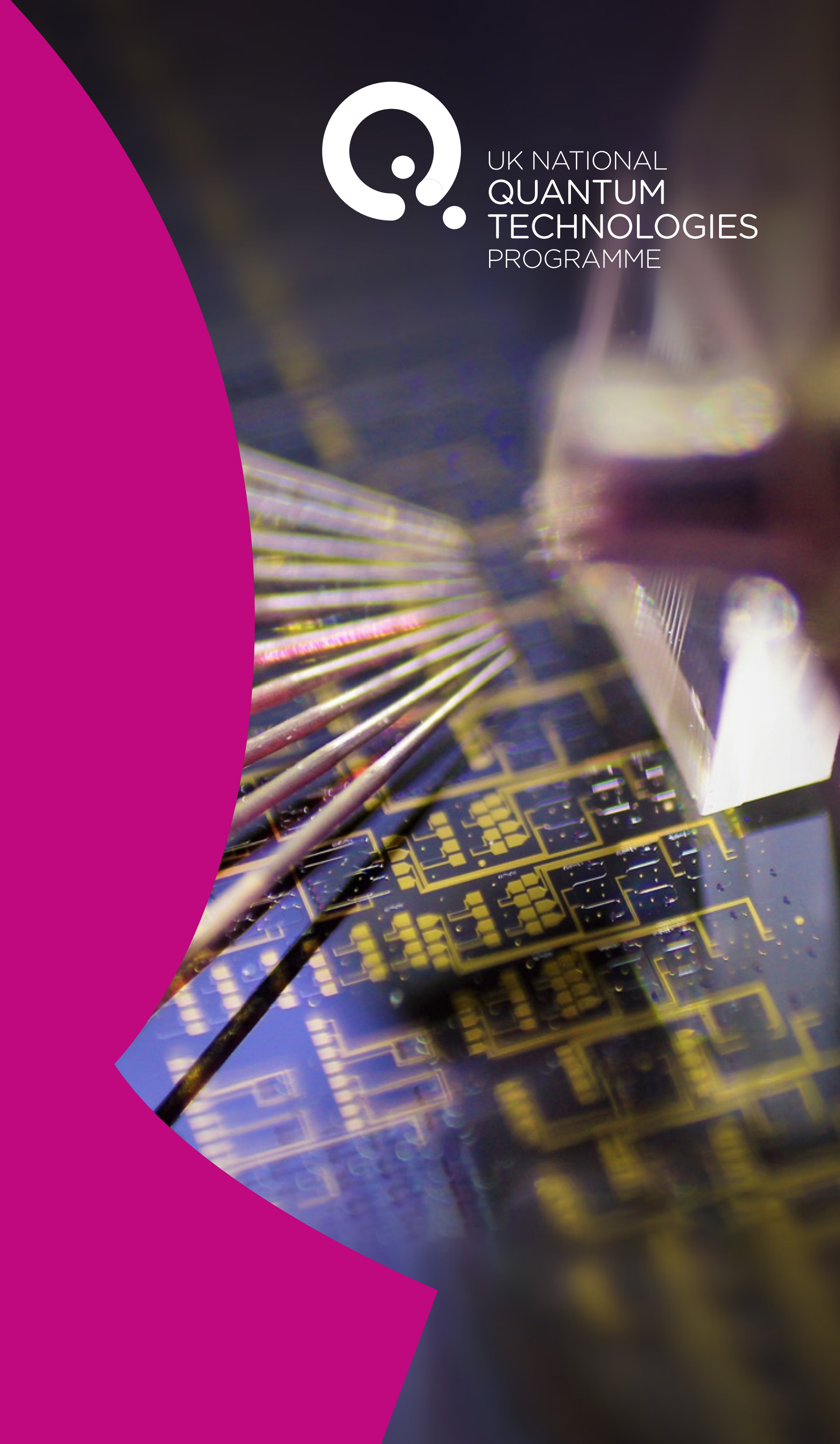
Quantum Computing & Simulation Hub

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

# Quantum Simulation

## An overview of quantum simulation and its applications

Summer 2022



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# Introduction

Quantum simulation is an often overlooked part of the Quantum Information Technology (QIT) revolution that is currently happening around the world. QIT promises new approaches to computing, inherently secure communications and the ability to solve intractable computational problems. However, perhaps one of the most essential offerings will be a better ability to understand nature and its fundamentals.

Existing digital computers make valiant attempts to mimic the complex processes we find in nature, but despite the ever increasing and cheaper volumes of processing power, few can match the complexity of quantum physics. For many of the most fundamental problems – often the most valuable in chemistry and physics – classical computing proves to be inadequate. Quantum computers are expected to perform better in these areas, but the best modelling of quantum dynamics could be provided by a quantum system that we can manipulate. This is known as a quantum simulator.

Developing these tools faces tough technological challenges, but good progress is being made towards practical applications in industry and science. Quantum simulators offer unique strengths and should be considered as viable near-term solutions for high-value applications in fields such as logistics, materials discovery and chemistry. This report provides an accessible overview of quantum simulators, their technology and their likely applications.

Professor Dominic O'Brien
Director, Quantum Computing and Simulation Hub

*Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.*

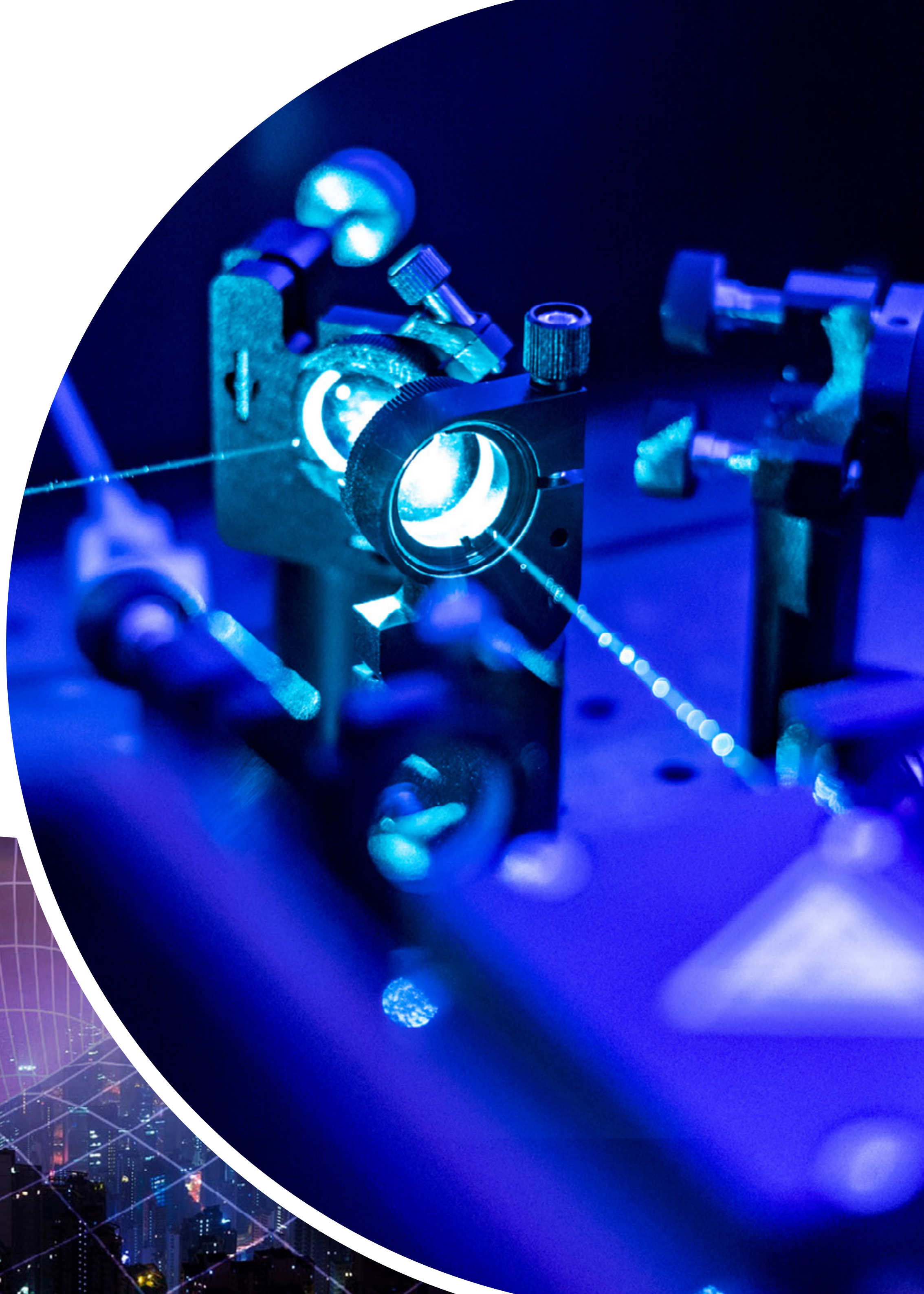
Richard Feynman

# What are quantum technologies?

The behaviour of nature at the atomic and subatomic scales has intrigued and divided scientists, writers and philosophers over many decades. This branch of physics, called 'quantum mechanics', has given us incredible insights in how nature operates beyond our everyday experience, and introduced new terms like ***superposition, entanglement, interference, tunnelling and teleportation.***

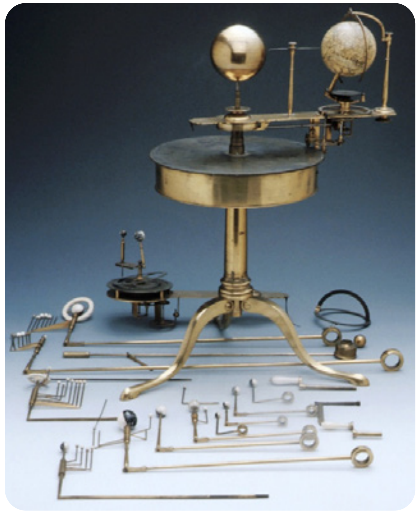
Now we are at the stage where we can harness these unique properties of the quantum world and, coupled with quantum information science, engineer entirely new technologies across imaging, sensing, timing, communication, computation and simulation.

Imagine being able to discover new materials and medicines, optimise logistics, and enhance online security – these are just some of the applications being pursued by researchers and businesses across the world.



# Why simulation matters

Simulation is the representation of some physical or natural system by another, in order to advance understanding, explore theories and predict outcomes. Simulation is not a new concept – planetary motion, for instance, has long been of interest and various physical models have been constructed throughout the ages. [1]



The first modern orrery can be traced to English clockmakers George Graham and Thomas Tompion in 1704.

Image © History of Science Museum, University of Oxford, inventory no. 45104

Electronics and digital computing have played an important role in advancing simulation techniques. The first electronic analogue simulator was proposed and developed in 1938 by George A. Philbrick, an 'Automatic Control Analyzer' which saw considerable use as a training tool. [2] Analogue computers have seen use in subsequent decades in applications such as modelling control systems (e.g. flight simulators). [3]

> *In just a few minutes of demonstration, it could impart considerable knowledge of process dynamics, controller tuning, and the effects of load and control-point upsets.*

George A. Philbrick [2]

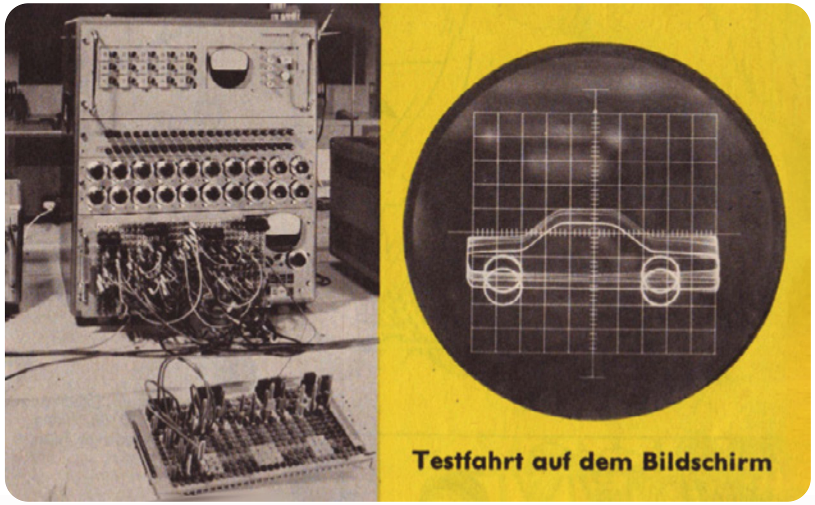
Nowadays, common applications for simulation include: designing buildings and other complex structures, studying chemical processes, analysing vehicle aerodynamics, and modelling geological activity, the behaviour of crowds and even the spread of disease. [4] [5]

## Simulation vs Emulation

The terms ***simulation*** and ***emulation*** are often used interchangeably to suggest the representation of one system on another but in the context of this report, they are different entities.

A ***quantum simulator*** is a physical quantum system used to model another quantum system (or a problem that can be mapped to it, such as optimising traffic routing for example).

An ***emulator*** is used to represent hardware. For example, quantum computers can be emulated in software (up to a point) while the hardware is being developed. The open source software QuEST is one such emulator, used by researchers to run quantum algorithms on a variety of problems. [6]



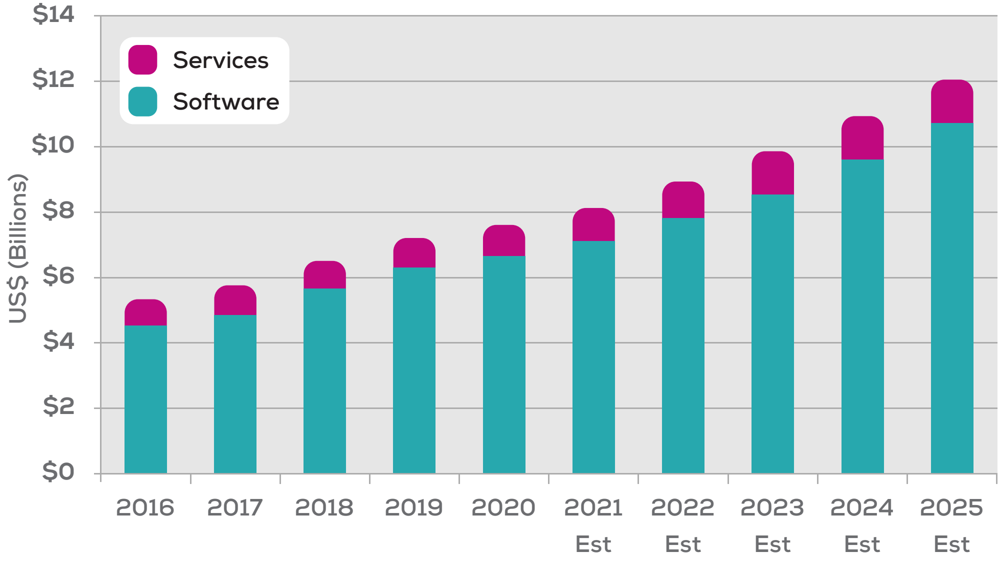

A RAT 700 analogue computer (left) simulating a car suspension system in the scope (right)

Source: Hobby - Das Magazin der Technik, issue 6, 1965

# Simulation and analysis market history and forecast

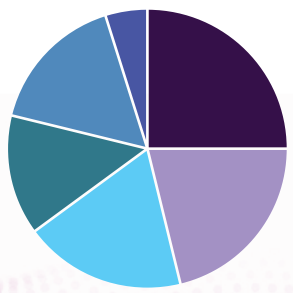
With digital computers becoming more powerful and cheaper, there is an increasing demand for engineering simulation and tools, with the global market for the simulation and analysis industry forecast to exceed $10 billion by 2024. [7] Analogue quantum simulation will be a very interesting addition to this growing field.

## CIMdata Publishes Simulation and Analysis Market Report. [7]




Source: www.cimdata.com

## Global simulation software market share, by end-use, 2020 (%)




Source: www.grandviewresearch.com

## Simulation

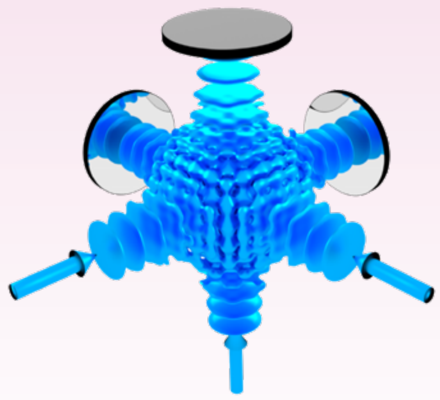


Image Credit: Ulrich Schneider

Simulators can help us to understand real-world behaviours that are too big, too small, too expensive, too far away or too dangerous to study directly. As this report shows, they are emerging as a key tool in areas that cannot be tackled using existing technologies, including natural quantum systems (e.g. in chemistry or particle physics) and similarly complex phenomena.

The advent of quantum simulators brings new tools for studying systems and quantum systems in particular, offering capabilities beyond the reach of classical computers. [8]

## Digital vs Analogue

"When we speak of an analog quantum simulator we mean a system with many qubits* whose dynamics resembles the dynamics of a model system we are trying to study and understand. In contrast, a digital quantum simulator is a gate-based universal quantum computer which can be used to simulate any physical system of interest when suitably programmed, and can also be used for other purposes.

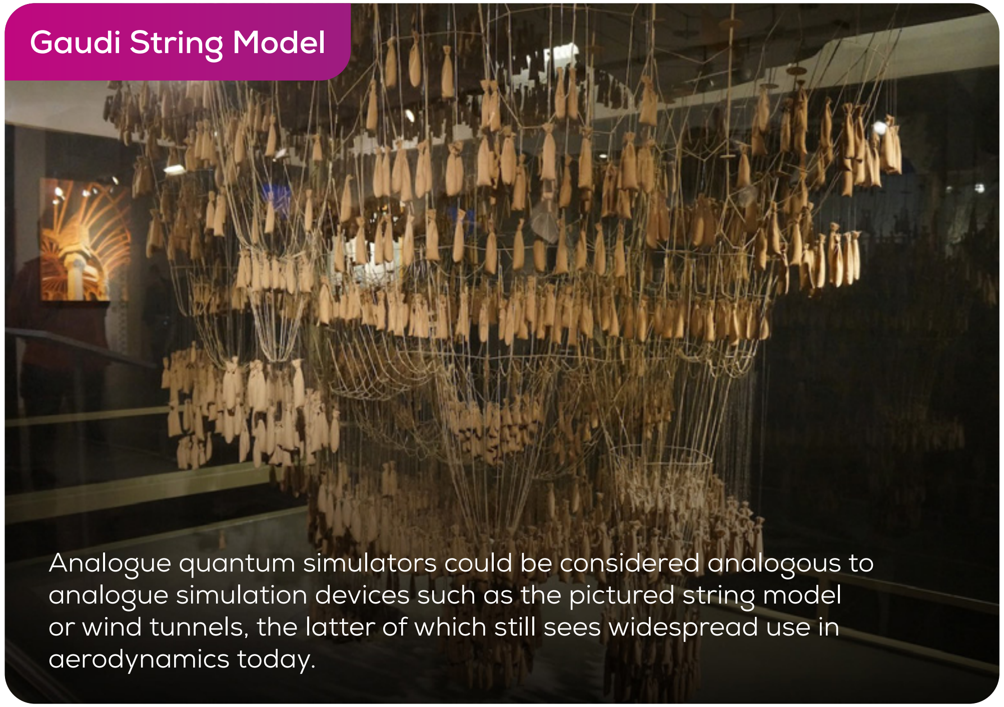
Analog quantum simulation has been a very vibrant area of research for the past 20 years while digital quantum simulation with general purpose circuit-based quantum computers is just now getting started."

John Preskill [8]

* A qubit is the most basic unit of information in QIT.

# Building analogue quantum simulators

## Gaudi String Model



Analogue quantum simulators could be considered analogous to analogue simulation devices such as the pictured string model or wind tunnels, the latter of which still sees widespread use in aerodynamics today.

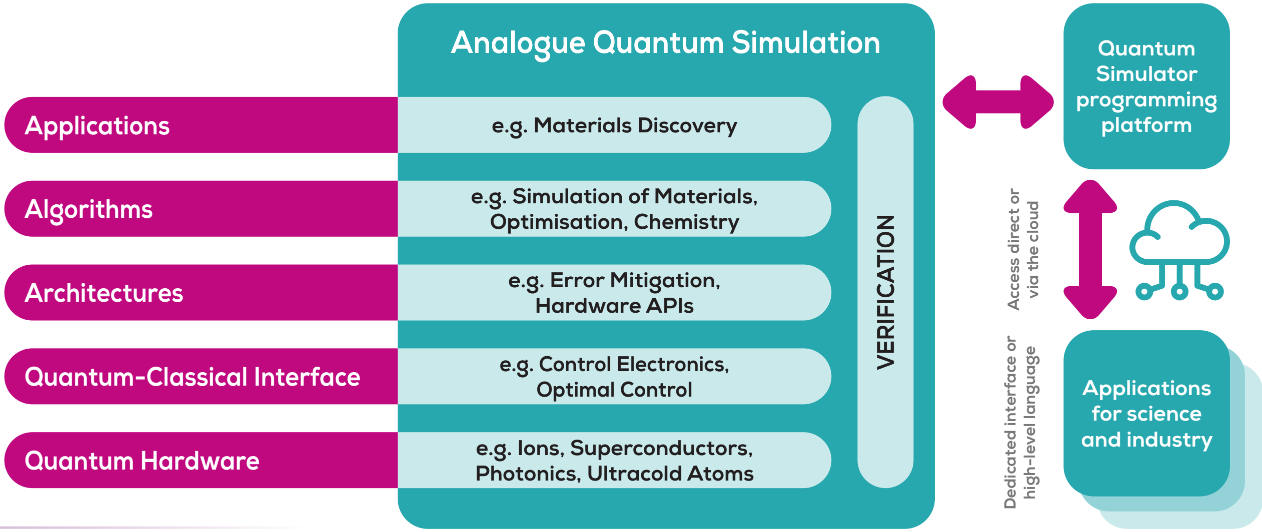
Image Credits: (Top) KK Clark / Blogspot • (Bottom) Memetician / Livejournal

| | |
|---|---|
| **Specialised devices** | Accelerate progress using real hardware dedicated to a particular class of problem. A 'family' of simulators can target related or different problems of interest. |
| **Performance** | Some problems that are intractable today can be addressed in a practical manner. For instance, it would take thousands of years to compute the equations of motion for 100 atoms on a classical computer, but could take seconds on a quantum simulator. [9] |
| **New frontiers in science and technology** | The potential to study complex quantum systems with ground-breaking tools will enable new discoveries, and transform our understanding of nature, with the potential to translate research innovation to benefit wider society. |
| **New tools for industry** | Analogue simulators can help industry address a variety of use cases in materials design, optimisation problems and chemistry. |
| **Skills and training** | Resources for quantum educators and the next generation quantum workforce. |
| **Fill a gap** | Alongside the so-called NISQ devices, quantum simulators can occupy the space between conventional supercomputers and universal fault-tolerant quantum computers, which may be many years away |

NISQ: Current digital quantum devices are error-prone, and typically limited in size to tens of qubits. We refer to the era as noisy intermediate-scale quantum, or NISQ.

# A System View

Various technologies may be used to build quantum simulators. Each approach requires a multidisciplinary effort to integrate hardware and software, possibly with cloud services potentially providing remote access to a range of global users.




**Right:** High-level system view of the components required for useful quantum simulators

There are other important considerations in the development of quantum simulators:

**Supply Chain**

Quantum simulators rely on a range of existing technologies in the supply chain, such as lasers, microwaves, electronics, vacuum systems and cryogenic refrigeration. [10] For high-performance devices, new technologies and methods will require development in areas such as lasers, optics, and chip fabrication.

**Investors**

Quantum simulators require significant investment to develop and this can be supported by "deep tech" investors who are excited by the potential applications and their benefits.

**Cloud Services**

Cloud services can provide access to a new set of tools and possibilities, without the investment and maintenance costs for users.

**Networks**

Quantum simulators as nodes, in a hybrid or fully quantum network, could form an important part of the overall solutions delivery for complex problems.

**Government**

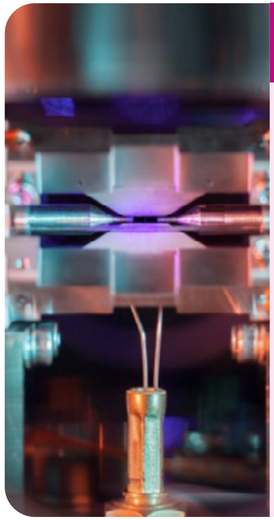
Governments play a crucial role to balance national interests, commerce and collaboration to foster innovation and growth, as well as fund dedicated programmes to accelerate progress.

**Skills**

It is important to develop and attract a highly-skilled workforce into the field of QIT. This relies on and benefits both educators and industry.

# Quantum Simulator Technologies

Quantum simulators share many of the same base technologies as quantum computers. These include ultracold (aka neutral) atoms, trapped ions, superconducting, and photonic systems. A comparison of these is shown below. Other candidate technologies include quantum dots and colour-centres in diamond, which are still relatively early in their development phase and are not included here.

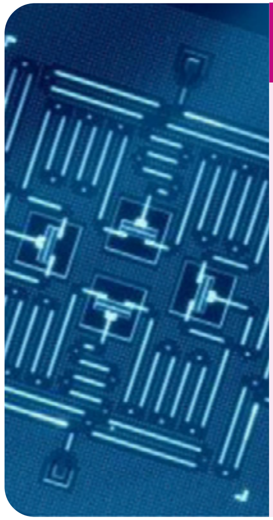


## Trapped Ions

### Charged particles trapped in electromagnetic fields.

Trapped ions (based on a chain of ionised atoms trapped in rotating electromagnetic fields) are heavily developed for digital quantum computing. Spins can be encoded on the internal electronic states, and controlled with laser light. Spin models with long-range interactions can be implemented directly, mediated by the collective motional modes of the system of trapped ions. In the last few years they have been used to study out of equilibrium dynamics, and to implement variational quantum eigensolver routines. The challenge is to scale this beyond ca. 50 ions in a single trap, either by working with 2D arrays of ions, or by generating electronic or photonic interconnects between traps

**Examples: IonQ, Quantinuum, Universal Quantum**

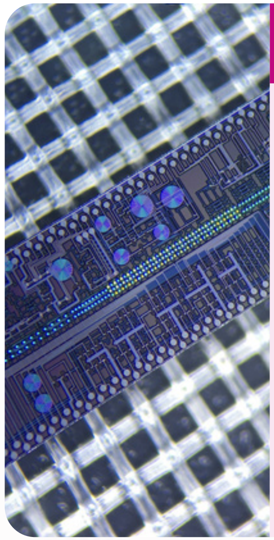


## Superconducting Circuits

### Superconducting electronic circuits.

Superconducting qubits are presently one of the most developed architectures for quantum computing, based on well-developed microwave technologies and micro- or nano-electronic circuits that are cooled to milliKelvin temperatures. For quantum simulation, these platforms can also be used to explore the dynamics in a variety of spin and bosonic models. Existing systems with around 100 qubits have been used to study advanced models of condensed matter physics, demonstrating the applications of these hardware platforms for fundamental science. The next stage of development will involve scaling to larger numbers of qubits while improving the local calibration of qubits.

**Examples: Google, IBM, Rigetti**

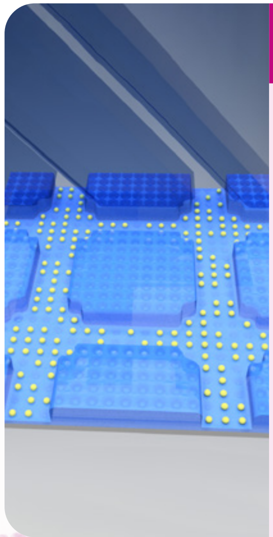


## Photonics

### Uses photons as information carriers.

Programmable photonic circuits are well suited to simulating so-called "bosonic" systems, such as vibrations in molecules. Quantum states of light such as ensembles of photons or squeezed states can be injected into miniaturised and interferometrically stable chips, made from silicon or other materials. Chip-scale reconfigurable systems with up to 18 photons have been demonstrated, within the limit of what can be simulated with classical computers. Larger scale systems of >100 photons with small levels of programmability have challenged the capabilities of supercomputers to simulate experiments at this scale. The next stage of development will include the introduction of programmability and error mitigation.

**Examples: Duality Quantum Photonics, Orca Computing, Photonic Inc, Xanadu**



## Ultracold Atoms

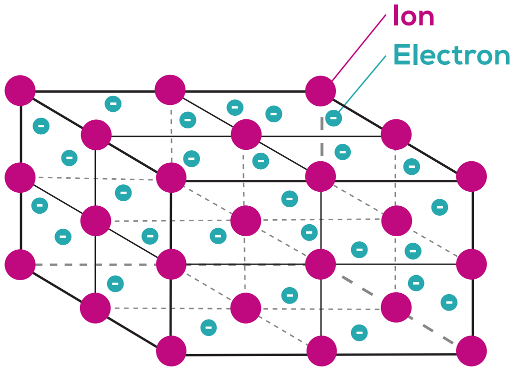
### Programmable lattices of cold atoms.

Ultracold atoms trapped in laser light can be used to build lattice models usually used to describe electrons moving in a solid crystal, with atoms moving in crystals of laser light (an "optical lattice"). Neutral atoms have the unique benefit that they can directly implement models for fermions (like electrons), and this has been applied to study problems in condensed matter physics in the past few years. The state of the art involves over 1000 atoms in a 2D lattice (or ca. 250 trapped in optical tweezers, implementing spin models through Rydberg excitations). Individual addressing has been realised in quantum gas microscopes, and the next steps will involve improvement of local calibration.

**Examples: Atom Computing, Pasqual, QuEra**

# Illustration of an optical lattice-based quantum simulator

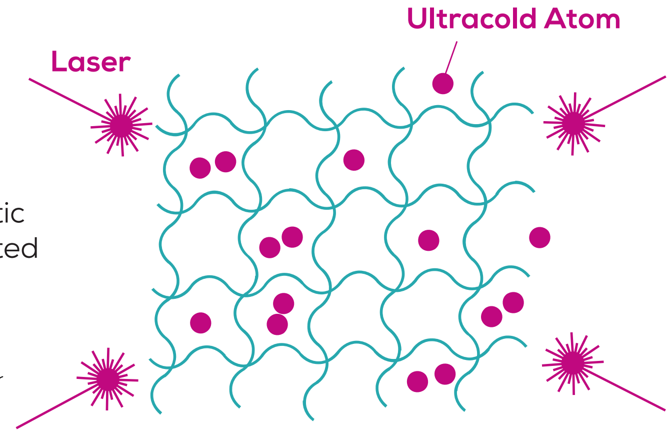
An overview of a cold atom-based quantum simulator is shown below.




**1** The rules by which electrons move in a material are often known. However, the dynamics are in many cases too complex to be classically simulated.

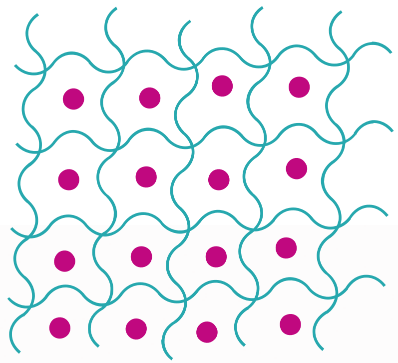
**2** In a quantum simulator, synthetic quantum systems are constructed that implement these rules.

$$\hat{H} = -\sum_{i,j} t_{i,j}\, \hat{a}_i \hat{a}_j^\dagger + \sum_i g_i\, \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$



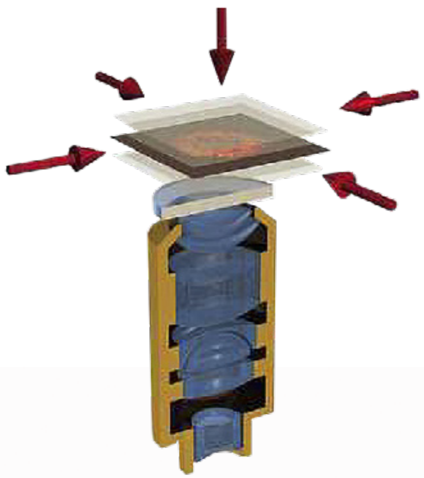

**3** In the interference pattern of laser beams ultra-cold atoms move not like the electrons in the crystal structure on the left. The rules – the Hamilton operator of the system – are set by the laboratory.

**4** Now one can gradually change the Hamiltonian into one whose ground state is not known.



**5** The atoms keep rearranging to find their lowest energy configuration – the unknown ground state.

**6** At the end, the position (or other properties) of the atoms can be imaged, thereby providing information about the state in question.



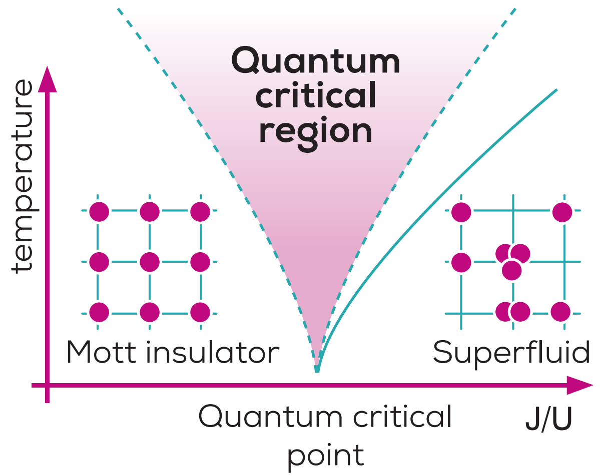
**Quantum-Gas Microscope.**
A Quantum gas microscope enables one to observe individual atoms with single-site spatial resolution.

Image Credit: CHIP magazine / Immanuel Bloch • https://tinyurl.com/chip-magazine

# The practical uses: applications

The range of applications for quantum simulators covers fundamental areas from science and metrology through to industrial processes. Examples in various categories are shown.

## Fundamental Physics




2-D Bose-Hubbard model

## Metrology

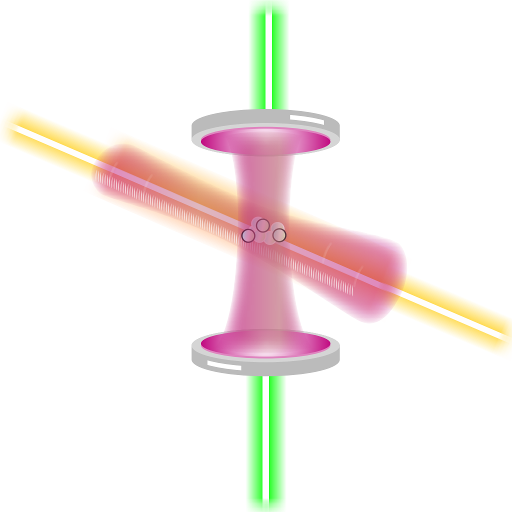
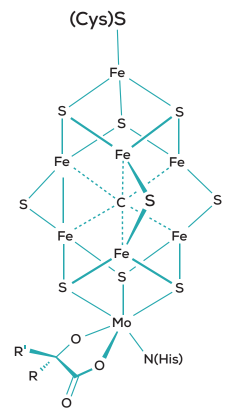


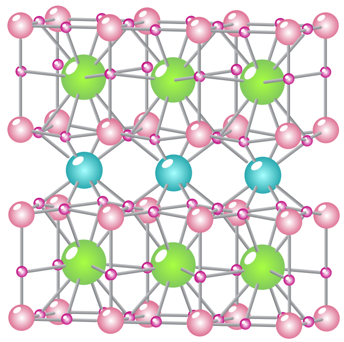
Illustration of an atomic clock

## Programmable Simulation

**Promising applications of quantum simulators**




Simulating **complex molecules** with possible applications in pharmaceuticals and battery chemistry



**Correlated Quantum** Materials with applications including high-temperature superconductors

## Categories of use cases

- Many-body physics
- Quantum phases
- Non-equilibrium dynamics
- Gravity
- Particle physics
- Cosmology

- Precision measurement
- Quantum sensing
- Next-generation clocks

- Materials science
- Optimisation problems
- Quantum chemistry

SPOTLIGHT

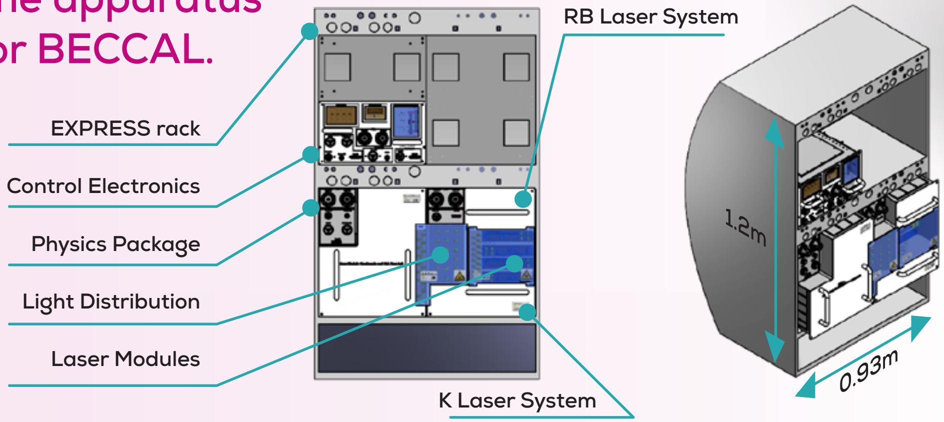
# Cold Atoms in Space – CAL and BECCAL.

In 2018, NASA launched "CAL", the Cold Atom Lab, to the International Space Station (ISS). CAL's purpose is to study quantum phenomena and future quantum sensors based on laser-cooled atoms of rubidium and potassium. [11]

In contrast to earth-based laboratories, the microgravity environment of the ISS enables longer observation times (over 10 seconds) and even cooler temperatures (< 100 pK is possible) making a wider range of experiments possible. [12]

The successor to CAL, called "BECCAL" – Bose-Einstein Condensates and Cold Atom Laboratory (Below), is being planned in collaboration with DLR, the German Aerospace Centre, to be launched in 2025. [13]

## The apparatus for BECCAL.




Source: https://arxiv.org/pdf/1912.04849


Nature cover from June 2020: Bose-Einstein Condensates created in orbit for the first time.

Read more here: https://coldatomlab.jpl.nasa.gov/news/nature-cover/

# Quantum simulator specialists

The majority of expertise in quantum simulation lies in university research groups world-wide, funded by government or through international collaboration, such as the EU Quantum Flagship*. This field is nascent but growing, and continued international cooperation is essential to accelerate innovation.

QUANTUM FLAGSHIP

The shoots of progress can be seen in the emergence of commercial entrants with a small user community. Some organisations have been given early-access to prototype devices, while others are actively exploring applications on more mature platforms that could give them a business advantage across a variety of industry sectors.

A research group, businesses and a large-scale project are highlighted on the next page to illustrate activities in the field.

* One of the largest and most ambitious research initiatives of the European Union, with a budget of at least €1 billion and a duration of 10 years. [14]

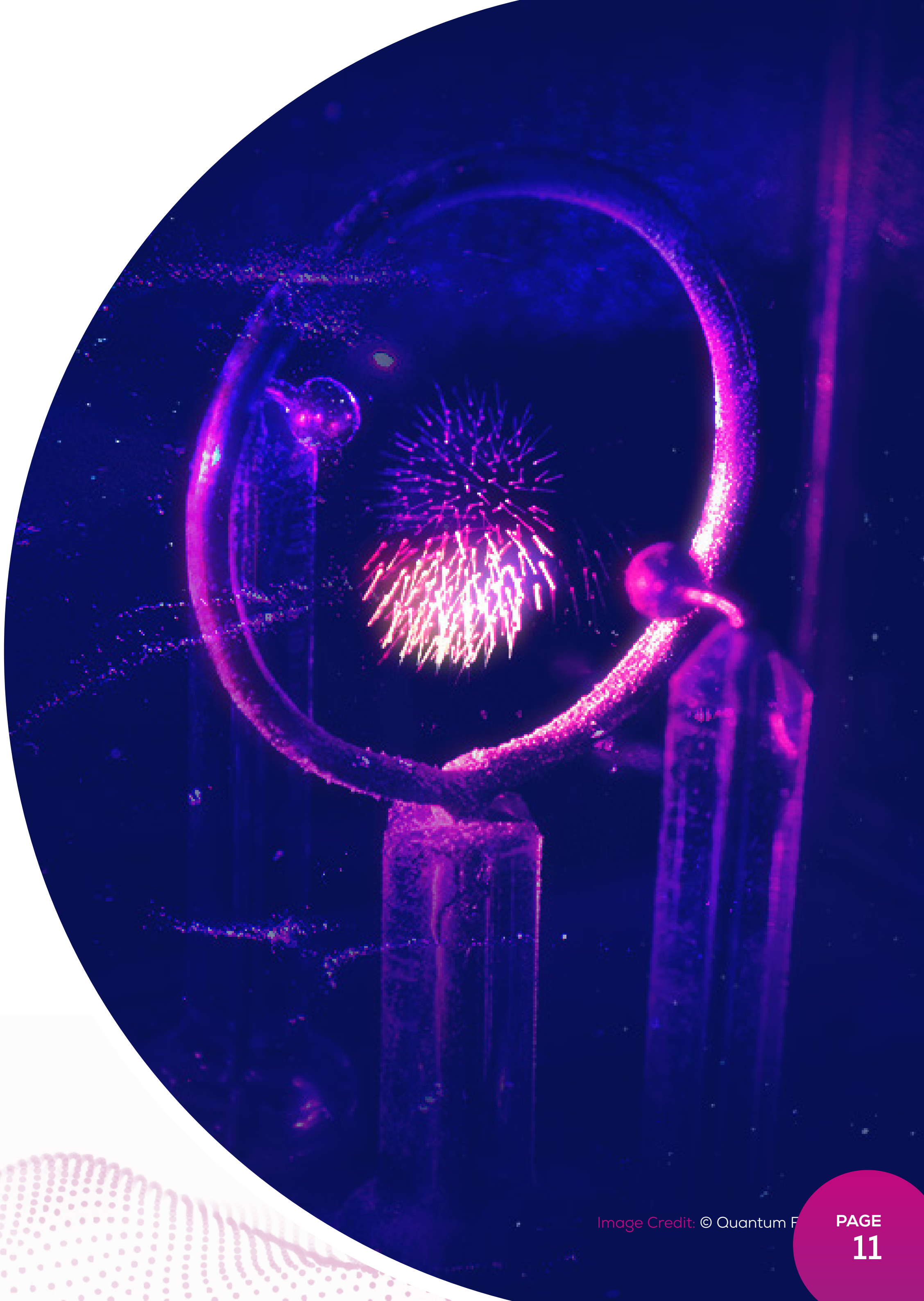


Image Credit: © Quantum F

SPOTLIGHT

## From 51 to 256 atoms in 3 years

rle.mit.edu

In 2017 a team led by the MIT-Harvard Center for Ultracold Atoms announced a 51 qubit neutral atom simulator to model interactions between certain atoms. [15]

Three years later this team demonstrated a substantial update – a programmable 256 atom simulator to explore quantum phases of matter. [16]

## PASQuanS – A €10m, multinational Flagship project

pasquans.eu

PASQuanS is an EU Quantum Flagship project, which ran from 1st October 2018 to 31st March 2022. 14 partners across 5 countries (Austria, France, Germany, Italy and the UK) collaborated to improve control methods and develop fully programmable simulators, with an ambition to scale from 20 to more than 1000 atoms or ions. [17]

## QuEra – Cloud access to a programmable simulator

quera.com

QuEra launched in 2019, with a team including leading researchers from the aforementioned 256 atom simulator. It exited stealth mode in 2021, with $17 million in funding, and is providing customers access to its neutral atom-based development machines with full-stack software. Its current analogue simulator has a specialized application in sampling probability distributions. [18]

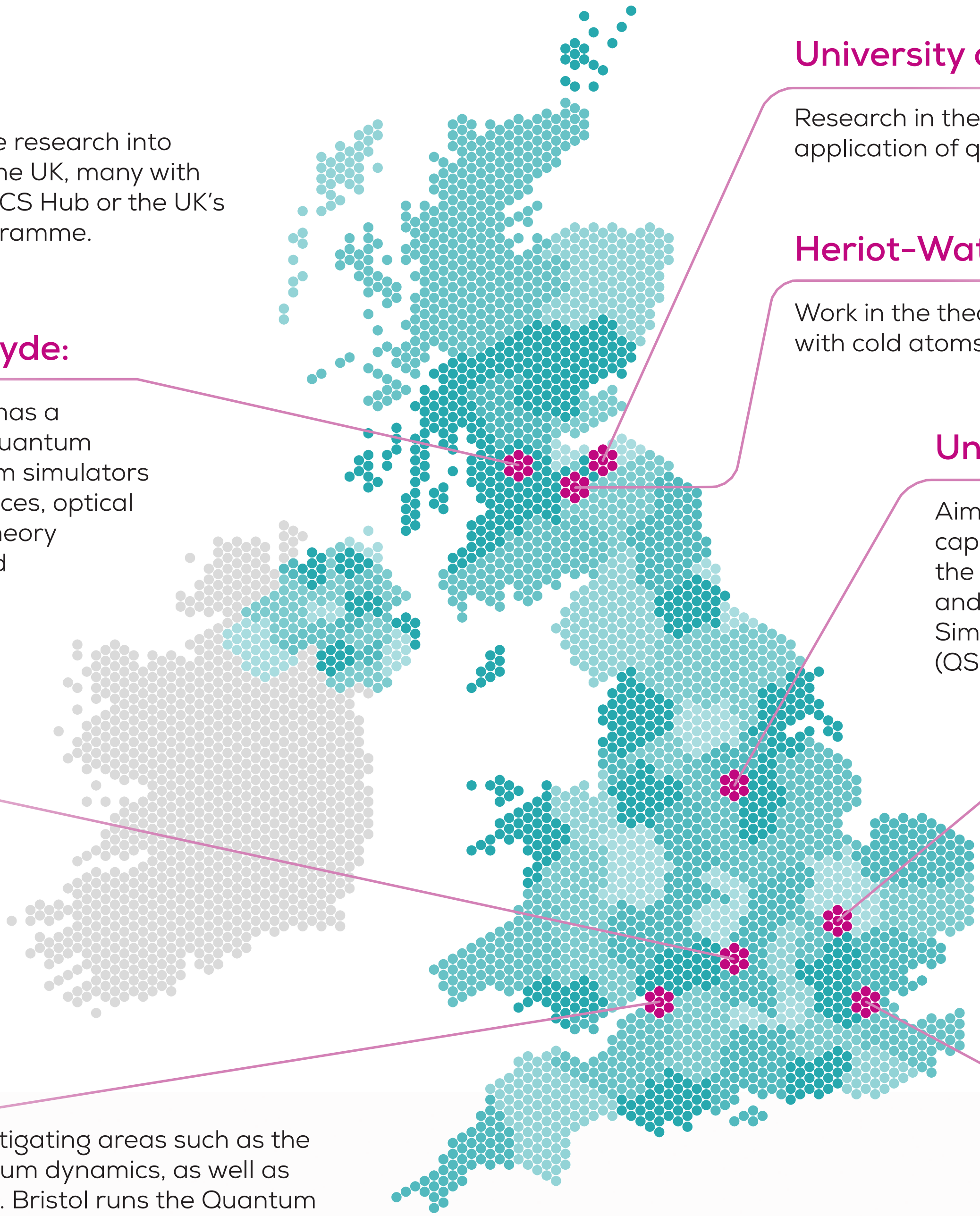
## Pasqal – 1000 qubits in 2023?

pasqal.io

PASQuanS is co-ordinated by Antoine Browaeys, who is also the co-founder and Chief Science Officer of Pasqal. Pasqal see quantum simulation as one of the most promising applications of their neutral atom technology [19] and, following their 2022 merger with Qu&Co, have announced a 1000 qubit quantum solution to be delivered in 2023. More information on Pasqal is available in the **Commercial Activities** Appendix.

# UK Activity

Below is a map showing some of the research into quantum simulators happening in the UK, many with direct involvement with either the QCS Hub or the UK's National Quantum Technology Programme.



## University of Edinburgh:

Research in the verification and application of quantum simulators.

## Heriot-Watt University:

Work in the theory of quantum simulation with cold atoms and photons.

## University of Strathclyde:

The University of Strathclyde has a large expertise in cold atom quantum simulation, with three quantum simulators with cold atoms in optical lattices, optical tweezer arrays, and a large theory programme on the design and application of quantum simulators.

## University of Nottingham:

Aiming to develop quantum simulators capable of providing insights into the physics of the very early universe and black holes. Part of the Quantum Simulator for Fundamental Physics (QSimFP) consortium.

## University of Oxford:

Work across quantum simulation, including with cold atoms, trapped ions and superconducting systems, in both theory and experiment.

## University of Cambridge:

Significant experimental programme in quantum simulation using cold atoms in optical lattices and in continuum (QSimFP), as well as color centers in diamond. Related theory of condensed matter systems.

## University of Bristol:

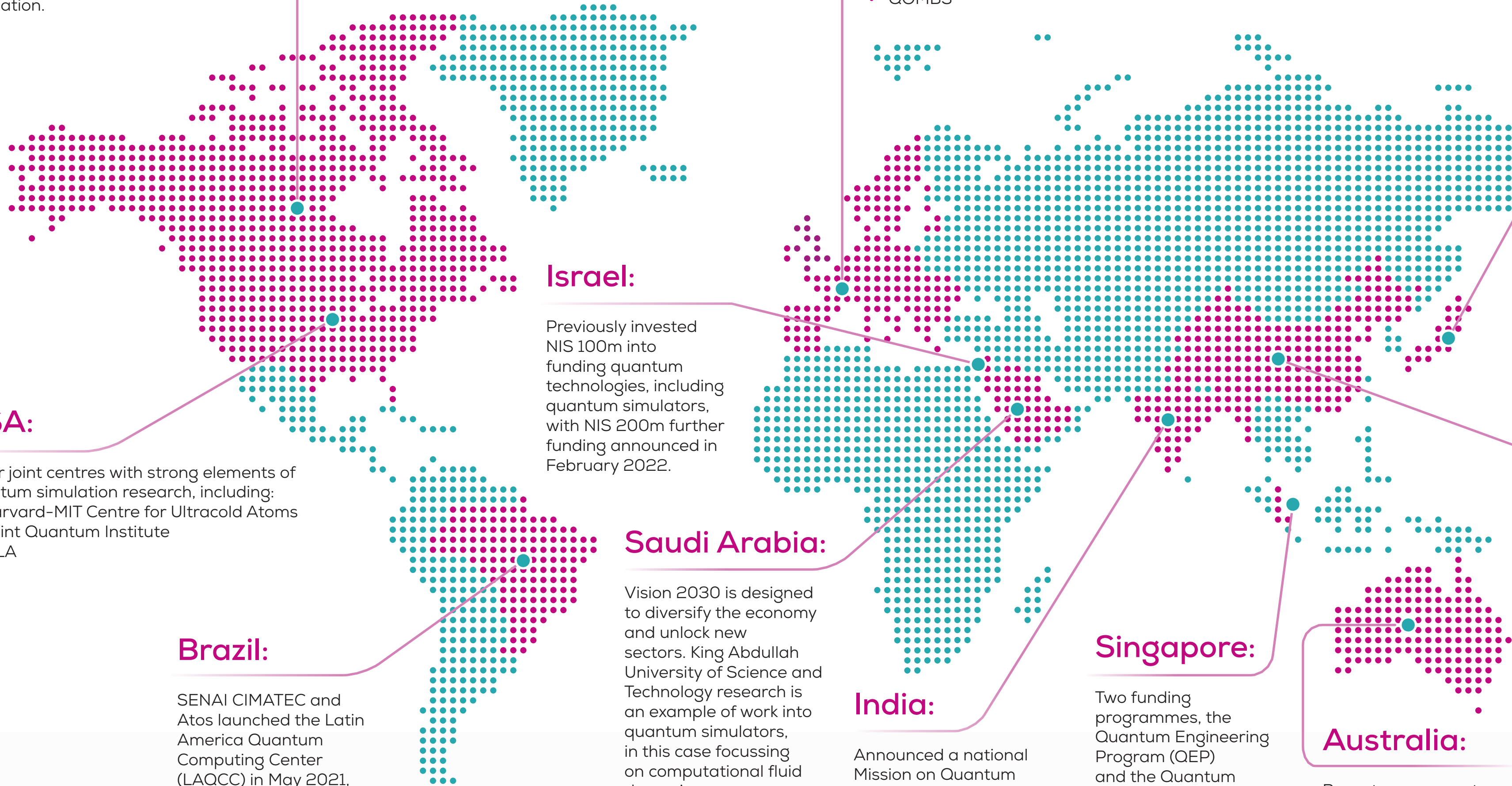
Specialises in photonics, investigating areas such as the simulation of molecular quantum dynamics, as well as theory of quantum simulators. Bristol runs the Quantum Engineering Technology Labs with over 100 academics, and has spun out Duality Quantum Photonics (see **Commercial Activities** appendix).

## London:

Several London-based universities are actively conducting research into quantum simulation including QCS Hub partners Imperial College and UCL, with the latter also setting up the QLABS innovation centre. King's College are a QSimFP partner.

# Research groups around the world

Below is a map showing some of the major national programmes and projects in quantum simulation around the world.



## Canada:

Launching a National Quantum Strategy. The Institute for Quantum Computing, based at the University of Waterloo, is active in trapped-ion-based quantum simulation.

## USA:

Major joint centres with strong elements of quantum simulation research, including:

- Harvard-MIT Centre for Ultracold Atoms
- Joint Quantum Institute
- JILA

## Brazil:

SENAI CIMATEC and Atos launched the Latin America Quantum Computing Center (LAQCC) in May 2021, hosting Atos's Quantum Learning Machine.

## Israel:

Previously invested NIS 100m into funding quantum technologies, including quantum simulators, with NIS 200m further funding announced in February 2022.

## Saudi Arabia:

Vision 2030 is designed to diversify the economy and unlock new sectors. King Abdullah University of Science and Technology research is an example of work into quantum simulators, in this case focussing on computational fluid dynamics.

## European Union:

The EU has strong capability in both theory and experiment, with major projects in the Quantum Simulation Pillar of the EU Quantum Technologies Flagship, namely:

- PASQuanS
- QOMBS

Major national programmes investing in quantum simulation **Austria** (Quantum Austria), **France** (Quantum Plan), **Germany** (Agenda Quantum Systems 2030), **Italy** (National Research Programme) and **Spain** (Quantum Spain).

## India:

Announced a national Mission on Quantum Technologies & Applications in 2020, with the Indian Institute of Science developing quantum simulators after previous funding from the earlier Quantum Enabled Science and Technology (QuEST) program.

## Singapore:

Two funding programmes, the Quantum Engineering Program (QEP) and the Quantum Technologies for Engineering Programme, with active research into quantum simulators notably taking place at the Centre for Quantum Technologies.

## Japan:

Q-LEAP (Quantum Leap) initiative launched in 2018, with quantum simulation and computation one of three key R&D areas. Research into simulators based on cold-atoms, trapped ions and photonics is happening at the National Institute of Informatics.

## China:

The latest five-year plan included quantum as one of the seven key technological development areas, with results in cold-atoms recently emerging from the University of Science and Technology of China.

## Australia:

Recent government investment with a focus on commercialising quantum technology, with active groups researching quantum simulations including:

- University of Queensland
- Australian National University

## New Zealand:

Strengths in photonics, with funding until 2028 for the Dodd-Walls Centre provided in summer 2021.

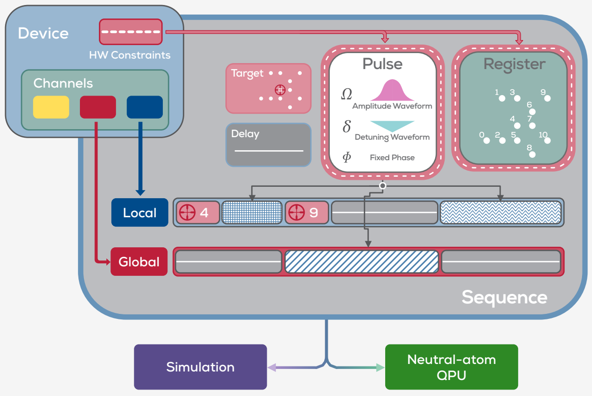
# Programming Quantum Simulators

The below examples illustrate the software which can be used when programming quantum simulators. There is not a hard boundary between quantum computing and simulation, and some of these will find application in both.

## Low-level Control Software

### Pulser from Pasqal

Pulser is an open-source software library (in Python) from Pasqal, a French startup developing neutral atom quantum technologies. Pulser facilitates the design and emulation of pulse sequences for neutral-atom quantum platforms, allowing for a range of tasks such as quantum-circuit programming and quantum simulation of many-body systems.

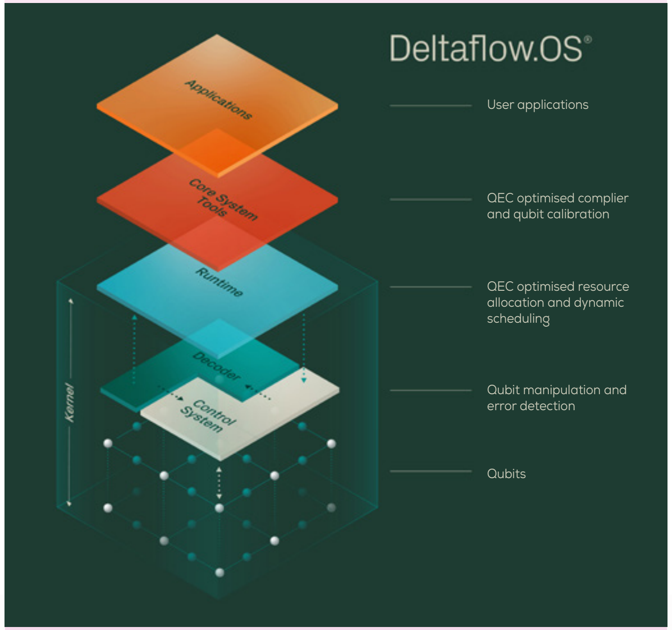



**Above:** Architecture of Pulser
Source:
https://arxiv.org/pdf/2104.15044

## Quantum Operating System

### Deltaflow.OS from Riverlane

Founded in 2016 in Cambridge, UK, quantum software company Riverlane is developing Deltaflow.OS, a quantum operating system for QIT devices.




**Above:** How Deltaflow.OS works.
Source: Riverlane
https://www.riverlane.com/products/

## High-level Programming

### Leap from D-Wave Systems

Launched in 2018, Leap is a quantum cloud service to access D-Wave's hybrid solver and QPUs (Quantum Processing Units) through an integrated development environment.


**Above:** Code sample
Source:
https://www.dwavesys.com/take-leap

# How can my business leverage quantum simulation?

Quantum simulation requires a different approach to the usual 'wait until it's ready' adoption pattern. This is because it takes time to understand the technology, identify its potential value and impact, and build the necessary skills and partnerships to become quantum ready. The QCS Hub is available to assist businesses with this journey.

## 1 Engage Early

It's essential to engage early in the development phase in order to:

- **learn** the new capabilities
- influence technological evolution
- identify potential applications
- **develop the know-how** to find solutions
- **exploit** first-mover advantage.

## 2 Get Access

Some quantum simulators are lab-based and dedicated for scientific experiments, while others are more commercially focused. In either case, **cloud access** is important to connect global users to the quantum simulator platforms and catalyse community building.

Working alongside **specialist providers** allows users to get ahead, with **early-access to new devices.**

## 3 Identify use cases

Certain problems are handled better by some simulators than others. It takes time to **understand what use-cases can be addressed**, how to efficiently map them to the device, and how to verify the solutions.

## 4 Determine the impacts

Assessing the **near, medium and long-term impacts** are important.

For instance, **how will it change the way you operate? What future skills** will be needed? How can innovation be accelerated to **deliver value?**

## 5 Develop a roadmap to solutions

Starting with simple problems and increasing **complexity over time,** allows you to create a roadmap that estimates the **'simulation power'** required and potential timelines to address them.

For instance, devices with tens of qubits today may evolve into devices with **hundreds of qubits in the near future.**

## Why invest?

New and emerging quantum simulators will support fundamental research in the laboratory, whilst commercial efforts are already producing early entrants into the market. Practical applications are imminent, with the capabilities of these devices applicable to fields outside of quantum – such as in logistics, whose total market value is estimated at circa $10 trillion. [20]

# Commercial Activities

There are a growing number of companies building quantum simulators for commercial exploitation. Some have been active for some time, others are very recent. A selection are shown below to illustrate activity in this field.

## ColdQuanta

coldquanta.com

**Founded 2007**

**2007** – Founded as a spin-off from the JILA Institute and Physics Department at the University of Colorado

**Jan 2018** – Announces the first commercial Bose-Einstein condensation system.

**May 2018** – ColdQuanta's QuantumCore is deployed aboard the International Space Station, as part of the Cold Atom Laboratory

**July 2018** – Raises $6.8m in a seed funding round led by Global Frontier Investments.

**Apr 2020** – US $7.4M DARPA award to develop a scalable, cold-atom-based quantum computing hardware and software platform.

**Aug 2020** – ColdQuanta selected as Industry Partner for US Department of Energy's Quantum Science Center, headquarters at Oak Ridge National Laboratory.

**Sep 2020** – £2.8M (US $3.5M) award to ColdQuanta UK to commercialise quantum technologies for quantum sensing using cold atoms.

**Sep 2020** – ColdQuanta joins steering committee of the US Quantum Economic Development Consortium (QED-C)

**Oct 2020** – ColdQuanta Announces Quantum Matter on the Cloud with the launch of Albert.

**July 2021** – ColdQuanta announces a successful trapping and addressing of 100 qubits in a large, dense 2-D cold atom array.

At a glance: Coldquanta is a spinout from the University of Colorado and develops quantum computers and quantum sensing technologies based on cold atoms. They offer a wide range of products and services, with a 100 qubit cloud-based quantum computer and high precision clock prototypes due to launch this year.

Total Investment raised:
US $71.6M over 5 rounds [21]

**Main office:** Boulder, Colorado, US.
Additional offices: Madison, Wisconsin (US) and Oxford (UK)

**Albert, an illustration of an early testbed**

## Duality Quantum Photonics

www.dualityqp.com

**Main office:** Bristol, UK

At a glance: Duality Quantum Photonics is a spinout from the University of Bristol, with a goal to design and fabricate photonic quantum processors that can simulate phenomena relevant to drug design in the pharmaceutical industry.

Total Investment raised: Undisclosed

**May 2020** – Partner in Riverlane led consortium to develop new quantum operating system, Deltaflow.OS. The project is funded by a £7.6M award from UK Research and Innovation.

**Nov 2020** – Partner in BT led consortium to trial end-to-end quantum secured encryption for 5G and connected cars. The 3-year trial is funded with £7.7M by UK Research and Innovation.

Commercialising Quantum Technology Large Collaborative Projects Round 1.pdf

**Mar 2021** – Connectorising Integrated Quantum Photonics Devices – a joint UK-Canada funded project with partners from both countries – kicked off, with a goal to develop efficient and robust fiber connections for integrated quantum photonic devices operating at low temperature.

**Sep 2021** – The Riverlane led consortium announce a new open-source hardware abstraction layer (HAL) that will enable users to write programs that will be interoperable with multiple kinds of quantum hardware.

## D-Wave — The Quantum Computing Company

www.dwavesys.com

At a glance: D-Wave develops quantum computing systems based on low-temperature superconducting technologies that operate using quantum annealing (in contrast to circuit-based quantum computers). In this technique, an energy 'landscape' of 'hills and valleys' is simulated where the lowest valley corresponds to the solution for a particular problem of interest. D-Wave holds 160+ patents, has published more than 100 peer-reviewed scientific papers.

**Main office:** Burnaby, Canada

Total Investment raised:

US $256.2M [22]

- **Founded 1999** — Haig Farris, Geordie Rose, Bob Wiens and Alexandre Zagoskin launch D-Wave
- **May 2011** — 128 qubit D-Wave One launched, described as the world's first commercially available quantum computer.
- **Aug 2012** — D-Wave One used by Harvard University to solve protein folding problem.
- **Oct 2018** — Leap™ quantum cloud service and Quantum Application Environment launched.
- **Sep 2020** — D-Wave launches it's 5,000+ qubit "Advantage" system
- **May 2020** — Pharma giant, GlaxoSmithKline, uses D-Wave Advantage on mRNA codon optimisation problem
- **Feb 2021** — Collaboration with Google demonstrates 3 million times speed-up of simulation of exotic magnetism (compared with classical approaches).
- **Apr 2021** — NEC Australia and D-Wave selected by the Australian Department of Defense on the "last mile resupply" problem.

## PASQAL

pasqal.io

At a glance: Pasqal is a spinout from the Institut d'Optique, France, building "quantum processing units" made of neutral atoms in large 2D and 3D arrays for computing and simulation of quantum systems. Their aim is to bring their processors to market, working in a hybrid scheme with supercomputers in France and Europe

**Main office:** Palaiseau, Ile-de-France, France

Total Investment raised:

$30.4m [23]

- **Founded 2019** — Pasqal founded by Georges-Olivier Reymond, Christophe Jurczak, Professor Dr. Alain Aspect, Dr. Antoine Browaeys and Dr. Thierry Lahaye
- **Apr 2020** — Partnership with Muquans (quantum sensing company) to accelerate development of Pasqal's processors.
- **Jun 2020** — 2-year collaboration with UK quantum start-up, Rahko, to advance quantum chemistry
- **Jul 2020** — Partnership with EDF to tackle smart charging challenges
- **Jul 2020** — Partnership with Cambridge Quantum Computing (CQC) to support Pasqal's quantum information processors on CQC's quantum software development platform
- **Oct 2020** — A 3-year collaboration with ParityQC to build the first fully parallelizable quantum computer
- **Nov 2020** — Partnership with Atos to develop a neutral atom 'quantum accelerator' for High-Performance Computing (HPC) systems
- **Dec 2020** — €7M award from European Commission EIC Accelerator program
- **Jan 2021** — Release of open source software "Pulser" to control neutral atoms-based processors at the level of laser pulses
- **Dec 2021** — Announcement of a collaboration with NVIDIA to build a Quantum Computing Center of Excellence
- **Jan 2022** — Merger with Qu&Co, a quantum algorithm and software developer, announced. The combined company will continue as Pasqal, and a 1000-qubit quantum solution in 2023 has been announced.

## INFINITY|Q⟩

www.infinityq.tech

At a glance: infinityQ Technology is a Canadian-based organisation focused on developing quantum analog computing solutions, targerting a range of industries including finance, pharmaceuticals, logistics and chemistry.

**Main office:** Montreal, Quebec, Canada

Total Investment raised:

$4.8M [24]

- **Founded 2020**
- **Mar 2020** — $1m raised in a pre-seed funding round, led by Investissement Quebec
- **Apr 2021** — infinityQ announces cloud access to infinityQube, its first-generation machine.
- **Apr 2021** — A further $3.8m raised in a seed funding round, led by Hevella Capital
- **May 2021** — infinityQ announces cooperation with Sofia Tech Park to install a quantum-analog computing module with the discoverer supercomputer

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