Institution: University of Sussex

Unit of Assessment: 9 – Physics

Title of case study: Impact of Sussex research on enhancing public interest, awareness and commercial investment in the development of practical quantum computers

Period when the underpinning research was undertaken: 2007 – 2017

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Winfried Hensinger	Professor	2005 – present
Sebastian Weidt	Lecturer	2013 – present

Period when the claimed impact occurred: 2013 – 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Research at Sussex, demonstrating that it is possible to build practical quantum computers, has underpinned extensive public and media engagement work to increase public and industry understanding of – and confidence in – this new technology and its potential. Through award-winning installations and interactive exhibitions, broadcast and news coverage, public lectures and art collaborations (including documentary filmmaking and musical composition), Hensinger's research has reached vast and diverse audiences of many millions, creating and catering to the public's increasing appetite to learn about, and get involved with, the future of quantum computing. It has been successful in generating awareness and understanding, as evidenced by a range of outcomes and indicators (including audience feedback, testimonies and awards). The work has generated measurable economic prosperity, for example private investment of GBP4,800,000 resulting in the formation of successful spinout company Universal Quantum. The company develops practical quantum computers using Sussex research and has already created [text removed for publication] jobs in its first year while also influencing investor behaviour and regional planning.

2. Underpinning research

Practical quantum computers have been described as one of the holy grails of science due to their disruptive capabilities across a wide range of sectors such as finance, drug discovery, and breaking encryptions to name a few. Yet the challenge to build such a machine has been viewed as vast, and possibly insurmountable.

Trapped ions have been considered as one of the most promising hardware platforms to build practical machines. However, practical quantum computers, capable of solving the most interesting problems, would require millions of qubits. While trapped ion systems have been viewed as promising because of the ability to implement the required quantum operations with small errors, the actual scalability of the platform had been questioned. Traditionally trapped ion quantum computing makes use of laser beams to execute quantum gates where the number of laser beams required scales with the number of qubits (ions) used in the quantum computer. While this is easily achievable with tens or hundreds of quantum bits, it is very difficult to imagine building a quantum computer with millions or billions of quantum bits where millions or billions of pairs of laser beams would need to be aligned with an accuracy of 10μm. Research at Sussex focussed on developing an alternative solution, namely to use global microwave fields (instead of laser beams) for quantum gate execution, therefore avoiding having to align millions or even billions of laser beams in a practical quantum computer (R2, R4, R5). Instead of using laser beams for quantum gate execution, their approach makes use of proven microwave technology. Quantum gates are executed by applying semi-static voltages to a microchip in a manner very similar in nature to the operation of classical transistors (R5).

Another challenge for building a trapped ion quantum computer is the proposed architecture for such a machine. Early ion traps were constructed from metal rods. A practical quantum computer would require millions of trapping zones, so it is inconceivable a quantum computer could be constructed in this way. A much more suitable approach consists of silicon microchips as a fully scalable architecture. The Sussex group made significant breakthroughs in the practical realisation and operation of such an ion microchip (R1, R3). This includes the creation of a chip allowing the application of the largest voltage applied to an ion microchip allowing for very deep trapping potentials capable of holding ions for extended periods of time, giving confidence in the use of such chips for the operation of a quantum computer (R3).

Any practical quantum computer would require a modular architecture since it would likely be impossible to fit sufficiently many qubits onto a single module. A known approach for modularity consisted of connecting modules via a technique referred to as photonic interconnects. However, even after 15 years of development, the connection speed is extremely slow while the required engineering is very difficult. The Sussex group invented a new approach to modularity, where electric field links between modules are used to allow for ion transport, giving rise to orders of magnitude improvement in connection speed while dramatically reducing the engineering difficulty required for implementation (R6).

In 2017, Hensinger led an international team consisting of scientists from Google, Aarhus University, Riken and Siegen University in publishing the world's first blueprint for a Quantum Computer (QC) capable of solving real-world problems (R6). This blueprint showed that it is now possible to build a practical quantum computer featuring millions of qubits, substantially advancing the credibility of producing a commercial device. The work was published in Science Advances, received extensive media attention and achieved an Altmetric score of 634, placing it in the top 5% of papers of the same age in this journal. Hensinger made a live appearance on primetime Sky News and the paper was covered by all major news agencies.

3. References to the research

R1: Versatile ytterbium ion trap experiment for operation of scalable ion-trap chips with motional heating and transition-frequency measurements, J.J. McLoughlin, A.H. Nizamani, J.D. Siverns, R.C. Sterling, M.D. Hughes, B. Lekitsch, B. Stein, Seb Weidt, and W.K. Hensinger, Phys. Rev. A 83, 013406 (2011), DOI: 10.1103/PhysRevA.83.013406 – 49 citations

R2: Simple Manipulation of a Microwave Dressed-State Ion Qubit, S.C. Webster, S. Weidt, K. Lake, J.J. McLoughlin and W.K. Hensinger, Phys. Rev. Lett. 111, 140501 (2013), DOI: 10.1103/PhysRevLett.111.140501 – 63 citations

R3: Fabrication and operation of a two-dimensional ion-trap lattice on a high-voltage microchip, R.C. Sterling, H. Rattanasonti, S. Weidt, K. Lake, P. Srinivasan, S.C. Webster, M. Kraft & W.K. Hensinger, Nature Communications 5:3637 (2014) DOI: 10.1038/ncomms4637, preprint published in 2013: https://arxiv.org/abs/1302.3781v1 – 70 citations

R4: Ground-state cooling of a trapped ion using long-wavelength radiation, S. Weidt, J. Randall, S.C. Webster, E.D. Standing, A. Rodriguez, A.E. Webb, B. Lekitsch and W.K. Hensinger, Phys. Rev. Lett. 115, 013002 (2015), DOI: 10.1103/PhysRevLett.115.013002 – 25 citations

R5: Trapped-ion quantum logic with global radiation fields, S. Weidt, J. Randall, S.C. Webster, K. Lake, A.E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker and W.K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016), DOI: 10.1103/PhysRevLett.117.220501 – 79 citations

R6: Blueprint for a microwave trapped ion quantum computer, B. Lekitsch, S. Weidt, A.G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich and W.K. Hensinger, Science Advances 3, e1601540 (2017), DOI: 10.1126/sciadv.1601540; *author contributions explained in manuscript*; preprint published in 2015: https://arxiv.org/abs/1508.00420v1 – 203 citations

(Citations from Google Scholar; R3, R5 and R6 were collaborative work with majority of work carried out at Sussex; R1 – R6 were all led and planned by W.K. Hensinger)

4. Details of the impact

1. Stimulating public interest in – and understanding of – Sussex quantum computing breakthroughs through innovative, interactive installations and exhibitions

In July 2017, Hensinger and his team created and hosted a walk-in quantum computing (QC) installation inside a shipping container, featuring authentic QC exhibits to demonstrate how a quantum computer could be built according to Sussex research (R6) and explaining how this technology affects different industry sectors (S1). It was placed in the centre of London's financial district, Spitalfields Market, to engage passing pedestrians, particularly those working in the banking sector. This installation was the first time a UK university has taken QC to an open public space and allowed people to interact with authentic exhibits. The walk-in QC installation also featured as an exhibit at the 2017 British Science Festival. Across the two locations, the exhibition was visited by thousands of people (S2), including school groups, banking executives, and a wide range of invited stakeholders; a simultaneous Ask Me Anything on Reddit (S3) was carried out where the team answered 127 questions related to Sussex QC research and its applications. Reporting on the British Science Festival, the editors of The Conversation identified the installation as '*the coolest thing at the British Science Festival*' in their podcast (S2), certifying its ability to raise interest within a wider audience. As an indicator of its efficacy, the QC installation received Gold in the 2018 national Heist Awards for 'Best Community / Business Engagement Campaign or Initiative', where the judges commented: '*This is an innovative and creative approach by the University of Sussex that shows a willingness and investment in reusable resources to deliver real impact. This is a fantastic example of how research can be commercialised and a great project to get the subject of Quantum Physics to the heart of the financial centre.*' (S2). In February 2018, Weidt was invited to collaborate with London's Science Museum to develop a dedicated exhibition about quantum computing as part of the *Tomorrow's World* gallery (S4), which showcased the Sussex blueprint concept (R6). Running for 8 months, the museum measured over 70,000 interactions with the interactive exhibition items (S5), and its success resulted in an invitation to contribute to another exhibition on breaking encryptions (Science Museum, July 2019 - February 2020). [text removed for publication].

In 2019, in collaboration with FuseBox Brighton, Weidt co-created the world's first virtual reality quantum computing (VR) experience to enable users to learn interactively about the QC proposed in the group's blueprint (R6, S6). As part of Brighton Digital Festival, an event was organised that included interactive demonstrations, premiering the VR experience and concluded with a public lecture by Hensinger. Among the audience was Geoff Raw, Chief Executive of Brighton & Hove Council, who noted: '*The event appeared to be highly effective in giving attendees a new perception of [..] quantum computing research breakthroughs at Sussex. This event allowed me to appreciate the opportunities of quantum technologies as an economic benefit for the city. Indeed, I subsequently initiated a sequence of work, [..], which has resulted in the Greater Brighton Economic Board's formal support for the establishment of Brighton as a 'quantum city' in its COVID 19 Sustainable Recovery Plan*' (S6). The VR experience has since been used at multiple events and was selected from 45 submissions as 1 of 11 exhibits to be included in the 2019 EPSRC Physical Sciences Showcase event, illustrating its efficacy in demonstrating impact of EPSRC-funded research to key stakeholders (S7).

Hensinger frequently receives communications from attendees of his events, which includes 27 popular science lectures (S7), lauding the effects his words and work have had on their and others' understanding of QC. For example, after attending a New Scientist Instant Expert event, one audience member wrote: '*I found his presentation nothing short of spectacular, and it sparked my interest in the area, which has continued to date. I believe I wasn't the only one – I spoke to New Scientist staff afterwards […], and they stated that Prof. Hensinger got rave reviews in the audience feedback forms.*' (S8). [text removed for publication], wrote after attending one of Hensinger's public lectures: '*It takes a highly gifted speaker to be able to simplify quantum mechanics to an understandable level and at the same time keep it interesting. The last time I saw physics presented in as understandable manner was the Feynman Lecture series during my days at Johns Hopkins University*' (S8). Working together with the Institute of Physics, Hensinger co-created a commemorative event for physicist John Bell as a highlight of the NI Science Festival, attended by Bell's descendants. Its organiser, Dr Sheila Gilheany, described the talk as *'outstanding, pitched exactly right for the very eclectic audience*' and confirmed that it '*attracted interest from people working in the arts as well as from science backgrounds'* (S8). After a public lecture at the 2017 British Science festival, 94% of attendees responding indicated their awareness of QC had increased (S8).

2. Inspiring / creating artistic and media works to bring QC awareness to new audiences

Sussex's quantum research has reached, informed and inspired audiences beyond the domain of science education and exhibition. For example, musical composer Steve Thompson approached Hensinger keen to compose a music piece inspired by an interview with Hensinger on QC; the piece formed part of an album and was performed at a live event that included the live demonstration of a quantum computer (S9), reaching an audience that would unlikely have otherwise become aware of quantum computing. The album made it to number 5 in the iTunes jazz chart and received a 4.5 star review from Sammy Stein (one of the 10 most influential jazz critics in the world) (S9). Hensinger has worked with broadcast channel CGTV to produce a documentary about Sussex research on how to build QCs. A Facebook Q&A advertising its screening was confirmed by CGTV to have led to the largest engagement ever measured on their site, with over 600,000 views (S10). Together with producers from Channel 5, Hensinger co-created a documentary about his research for the iconic TV program, The Gadget Show (S3, 24/3/2017), reaching an audience of around 500,000 (S10). He was invited to write a chapter on quantum computing for a popular science book, "What's Next? Even Scientists Can't Predict the Future - or Can They?" published by Profile Books (2017). The book, which was sold 16,300 times, was featured for several months in the national WHSmith book charts and translated into 9 other languages (S11). An article he wrote about his research for *The Conversation* was subsequently published for a wider mainstream audience by *The Independent* (attracting more than 10,000 reads, and 130 Facebook shares) and the *i paper* (print, circulation: 200,000) (S12).

3. Raising awareness of – and investment in – quantum computing production and commercialisation, culminating in a fast-growing spin-out company

Hensinger's extensive media engagement has raised public and private investor awareness that practical quantum computers will soon become a key technology in everyday life. Major news agencies Reuters, AFT, PA, AP and numerous outlets across the world have featured Hensinger and his research including BBC television and radio news, Sky News Tonight With Dermot Murnaghan (Hensinger was a live guest), *VICE, Daily Mail, Sun, Metro, Financial Times, Wired, Scientific American* reaching as far as Russia (RT), Nigeria (Latest Nigerian News) and Australia (News.com.au) (S3). In 2017 alone, Kantar measured a total reach of more than 41,000,000 (S12), with extensive participation via comments, likes and shares (S3). Hensinger has featured three times on the Radio 4 Today Programme (recently voted the most influential news programme in the UK); these repeated invitations indicate the producers' confidence that his explanations meet their audiences' demand for informative, engaging and inspiring content.

Among these audiences was Andrew Scott (co-founder and General Partner at venture capital firm 7percent Ventures), who states: '*I first became aware of the research at Sussex to build practical quantum computers from researching online, finding a public lecture Dr Winfried Hensinger had given at the US Department of Energy, and subsequently Winfried appearing on the Radio 4 Today Programme on the 25 November 2016. In particular, his work published in the Sussex article "Blueprint for a microwave trapped ion quantum computer" excited our interest, particularly its level of ambition and focus on delivering a truly useful, scalable quantum machine, and purporting to have a feasible way of achieving this. Following an exchange of emails, I started working with Winfried and his early team towards creating a company to build practical quantum computers*' (S13).

Following Hensinger and Weidt setting up their spin-out company Universal Quantum (UQ) in 2018, Scott's firm (along with 10 other venture capital firms and high net-worth individuals) found sufficient confidence in the key research achievements at Sussex (R1 - R6) to invest. Scott writes: '*Due diligence of the research and the team gave us sufficient confidence to make our first investment in quantum computing.*' (S13). Lomax Ward, co-founder at venture capital firm Luminous Ventures, explains their reason to invest: '*In particular, their publication "Blueprint for a microwave trapped ion quantum computer" […] showcases a convincing roadmap to how the approach followed by Universal Quantum can get to quantum computers with millions of qubits*'. He adds: '*the public engagement work […] which we discovered as part of our due diligence work has helped us better understand quantum computing as a whole and their vision going forward*' (S13). The spin-out – established to develop and commercialise large-scale quantum computers whose design is based on Sussex research (R1 - R6) – raised initial private investments of GBP4,800,000, [text removed for publication] (S14). Indeed, Universal Quantum managed to attract highly-respected venture capital funds, including Hoxton Ventures (early investors in Deliveroo) and Village Global (backed by Bill Gates, Mark Zuckerberg and Jeff Bezos). [text removed for publication].

The company has been growing very fast; by the end of 2020, it had directly generated [text removed for publication] jobs [text removed for publication] (S14). Universal Quantum has already become a key partner in a drive to establish global software standards for accessing quantum computing hardware, receiving GBP700,000 (S14) as part of a GBP7,000,000 Innovate UK industry consortium grant. It has established a quantum computing supply chain with more than 15 suppliers in the UK, Europe and US and has spent over GBP1,000,000 on quantum computing development in the last 12 months. UQ has entered into licensing, collaboration and secondment agreements with the University of Sussex; [text removed for publication] (S14). The creation of the company has retained and attracted top quantum experts to the UK, helping to build a lead in this emerging sector. Lomax Ward states '*great progress has been made, including [...] their success at attracting some of the best minds in their respective fields to the area.*' (S13).

For 10 of its 11 initial investors, UQ was their first ever investment in quantum technology. The funds have now incorporated quantum into their investment strategies following their involvement with Universal Quantum. And Sussex quantum computing research is also beginning to help catalyse growth of a private investment sector for this new technology, beyond the UQ spin-out. Lomax Ward (Luminous) writes: '*Our investment into Universal Quantum has certainly caused a change in our investment behaviour in that it has accelerated our involvement with the field and as a result we now analyse at least 3 quantum investments per month*' (S13). Andrew Scott (7percent) adds: '*The progress that has been made at Universal Quantum since then has been impressive and has increased 7percent's confidence in the quantum computing sector. As a result, we have been looking at further investments in the UK quantum sector. In 2020 we have evaluated >10 quantum deals. Our experience with Universal Quantum and the research done at the University of Sussex was a significant part of our decision to move in this new direction. We anticipate deploying ~£5m or more of capital into quantum technology in the next two to three years.*' (S13).

It has been a government ambition to jump-start a new quantum computing industry sector, substantially increasing private investment into the development of quantum technologies in the UK (S15, p. 22) so the creation of UQ helps to meet this government key performance indicator. Chief Executive of Brighton & Hove Council Geoff Raw notes: '*While the Fusebox event really helped me to learn and fully appreciate the potential of quantum computing for the city, the creation of spin-out company Universal Quantum – especially as it's backed by household name investors – further convinced me to pursue this ambition to make Brighton and Hove a quantum city […]. Additionally, I can confirm that the emergence of Universal Quantum and the research activity at Sussex has also led to the inclusion of quantum computing in the Coast to Capital Local Enterprise Partnership (LEP) regional development strategy.*' (S6).

5. Sources to corroborate the impact

S1: Walk in quantum computer installation (2017): Video and NQIT Annual Report 2018 (p.45)
S2: Evaluation of 2017 installation: Heist award (2018), Conversation podcast (2017), Science Festival Report (2017)
S3: List of media engagement (2013 - 2020)
S4: London Science Museum Blog on the quantum computing exhibition (2018)
S5: Testimony letters: [text removed for publication]
S6: Testimony letter from Geoff Raw, Brighton and Hove City Council Chief Executive
S7: EPSRC showcase press release (2019), list of popular science lectures given by Hensinger
S8: BSF audience data for popular Science lecture by Winfried Hensinger (2017), Testimony letters: Wojtek Buczynski, [text removed for publication], Dr Sheila Gilheany
S9: Testimony letter by composer Steve Thompson
S10: Testimony letter Dr Shini Somara, CGTN facebook Q&A (2019), Gadget show website
S11: Testimony letter [text removed for publication]
S12: Engagement dashboard from The Conversation, Kantar data showing media reach in 2017
S13: Investor Testimony letters: Andrew Scott and Lomax Ward
S14: Testimony letter [text removed for publication]
S15: UK National Quantum Technologies Programme | Strategic Intent (2020)