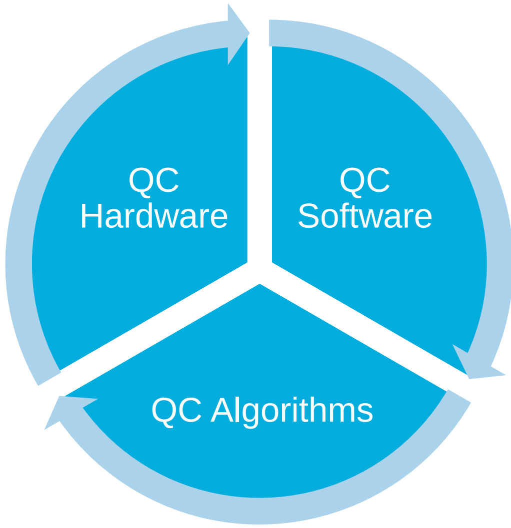
HYPERION RESEARCH

Quantum Computing: Moving Out of the Lab and Into the Real World (?)

Bob Sorensen
Chief Analyst for Quantum Computing

Hyperion's 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

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.

Significant Technical Challenges Ahead

- **Materials Research**
  - Coherency, defect management, power
- **Device and Processor Development**
  - Gate/logic designs, Coherency, Entanglement, Control,
  - Measurement, Error Rates and Error correction schemes
- **Architecture: Memory, Interconnect, Storage, Accelerators**
  - Heterogeneity
  - No Cloning Theorem, No Broadcast Theorem
  - Integration and control
  - Error Correcting or Error Tolerant Designs
  - Designs absent applications

Significant Technical Challenges Ahead

- **Software**
  - QC Assembly, Instruction sets, Programming Language and Tools
  - QC interfaces to von Neumann systems
  - Validation and Verification
- **Algorithms**
  - A Wide Open Field
  - The single greatest value of the QC systems currently under development is that they serve as tools for QC algorithmic development, not as end-use systems

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**
  - D-Wave, 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

First Steps: 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*

The QC Experts Panel

- **We are contacting thought leaders throughout the global QC community to join the panel**
  - Invitations are being sent across the QC ecosystem including HW researchers, algorithm developers, QC solutions providers, and the growing QC user base
  - Positive returns are coming in
- **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

If interested in participating, let us know

Results of First Survey of QC Experts

First Survey of QC Experts: Questions

We are seeking to establish the big picture for QC:

1. **Which organizations (government, academic, corporate) are conducting some of the most advanced QC activities today?**
2. **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
3. **What are some of the key technical challenges/roadblocks facing QC developers today?**
4. **What are some of the most compelling quantum computing applications currently under development?**
5. **What kind of schedule do you see for the roll out of key quantum computing systems or application?**

Summary of Answers: Q1

Which organizations (government, academic, corporate) are conducting some of the most advanced QC activities today?

- **Government:**
  - NASA Ames, DOE, Office of Science in general (with a 100M budget plus up in FY19), LBL, SNL, LANL, ORNL, ANL, NIST, NSF

- **Academia:**
  - U of Maryland, Perimeter Institute, UCSB, MIT, Caltech, Oxford, University of Waterloo, University of Delft, University of Sydney, University of Bristol, University of Chicago, University of Texas at Austin, USC, UCB, Princeton, Harvard, Arizona

- **Commercial:**
  - Intel, Google, IBM, Microsoft, Alibaba, D-Wave
  - Start-ups: IonQ, D-Wave, Rigetti, others

Summary of Answers: Q2

What are some of the key QC technology developments currently underway at these locations?

- Superconducting qubit quantum computing – Google, IBM, Intel, Rigetti, Yale, (Caltech)
- Topological quantum computing – Microsoft, Delft, UCSB
- Photonic quantum computing – University of Bristol
- QC theory and Quantum error correction – University of Waterloo
- Silicon spin donors – Silicon Quantum Computing and University of Sydney
- Trapped Ions – IonQ, Oxford

Summary of Answers: Q2 (cont.)

What are some of the key QC technology developments currently underway at these locations?

- **Architectures:**
  - Programming languages and frameworks (Microsoft Q#, Rigetti Forest, IBM Q)
- **Simulators:**
  - Ever more scalable through classical code and method optimization and “shortcut”-identification.
- **Algorithms:**
  - Quantum chemistry.
  - Hybrid classical-quantum algorithms,
  - Approximate optimization algorithms,
  - Quantum machine learning algorithms
  - Mostly old but some new ones popping up from time to time,
  - Some efforts to use the “old” algorithms on current QCs in a meaningful way

Summary of Answers: Q3

What are some of the key technical challenges/roadblocks facing QC developers today?

- Qubit quality still needs improvement: longer coherence times and more accurate gates
- Qubit connectivity is at least as much of an issue as sheer number of qubits
- Maturity of quantum frameworks (they are at assembler level)
- Patience : It will take time, both in development and return-on-investment)
- Access to quantum computers (there are some but it is not real time)
- Money

Summary of Answers: Q3 (cont.)

What are some of the key technical challenges/roadblocks facing QC developers today?

- Crosstalk between matter-based qubits
- Operation at sub-1K for most technologies
- Scalable interface architectures
- Enormous cooling power requirements
- Quantum Error Correction overhead
  - Even larger overhead for error corrected logical operations
- Lack of quantum algorithms that will run with small numbers of logical qubits
- Engaging domain experts to develop new quantum algorithms and applications
- People don’t think in quantum algorithms
- **Demonstration of logical qubit with sufficiently good performance**

Summary of Answers: Q4

What are some of the most compelling quantum computing applications currently under development?

- Quantum chemistry.
- Simulation of condensed matter systems
- Interesting developments in sampling and matrix inversion.
- Quantum machine learning
- Quantum implementations of linear algebra problems
- Simulation of chemical reactions and analysis of novel material properties

Summary of Answers: Q5

What kind of schedule do you see for the roll out of key quantum computing systems or application?

- Still 10 years.
- In 2-4 years we will see more use of quantum simulations.
- In 3-5 years we will have an instance of relevant quantum supremacy. (There will be some quantum supremacy apps in 1-3 years but in a special non-practical use case)
- In 7-15 years there will be relevant size low noise QCs, even for breaking some public keys.
- 5+ years: On-demand cloud-based devices used for quantum simulation tasks
- 10+ years: Larger scale on-demand services for big data and ML applications
- First application in chemical reaction and material simulation within 5 years.

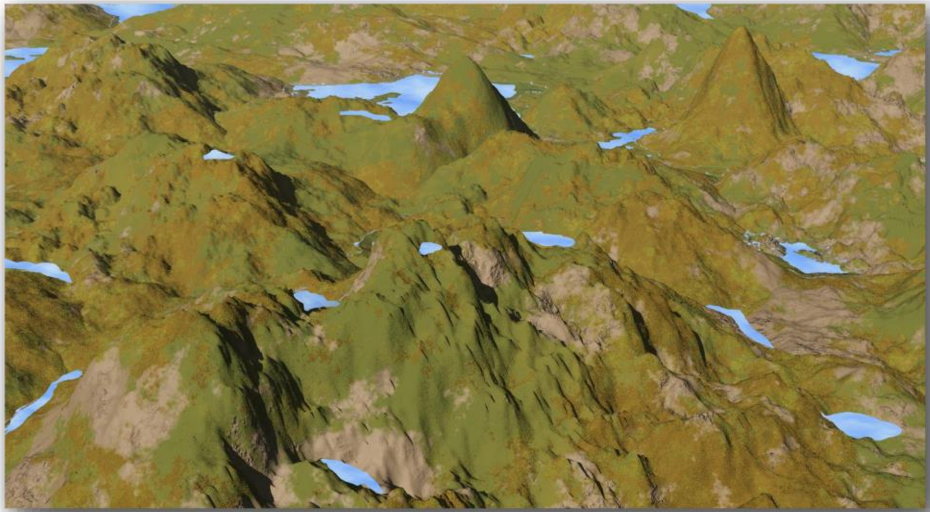
Sampling the Quantum Computing Landscape

Many Developers, Many Approaches

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

D-Wave: 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: Looking for Applications

Research Hubs

- The IBM 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.

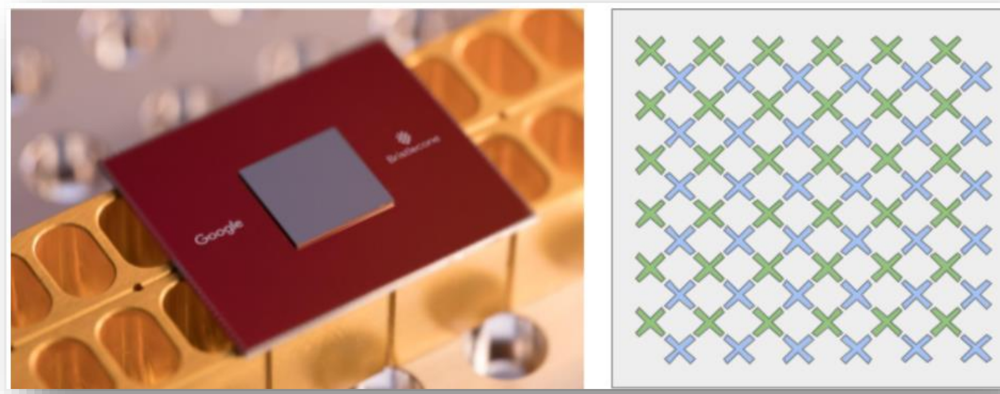
Direct IBM Partnerships

- **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. **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

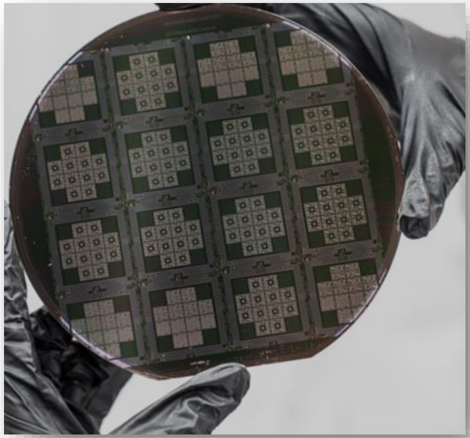
Bristlecone, Google's New Quantum Processor

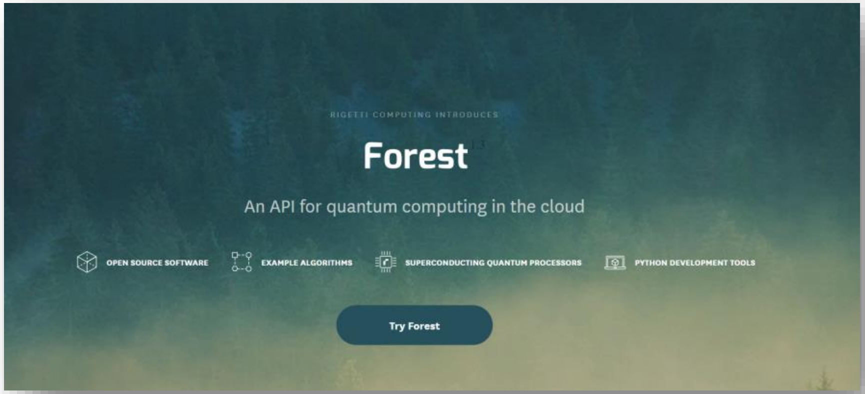
- 'The guiding design principle for this device is to preserve the underlying physics of our previous 9-qubit linear array technology, which demonstrated low error rates for readout (1%), single-qubit gates (0.1%) and most importantly two-qubit gates (0.6%) as our best result.'
- This device uses the same scheme for coupling, control, and readout, but is scaled to a square array of 72 qubits.



- Google has also been working together with NASA and the Universities Space Research Association (USRA) to operate D-Wave system processor at the NASA Ames Research

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:

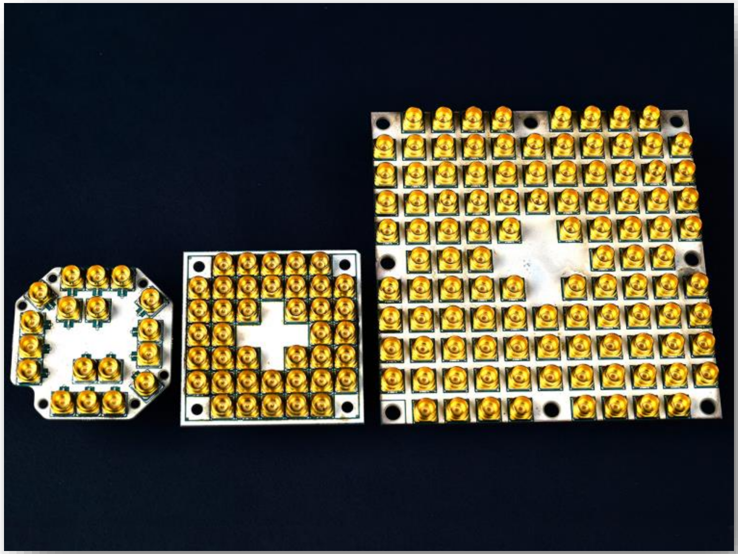
- New architecture allowing improved reliability, thermal performance, and reduced radio frequency (RF) interference between qubits
- A scalable interconnect scheme that allows for 10 to 100 times more signals into and out of the chip as compared to wire-bonded chips
- Advanced processes, materials and 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

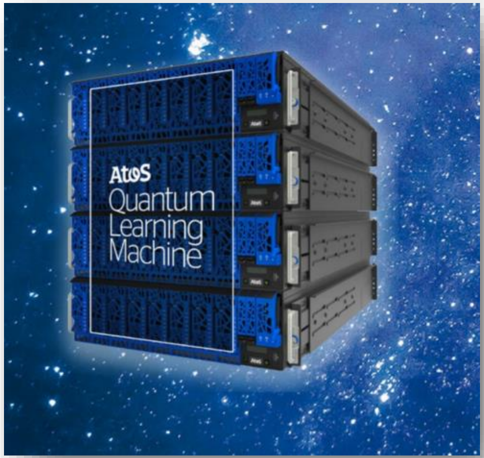
- The chip is named after a chain of lakes in Alaska, a nod to the extreme cold temperatures and the entangled state that quantum bits require to function

- 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

Government QC Activities

- **US**
  - U.S. House Science Committee will introduce legislation to launch a 10-year National Quantum Initiative
  - Three to six new facilities
    - Quantum Innovation Laboratories (QILabs)
    - Quantum Research Network(QRNet)
    - Quantum Computing Access Program (QCAP)
  - Each QILab will be located at a central facility in the U.S.
    - distinct and focused research and development mission and may include satellite QILab participants and facilities as appropriate
  - The QILab, QRNet and QCAP components of NQI will be administered through the civilian agencies NSF, NIST, and DOE with an overall budget of $800 million over an initial 5-year phase.

Government QC Activities

- **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.

Government QC Activities

- **EU**
  - The European Commission announced in 2017 plans to launch a €1-billion (US$1.13 billion) project to boost a raft of quantum technologies — from secure communication networks to ultra-precise gravity sensors and clocks.
  - In November 2017, a final flagship report was released as a blueprint for combining and coordinating Europe's strengths in this area.
  - On the basis of this report, the Commission will start the implementation of the Quantum Flagship. This will be done through Horizon 2020 research projects, to be launched in 2018.

Quantum Computing Summary

- **A wide and diverse range of QC suppliers are emerging to develop a QC ecosystem**
  - Legacy Players (D-Wave, IBM)
  - New Entrants :
    - Pure Play: ionQ: Rigetti,
    - Product add-ons: Intel, ATOS
  - Non-traditional player (Google, Microsoft)
- **Government interest is very high**
- **Hardware/software development is outpacing algorithms right now**
- **It’s just not as easy as some are making it sound**

One Last Thing … Actually 2

1. **QC Benchmarks**
   - Coherence time
   - Quantum gate error rates
   - Shor's Algorithm factoring rate
   - Quantum volume (qubits X gate coherence time X number of gates X connectivity X error rate (operation ^ read))
   - Use case-based
2. **QC Grand Challenge Problems**

One Last Thing … Actually One More

A Gentle Reminder

- 1834 Charles Babbage's Analytical Engine
- 1968 Knuth's The Art of Computer Programming
- 1976 Seymour Cray's Cray-1

Currently, QC is closer to Babbage than it is to Cray

Thanks

bsorensen@hyperionres.com