Institution: University of Oxford		
Unit of Assessment: 9: Physics		
Title of case study: Supporting the creation of a UK Quantum Industrial Revolution		
Period when the underpinning research was undertaken: 2001 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed:**
Dr Chris Ballance	Research Fellow	2015 – Present
Dr Joe Goodwin	Research Fellow	2016 – Present
Dr Thomas Harty	Research Fellow	2013 – 2019
Professor Dieter Jaksch	Professor of Physics	2003 – Present
Dr Steven Kolthammer	Research Fellow	2011 – 2017
Professor Axel Kuhn	Professor of Physics	2005 – Present
Dr Peter Leek	Lecturer in Physics	2011 – Present
Professor David Lucas	Professor of Physics	1998 – Present
Dr Joshua Nunn	Research Fellow	2009 – 2017
Professor Andrew Steane	Professor of Physics	1995 – Present
Professor Ian Walmsley	Professor of Physics	2001 – 01/09/2018
Period when the claimed impact occurred: 2017 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Research by Oxford Physics developing quantum technologies has supported the first steps of commercialisation of quantum computing in the UK. Industry engagement with our research has enabled businesses in the quantum computing supply chain to develop new products and our research has attracted substantial investment. We describe 10 companies that have benefitted from our research and four of our own spin-out companies that have licensed our patents and were employing over 40 people by December 2020. Together, our hardware, software and expertise has contributed significantly to a new technology industry in the UK.

2. Underpinning research (indicative maximum 500 words)

Key highlights, selected from across the span of underpinning research, range from high-precision quantum systems, to photonic networking technologies, to quantum algorithms needed to enable a practical quantum computer to be built and programmed, include: ion traps (Ion Trap group – Ballance, Goodwin, Harty, Lucas, Steane) and superconducting circuits (Leek) which form the quantum bits (qubits) performing quantum calculations; atom-photon interfaces (Kuhn) and photonics (Kolthammer, Nunn, Walmsley) which enable the readout, manipulation and storage of outputs of quantum calculations; and algorithms, including hybrid quantum-classical algorithms (Jaksch).

Lucas and Steane of the Ion Trap group performed the UK's first (and world's third) two-qubit quantum logic gate in 2005, and the group have delivered a steady stream of records for qubit performance across all platforms, including the world's highest fidelity single-qubit (99.9999%, 2014) **[1]** and two-qubit gates including laser-driven (99.9%, 2015), microwave-driven (99.7%, 2016), and mixed-species gates (99.8%, 2015), as well as the first demonstrations of sub-microsecond trapped-ion entangling gates (480ns, 2017) and part-per-million qubit memory errors (2019). The group also led the work on an elementary quantum network demonstrating photon-mediated entanglement between physically remote qubits at a combination of rate and fidelity ($182s^{-1}$, 94%, 2019) **[2],** far higher than previously achieved for any platform.

Leek moved from ETH Zurich in 2011 to found a research group in Oxford Physics on superconducting quantum circuits. Leek invented (2015) and his group developed a 3D coaxial circuit architecture **[3]** designed to simplify the task of scaling highly coherent circuits to the many qubits needed for useful computing. The group has since demonstrated state-of-the-art quantum coherence and quantum logic gates.

Walmsley's ultrafast quantum optics group in Oxford Physics (2001 - 2018) pioneered work covering the three pillars of experimental quantum-optics research: quantum-state engineering, state manipulation, and the detection of quantum states of light. Notable achievements include novel detection schemes using optical fibres to resolve photon number (2003), the design of heralded sources of pure quantum photonic states (2008), photonic quantum-computing demonstrators including one of the first demonstrations of boson sampling (2013), the introduction of new off-resonant techniques for atomic-vapour quantum memories (2010, 2018) **[4]** and an ultrafast optical quantum random number generator (QRNG) that uses a totally untrusted photonic source.

Jaksch's Quantum Systems Engineering group investigates the dynamics of many-body quantum systems and their applications in quantum technologies and has made several significant contributions towards the development of quantum-classical hybrid algorithms for solving real-world problems, e.g. a scheme for quantum-classical dynamical mean-field theory calculations (2016). They subsequently determined the minimal hardware requirements of this scheme via numerical emulations (2020), predicting that it can be run on next-generation noisy intermediate-scale quantum devices. A key result **[5]** shows how variational quantum computing can be extended to solve nonlinear problems and partial differential equations, which are ubiquitous in science and engineering.

Kuhn's group focuses on the development and exploration of coherent control methods to interface matter and light in high-Q cavities at the single-particle level, with emphasis on quantum networking and entanglement distribution. This work has been very influential and now represents textbook knowledge **[6]**, widely adopted in numerous other fields as a key enabling technology. Results include deterministic entanglement of a single atom's spin with the polarisation of a single photon, control schemes to command atom-photon coupling in cavities, and the encoding of quantum bits within the temporal envelope of a photon. This culminated in demonstrating quantum gate operations, photon-photon entanglement and cluster state distribution across hybrid quantum networks in a collaboration with Bristol (2020).

3. References to the research (all journal articles unless stated)

1. High-fidelity preparation, gates, memory and readout of a trapped-ion quantum bit T. P. Harty, C. J. Ballance, D. M. Lucas et al. Phys. Rev. Lett., Vol. 113, Issue 22, pp. 220501 (2014) https://doi.org/10.1103/PhysRevLett.113.220501
2. High-Rate, High-Fidelity Entanglement of Qubits Across an Elementary Quantum Network. J. F. Goodwin, D. M. Lucas, and C. J. Balance et al. Phys. Rev. Lett. Vol. 124, 110501 (2020) https://doi.org/10.1103/PhysRevLett.124.110501
3. P Leek (2015). Quantum information processing system. Patent WO2017021714A1
4. High-speed noise-free optical quantum memory J. Nunn, I. A. Walmsley et al. Phys. Rev. A, 97, 042316 (2018) https://doi.org/10.1103/PhysRevA.97.042316
5. P. Moinier, D. Jaksch et al, Variational Quantum Algorithms for Nonlinear Problems, Phys. Rev. A 101, 010301(R) (2020). https://doi.org/10.1103/PhysRevA.101.010301
6. Cavity induced interfacing of atoms and light, Chapter 1 of Engineering the atom-photon interaction, Eds Predojevic and Mitchell, Springer 2015, ISBN 9783319192307, supplied on request (book chapter)

4. Details of the impact (indicative maximum 750 words)

Quantum technologies utilise the unique phenomena of quantum superposition and entanglement to encode and process information, with potentially profound benefits to a wide range of information technologies from communications to sensing and computing. Technologies required to build these devices have been developed by Oxford Physics and commercialised through collaboration with industrial partners.

Commercialisation of Ion Trap technology: The Ion Trap group's reputation for setting benchmarks across a wide range of qubit performance metrics has helped cement them as the go-to academic partner for many commercial enterprises in the sector. Within the UK, a collaboration with Gooch&Housego (a company with a Market Cap of USD254,000,000) led to the development of a commercial high-power UV fibre-coupled acousto-optic modulator system. Collaboration with M Squared Lasers (a company that employs 98 people) helped develop a frequency-doubled phase-locked TiSapph Raman laser system, sold to leading quantum-computing groups and businesses worldwide. M Squared Lasers CEO said: *"The [Ion Trap] group's world-leading demonstrations of ion-based quantum gates and devices offers exciting prospects for the commercialisation of quantum computing hardware... This is shown clearly through our joint work on the development of the ground-breaking phase-locked laser system to drive Raman transitions in Ca+ ions that was then developed into a product used* *globally amongst the leading cold matter-based quantum computing companies."* He further highlighted their collaborative work "*to deliver a ground-breaking phase-locked laser system to drive Raman transitions in Ca+ ions. In addition, integrated system developments, building upon this hardware and expertise, which have seen the UK's first commercial demonstrations of field-tested cold atom sensors and a variety of emerging laser and peripheral systems for quantum computing platforms"* **[A]**. The group has also collaborated with start-up VeriQloud (a company that employs 8 people) to provide web connectivity to an ion-trap-based 'quantum server' via a secure quantum network, effectively setting the foundations for cloud-based quantum computing. VeriQloud's CEO said: "*The ion trap technology developed at the physics department of Oxford is probably the best candidate to combine scalability and connectivity in the world… This makes Oxford's technology very suitable for a testbed of client-server quantum communication… this collaboration has allowed us to improve greatly our understanding of the networking of quantum computers…Since VeriQloud's development are mostly on the software side, it is crucial to have access to real hardware for testing and integrating « real-world constraints » to our designs. Getting access to Oxford's quantum computer was a real chance for us, and allowed us to get a much better picture of the horizon we are looking at: quantum cloud computing and the quantum internet"* **[B]**. The group's results have set the stage for much larger networked quantum computers with thousands of ion-trap nodes, demanding ever-closer integration and miniaturisation of the components. The ion trap work led to numerous collaborations, including two projects with ColdQuanta UK (CQUK, a company that employs 50 people): to develop optically-heated atomic sources and to greatly simplify in-vacuum component assembly for ion-trap systems. ColdQuanta, Inc., the US-based parent company of CQUK, manufactures components and systems for a broad range of quantum technology applications. The company chose Oxford as its UK base in 2017 to better facilitate engagement with the UK's quantum technology programme, and particularly the research of the Lucas group, from which it hired a postdoc to be Lead Scientist. The Chief Technology Officer of ColdQuanta Inc. said: "*Our collaboration with Oxford physicists and engineers to develop miniaturized ion trap systems gave us early traction toward establishing a significant commercial as well as government R&D activity in the UK. Given the nature of our work, as well as our aspirations to be an international leader in quantum, there is simply no place better for us to be housed than within the wings of Oxford University. We are growing, thanks in no small way to the high-caliber efforts of the Oxford team and our relationship with the University"* [**C**]. Furthermore, the group's work with Swiss manufacturer FEMTOprint (a company that employs 16 people) to provide 3D glass microfabrication services for ion-trap system development yielded significant benefits for the company. FEMTOprint's CEO said: *"Working with you and your team in the Oxford Ion Trap Quantum Computing group has benefitted the company by increasing our understanding of the current and future needs of the quantum technology sector. Moreover, the interactions with your group, with cutting edge knowledge in this field, have helped us develop a production line for off-the-shelf ion traps for academic and industrial quantum computing research"* **[D].** In 2019, the Ion Trap group founded Oxford Ionics (OI) to commercialise their unique electronically-controlled trapped-ion technology and to build a cloud-based platform offering high-performance quantum computing as a service to customers in sectors ranging from pharmaceuticals to defence. OI has quickly grown to 10 employees (headcount: 10) and had raised GBP5,000,000 by December 2020. OI's CEO comments that: *"Oxford Physics played a key role in enabling this success. Our technology builds on the ion trap research conducted in the Department. Amongst other achievements, this research set the world record for the lowest error rates in all key quantum operations. These low error rates are critical to Oxford Ionics' mission to build a commercial platform to solve real-world problems. We currently have a collaborative research project in the Department developing a supply chain for advanced ion traps as well as a rapid turn-around test facility for those traps. This project provides an ideal environment for bi-directional skills transfer and allows us to de-risk our technology without huge capital investment and setup costs"* **[E]**. OI has since collaborated with the Ion Trap group and Riverlane, a company that develops operating systems for quantum computing, which saw a successful trial of a universal quantum operating system on one of the group's ion trap processors. *"It's a technical breakthrough but there's also an enormous commercial breakthrough,"* commented the UKRI Challenge Director for Quantum Technologies **[F]**.

Commercialisation of Superconducting Circuit design: In 2017 Leek founded the spinout Oxford Quantum Circuits (OQC), which employed 20 people (headcount: 20) by December 2020, raised substantial private investment and has developed the first commercial qubits in the UK. OQC utilises the coaxmon patented IP **[3]**, a novel qubit that enables flexible, scalable quantum computers based on simple superconducting circuits, and continues to sponsor research at Oxford Physics. OQC's CEO said: "*Dr Peter Leek and his research group met all the initial research agreement goals and have successfully showcased this core technology development from concept to a highly competitive quantum computer - arguably the most advanced in Europe. The relationship with Dr Peter Leek and the University of Oxford serves as an excellent talent pipeline, both directly from Dr Peter Leek's research group, as well as opening up a wider network to OQC with candidates attracted to OQC by reputation. It is without a doubt that the reputation of Oxford University, the core IP and Dr Peter Leek's academic reputation helped enable this*" **[G]**. Leek and OQC have collaborated with Riverlane (a company that employs 23 people) to develop software for chemical simulation. Riverlane's CEO said: "*Dr Leek's research has had two key impacts on the development of Riverlane, both as a company and on our operating system product, Deltaflow. These are: 1. Improvements to the performance of quantum hardware where Dr Leek has continued to reduce two-qubit error rates – the key performance indicator in quantum computers. Moreover he has been able to achieve this in a system architecture that is inherently scalable through the development of the coaxmon qubit. Taken together these accelerate the development of quantum computers as commercial products. 2. Providing a deep understanding of the underlying quantum hardware, the physics of superconducting systems and the control electronics that are used to perform operations on the system function. This deep insight from a leading quantum computing lab enabled us to understand what it would take from a product perspective to build an OS for a superconducting system and how early applications might be best mapped on to the hardware. The published research conducted by Dr Leek and his group has been instrumental in our decision as a company to focus on building an operating system for quantum computers. The effect of that decision has already been felt strongly in the company and resulted in significant shareholder value"* **[H].** Leek has also collaborated with Cambridge Quantum Computing (CQC, a company that employs over 70 people), which develops architecture-agnostic quantum computing software for industry. CQC's General Counsel said: *"CQC's interactions with OQC and Leek Lab has had a significant impact on CQC's expertise in this field of experimental quantum computing… the collaboration has assisted in strengthening CQC's expertise on superconducting circuit computers and qubit routing… It is precisely this type of collaboration that promotes technological credibility in the field. CQC has been able to raise investments from US Fortune 100 multinationals such as IBM and Honeywell... CQC attests to the substantial research impact brought about by Leek Lab and the University of Oxford's Physics Department. Our collaboration with Leek Lab and the University demonstrates the true value of high-quality collaboration between academia and industry and its indispensable impact on the advancements in the field of quantum computing research, which ultimately places the United Kingdom at the forefront of the global quantum effort"* **[I]**.

Commercialisation of Quantum Optics: In 2019 ORCA Computing (ORCA) was spun out of Oxford based on Walmsley and Nunn's propriety quantum memory technology (licensing 2 patents), with the aim to build a quantum computer using off the shelf optical fibre technology, allowing greater scalability and flexibility at a lower cost. ORCA's CEO said: "*Despite being in the middle of the COVID crisis ORCA has grown from 2 employees to more than 12 [headcount: 12] within 1 year… the company has secured £1.4m [GBP1,400,000] of Venture capital funding, and has won 4 Innovate UK projects… As a research and manufacturing company, ORCA also supports a large, high tech supply chain, which supports further high skilled jobs and R&D investment throughout the supply chain. Our UK supply chain partners include [photonics SMEs]: Covesion LTD [Southampton], Laser 2000 LTD [Huntingdon] and Caledonian Photonics [Scotland]. It is fair to say that ORCA would not exist if it were not for research undertaken and support provided by the university of Oxford…Through our relationship, we are able to build a world-leading computing company that takes university research and skilled people, and translates them into high-tech jobs, a supply chain and a technology ecosystem that will support the UK economy and society for many decades into the future"* **[J].** Their quick success has been recognised with the Institute of Physics start-up of the year award 2020. The company Quantum Dice, based on Kolthammer and Walmsley research on self-certified Quantum Random-Number Generators (QRNG), was spun out in 2019. QRNGs are an important enabling technology in classical encryption hardware, communications security and stochastic modelling; they generate cryptographically secure random numbers in a wide range of commercial settings. Quantum Dice's CEO said: "*Beyond the licensing agreement, support from researchers and technology transfer officers at the physics department has been crucial to the success of the Quantum Dice….They have also provided crucial support during our early R&D development helping us formulate the optimal plan to take this innovative technology from the lab to the customer"* **[K]**.

Quantum software development with industry: The Jaksch group collaborated with BAE Systems **[5]** to develop hybrid quantum-classical software to solve Computational Fluid Dynamics problems, demonstrating the feasibility of the approach on the IBM Quantum Computer. The Lead Engineer at BAE Systems said, "*Their expertise and skills have allowed us to develop leading edge solutions to a problem no-one had managed to solve. This collaboration has been pivotal to better understand the potential impact of Quantum Computing and aspects of the technology itself. BAE Systems views on-going research work in the development of quantum algorithms as potentially critical to the development of future discriminative high-performance airframes, and capabilities in general. Dieter [Jaksch] and his team are part of this vision"* **[L]**. In 2018, Oxford entered into an agreement with IBM Q to work jointly on quantum readiness, which enabled companies such as Rolls Royce, Barclays and Johnson Matthey to explore IBM's quantum-computing systems supported by Oxford's researchers. IBM's Distinguished Engineer and Master Inventor stated that IBM "*views [Jaksch's] research with the University of Oxford to improve [our] Qiskit open source software platform as very important in the advancement of quantum computing to the point where it can be of benefit to the scientific and developer communities*" **[M].**

Quantum-enhanced sensing with industry: The Kuhn group's proven expertise with cavity-enhanced Raman processes developed for quantum networking has provided the basis for the application of such techniques to more diverse fields. In 2017 the group collaborated with VeriVin (a company that employs 7 people) to develop quantum-enhanced sensing to detect chemical trace compounds in complex liquids in sealed transparent containers. The technique exploits the superposition of molecular quantum states and the quantum states of the radiation field inside an optical cavity in a Raman-type process to selectively detect compounds at the single-particle level. VeriVin's CEO said: "*Collaboration with Axel [Kuhn] was instrumental in getting VeriVin off the ground...Collaboration with Axel was instrumental in us attracting investment and more importantly, the Innovate UK grant funding that eventually got us off the ground...Axel agreed to pursue a collaborative project funded by Innovate UK with me to explore how certain quantum techniques used in his research could be used to enhance the faint spectroscopic signal we were grappling with. I stress that without these 18 months of Innovate UK funded work (and I refer here not just to the money but to the structure and brain power it provided), VeriVin would not be where it is today"* **[N]**. This collaboration enabled VeriVin to raise investment to develop a new device that is capable of generating a molecular fingerprint of beverages, such as wine and beer, without opening the bottle. This success was recognised with the Institute of Physics start-up of the year award 2019.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Letter from M Squared Lasers; **[B]** Letter from CEO of VeriQloud; **[C]** Letter from CTO of ColdQuanta Inc.; **[D]** Letter from CEO of FEMTOprint; **[E]** Letter from CEO of Oxford Ionics **[F]** Financial Times article on Riverlane, quoting UKRI Challenge Director for Quantum Technologies; **[G]** Letter from CEO of Oxford Quantum Circuits; **[H]** Letter from Riverlane; **[I]** Letter from General Counsel, Cambridge Quantum Computing; **[J]** Letter from CEO of ORCA Computing; **[K]** Letter from CEO of Quantum Dice; **[L]** Email from Lead Engineer, BAE Systems; **[M]** Quote from Distinguished Engineer and Master Inventor at IBM **[N]**; Letter from Founder and CEO, VeriVin