] Michael J. Bremner,[4] John M. Martinis,[2,5] and Hartmut Neven[1]

[1]*Google Inc., Venice, CA 90291, USA*
[2]*Google Inc., 8002 Zurich, Switzerland*
[3]*QuAIL, NASA Ames Research Center, Moffett Field, CA 94035, USA*
[4]*SGT Inc., 7701 Greenbelt Rd., Suite 400, Greenbelt, MD 20770*
[5]*Centre for Quantum Computation and Communication Technology, Centre for Quantum Software and Information, University of Technology Sydney, NSW 2007, Australia*
[6]*Google Inc., Santa Barbara, CA 93117, USA*
[7]*Department of Physics, University of California, Santa Barbara, CA 93106, USA*
(Dated: April 6, 2017)

A critical question for the field of quantum computing in the near future is whether quantum devices without error correction can perform a well-defined computational task beyond the capabilities of state-of-the-art classical computers, achieving so-called quantum supremacy. We study the task of sampling from the output distributions of (pseudo-)random quantum circuits, a natural task for benchmarking quantum computers. Crucially, sampling this distribution classically requires a direct numerical simulation of the circuit, with computational cost exponential in the number of qubits. This requirement is typical of chaotic systems. We extend previous results in computational complexity to argue more formally that this sampling task must take exponential time in a classical computer. We study the convergence to the chaotic regime using extensive supercomputer simulations, modeling circuits with up to 42 qubits – the largest quantum circuits simulated to date for a computational task that approaches quantum supremacy. We argue that while chaotic states are extremely sensitive to errors, quantum supremacy can be achieved in the near-term with approximately fifty superconducting qubits. We introduce cross entropy as a useful benchmark of quantum circuits which approximates the circuit fidelity. We show that the cross entropy can be efficiently measured when circuit simulations are available. Beyond the classically tractable regime, the cross entropy can be extrapolated and compared with theoretical estimates of circuit fidelity to define a practical quantum supremacy test.

I. INTRODUCTION

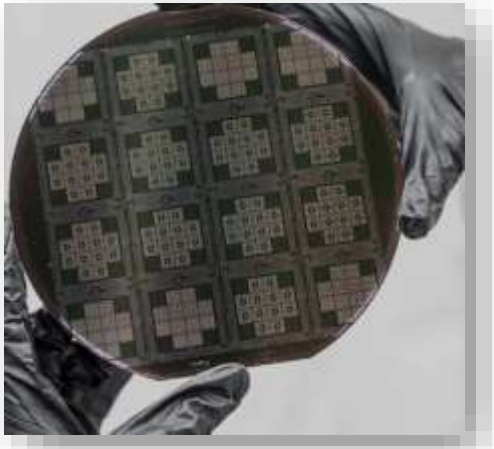
Despite a century of research, there is no known method for efficiently simulating arbitrary quantum dynamics using classical computation. In practice, we are

computer in a reasonable amount of time.

In this paper we show how to estimate the cross entropy between an experimental implementation of a random quantum circuit and the ideal output distribution simulated by a supercomputer. We study numerically the convergence of the output distribution to the Porter-

- Late 2017, *"rumors have swelled that Google will announce "quantum supremacy" soon—essentially, that they will have created a quantum processing device (49-50 qubits) that can solve a problem provably and unequivocally faster than a regular computer can."*

Rigetti Goal: To Be A Full Stack Solution



Unsupervised Machine Learning on Rigetti 19Q with Forest 1.2

by Will Zeng, Rigetti Computing

We are excited to share that our team has demonstrated unsupervised machine learning using 19Q, our new 19-qubit general purpose superconducting quantum processor. We did this with a quantum/classical hybrid algorithm for clustering developed at Rigetti.

Intel: Leveraging Its Chip-Making Expertise

In 2015, Intel established a collaborative relationship with QuTech to accelerate advancements in quantum computing

- The collaboration spans the entire quantum system — or “stack” — from qubit devices to the hardware and software architecture, quantum applications
- Intel invested US$50 million with QuTech, the quantum research institute of Delft University of Technology (TU Delft) and TNO, and will dedicate engineering resources to advance research efforts

In late 2107, Intel delivered a new 17-qubit test chip to Delft that was about the size of a quarter for evaluation, the new features included:

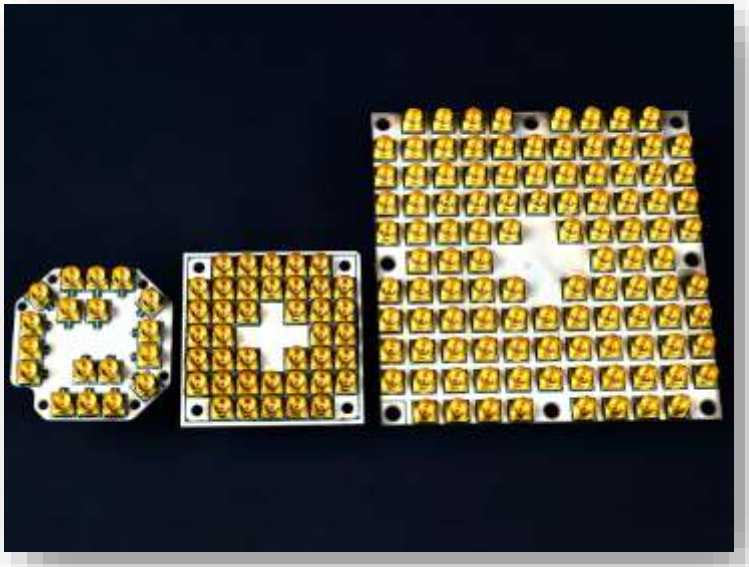
- New architecture allowing improved reliability, thermal performance, and reduced radio frequency (RF) interference between qubits
- A scalable interconnect scheme that allows for 10 to 100 times more signals into and out of the chip as compared to wire-bonded chips
- Advanced processes, materials and designs that enable Intel’s packaging to scale for quantum integrated circuits, which are much larger than conventional silicon chips

Intel: Impressive Recent Progress

In January 2018, just two months after delivery of a 17-qubit superconducting test chip, Intel unveiled "Tangle Lake," a 49-qubit superconducting quantum test chip

- The chip is named after a chain of lakes in Alaska, a nod to the extreme cold temperatures and the entangled state that quantum bits require to function

- Tangle Lake represents progress toward Intel's goal of developing of a complete quantum computing system – from architecture to algorithms to control electronics
- Achieving a 49-qubit test chip is an important milestone because it will allow researchers to assess and improve error correction techniques and simulate computational problems



ATOS: Quantum Learning Machine

The Atos Quantum Learning Machine (Atos QLM) is a complete on-premise environment designed for quantum software developers. It is dedicated to the development of quantum software, training and experimentation

- A specific hardware infrastructure, with large in-memory capacity and – available soon – a dedicated hardware accelerator
- An extensible quantum circuit model (data representation model)
- A universal quantum assembly programming language (AQASM, Atos Quantum Assembly Language)
- A high-level quantum hybrid language, built on top of the popular Python language

Appliance	Power	Software Kit	CPU	Memory
Atos QLM-30	30 Qubits	AQASM	2	1TB
Atos QLM-35	35 Qubits	AQASM	4	3TB
Atos QLM-38	38 Qubits	AQASM	8	6TB
Atos QLM-39	39 Qubits	AQASM	16	12TB
Atos QLM-40	40 Qubits	AQASM	16	24TB

- Oak Ridge National Lab (US) procured Atos QLM-30 in Nov 2017

Quantum Computing Summary

- **A wide and diverse range of QC suppliers are emerging to develop a QC ecosystem**
  - Legacy Players (Dwave, IBM)
  - New Entrants :
    - Pure Play: ionQ: Rigetti,
    - Product add-ons: Intel, ATOS
  - Non-traditional player (Google, Microsoft)
- **China ($11 Billion Facility)**
- **EU (€1 billion quantum technologies flagship project)**
- **Hardware/software development is outpacing algorithms right now**
- **Its not as easy as some are making it sound**

One Last Thing … Actually 2

1. QC Benchmarks
2. QC Grand Challenge Problems

HYPERION RESEARCH

QUESTIONS?

ejoseph@hyperionres.com

sconway@hyperionres.com

bsorensen@hyperionres.com

anorton@hyperionres.com

jeansorensen@hyperionres.com

mthorp@hyperionres.com

kgantrish@hyperionres.com