Institution: Lancaster University

Unit of Assessment: 9, Physics

Title of case study: Increasing public understanding of research in quantum technologies through showcasing at exhibitions and media reports

Period when the underpinning research was undertaken: 2012 to 2020.

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:
Professor Manus Hayne	Professor	01/06/2006 to present
Dr Samuel Jarvis	Lecturer	10/10/2016 to present
Dr Ben Robinson	Senior Lecturer	01/07/2010 to present
Professor Robert Young	Professor, Director Lancaster Quantum Technology Centre	01/09/2009 to present

Period when the claimed impact occurred: 2017 to 2020

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

1. Summary of the impact

Through prestigious events such as the annual Royal Society (RS) exhibition and extensive media coverage, researchers from the Lancaster Quantum Technology Centre (LQTC) have impacted public engagement with, and understanding of, physics and its applications. They showcased their research on quantum devices for four consecutive years at the Royal Society Summer Science Exhibition (RS SSE). Research pertaining to quantum unique identifiers and random number generation was showcased in 2017 and 2018, while the exhibit that followed in 2019 focused on the importance of low-noise measurements for studying quantum devices. A video detailing the progress made on the quantum identifier project since 2017 was made for the online-only exhibition in 2020. This level of engagement with the RS SSE by a single research centre within a university is highly unusual, and unprecedented in this REF period. 642 teachers surveyed at the SSEs between 2017 and 2019 gave overwhelmingly positive feedback, with the vast majority gaining new scientific knowledge and novel ideas for lessons, and reporting that their students gained a deeper understanding of the importance of studying science. A 2020 follow-up survey of schools that had attended one of the exhibitions between 2017 and 2019 showed that over 70% thought that Lancaster's contribution to the SSE had a positive impact on their teaching. Companies that collaborated in delivering the exhibits saw direct commercial benefit as a result of the exposure they received, attracting new customers and investment exceeding GBP100,000. In addition, LQTC research was presented at New Scientist Live 2018 and at a four-week installation in the London Barbican 'Hub'. The footfall at each of the public engagement events ranged from 12,000 to 18,000 people, totalling nearly 160,000 people across five events, whilst it is estimated that the total media coverage including the online video reached more than 120 million people. Intensive global media activity following the demonstration of a novel memory technology emerging from the LQTC had a reach in excess of 78 million people.

2. Underpinning research

The public engagement activities detailed in this case were all based on original research conducted in the LQTC during the reporting period that developed and/or studied novel devices whose operation is underpinned by quantum physics.

2.1. Quantum identification

All materials have imperfections. At the atomic scale, quantum physics amplifies these irregularities, hindering the mass manufacturing of quantum devices that perform uniformly. A physical unclonable function (PUF) turns this perceived flaw into a primary attribute, harnessing imperfections traditionally seen as undesirable and making it possible to 'fingerprint' them in simple electronic devices [3.1], and optical tags [3.2]. Research led by Young utilising quantum

effects in PUFs for the first time, demonstrated their striking appeal; the randomness inherent in these structures is far more complex than the uniqueness that can be deterministically programmed into a memory element. In 2015, Young's team developed the first electronic device that can be identified from atomic imperfections, reaching the physical limit of security: the quantum-confinement PUF. This work resulted in high-impact publications, significant peer-reviewed research grants and was the subject behind EPSRC's ICT Pioneers award in 2015.

2.2. Quantum random number generation

True random number generators (TRNGs) are systems whose outputs cannot be determined, even if their internal structure and response history are known. Noise, chaotic systems and quantum phenomena are sources of true random numbers. The main advantage of using sources of quantum noise is its intrinsic uncertainty, as opposed to the predictability of traditional sources of noise. Young's team developed a novel, quantum TRNG, Q-RAND®, based on a semiconductor resonant tunnelling diode [3.3]. The device is much more practical and scalable than other quantum-based sources, and can be integrated into digital circuits. The potential to integrate Q-RAND® into current technologies makes them resistant to frequency injection and biasing attacks, which affect state-of-the-art TRNGs, such as those based on free-running oscillators. The output of Q-RAND® devices can be directly used as a random stream of bits, or these can be further distilled using randomness extraction algorithms, depending on the application. This research was shortlisted by *Times Higher Education* for their 2019 STEM Research Project of the Year award.

2.3. Studying quantum systems at IsoLab

IsoLab is a state-of-the-art, low-noise facility providing the most advanced environment for studying quantum systems in controlled conditions. Key research includes imaging of novel, molecular-scale structures on surfaces using scanning probe microscopy [3.4], and room-temperature quantum interference effects for the generation of electricity from waste heat [3.5]. Typically, such characterisation is only achieved in high-vacuum, cryogenic environments or on atomically-flat conductive surfaces. However, these approaches limit the rapid development of practical, scalable devices. The aim, therefore, is to achieve equivalent topographical, electrical and thermal resolution in ambient conditions, and on a wide range of surfaces. This aim has been achieved using IsoLab's unique design. Opened in 2017 by the then CEO of EPSRC, the building sits on its own massive concrete foundation, with three above-ground laboratories each contained in their own separate pod. Each pod is floating on its own 50-ton concrete isolation block and is lined with material to shield acoustic and electromagnetic disturbance.

2.4. ULTRA**RAM™**

A 'universal memory' combines the advantages of fast but volatile DRAM, and slow but non-volatile flash memory. Achieving this was seen as unfeasible, or '*almost impossible'* [IEEE Solid-State Circuits Mag. Spring 2016, p. 43]. By exploiting the properties of a triple-barrier resonant tunnelling structure, Hayne developed a low-voltage, charge-based, non-volatile memory with non-destructive read and a switching energy that is 100 times lower than DRAM per unit area [3.6]. Its implementation as a hybrid main/data-storage memory in computers and electronic devices would have huge consequences for energy consumption of digital technologies, reducing the inefficiencies of the memory hierarchy, and allowing them to switch on or off instantaneously.

3. References to the research

[3.1] Y. Cao, A. J. Robson, A. Alharbi, J. Roberts, C. S. Woodhead, Y. J. Noori, R. B. Gavito, D. Shahrjerdi, U. Roedig, V. I. Fal'ko and **R. J. Young**, "Optical identification using imperfections in 2D materials", 2D Mater. 4, 045021 (2017). Altmetric – 265

[3.2] J. Roberts, I. E. Bagci, M. A. M. Zawawi, J. Sexton, N. Hulbert, Y. J. Noori, M. P. Young, C. S. Woodhead, M. Missous, M. A. Migliorato, U. Roedig and **R. J. Young**, "Using quantum confinement to uniquely identify devices", Sci. Rep. 5,16456 (2015). Altmetric – 470

[3.3] R. B. Gavito, I. E. Bagci, J. Roberts, J. Sexton, B. Astbury, H. Shokeir, T. McGrath, Y. J. Noori, C. S. Woodhead, M. Missous, U. Roedig and **R. J. Young**, "Extracting random numbers from quantum tunnelling through a single diode", Sci. Rep. 7, 17879 (2017). This research was shortlisted by *Times Higher Education* for their 2019 STEM Research Project of the Year award.

[3.4] **B. J. Robinson**, S. W. D. Bailey, L. J. O'Driscoll, D. Visontai, D. J. Welsh, A. B. Mostert, R. Mazzocco, C. Rabot, **S. P. Jarvis**, O. V. Kolosov, M. R. Bryce and C. J. Lambert, "Formation of two-dimensional micelles on graphene: multi-scale theoretical and experimental study", ACS Nano 11, 3, 3404-3412 (2017).

[3.5] X. Wang, T. L. R. Bennett, A. Ismael, L. A. Wilkinson, J. Hamill, A. J. P. White, I. M. Grace, O. V. Kolosov, T. Albrecht, **B. J. Robinson**, N. J. Long, L. F. Cohen and C. J. Lambert, "Scale-up of room-temperature constructive quantum interference from single molecules to self-assembled molecular-electronic films", J. Am. Chem. Soc., 142, 19, 8555-8560 (2020).

[3.6] O. Tizno, A. R. J. Marshall, N. Fernández-Delgado, M. Herrera, S. I. Molina and **M. Hayne**, "Room-temperature Operation of Low-voltage, Non-volatile, Compound-semiconductor Memory Cells", Sci. Rep. 9, 8950 (2019). Altmetric 201, #2 in 'Top 100 in Physics' and #41 in 'Journal Top 100' for 2019 Sci. Rep.

4. Details of the impact

4.1. The Royal Society Summer Science Exhibition

The RS SSE is a week-long festival in central London celebrating cutting-edge UK science. Unlike many science festivals, it is free to exhibit, but with a highly competitive selection process driven by the international reputation of the RS. Successful selection requires teams to come up with novel and engaging ways of highlighting their work to the widest possible cross-section of the public. Visitors are led along the path of exhibits that winds through the RS headquarters, so that they typically attend all stands (approximately 20), and feedback reports and statistics gathered by the RS generally apply to all stands. Visitor surveys show that 97% of visitors rate the RS SSE as 'excellent' or 'good' and that 93% would visit again and recommend it to a friend [5.1]. Researchers from the same team exhibiting at four successive events (three live, one virtual) is highly unusual in the long history of the event. Visitor numbers at the RS SSE are limited by the building's 1,000-person capacity and were 13,611 (2017), 11,694 (2018) and 12,653 (2019) [5.1]. Nevertheless, the impact of the exhibition goes far beyond sheer visitor numbers, as evidenced by the associated media impact for each event (detailed below), by their influence on decision-makers and other invited guests at the 'soirées' (typically between 1,100 and 1,500 VIPs, including MPs, CEOs and Fellows of the Royal Society) [5.1]), and by their impact on teachers and their students. Each RS SSE attracts between 180 and 270 teachers and 1,500 to 2,000 students in school groups, with visitors between 13 and 17 years old making up 20% to 30% of the total footfall [5.1]. RS SSEs thus have a significant influence on decisions about future study and careers, which was strongly reflected in the RS survey feedback [5.1]. 84% of respondents agreed or strongly agreed that the exhibition increased their interest in science (2017), 82% agreed or strongly agreed that the exhibition had increased their understanding of how science impacts daily lives (2017), 98% of teachers agreed that by attending the exhibition their students gained a greater understanding of the relevance of science to the world around them, and 98% of teachers agreed their students had gained a greater understanding of the range of scientific careers (2019). Across all three exhibitions (2017 to 2019), approximately 96% of teachers agreed that they had learnt new scientific knowledge, and approximately 75% of teachers agreed that the exhibition had given them new ideas for lessons.

Lancaster's individual exhibits have also been shown to have had a direct impact in schools. In 2020, schools who had attended the SSEs with school groups between 2017 and 2019 were surveyed. 6 out of 7 (86%) of respondents agreed that they and their students had learnt something new from Lancaster exhibits, and that their awareness of research had increased. 5 out of 7 (71%) reported that the exhibits had encouraged them to recommend studying physics beyond GCSE, and 3 out of 7 (43%) confirmed that they had already incorporated information from the exhibits directly into their teaching, *"I've been able to set these resources for my students to view during covid-19 virtual schooling with the mid-term view of encouraging them to pursue A level Physics. They are fun and make a positive contribution to emotional well-being."* [5.2]

4.1.1 2017 and 2020 'A Future Without Fakes' (Q-ID®)

The 2017 exhibit increased awareness of the harm that results from counterfeiting and the emergence of quantum technologies as a viable solution, based on [3.1] and [3.2]. The exhibit

received broad media coverage from over 100 news outlets including the BBC News online, *Physics World*, *The Times*, *New Scientist*, *Mail Online*, *The Economic Times* and *Wired*. Young was interviewed on Sky News, BBC Breakfast, EurObsIT and Stobbs IP. A specifically commissioned 'Future Without Fakes' video was made available on YouTube (more than 50,000 views), including via BBC's Tomorrow's World [5.3a]. International engagement, with popular science articles, videos and interviews in many different languages had a reach of more than 100 million people. As a result of the media attention and exposure to influential business leaders at the soirées, a Lancaster spin-out, Quantum Base Ltd., attracted new commercial partners and investment in excess of GBP100,000 [5.4]. A video was featured in the 2020 Summer Science Online Exhibition that detailed the further scientific and commercial development of this technology.

4.1.2. 2018 'The Random Revolution' (Q-RAND®)

This exhibit highlighted the importance of random numbers and that 'random' numbers from many sources are potentially predictable. The solution developed at Lancaster University was advocated [3.3]. Social media content produced by the team and supported by New Scientist and the RS is estimated to have been engaged with over 0.5 million times. Website content was accessed by more than 5 million people. Animated videos explaining the science to a non-specialist audience have recorded over 70,000 views. The team also received a great deal of media coverage, furthering societal impact (through channels with a reach of more than 14 million people in the UK alone) [5.3b], including 24 news articles covering the application of quantum technology to cybersecurity from, for example, *The Times*, *New Electronics*, Phys.org and CSO Online. Young was interviewed about quantum computing in pieces for the BBC News Online and by *BBC Focus* magazine about the application of quantum technology to eradicate election hacking (both online and in print). 'The Wired World in 2019', a publication from *Wired* magazine, included an invited article by Young on quantum technologies, and *Physics World* produced a landscaping article of quantum technologies featuring research from the team. Appleyard Lees, a leading intellectual property (IP) law firm who are handling IP related to this research, sponsored Lancaster's exhibit. As a direct result of their ties to this event and the exposure that resulted, they gained new business from customers working in related fields, helping the company to expand further into quantum technology [5.5].

4.1.3. 2019 'Art of Isolation'

By the 2019 RS SSE, LQTC's consistent involvement was so evident that the Executive Director of the RS quipped in her opening speech that, *"The Royal Society Summer Science Exhibition wouldn't be the Royal Society Summer Science Exhibition without Lancaster"*. The exhibit, which was one of six featured on the RS SSE homepage for the event [5.6], likened vibrational noise to the oscillations of a guitar string or a drum skin, and electrical interference, such as blocking Wi-Fi signal in a domestic home and mobile phone reception, were demonstrated. These phenomena were shown to be just as important in extreme, ultra-sensitive measurements in quantum and molecular-scale devices, linking to Lancaster University research [3.5]. Two such measurements were brought to life at the exhibit, a microscope for imaging atomic structure [3.4], and remote operation of one of the coldest 'fridges' in the universe. The exhibit was featured in articles in *The Times*, *Al Jazeera*, *Wired* and various blogs and websites. There were interviews on Radio 4's *The World at One* and with the *Daily Mail* and *The Economist*. The reach for *The Times* and *The World at One* alone is more than 3 million people. In terms of social media activity, there were 350,200 impressions across a range of Twitter accounts, yielding 30,466 video views [5.3c].

4.2. New Scientist Live

From the 20th September 2018 to 23rd September 2018, Jarvis led a team of fifteen people to exhibit research from LQTC's IsoLab at New Scientist Live, in the ExCeL Centre, London. New Scientist Live is one of the largest scientific festivals in the world, bringing together more than 140 speakers and almost 150 exhibitors [5.7c]. The event had 39,582 in-person visitors, 54% of whom were female [5.7a]. Remarkably, 84% of the attendees spend over 6 hours at the event, *i.e.* visiting many exhibits, but "*82% of attendees don't attend any other events, ensuring a unique and engaged audience"* [5.7a]. At the exhibit, visitors discovered how some of the most sensitive experiments in the world [3.4, 3.5] are performed, with hands-on activities and working demos exploring different aspects of quantum mechanics and nanotechnology. The exhibit was

one of five featured in the event guide for the Technology zone [5.7c]. The dedicated social media campaign saw engagement with an audience of more than 0.5 million people.

4.3. 2019 - London Barbican Centre 'Random Revolution'

Following the success of the 2018 RS SSE exhibit, the RS sponsored a collaborative partnership between Young and Cellule Studio to bring Random Revolution (4.1.2) to the Barbican Centre in London. The exhibit was reimagined as an immersive sound and light installation which explained the narrative of quantum-derived randomness. The installation was located in an experimental venue - The Life Rewired Hub - whose exhibits were free to enter and visible across the entire public foyer. It was open to the public from 21st November 2019 to 18th December 2019. According to the Programme Producer at the Barbican, *"Rob [Young] and the Cellule team created a truly captivating installation which communicated the otherwise complicated concept of quantum computing through an experience that was both coherent to understand and mesmerising to experience."* The Barbican is internationally important, attracting a general audience in excess of 1.5 million people per year [5.8], so the estimated footfall for the 4-week exhibition is approximately 120,000 people.

4.4. Media coverage of ULTRA**RAM™ and resulting commercial interest**

An online media storm followed a Lancaster press release (29th June 2019), resulting in over 220 online articles, blogs and vlogs with a combined reach of more than 50 million people [5.9], culminating in a 6.5-minute piece on BBC World Service's *Digital Planet*. The paper [3.6] has been accessed 23,000 times to date, and was the 2nd most accessed physics paper and the 41st most accessed paper across all subjects in *Scientific Reports* in 2019. A follow-up paper in 2020 lead to a new wave of publicity, including the front cover of the 29th January issue of *Electronics Weekly* and a two-page feature article in the May 2020 print issue of high-street magazine *PC Gamer*, bringing the overall combined reach to more than 78 million people [5.9]. The technology has attracted the attention of world-leading microelectronics research centre IMEC, BT, IBM, IQE and Huawei [5.10]. On 24th June 2020, the Department for International Trade issued an export licence for the technology.

5. Sources to corroborate the impact

[5.1] RS SSE Exhibitor Reports for (a) 2017, (b) 2018 and (c) 2019 to corroborate attendance.

[5.2] Results from a questionnaire sent to teachers who led groups that visited the 2017-19 RS SSE, showing Lancaster University's influence on their teaching. Dated August 2020.

[5.3] Lancaster University Press Office report summarising RS SSE media coverage for (a) 2017, (b) 2018, (c) 2019

[5.4] Letter from Quantum Base Ltd dated 31st August 2020. Details impact on their business as a result of participation at the 2017 RS SSE.

[5.5] Statement from Appleyard Lees, detailing impact on their business as a result of links to 2018 RS SSE exhibition.

[5.6] RS SSE Homepage 2019 showing the "Art of Isolation" as one of only six exhibits on the homepage.

[5.7] New Scientist Live 2018 (a) Initial Report, (b) Sales Brochure, (c) Event Programme.

[5.8] Barbican Centre Visitor Management Plan (2016) corroborating average footfall.

[5.9] Lancaster University Pres Office report showing online coverage of ULTRA**RAM**™, dated July 2020.

[5.10] Letters of support from BT, Huawei, IBM, IMEC, and IQE for ULTRA**RAM**™ EPSRC proposal (all dated July 2020).