

Chicago Quantum

US ADVANCED COMPUTING
INFRASTRUCTURE, INC.

Quantum Computing Providers



*By Jeffrey Cohen, President
Chicago Quantum
US Advanced Computing Infrastructure, Inc.
February 7, 2020*

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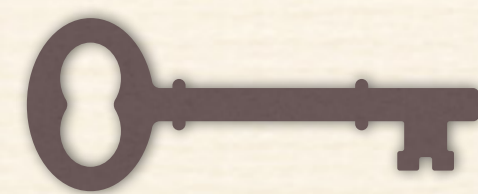
<https://www.chicagoquantum.com>

Quantum Computing Providers

February 7, 2019

Groupings of Quantum Computing Providers

- ❖ Hardware - 1/full stack quantum computer providers, 2/component or solution manufacturers, & 3/start-ups
- ❖ Software platform and tool providers
- ❖ Access providers - multi-vendor
- ❖ Consultancies & ISVs



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“Contact us for more information or to create your own quantum advantage”

Notes & Acknowledgements

“All data is publicly available”

“This list may not be comprehensive as it is based on team experience & research”

“All providers are listed only once even if they serve multiple markets”



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Quantum Computing Hardware Platform Manufacturers

- ❖ Alibaba Cloud (with CAS)
- ❖ AQT GmbH
- ❖ ATOS / Bull
- ❖ D-Wave Systems
- ❖ Fujitsu IT Ltd.
- ❖ Google AI
- ❖ Honeywell Quantum Solutions
- ❖ IBM Research
- ❖ IonQ
- ❖ NTT Phi Laboratories
- ❖ Rigetti Computing
- ❖ Xanadu

- ❖ Approaches: 1/ annealing (QUBO & Ising), 2/ universal or gate-based systems, or 3/ simulators (full stack)
- ❖ Technologies: Current: superconducting, ion traps, & photonics. Future: neutral atoms, CMOS, spin & topological qubits
- ❖ Access methods: 1/ on-premise hardware, or 2/ public cloud access
- ❖ Simulators currently offer comparable performance
- ❖ Competition between F100 public and small VC/ private firms
- ❖ No commercial 'production' workloads

* Excludes start-ups without a demonstrated hardware platform (e.g., PsiQuantum).

* Most providers build or systems integrate a full hardware and software stack (think IBM PCs before MS/DOS), with some recent software and access cross-compatibility.

* No supplier offers quantum memory, storage, I/O, networking or DBMS; nor fault tolerant or error corrected systems.

Quantum Hardware Component or Solution Manufacturers

- ❖ Bluefors
- ❖ Cold Quanta
- ❖ Hitachi Cambridge Labs
- ❖ ID Quantique
- ❖ Infineon Technologies
- ❖ Intel Corporation
- ❖ InfiniQuant
- ❖ M Squared
- ❖ Quandela
- ❖ QuiX
- ❖ Qunnect
- ❖ Silicon Quantum Computing
- ❖ Toshiba Research Europe Limited

- ❖ A growing ecosystem of component makers (and we recognize this is an incomplete list)
- ❖ Significant efforts creating quantum processing units (CPUs for quantum computing)
- ❖ Existing component makers extending addressable market into quantum computing
- ❖ Mix of academic spinoffs, large corporate research groups, and small startups.
- ❖ Growing number of quantum safe communications solutions (e.g., QKD)

* No supplier offers quantum memory, storage, I/O, networking or DBMS; nor fault tolerant or error corrected systems.

* Includes primarily QPU, QKD and system component manufacturers (e.g., dilution refrigerators). Excludes Cryogenic DRAM providers (2)

Quantum Computing Hardware Start-ups

- ❖ Atom Computing
- ❖ Bleximo
- ❖ BraneCell
- ❖ IQM OY
- ❖ ORCA Computing
- ❖ Pasqal
- ❖ PSI Quantum
- ❖ Quantum Circuits Inc.
- ❖ Quantum Motion (TBC)

- ❖ Technology: 1/ neutral atoms, 2/ photonics, or 3/CMOS (current CPU technology) to improve scalability
- ❖ Some firms are lightly funded (small ranges from \$1.5M to \$20M)
- ❖ Largest funding is \$230M for PsiQuantum, which rivals corporate research scale
- ❖ Quantum Circuits is a Microsoft Quantum Azure partner

Quantum Computing Software Platform & Tools Providers

- ❖ IQBit
- ❖ Aliro
- ❖ Artiste
- ❖ Cambridge Quantum Computing
- ❖ ETH Zurich (Project Q)
- ❖ ISARA Corporation
- ❖ QuTech
- ❖ Q-CRTL
- ❖ Quantum Benchmark Inc.
- ❖ Riverlane
- ❖ Strangeworks

- ❖ Some firms are targeting the quantum computing industry to help manufacturers scale
- ❖ Some firms target developers and enterprise customers looking to adopt quantum computing with simulation and cross-platform software and algorithms
- ❖ One provides post quantum cryptography software (and consulting / project services)
- ❖ One is offering a scalable quantum simulator (without a bundled hardware capability)
- ❖ All are small VC/private/spinout firms

Quantum Computing Multi-Vendor Platform Access

- ❖ Amazon Web Services / Braket
 - ❖ Microsoft Azure Quantum
 - ❖ QC-Ware
- ❖ AWS and Microsoft offer a full set of services along with quantum computing platform access
 - ❖ QC-Ware offers software and consulting services in addition to cross-platform quantum computing access
 - ❖ We see this emerging capability of providing multi-vendor platform access continuing

* We exclude providers that offer access to their own platforms only, or were mentioned as offering their own platforms (e.g., Google, IBM & Rigetti)

Quantum Computing Consultancies & ISVs

- ❖ Accenture Research
- ❖ Boston Consulting Group
- ❖ Chicago Quantum
- ❖ h-Bar Quantum Consultants
- ❖ Max Kelsen
- ❖ QuantFi
- ❖ Zapata Computing

- ❖ We acknowledge this list is incomplete, and is based on our own experience and access to firm members
- ❖ Typically small teams serving clients around specific use cases (e.g., chemistry, financial services), whether independent or within larger firms
- ❖ Teams require diverse skillsets (physics, computer science, mathematics, industry domain, functional domain) and typically require programming and algorithm skills.

- * We see research and speakers from both Accenture and Boston Consulting Group on the conference circuit.
- * We have met with Zapata, QuantFi, Max Kelsen, and h-Bar in our daily work.

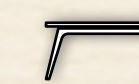
Full Stack, Universal, Gate QC Providers

Superconducting

Neutral Atoms



Ion Trap



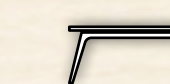
CMOS

Photons



Vendor / Country	Quantum Scope	Access Model
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Alibaba Cloud (Aliyun) & Chinese Academy of Sciences / China	11 Qubits (made by CAS) Quantum Simulation (up to 81 Qubits TaiZhang)	Cloud Access - CAS computer via Aliyun cloud
AQT / Austria	5 Qubits (U of Innsbruck) Quantum simulator 08/2019: raised another 10M Euros	Accessed @ University of Innsbruck directly, supports CIRQ and IBM Qiskit
Google AI / USA	54 Qubits (Sycamore) (53 qubits were working in 2019) & Quantum Simulators & advanced research	Cloud Access (for expert users)
Honeywell Quantum Solutions / USA	First system expected soon. 99.997% individual qubit fidelity. Size not disclosed.	Future: via Microsoft Azure Quantum
IBM Research / USA	10 systems, 5-20 Qubits, in IBM Q Network via IBM Cloud, plus 2 most advanced systems (latest has 53 qubits)	Accessed via IBM Qiskit, the IBM Cloud & the IBM Q Network. There are multiple levels of agreement.



- Difficult to determine qubit counts on Trapped Ion or Photonics systems
- Firms tend to manufacture their own processors

Full Stack, Universal, Gate QC Providers

Superconducting

Neutral Atoms



Ion Trap



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Photons



Vendor / Country	Quantum Scope	Access Model
IonQ / USA	11 fully connected Qubits (79 ion chain, & 55 addressable pairs) Built 3 QC, not publicly available Raised \$77M through 2019	Direct Access, AWS Braket & Microsoft Azure Quantum
Rigetti Computing / USA Acquired QxBranh / USA	Quantum Machine Images, Quantum Lattices, and Quantum Simulator. 32 Qubits (on AWS and QCS) Aspen-7 AWS Partner Network Raised \$119.5M in 9 rounds Consulting & Software Dev	Cloud Access via their quantum cloud Rigetti QCS and AWS Braket. Uses the Forest SDK
Xanadu / Canada	Hardware Agnostic Software Platform (PennyLane) runs on IBM, Google and Rigetti with ML toolsets Hardware Manufacturer photon-based QPUs. Qubit count unknown USD \$45M raised to date (Jan 2020)	Cloud Access via PennyLane and Strawberry Fields SDK / Simulator



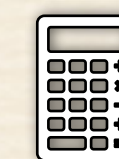
- Xanadu building a continuous variable (CV) model, and operates in qumodes (not qubits).
- Difficult to determine qubit counts on Trapped Ion or Photonics systems

Annealing & Simulation Providers

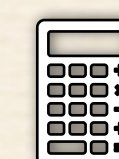
Superconducting



Simulator



Vendor / Country	Quantum Scope	Access Model
ATOS Bull / France	Quantum Simulation on high-DRAM Bull server Universal Quantum / Gates	On-Premise Installation Remote Access - TBC
D-Wave Systems / Canada	Full Stack Solution Quantum Annealers / Adiabatic Optimization, ISING & QUBO 2048 Qubits (DW_2000Q), 5,000+ Qubits (Advantage)	On-Premise Installation; Cloud Access (Leap), Demo & Timeshare
Fujitsu IT Ltd. / Japan	Quantum Annealing Simulation Digital Annealing Unit (DAU) Optimization, ISING & QUBO Quantum-Inspired Hardware 8,192-bit with full connectivity	On-Premise Installation Cloud Access - TBC
NTT Phi Laboratories / Japan	LASOLV (Laser & Solve) Quantum Computer based on photonics ((optical fiber) to solve optimization problems (Coherent Ising Machine)	TBD



- D-Wave and Fujitsu are the only two quantum hardware providers to sell and ship a completed, customer-ready system.
- There are many other providers of simulation software (including open source Python libraries).

Hardware Component Providers

Superconducting

Neutral Atoms



Ion Trap



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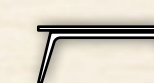


Vendor / Country	Quantum Scope	Access Model
Bluefors Ltd / Finland	Dilution Refrigerators	NA
Cold Quanta	Quantum communication (including transduction, frequency conversion) >\$20M in funding to date	Research efforts
Hitachi Cambridge Laboratory (HCL)	Hardware: QPU processors Spin Qubits using CMOS technology	NA
ID Quantique / Switzerland	Secure Communications (QKD) and random number generators (QRNG)	Hardware sales (data center and end-user devices)
Infineon Technologies AG / Germany	Trapped Ion manufacturing as part of Horizon 2020 project Piedmons Working with U Innsbruck, ETH Zurich, and IFEV SRL from Italy.	TBD, probably through U Innsbruck (with AQT)
Intel Corporation / USA	Quantum Processors (semiconductor and spin qubit) & Full Stack Software 49 Qubits (Tangle Lake) Quantum simulator qHiPSTER	NA; sends silicon wafer output to TU Delft & QuTech (research partners) Software available online

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Photons



Superconducting



- Intel seems to be far along, and is investigating two technologies: Supercomputing & Silicon Spin qubits
- Quantum RAM and Quantum Networking are significant technology research challenges
- We believe hardware components manufacturers have a significant market opportunity (think DASD/SAN/NAS markets)

Hardware Component Providers

Superconducting

Neutral Atoms

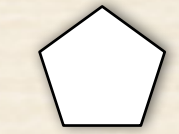


Ion Trap

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Vendor / Country	Quantum Scope	Access Model
InfiniQuant / TBD	QKD (space based)	NA
M Squared LTD / UK	Lasers and photonics	NA
Micron Technologies / USA	Cryogenic DRAM	NA
Quandela / France	Photonics (high quality photons)	
QuiX / Netherlands	Integrated Photonics Processors (and control boxes) programmable for high-end applications	Devices to integrate
Qunnect / USA	Field deployable hardware to support quantum safe communications (QKD) SBIR funding from DoE Spinoff from Stony Brook University	FPGA devices to deploy

Ion Trap



Photons



Photons



- Quantum Key Distribution (QKD) is an early hardware manufacturing solution for the use case to use quantum effects to secure against quantum computing
- Quantum RAM and Quantum Networking are significant technology research challenges (not yet discovered)
- We believe that hardware components manufacturers have a significant market opportunity (think DASD/SAN/NAS markets)

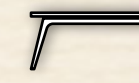
Hardware Component Providers

Superconducting

Neutral Atoms



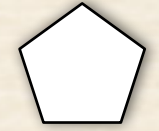
Ion Trap



Photons



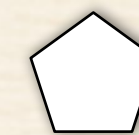
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Vendor / Country	Quantum Scope	Access Model

Rambus / USA	Cryogenic DRAM	NA
Silicon Quantum Computing Pty Ltd / Australia	CMOS Silicon Quantum Chip Technology A\$83M initial seed funding	Chips - experimental stage, hiring 25 PostDoc and 12 PhD students.
Toshiba Research Europe Limited's (TREL) / UK Quantum Information Group (QIG)	QKD and secure Quantum Cryptography SBM Software (Annealing Simulator) QIG - Research Group in TREL	Cloud Access to SBM software via AWS

CMOS



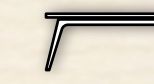
Hardware Startups - Funded to build a computer

Superconducting

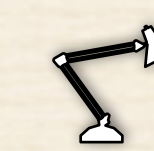
Neutral Atoms



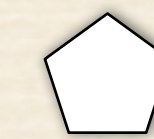
Ion Trap



Photons



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Vendor / Country	Quantum Scope	Access Model
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Atom Computing / USA	Neutral Atom Trap Hardware (like an Ion Trap but scales with neutral atoms) \$5M funding, including NSF SBIR	TBD
Bleximo / USA	Application specific supercomputing hardware & quantum accelerators USD \$1.5M funding	TBD
BraneCell / USA & Germany	Neutral atom qubit for 'edge hardware' at room temperature	TBD, but meant to be distributed and easy to afford/operate.
IQM Finland OY / Finland	Quantum hardware USD \$13M funded spinout from Aalto University & VVT	TBD
Orca Computing / TBD	Photonics Computer (based on ORCA quantum memory)	TBD
Pasqal / France	Neutral Atom Traps (3D) hardware	TBD
PSI Quantum / TBD	"At PsiQ we're building a general purpose silicon photonics quantum computer" Raised \$230M funding	

Neutral Atoms



Neutral Atoms



Photons



Neutral Atoms



Photons



CMOS



- This list is growing.

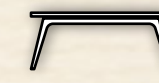
Hardware Startups - Funded to build a computer

Superconducting

Neutral Atoms



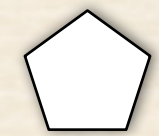
Ion Trap



Photons



CMOS



Vendor / Country	Quantum Scope	Access Model

Quantum Circuits Inc. / USA	Mukai - Quantum AppDev Platform Possibly a hardware stack USD \$18M Series A funding to build a QC	Microsoft Azure Quantum & TBD
Quantum Motion / TBD	Startup looking to create a 1 million qubit quantum computer (postage stamp, not stadium sized)	TBD

- More are being added over time. This is an area of VC/funding interest.

Software Vendors

Vendor / Country	Quantum Scope	Access Model
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1QBit / Canada	Hardware agnostic platform and services to host quantum and inspired pharmaceutical & chemistry applications. USD \$45M Series B funding	Consulting & Projects, TBC
Aliro / USA	Hardware agnostic software platform (write once, run anywhere in QC) Raised USD \$2.7M	Consulting
Artiste / Canada	Data analytics and machine learning open source software and project services. Including QC software for D-Wave, IBM and Rigetti.	AWS or Tencent cloud, or GitHub
Cambridge Quantum Computing / USA	Quantum computing solution provider, including t ket> compiler, EUMEN chemistry & materials platform, +	Software & Consulting
ETH Zurich (Project Q) / Switzerland	Software to access and use IBMQ or local simulation hardware	TBC
ISARA Corp / Canada	Quantum safe security solutions, including software and project services	Solutions and Consulting
QuTech / Netherlands	Quantum simulation - Quantum Inspire	https://www.quantum-inspire.com/

- Quantum computing software providers typically support multiple simulation and quantum computing approaches

Software Vendors

Vendor / Country	Quantum Scope	Access Model
Q-CTRL Pty. Ltd. / Australia	Help visualize and mitigate noise, decoherence, and errors in quantum computers. Black Opal & Boulder Opal Quantum Firmware USD \$15M funding	TBC
Quantum Benchmark Inc. / Canada	Help quantum computer manufacturers scale Cycle Benchmarking of QC Spun out from University of Waterloo Institute for Quantum Computing	Term licensed software & consulting
Riverlane / UK	Gate-based software (platform and algorithms) Pioneering quantum software (TM) Academic QC conferences	riverlane.io
Strangeworks / USA (Austin)	Platform provider to access multiple quantum vendors. Software development & standards. \$4M seed funding	Open Community Provider https://quantumcomputing.stackexchange.com/ https://quantumcomputing.com/

- Quantum computing software providers typically support multiple simulation and quantum computing approaches

Multi-Vendor, Platform Access Vendors

Vendor / Country	Quantum Scope	Access Model
Amazon Web Services (Braket) / USA	Quantum Simulation and access to multiple quantum vendor platforms & consulting partner network	Sign up for BETA access, or contact AWS for consulting support (for a project) Access to D-Wave, IonQ & Rigetti
Microsoft Azure Quantum Microsoft Station Q / USA	Access to multiple quantum systems Quantum SDK & Simulator Quantum hardware research into topological qubits	Access to IonQ, HQS & Quantum Circuits, Inc. Q# / SDK Open Source Software Runs on Microsoft Azure
QC-Ware / USA	Provide access to quantum multiple computers & simulators. Consulting Funded by Citi & Goldman Sachs +	Membership and time sharing Access to simulators and quantum computers. TBC: CIRQ, QISKIT & Ocean

- Access Providers typically offer a mix of simulation, software development and quantum computing approaches (only listed once)

Consultancies / ISVs

Vendor / Country	Quantum Scope	Access Model
Accenture Research / Global	Full scope consultancy	Account consulting leaders
Boston Consulting Group / USA	Full scope consultancy	Account consulting leaders
Chicago Quantum / USA	Quantum Strategy & Software, PQC & Vendor & IT Management	Consulting & Projects
h-Bar Quantum Consultants / Australia	Media, Podcasts, etc. (from Australia)	Spotify podcasts and online inquiry
Individuals	Quantum Games (Google Play Store) Quantum books, Social media, Training & Market intelligence	Access via the WWW and mobile devices
Max Kelsen / Australia	Data Analytics and Algorithms on IBM Q	Consulting & Projects
QuantFi / France	Create quantum algorithms in financial services	Consulting
Zapata Computing / USA	Consulting services (to become quantum ready) and Zapata OS (hardware agnostic quantum toolkit) Consulting firm Raised USD \$21M in April	Consulting & Projects

In hardware...we see:

- ❖ *Universal, gate-based systems (superconducting qubits) were used to show quantum supremacy by Google, and are used by IBM and Rigetti.*
- ❖ *Ion Trap hardware is the focus of Honeywell, IonQ, AQT, and others.*
- ❖ *Other QPU technologies: (e.g., CMOS, photons, electrons, single atoms, quantum dots, & diamond NV cavities)*
- ❖ *Annealing, a specific QUBO & Ising hardware use-case (optimization), and an analog system looking for lowest energy level solutions, is the domain of D-Wave Systems, Fujitsu, and NTT. We see simulation of this technology by Toshiba (SBM).*
- ❖ *We see competitive performance between today's quantum computers and simulators*
- ❖ *Most providers are offering access to their quantum computers via public cloud; only D-Wave Systems and Fujitsu have shipped product.*
- ❖ *No vendor has 'cracked the code' on many elements of the hardware stack required for scaling and commercial enterprise usage (e.g., Quantum RAM, entangled disk & tape, I/O, networking, operating systems, and database systems).*
- ❖ *Most systems are accessed via graphical, low level programming languages or via common 'code as you think' languages like Python with open source libraries, that are compiled at run-time.*
- ❖ *We see valuable 'white space' in supporting 'stack' technologies*
- ❖ *Due to the bimodal split of hardware vendors (F100 vs. VC/private firms), we believe successful smaller firms will be acquired by larger firms as they develop scalable and deployable technologies.*



In the software platform stack...

- ❖ *Microsoft, IBM, Intel, Google & Xanadu have open sourced their software platforms.*
- ❖ *D-Wave has Ocean SDK and Rigetti has Forest SDK, which are proprietary.*
- ❖ *1QBit has partnered with Microsoft and focuses on the chemicals and materials sciences use-cases*
- ❖ *QC-Ware has created a cross-platform stack, agnostic stack and sells run-time per hour (e.g., with expert support)*
- ❖ *Smaller providers are creating stacks, platforms, or application development environments to help developers use new quantum computing concepts.*
- ❖ *Proprietary applications to help quantum computing manufacturers include Quantum Benchmarking and Q-CTRL.*
- ❖ *We plan on using simulators, quantum computers, and annealers for our research into portfolio optimization, and will provide more information in the coming months.*



In applications, we see:

- ❖ *A new set of heuristic algorithms that do not require quantum error correction (e.g., VQE, QAOA) are being used on today's NISQ quantum computers. We are testing these vs. classical, deterministic logic.*
- ❖ *We see applications to help quantum computer makers by Quantum Benchmarking Inc., and Q-CTRL).*
- ❖ *We see end-user games using, teaching, or simulating quantum computing*
- ❖ *Applications, libraries, algorithms, and procedures are written and run via Python language.*
- ❖ *Applications (mostly functions) can also be written via gate operations (graphical programming language)*
- ❖ *Application code is compiled to run on specific hardware platforms (and sometimes tailored for specific processors and methods (e.g., parsed to fit on available qubits, forward and reverse annealing, with pause)*
- ❖ *The programs are loaded, run, and results are provided in a binary string (1s and 0s). There is no storage of interim data (e.g., no batch or checkpoint/restart).*
- ❖ *Due to short run times (< 1 second), we need to write short, recursive programs with shallow logic strings*
- ❖ *Creating applications requires deep, multi-disciplinary expertise to create inputs, outputs, logic and user experience.*



In Consulting and ISV markets, we see:

- ❖ *Very little activity in the public domain, very little hiring, and few announced 'independent' engagements.*
- ❖ *We see patents and proprietary toolsets to protect IP and create differentiation*
- ❖ *In our space, potential clients are placing a low priority on quantum computing business projects.*
- ❖ *There is no 'quantum advantage' in the public domain to drive consulting...yet*

