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Development of an Undergraduate Quantum Engineering Degree

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ABSTRACT Quantum computing, communications, sensing, and simulations are radically transformative technologies, with great potential to impact industries and economies. Worldwide, national governments, industries, and universities are moving to create a new class of workforce—the Quantum Engineers. Demand for such engineers is predicted to be in the tens of thousands within a five-year timescale, far exceeding the rate at which the world's universities can produce Ph.D. graduates in the discipline. How best to train this next generation of engineers is currently a matter of debate. Quantum mechanics—long a pillar of traditional physics undergraduate degrees—must now be merged with traditional engineering offerings. This article discusses the history, development, and the first year of operation of the world's first undergraduate degree in quantum engineering to be grown out of an engineering curriculum. The main purpose of this article is to inform the wider discussion, now being held by many institutions worldwide, on how best to formally educate the Quantum Engineer.

INDEX TERMS Degree, education, engineering, quantum, undergraduate.

I. INTRODUCTION

In 2009, three academics (Andrew Dzurak, Robert Malaney, and Andrea Morello) in the School of Electrical Engineering and Telecommunications, University of New South Wales (UNSW), Sydney,[1] met to discuss a brand new concept—the creation of new university courses on quantum engineering. The UNSW was already a pioneer in the development of quantum computing hardware. It was clear to us that the need for engineers to participate in quantum technology research and development would become urgent. However, no clear template existed to guide the quantum training of electrical engineers. The anticipated audience of our courses was final-year electrical engineering undergraduates and new master's students in electrical engineering and telecommunications. Such students were highly skilled in the fundamentals of engineering but with a background in quantum mechanics, which was, at best, a few weeks of a standard Schrödinger equation-based introductory-physics course.

[1]The UNSW has several campuses, the largest one being based in Sydney (UNSW Sydney), where the new quantum engineering program runs. For simplicity, we refer to this campus in this article simply as UNSW.

Back in 2009, the enticement for electrical engineering students to participate in our new course offerings was the excitement surrounding emerging quantum technology [1]. Now, this excitement is even more tangible. Quantum computers are here in the sense that so-called quantum supremacy over the best classical computers has been delivered [2]; and quantum communications systems are available commercially [3], as well as having been deployed in space via the Chinese satellite, Micius [4]. Beyond this, quantum sensing is another technology now gathering attention [5].

Understanding these dynamics, national governments all over the world are now investing heavily in developing the new workforce that will underpin the emerging quantum economy [6]–[9]. Commercial organizations are also moving quickly in the same direction [10], [11]. Until now, the majority of R&D in quantum technologies has been conducted by Ph.D. graduates, mostly in physics or related disciplines. While Ph.D. degrees will remain essential at the forefront of research for the foreseeable future, the growth of the quantum industry will require a far larger workforce than the world's universities can produce at the doctoral level. This calls for a new generation of trained engineers—experts across both

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traditional engineering offerings *and* quantum technology. Within this background, the demand for quantum engineering degrees is now palpable and several authoritative papers on the subject of how universities can best plan for the new undergraduate quantum engineering degree have recently appeared in the literature [12]–[15].

The course offerings on quantum engineering first introduced at the UNSW ten years ago have now been taken by over approximately a thousand students. The program has grown substantially, and last year blossomed into the world's first undergraduate degree in quantum engineering offered by an Engineering Faculty [16]. As far as we are aware, it represents the first Bachelor of Quantum Engineering (B.Eng.) offered by any university. This article outlines the journey to this new degree, the lessons learned, and the challenges still to be faced. Hopefully, it can inform the wider educational discussion now being undertaken by the worldwide university community.

II. DEGREE STRUCTURE

The four-year Bachelor of Quantum Engineering intentionally preserves the pedagogy, philosophy, core structure, and attributes of other Bachelor of Engineering programs at the UNSW, which have a common set of program learning outcomes [17]. The pedagogy is based around key principles including the following:

1) a combination of diverse learning experiences that encourage the construction of deep conceptual knowledge and develop students' ability to apply technical and professional skills effectively [18];
2) Kolb's experiential learning [19], in particular, manifested as a design thread through every year of the program, with design courses taught predominantly using problem-based learning [20];
3) intentionally preserving (throughout the program structure) the pedagogy of the existing electrical engineering program of which the quantum engineering program is a specialization, an important consideration for accreditation and viability as discussed in Section IV.

In terms of structure (see Table 1), the first year is firmly grounded in fundamental sciences, particularly, mathematics and physics, while also introducing students to the engineering design process and electrical circuits. The second-year advances analog and digital circuit theory, signals and systems, and skills in parallel with more advanced mathematics. The Fundamentals of Quantum Engineering course, together with the third year of the program provide the foundational courses for each of the key quantum engineering subdisciplines (see Section III), and then, the final year offers elective courses and honors thesis choices for students to specialize further according to their professional interests and needs. Engineering design courses are a common thread throughout the entire degree program, and nearly every course includes a hands-on laboratory program that is either scaffolded to connect closely with the theory in the course, or adopts a problem-based learning approach intended to maximize self-learning of design and complex problem-solving skills. These courses also address the identified need for graduates to be effective in team projects and in communicating technical concepts to a less technical audience [12].

TABLE 1. Structure of Bachelor of Quantum Engineering Program at the UNSW

Year 1	Mathematics 1A	Mathematics 1B	Mathematics 2A
	Electrical Circuits	Physics 1A	Physics 1B
	Introduction to Engineering Design	Programming Fundamentals	
Year 2	Circuits & Signals	Mathematics 2B	[A]Fundamentals of Quantum Engineering
	Digital Circuit Design	Analog Electronics	Digital Signal Processing
	Electromagnetic Engineering	Engineering Design	*General Education*
Year 3	[B]Quantum Communications	Quantum Physics of Devices & Solids	Electrical Design Proficiency
	Electronics	Control Systems	
	General Education	Electrical Engineering Design	*Elective L3/L4*
Year 4	Research Thesis A	Research Thesis B	Research Thesis C
	Strategic Leadership and Ethics		[D]Quantum Devices & Computers
	Elective L4	*Elective L4*	[C]*Quantum Control (Elective L4)*

The UNSW Bachelor of Quantum Engineering also inherits six courses from a conventional electrical engineering program. The reasons for this are several. Classical microelectronics already operates at a scale where quantum phenomena need to be understood and harnessed. Besides the emergence of the band structure in solids—a quantum phenomenon that can be in principle forgotten once it is understood how it affects charge transport in semiconductors—we now deal with such small-scale transistors that quantum tunneling and single-impurity effects [21] can have visible consequences. Another reason is that quantum-limited amplifiers are moving from fundamental research into engineering applications [22]. On the other hand, classical electronics and control systems are of paramount importance for the development of quantum technologies. For instance, large-scale quantum computers employing quantum error correction [23] need field-programmable gate arrays (FPGAs) for fast feedback [24], and enormous classical computational resources to interpret the outcome [25]. Virtually all examples of solid-state quantum computers require advanced microelectronic and microwave engineering for the generation [26]–[28] and delivery [29], [30] of the control signals. From the perspective of the emerging quantum industry, a recent study indicates that among a survey of 21 U.S. quantum companies, 95% of which employed engineers, 71%

employed electrical engineers, a significantly greater proportion than any other type of engineer [31]. The progress of quantum engineering thus hinges upon the availability of a workforce skilled across the broad spectrum of quantum technology and electrical and computer engineering.

Those courses in the degree program without "quantum" in their title are regular electrical engineering courses, with two exceptions to date. The first-year electrical circuits course, which covers fundamental principles such as the operation of logic gates, operational amplifiers and resistors, capacitors, and inductors, also contains a short introduction to qubits. This allows first-year quantum engineering students to begin making a direct connection with their discipline. The second-year electromagnetic engineering course covers phenomena in wave propagation such as discrete modes in waveguides, evanescent waves, and reflections from impedance mismatch, which are completely classical. Yet, their mathematical description and physical intuition apply similarly to the quantization of particle states in a confining potential or quantum tunneling and reflection by a potential barrier. These aspects are strategically emphasized so that students recognize their ubiquity once they encounter them again in the Fundamentals of Quantum Engineering course. These courses provide a solid basis for the core quantum engineering-specific courses, which are described in more detail in the following sections.

At the UNSW, apart from the newly developed quantum courses, there has also been a success in encouraging electrical engineering students to enter the field via our "Taste of Research" scholarship and final-year Honours thesis project. The Taste of Research scholarship program was introduced two decades ago by the Faculty of Engineering, where second or third-year undergraduate students can experience what research entails compared to ordinary lecture-style courses. Many electrical engineering students now choose research topics in the field of quantum engineering for their Taste of Research experience, believing this area is the new rising star. The Honours thesis topics have also provided a similar platform on drawing students from electrical engineering to quantum engineering. Both of the aforementioned programs have also contributed to quantum-research outcomes at the UNSW and led several students to continue onto quantum-based Ph.D. programs.

III. CORE QUANTUM COURSES

A. FUNDAMENTALS OF QUANTUM ENGINEERING

The first quantum-centered course encountered by the students is Fundamentals of Quantum Engineering, offered in the second year. This course derives from a former postgraduate course, quantum devices, and benefits from many of the lessons that were learned while developing such a course. The key insight was to recognize that, while an in-depth understanding of the quantum theory is important to gain proficiency in quantum engineering, the use of engineered quantum devices as "worked examples" to illustrate that quantum phenomenon at work is an extremely powerful tool to clarify and demystify quantum theory.

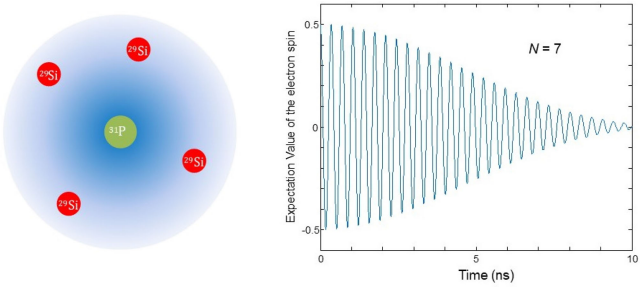

FIGURE 1. Example assignment for Fundamentals of Quantum Engineering: Calculate by "brute-force" the time evolution of an electron spin coupled to an increasing number *N* of nuclear spins. The concrete example shown here is a phosphorus donor coupled to ^{29}Si nuclei. The Python coding is straightforward to write, involving just the use of tensor products to construct the spin operators in the Hilbert space, and the unitary time-evolution operator to calculate the behavior of the electron. The result illustrates the key phenomenon of decoherence, which arises naturally by randomizing the electron-nuclear coupling strengths and the initial state of the nuclei. It also strikingly illustrates the computational challenge of simulating quantum systems on a classical computer, since the computation becomes very lengthy once $N > 10$. We let the students find this out the hard way, and the lesson learned is hard to forget.

The method we adopted to expose the students to quantum phenomena was the development of software that simulates the behavior of increasingly complicated quantum systems. This goes hand-in-hand with a focus on teaching quantum mechanics in a matrix-based form, which lends itself naturally to coding with software packages like MATLAB. In 2021, we switched the coding language to Python, in response to its widespread adoption in quantum technologies. The complexity of the systems that can be simulated this way is remarkable, and qualitatively changes the way in which students approach the subject. Traditional textbook examples are defined by the possibility of solving them analytically with manageable difficulty. Now, using numerical software and matrix algebra, students only need to learn the basic methods of writing down a Hamiltonian matrix and asking the computer to calculate its eigenenergies, or writing a time-evolution operator and programming its application to the quantum state of the system. Increasing the system complexity does not reflect increased difficulty in writing the code. It does, of course, reflect in the computational cost of matrix diagonalization as the size of the system grows. Asking the students to calculate the time evolution of an increasing number of coupled qubits (see Fig. 1) is a simple but effective exercise to make them aware of the exponential complexity of quantum systems! We insist that the students write the code themselves, from scratch, rather than use third-party simulation software. This ensures that there are no gray areas in their understanding of how the quantum theory gets translated into computable instructions. The MATLAB/Python coding exercises were consistently described as the most valuable and effective learning activity in the students' feedback.

The course begins with a brief historical exposition of how quantum mechanics emerged as a *necessity* to explain the empirical observation of the photoelectric effect and matter-wave interference. The Heisenberg uncertainty principle is "derived" from the properties of Fourier transforms, once wave-particle duality is established. Therefore, from the very beginning, we strive to introduce quantum phenomena as "the true behavior of physical systems," rather than coating them in an aura of mystery and weirdness.

Matrix-based quantum mechanics is then introduced, using the spin as the working example. Spin precession and spin resonance allow the illustration of many key aspects of quantum engineering while illustrating them in a system that students find easy to visualize. Students are immediately forced to internalize the dichotomy between "real" space and Hilbert space. Several pen-and-paper problems, as well as Python coding exercises, illustrate how to switch back and forth between the 2-D Hilbert space with complex coefficients, and the familiar space in which the spin precesses around a magnetic field in a way that reflects classical intuition. This has the explicit purpose of demystifying the presumed weirdness of quantum mechanics. The genuinely nonclassical aspects, such as the spinor and the geometric phase that arises from it, are introduced later in the course, for rigor and completeness.

Once the matrix formalism is established—both conceptually, and in its practical execution through Python code—it becomes easy to move to more complex systems where quantum issues are more striking. Entanglement arises naturally and intuitively from the eigenstates of coupled spins. There is no weirdness or mystery in showing that a singlet state cannot be written as a tensor product. Because entanglement is such a key component of quantum advantage, it is essential that its origin and application be demystified and framed as a resource that can be engineered and exploited.

Having established multiparticle statistics, interactions, and entanglement, we proceed with a brief discussion of the hydrogen atom, the covalent chemical bond, and the emergence of the band structure in semiconductors. The course is concluded with examples of quantum transport and quantum operations in semiconductor devices, and the use of single-electron transistors and quantum point contacts as sensitive electrometers.

Our student cohort is very diverse. In the original incarnation as a postgraduate quantum devices course, the diversity was even more extreme, because many students had completed their undergraduate degree at different universities, in different countries, speaking different languages. Out of acute necessity, we set out to teach quantum engineering while making close-to-zero assumptions on the background knowledge of the students. This naturally resulted in a strong focus on diversity and inclusion, embedded within the teaching rationale of explaining everything from the very beginning, taking nothing for granted, and ensuring that a shared vocabulary is established at every stage.

B. QUANTUM COMMUNICATIONS

The quantum communications course is offered as a third-year undergraduate course within the new Bachelor of Quantum Engineering program. However, it has been run since 2010 as a master's course, accessible to the traditional undergraduate stream as an elective fourth-year course. Approximately one thousand undergraduate and master's students have come through the course. Here, we first discuss the development of this course prior to its inclusion in the new degree.

The cohort of students initially entering the course was predominantly electrical engineering students with a strong background in electromagnetism, signal processing, telecommunications, and classical information theory. It was quickly learned during the first lectures that the best policy moving forward with the course was to assume no quantum mechanic prowess whatsoever within any incoming engineering cohort. We had to start from scratch.

A first challenge revolved around getting the student cohort to accept the core mystery of quantum mechanics as a fact of nature. The resolution to this issue for the class was the acceptance of the postulates of quantum mechanics, and a frank discussion on the meaning of true—yet unprovable—statements. As engineering students, the notion of building a mathematical framework upon solid foundations, known to be true through a century of experimental verification, was acceptable to the majority of the cohort. Accepting this foundation as the route to mathematical calculations and predictions that would ultimately be tested in real-world deployments was how the course moved forward. This approach, in conjunction with the strategies outlined in the Fundamentals of Quantum Engineering course, seemed to overcome the mystic of quantum mechanics for most of our cohort, allowing them to frame the subject within an engineering context.

Next, we had to decide what mathematical route through the communication journey would be adopted for the course. This would be a two-step process. The first step was to decide whether to adopt the wavefunction framework of Schrödinger's equation and the evolution and collapse of this complex wavefunction to the observable predictions or to adopt the more abstract formalism offered by time-dependent operators in matrix notation. As the cohort was well versed in matrix operations and eigenvalue analysis, through exposure to such techniques in other engineering courses, the latter formalism proved more effective. The second step was to decide what photonic technology was to be used as the basis of the course. Would this be the continuous variable approach to quantum communications based on the solid foundation of Maxwell's theory coupled to a series of Gaussian functions and well-known detection strategies of homodyne and heterodyne detection? At first pass, this appeared to be the obvious strategy, the cohort had a solid foundation in these concepts from their classical communication experience. However, the mathematical complexities of this framework coupled with quantum mechanics proved to be a bridge

too far for many in the class. The more successful route transpired to be the discrete variable single-photon technology and the embodiment of a superposition of polarized states as a pathway to the proverbial qubit—even though the notion of single-photon communication was alien to the cohort. However, the relative mathematical simplicity of the discrete variable framework allowed for easier inclusion of quantum mechanics, and faster acceptance of the key concepts underpinning the main functional applications of the course.

Based on these decisions, the course moved through its core objectives rather easily. The first of these was a deep understanding of the killer application in quantum communications, Quantum Key Distribution. Roughly half the course was spent on this application. Teaching this involved bringing together not only the conceptual quantum underpinnings of the application but also its critical dependence on classical communications—in particular, classical error correction as a means of reconciling the secure one-time-pad between transmitter and receiver. This connection back to a subject well known to the cohort appeared particularly motivational. It was a relief, it seemed, to know all that old-fashioned classical stuff will still be needed in the brave new world of quantum communications. Superdense coding, and a full conceptual understanding of entanglement and its distribution through networks followed thereafter. The third and final component of the course involved an elementary introduction to quantum error correction.

Throughout the course, the students were constantly reminded that the same concepts learned here could be immediately applied to quantum computer technology, but that the engineering solutions and applications being discussed found a "deployable-now" home in the communications arena. The knowledge that all they were learning had real-world application today always appeared to be a welcome message to the students, and help defeat any notion that quantum technology was all hype and no action.

As stated earlier, approximately one thousand students have traversed the UNSW Quantum Communications course. The feedback from students has been largely positive, many stating that the course was the most interesting one they had encountered in their entire degree. Initially, the numbers were small, some 20 students enrolling in the first year, climbing to a maximum of 120 students a few years ago. The course was given an enormous boost by the launch of the Micius satellite in late 2016 [4]. With quantum communications now proven to survive the rigors of space deployment and traversal through the Earth's turbulent atmosphere, any notion that quantum communications are not a here-to-stay technology was dispelled. Indeed, since 2016 the course leaned heavily on the implementation of the space-based quantum communications shown in Fig. 2, pioneered by the Micius collaboration [4]. It is safe to say the course gained enormous traction through the exciting results produced by Micius. Coupled with the new space paradigm of emerging low-cost satellite launches, many quantum-enabled satellites are soon to launch [32]. This new development in launch

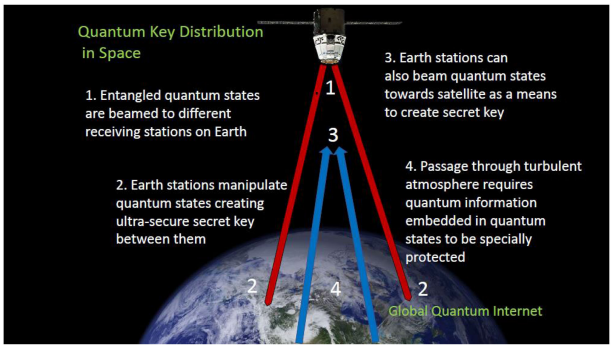

FIGURE 2. Quantum communications teaching in the degree is based on a thorough understanding of all quantum protocols implemented in space by the Micius collaboration [4]. That advanced quantum technology has been implemented in the hostile environment of space helped convince the class cohort that quantum engineering is an exciting "here and now" field.

availability for space-based quantum devices has added an exciting new element to the course dynamic.

As stated previously, the quantum communications course at the UNSW is now a core component of the new undergraduate Quantum Engineering degree [16]. A new aspect of the course for this degree is the introduction of a laboratory component. This new laboratory component, (not implemented in the master's degree) is described later (see Section III-E).

Challenges for the course remain. Providing for seamless coexistence with other courses in the Quantum Engineering degree is a work in progress. Particular issues around avoiding duplication of material yet allowing for each course to be self-contained is a challenge. The tradeoff between the consolidation of material already witnessed and avoidance of repetition is a challenge in quantum coursework as it is any other stream. However, given the conceptual leaps involved for the engineering cohort more weight to a revisit of material is currently given. The focus of single-photon technology within the course is also an issue to be resolved. A true quantum engineer emerging from their quantum-focused degree will meet a quantum-technology universe in which discrete variable technology and continuous variable technology are equally prevalent. Additional course offerings that meet this real-world issue will likely be needed as the degree matures.

C. QUANTUM CONTROL

A new course dedicated to control-theoretic aspects of quantum engineering forms part of the offering within our degree. A major consideration in the design of this course was the need to minimize barriers to entry. We assumed the students taking the course would be well-prepared fourth-year students who have completed a quantum mechanics course and a first electrical engineering control systems course with at least a state-space component. We also assumed the students would possess standard knowledge of topics in undergraduate level mathematics such as multivariable calculus, linear algebra, complex analysis, and probability and statistics. It is the case that traditional electrical engineering students at

the UNSW would already be equipped with this knowledge by the time they complete their third year. Given this background, the course has been designed to be as self-contained as possible. Additional elements of quantum physics (e.g., open quantum systems), probability theory, and control theory are weaved into the course to fill the remaining knowledge gaps.

Another important feature in the course design is that it approaches quantum control from an engineering viewpoint and builds upon well-established electrical engineering (systems and control) traditions in optimal control [33] and stochastic control [33], [34]. The approach adopted promotes a unified view of classical stochastic control and quantum feedback control, with the latter being viewed as a noncommutative generalization of the former to dynamical systems obeying the laws of quantum physics. This approach is in the spirit of the pioneering work of Belavkin in quantum filtering and feedback control, see, e.g., [35]–[37], which generalized the stochastic control theory to the quantum setting.

In terms of coverage, the quantum control course includes some of the materials proposed in [14, Modules 8–10] that cover topics on Hamiltonians and time evolution, dynamics with time-varying Hamiltonians and open quantum systems, respectively, but presented at a general level rather than delving into the details of specific physical settings. Beyond this, it includes optimal open-loop and feedback control of quantum systems. Basic elements of the modern probability theory [38] and classical stochastic control theory [33], [34] are gently introduced as a precursor to the quantum extension. This equips students with a broad awareness of both classical and quantum control theory. Starting with the classical control theory has the benefit of first introducing key concepts in a familiar classical (nonquantum) setting that students would be comfortable with, motivated by the engineering problems that they were developed to solve. The treatment of quantum feedback control then proceeds along with an approach that is standard in the systems and control context and utilizes the close connection and analogies between classical stochastic control and quantum feedback control. This approach is the well-established route of separating the feedback control problem into a stochastic filtering problem and a full-information control problem, known colloquially as the separation principle [33], [37]. Analogies with the classical setting treated earlier in the course can be drawn upon to treat the quantum setting with minimum additional technicalities. The approach emphasizes properties of quantum models for quantum feedback control that enable analogies from the classical theory to be carried over to the quantum setting.

D. QUANTUM DEVICES AND COMPUTERS

By the fourth and final year of study of our program, students have established foundational knowledge on quantum devices through their courses on Fundamentals of Quantum Engineering and Quantum Physics of Solids and Devices. Having already formed an intuition for quantum mechanics and developed both the analytical and numerical skills to simulate quantum systems, they are ready to explore one of the technologies synonymous with the second quantum revolution, quantum computers. The course quantum devices and computers aim to provide students with a comprehensive understanding of quantum computers from both a software and a hardware perspective, covering the basics of quantum gates and algorithms and examining several platforms for its implementation.

A central theme early in the course is how noise affects real quantum systems, a critical concept for understanding the challenges involved in building a quantum computer and in evaluating candidate physical platforms. We have found the filter function approach to understanding noise and dynamical decoupling [39] as an extremely effective tool for teaching this topic to our students. We describe decoherence as a noise sampling problem in the frequency domain, a concept that sits comfortably with the students who by this point in the program are well-versed in Fourier and Laplace transforms and filter design, knowledge developed in their second-year courses on Circuits and Signals and Digital Signal Processing. Noise spectroscopy and magnetometry are briefly covered to ground the filter theory in practical examples.

The course closely follows the style of Nielsen and Chuang [40] to introduce quantum gates and the concept of universal quantum computing. We take a system-agnostic approach in the presentation of this section, opting to investigate physical platforms in the second half of the course. A few key quantum algorithms are explored, including the quantum Fourier transform, the Grover search algorithm, and quantum simulation. These general examples cover a wide class of algorithms and provide enough depth for students to understand how to "program" a quantum computer and recognize the power and limitations of the technology.

The quantum harmonic oscillator (QHO) is an important topic that permeates the remainder of the course. In addition to being one of the most fundamental concepts in quantum mechanics, the physics of the QHO can be found in each of the platforms for quantum computation that are covered: semiconductor-based devices, photons/quantum optics, and superconducting quantum electronics. When exploring each physical system, the link to the QHO is made apparent: for semiconductor qubits the confining potential of electrons is parabolic and wavefunctions are given by the Fock-Darwin states, photons are excitations in a mode of an electromagnetic field, and superconducting qubits are electromagnetic modes with an anharmonic energy spectrum. Linking the seemingly very different systems back to the same underlying physics of the QHO establishes a sense of familiarity. The course also demonstrates the components needed in each physical system to implement single-qubit gates and

two-qubit gates, which provide students with an understanding of the hardware requirements for building a quantum computer.

Tutorials are run throughout the course to allow the students an opportunity to test their comprehension by solving a set of problems specific to each topic. In addition, a hands-on experimental laboratory (see Section III-E) is operated simultaneously with the lectures and tutorials and links to the sections on noise and quantum optics, with the latter providing an opportunity for the students to demonstrate the general concepts of single-qubit gates and entanglement. Together with the course assignment (a quantum algorithm programming task), these components are critical for developing a deep level of learning and rate highly in student course evaluation surveys.

E. DEVELOPING EXPERIMENTAL LABORATORIES

For a comprehensive education, the theoretical skills conveyed in the lectures and tutorials need to be augmented with practical skills, obtained through hands-on exercises and laboratories.

The matrix formalism that is used to introduce quantum mechanics in Fundamentals of Quantum Engineering, Quantum Communications, and Quantum Physics of Devices & Solids lends itself perfectly to performing numerical simulations in software packages like MATLAB or Python. A qubit state is simply depicted as a vector, a Hamiltonian as a matrix, and time evolution operators can be obtained by matrix-exponentiation—all simple linear algebra operations performed by the computer. Going through many examples and requiring students to code up their own solutions in homework tasks and tutorials, the courses provide students with a useful toolbox of codes and techniques that they can later extend and apply to simulate research questions. Examples of publications where the theoretical simulations are based on extended course codes include [41] and [42].

For Quantum Devices and Computers, we have implemented and developed hands-on practical teaching laboratories (see Fig. 3). Half of the teaching laboratories are based on an educational kit sold by the company Qubitekk [43]. Based on a 405-nm laser and a nonlinear down-converter, the kit allows students to generate pairs of entangled photons to learn about measurement bases, the photon statistics of nonclassical light sources, the indistinguishability of photons, and polarization-entangled pairs of photons. In the other half of the laboratories, we convey experimental aspects of qubit operation, by letting the students implement control of an ensemble of NV centers in diamond using magnetic resonance. Here, the students learn about Rabi oscillations, two-axis control on the Bloch sphere, coherence times, and dynamical decoupling, having to code and tune up the pulse sequences themselves.

The main technical challenge for the NV center experiment was to take a fragile quantum experiment out of a research laboratory and put it in front of students such that it

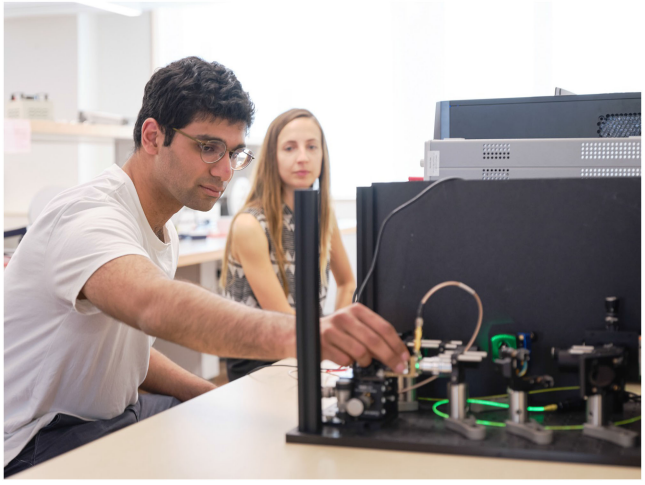

FIGURE 3. Two engineering students working on the NV center teaching-laboratory experiment. The laboratory components of the degree are critical in consolidating the quantum-mechanical concepts introduced in lectures.

produces the desired results consistently, in a short time period, and in an ill-controlled environment. While several spin control setups are now commercially available [44]–[47], we designed and built our own setup and made it robust to background light, vibrations, and movement of cables using lock-in amplification techniques [48], [49]. The main educational challenge for both experiments was to convey the necessary specialist knowledge to the students that is required to run the experiments. While the overarching concepts are covered by the lectures, the intricate details (e.g., quantum properties of the NV centers in diamond) and the measurement techniques are not part of the lectures. To overcome this, we found it helpful to have introductory minilectures at the beginning of each teaching laboratory that cover the relevant details. These were very well received by the students and partly moved online to save time.

For the quantum communications course, it was decided that although the course was based largely around single-photon technology, the use of weak laser pulses as the core signal carrier for laboratory purposes would be best. The relative ease-of-use, set-up, and lower cost of maintenance of simple lasers relative to single-photon sources was critical in this decision. This laser setup can be used to demonstrate the important principles of the BB84 Quantum Key Distribution protocol and can be set up using available optics packages [50]. The demonstration allows for full-encoding and decoding of the polarized light, full-blown classical reconciliation and privacy amplification, and the delivery of a final one-time pad. It even allows for interception attacks by a malicious eavesdropper. Due to the use of a many-photon pulse of laser light, this setup does not allow for an actual secured secret key. However, it was decided that a better understanding of the conceptual underpinnings of the protocol, outweighed the lack of a formally secured key.

IV. ADMINISTRATIVE CHALLENGES DURING ESTABLISHMENT

The main objections encountered to the introduction of such a new program were as follows.

1) *Is quantum engineering a discipline in its own right?* Quantum engineering is sufficiently distinct and significant to have multiple of its own subdisciplines (electronics, computing, communications, sensing, control). There is certainly no shortage of fundamental theory underpinning it, and it is clearly different from established electrical engineering theory. Indeed there is a "point of departure" in the middle of the undergraduate curriculum (ELEC3705) in the same way that, for example, the communications theory is a point of departure from electrical engineering toward telecommunications. From this perspective, it was generally not difficult to convince skeptics that quantum engineering is at least a specialization of electrical engineering in the same way that telecommunications is a specialization. Finally, we found that quantum engineering was changing the way we taught electromagnetism and even introductory circuits.
2) *Is quantum engineering too specific for a bachelor program?* As the aforementioned, if telecommunications, as a specialization of electrical engineering, can comprise a bachelor program, then quantum engineering can be similarly argued as a specialization of electrical engineering at the bachelor level.
3) *Is there a quantum engineering industry that needs bachelor graduates?* The authors in [31], as well as anecdotal evidence from industry, suggest that there is already a significant demand. At the UNSW, it helped significantly that an influential national report [6] had been released around the time the program was proposed. Since hard enrolment numbers are now available, it is clear that students have voted with their feet: enrolments (60 in first cohort) suggest that students are quite comfortable with quantum engineering as a program, even when electrical engineering is an obvious alternative.

There were three main administrative hurdles to overcome: the Head of Department, the Faculty/University, and the accrediting body. The Head of Department asked whether it was viable to run quantum engineering subjects, whether they were mature enough, and whether there was staff to teach them. In our case, most subjects had already been running viably for many years, and only one new subject was needed for the program. Academic staff was passionate about teaching these subjects. The Head of Department also asked whether we are going out on a limb, but understood that curriculum innovation is the lifeblood of university education and part of a risk-balanced portfolio of programs. At the UNSW, the BE in Electrical Engineering was introduced in 1948 and the BE Telecommunications in 1999, so there was capacity for an innovative program in 2020.

The Faculty/University and accrediting body (Engineers Australia) were mainly concerned about whether quantum engineering is a distinct discipline, its viability, and industry input to the curriculum. Concerning viability, it was helpful that we were part of a large Faculty in a STEM-heavy university with a reputation for quantum research.

V. INDUSTRY INTEREST AND GLOBAL PERSPECTIVE

With commercially valuable applications around the corner, the quantum industry is attracting significant investment. Start-ups are raising millions of dollars in private capital, large corporations are investing in quantum readiness and governments are subsidizing the creation of competitive ecosystems worldwide. Staffing these new companies is a challenge, and competition for talent is fierce.

An analysis of the quantum industry worldwide may provide some insight into the proficiency required by employers in this field. In a recent survey, 57 companies provided information about the roles they were offering or planning to offer in the near future. At the time of the survey, no undergraduate degree in Quantum Engineering was offered anywhere in the world other than UNSW, and all job titles referred to traditional fields in Engineering and Science, such as Test and Measurement Engineer, Control Systems Engineer and Experimental Physicist. An analysis of the responses on the survey [11] may be used to deduce what skills are most sought after by industry in the hiring of a quantum engineer.

Part of the difficulty faced by the industry is the lack of a single well-defined degree that immediately guarantees the employer that the candidate has the skills that are needed for the job. For most tasks, currently, it is necessary to hire scientists with either years of proven experience or some research postgraduate degree, such as a Ph.D.

Entry-level positions are extremely hard to fill. This presents several problems for the competitiveness of quantum companies when compared to other deep-technology industries. The backbone of a quantum company is a well-integrated team, which is easiest to achieve by hiring young talent and offering incentives (such as company shares) and a solid career progression. Hiring more experienced engineers strains the budget of a company in its early stages, in which research and development are intensive and the exact point of effective commercialization might be unclear.

An undergraduate-level quantum engineering program, such as that described here, addresses all these issues. The professional formation is typically achieved in half the time compared to the combination of a Bachelor of Engineering (or other disciplines) and Ph.D. graduates from formal quantum engineering programs will join companies straight out of college, receiving better compensation for their work and creating ties to their company early on. As they progress on the job, their salaries grow commensurately, which makes for a better-defined flow of funds for the company and ties the personnel expenses to the company progress—an attractive feature for investors.

Due to the fact that the UNSW Bachelor of Quantum Engineering degree has only launched in the past year, there are no statistics as yet regarding employment outcomes from the degree. Despite this, as noted earlier, the UNSW School of Electrical Engineering and Telecommunications has run courses related to quantum technologies now for over a decade, and graduates from these courses have gone on to jobs related to quantum computing in major corporations, quantum start-ups, and semiconductor entities including Intel in the USA, Microsoft Quantum in Europe and Australia, IMEC in Europe, and Quantum Motion in the U.K. A number of other graduates have moved on to academic positions teaching quantum engineering, particularly, in Australia. It will be important to collect statistics on graduate outcomes from the new Bachelor's degree program in the coming years.

The supply of bachelor-level quantum engineers will also lower the barrier for potential users to hire and develop internal quantum applications programs. The end-user will typically not be interested in developing their own quantum hardware and services, but only in judiciously consuming quantum technologies—a task easily performed by one or a few quantum engineers.

Finally, a quantum-ready workforce is an important instrument for sustained sovereignty. A locally trained cohort of quantum engineers allows nations to protect their existing technology, and staff their governmental and defense institutions with quantum-literate personnel.

VI. CONCLUSION

In this article, we have discussed the development of an undergraduate degree program in quantum engineering—aimed principally at electrical engineering students. This program, which was established over several years, is now running at the UNSW. From it, the world's first batch of undergraduate degree-qualified quantum engineers can be expected in the next few years. We hope the material provided here can inform the current worldwide discussion on the development of undergraduate quantum engineering degrees. In order to formally train a large number of quantum engineers widely predicted to be in high demand in the near future, such degrees will proliferate.

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