A Tour Through the Quantum Ecosystem

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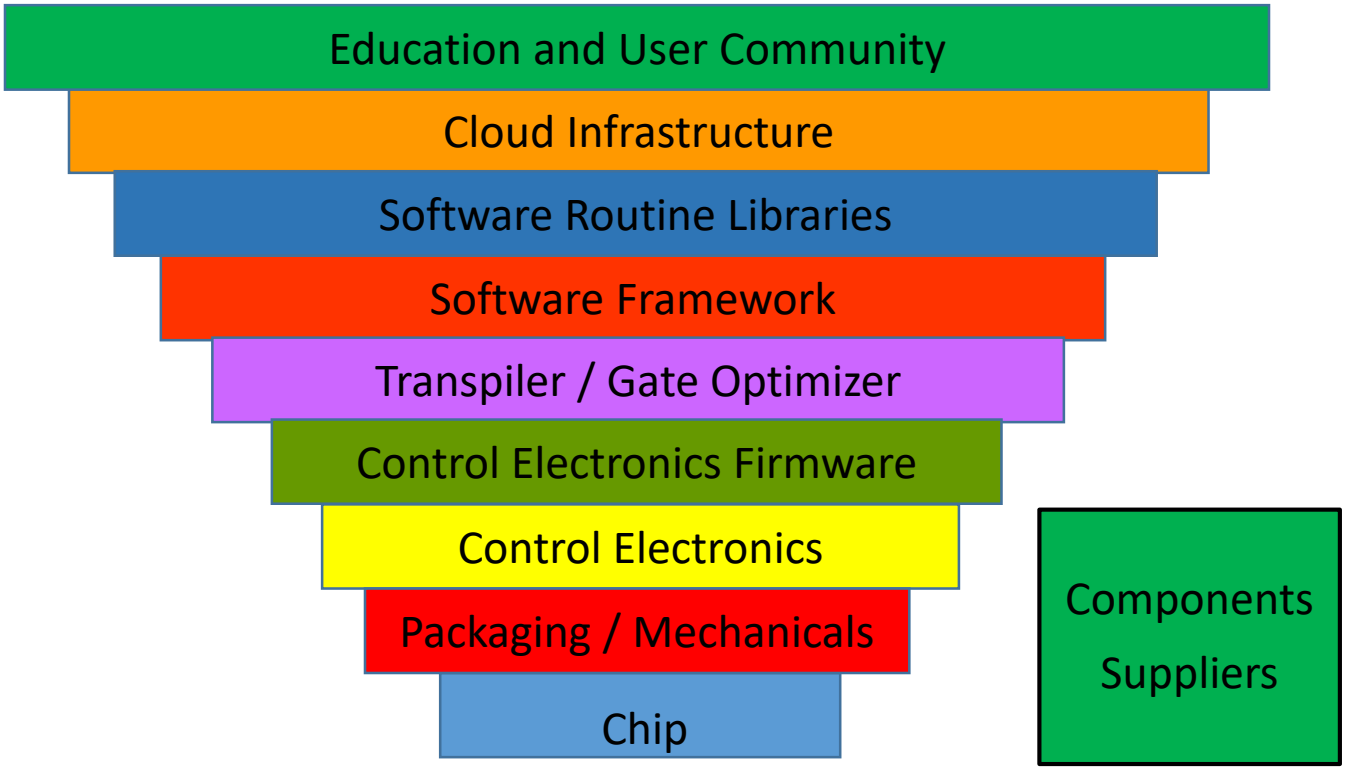
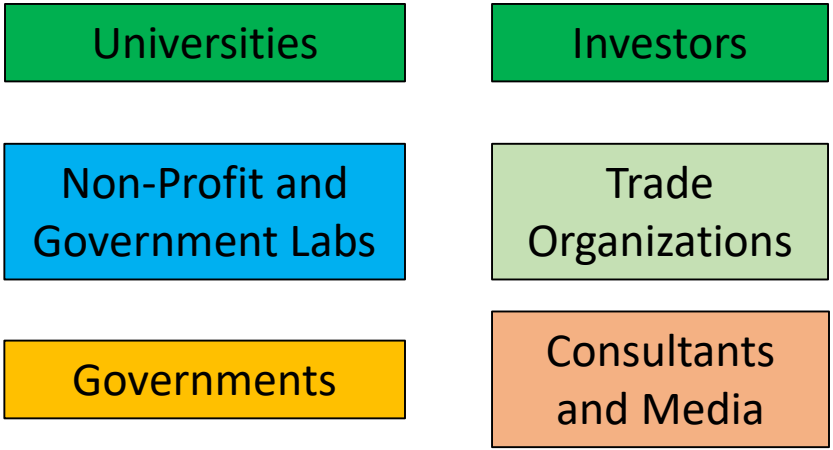
Introduction

- Purpose of this presentation is to show the breadth of different organizations working to develop and promote quantum computing technology and how they relate to each other.
- Today's presentation only covers quantum computing. It does not include quantum communications, quantum sensing, or quantum inspired computing.
- Organizations and activities classified by:
  - Technology Provider
    - Hardware
    - Software
    - Infrastructure
  - Support Organizations
- Many organizations are listed as examples, but my apologies in advance if your favorite organization is not shown. A more complete list is on the QCR.

Hardware and Software Technology Requirements to Provide a Complete Quantum Computing Capability to End Users



Support Organizations in the Ecosystem



Hardware Providers

Examples of Components Suppliers

Bluefors – Dilution Refrigerators

Zurich Instruments – Electronic Instrumentation

M Squared – Lasers

Single Quantum – Single Photon Detectors

Delft Circuits – Coaxial Cable Assemblies

XMA Corporation – Cryogenic Connectors, Terminators, & Attenuators

GlobalFoundries – Wafer Processing for PsiQuantum and equal1.labs

Goppian – Glass Enclosure for IBM Q System One

Qubit Development Research Projects Underway

Organization	Adiabatic/Annealing	Superconducting	Trapped Ion	Cold/Neutral/Helium Atom	Spin/Quantum Dot/CMOS	Photonic	NV Diamond	Topological
Organizations:89 Projects:115	7	25	20	10	19	21	7	7

- Full table by organization available on the QCR web site
- Includes projects at Universities, Government Labs, Public Companies and Private Companies

Examples of Public Companies Developing Quantum Chips

IBM – Superconducting

Google – Superconducting

Honeywell – Ion Trap

Intel – Superconducting and Spin Qubits

Microsoft - Topological

QC Startup Companies Developing Chips

Company	Country	Technology	Company	Country	Technology
Alice&Bob	France	Microwave Photonics with Superconductors	Pasqal	France	Neutral Atom
AQT	Austria	Ion Trap	PsiQuantum	U.S.	Photonic
Atom Computing	U.S.	Neutral Atom	Photonic Inc.	Canada	Spin Qubit & Photonic
Bleximo	U.S.	Superconducting	Qilimanjaro	Spain	Annealing
BraneCell	U.S.	Ambient Qubit Array	Quandela	France	Photonic
C12 Quantum Electronics	France	Spin Qubit	Quantum Brilliance	Australia	NV Diamond
ColdQuanta	U.S.	Cold Atom	Quantum Circuits Inc.	U.S.	Superconducting
D-Wave	Canada	Annealing	Quantum Factory	Germany	Ion Trap
EeroQ	U.S.	Electrons on Helium	Quantum Motion	United Kingdom	Spin Qubit
Equal1	Ireland/U.S.	Spin Qubit	QuEra Computing	U.S.	Neutral Atom
IonQ	U.S.	Ion Trap	QuiX	Netherlands	Photonic
IQM	Finland	Superconducting	Rigetti Computing	U.S.	Superconducting
NextGenQ	France	Ion Trap	Seeqc	U.S.	Superconducting
Orca Computing	United Kingdom	Photonic	Silcon Quantum Computing	Australia	Spin Qubit
Origin Quantum Computing	China	Spin Qubit	Tundra Systems	United Kingdom	Photonic
Oxford Ionics	United Kingdom	Ion Trap	Universal Quantum	United Kingdom	Ion Trap
Oxford Quantum Circuits	United Kingdom	Superconducting	Xanadu	Canada	Photonic

Note: Does not include component companies or companies providing quantum sensing, QKD or QRNG hardware.

Companies Specializing in Control Electronics Hardware and Software

Q-CTRL – Qubit Control SW for improved qubit quality

Quantum Benchmark – Qubit Control SW for improved qubit quality

Qblox – Qubit Control SW

Quantum Machines – Qubit Control HW and SW

Keysight/Labber Quantum – Qubit Control HW and SW

Software Providers

Backends/Transpilers/Translators

- We learn how to program quantum computers with standard gates such as Pauli gates, Hadamard, CNOT, Toffoli, etc.
- But the hardware only implements specific native gates which can be much different
- A transpiler will convert a program with standard gates to the machines native gates.
- An optimizing transpiler will convert a program to have fewer gates, fewer qubits, lower circuit depth, or lower error rate
- A translator will convert a program from one architecture to another.

Examples of Backends/Transpilers/Translators

Supplied by HW Providers for their Own Machines

- IBM Qiskit Terra
- Google CIRQ
- Rigetti Forest
- D-Wave Leap2

Supplied by Others for Different HW Architectures

- IBM – Backend for AQT Ion Trap
- CQC – Backends for IBM Q and Honeywell
- Project Q – Backend to IBM Qiskit and Google CIRQ
- Honeywell – Backend from IBM Qiskit Source
- Quantastica – Backend from Qiskit to Rigetti Forest
- QC Ware – Backends for D-Wave, IBM, and Rigetti
- Xanadu Pennylane - SW Backend for IBM
- Microsoft – Q# to MS Azure Quantum HW Partners (TBD)
- Amazon AWS - TBD

Frameworks/Operating Systems/Simulators

Major Frameworks

- IBM Qiskit
- Google CIRQ
- Rigetti Forest
- Microsoft Quantum Development Kit
- D-Wave Leap 2

Additional Frameworks

- DeltaFlow.OS – New UK effort led by Riverlane
- ProjectQ – Open Source Framework from ETH Zurich
- Xanadu – Strawberry Fields
- Amazon AWS – TBD

Quantum Simulators

- Atos – Dedicated hardware box for simulation
- Many different software simulators in the major frameworks & standalone

Workflow Managers/Development Platforms

- Zapata Orquestra
- Strangeworks

Examples of Software Libraries

- IBM Qiskit Aqua – Chemistry, AI, Optimization, Finance and quantum algorithms
- OpenFermion – Chemistry
- Microsoft Quantum Development Kit Chemistry Library
- TensorFlow Quantum – Quantum Machine Learning
- Baidu Paddle Quantum – Quantum Machine Learning

Application Software Companies

- More than 70 startup companies working on application software and end user support
- Some provide general applications support and consulting. Examples: QC Ware, 1QBit, Zapata
- Some focus on specific segments. Examples:
  - Finance: QuantFi, Multiverse, JoS Quantum
  - Computational Chemistry: Qulab, Menten, Netramark, ProteinQure
  - Logistics: Qubit Engineering
  - Artificial Intelligence: QbitLogic
  - Image Rendering: Boxcat
- Some provide miscellaneous tool for simulations, programming, design, etc.

Cloud Infrastructure, User Communities, and Partnerships

Cloud Infrastructure

Challenges Providing Quantum Cloud Services

- User access permissions and billing
- Queueing and scheduling jobs
- Maintaining uptime (including calibration, maintenance)
- Hybrid classical/quantum computing support

Current Providers

- IBM
- D-Wave
- Rigetti
- QuTech Quantum Inspire
- CAS-Alibaba Quantum Cloud
- University of Bristol
- Amazon AWS (Beta)
- Microsoft Azure (Beta)

Education & User Community

- Purpose: Convince end users to learn on your architectures so they become loyal to you and use your systems for production
  - Analogy: Apple versus Android
- Largest effort so far is the IBM Q Network
  - Partners
  - Documentation and Videos
  - Education
  - Challenges and Qiskit Camps
- Other significant efforts from D-Wave, Microsoft, and Rigetti
- Key Tactic: Establish partnerships with compatible software and hardware companies to provide a more complete solution to an end user

Supporting Organizations

Other Organizations

- Universities: 133 worldwide, 52 in the U.S.
- Non-Profits/Government Labs: 40 worldwide
- Investors: 239 organizations investing into 82 companies
- Trade Organizations and Other Associations
  - Quantum Economic Development Consortium (QED-C)
  - Quantum World Association
  - Quantum Industry Coalition
  - OneQuantum
  - Quantum Flagship
  - Swiss Quantum Hub
  - Association Quantum
  - Many QC Meetup Groups (> 50 worldwide)

Government Funding for Quantum Technology

Australia	$94
Canada	$766
China	$10,000
European Union	$1,100
France	$1,600
Germany	$3,100
India	$1,000
Israel	$360
Japan	$470
Netherlands	$177
Russia	$663
Singapore	$109
South Korea	$37
United Kingdom	$1,300
United States	$1,200
Total	**$21,976**

Source: Article on Overview on Quantum Initiatives Worldwide, September 2020

- National quantum strategy documents released recently from the U.S., Netherlands, France, and Australia

Summary

It takes a village to build a quantum industry!

- Hundreds of different organizations involved with quantum computing
- Spanning commercial companies, governments, non-profits, and various associations
- Partnerships will be vital for success
- The ecosystem will be extraordinarily dynamic for the next several years as new players join and others leave or are merged together