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Building the Case for Quantum: Motivating Engineers Towards a Quantum Future

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Abstract

Over the past several decades, quantum technology has become increasingly prevalent and quantum education therefore increasingly relevant to engineers. However, physics education in engineering curricula often ends following electromagnetism, leaving advanced physics topics to physics majors or senior students who actively seek out coursework in, for example, quantum computing. Most engineering graduates are then at a disadvantage to joining a growing quantum workforce or are even unaware that such a sector is available to them.

The barriers to including quantum physics in core engineering curricula are many, from the institutional (e.g., a reduction in science coursework in favor of disciplinary curricula, lack of funding/resources) to the motivational. Here, we focus on the motivational: even when quantum topics are included in required pre-requisite coursework, engineering students early in their academic careers often believe the material is irrelevant to their engineering practice or too challenging. We present a series of case studies designed to rectify these misconceptions and provide sources of both intrinsic and extrinsic motivation for students as they embark on their quantum journeys. Even in cases where quantum topics are not included in the required curriculum, these examples can be included in introductory engineering or physics classes in order to encourage students to seek out quantum in their extracurricular activities or electives. These minimal interventions can help open students' minds to a field that is too often dismissed as "not engineering" and, hopefully, inspire them to participate in a quantum future.

Keywords: Engineering curriculum, Scientific literacy, Quantum mechanics, Motivation

Introduction

As quantum technologies have become increasingly viable, the need for engineers trained to develop and deploy these technologies has become both more pressing and increasingly underserved. Indeed, the share of US job postings soliciting quantum skills tripled from 2011 to 2024 and there are currently more quantum-related job openings than qualified workers [1]. These opportunities are not limited to any single engineering discipline. The thought of quantum technologies may conjure an image of powerful quantum computers, suggesting, for some, that deployable quantum technologies are limited to the domain for electrical engineers. However, modern advances in quantum technology have enabled the development of quantum sensors, imaging, and materials [2], requiring the expertise and guidance of engineers of all fields.

Engineering educators, then, are faced with the challenge of training this quantum-competent workforce. This is a nontrivial challenge with a wide array of obstacles and possible solutions. Who will teach quantum engineering courses? In what department should these courses be housed? What students will take these courses? And, crucially for the present work, what will their prior training in physics look like? Many of these challenges are institutional. The creation of new coursework (or, more boldly, new departments) is resource-intensive, and pressures on the credit-hours available to students can lead to reductions in required science curricula, rather than the increases that would be necessary to adequately prepare students to participate in a quantum future. As a result, many of the existing efforts to integrate quantum education into engineering curricula have been limited to modifications to existing courses or the development of upper-level electives (e.g., [3], [4]).

Efforts to prepare students for a quantum workforce are further complicated by motivational challenges. Anecdotally, engineering students often believe quantum to be irrelevant to their engineering practice or inaccessible to them; there is relatively little research on attitudes in this space, but the existing research does indicate that exposure increases perceived ability and relevance [5]. In the present work, we focus on solutions to this motivational challenge. For those educators inclined to teach quantum coursework to students and with the bandwidth to do so, how can we convince the students that they should care about this material? We base our approaches in prior work on theories of motivation as applied specifically to engineering students and our experience teaching quantum to engineering students. We hope that this work may be used as a framework for the development of relevant and compelling quantum curricula for engineering students.

Motivating engineering students

Many theories of motivation have been proposed and may be used to guide educators as they seek to engage students in new fields. In this section, we will highlight some relevant theories and discuss their application to teaching quantum to engineering students. Motivating factors are commonly divided into the intrinsic and the extrinsic, where intrinsic motivation refers to doing something because it is inherently interesting or enjoyable and extrinsic motivation refers to doing something because it leads to a separable outcome [6], [7]. Intrinsically motivating factors can therefore include things like personal growth, intellectual curiosity, whereas extrinsically motivating factors can include a desire for good grades or a good job. Educators can appeal to both intrinsic and extrinsic motivating factors when teaching quantum.

The proliferation of quantum-related jobs provides clear extrinsic motivation for students. Particularly given the stereotypical view of quantum as mainly relevant to electrical engineering or other quantum computing-related disciplines, we believe that highlighting the broader career opportunities available in this growing field can help extrinsically-motivated students gain interest in quantum coursework. Where possible, faculty should strive to ground their teaching in current opportunities for engineers in the field to provide concrete examples of the possibilities for practice in this area [8], [9]. For example, faculty could discuss topics like quantum sensing and imaging, which are both appropriate in many classes and propose significant advantages as compared to their classical counterparts. Faculty can also provide data on the availability of jobs in the quantum workforce, which span technical roles in hardware, software, and research in many engineering subfields as well as public-facing and business roles (e.g., by pulling resources from [10], [11], [12], [13]).

Self-determination theory posits that intrinsic motivation can be fostered by three psychological needs: autonomy (an individual’s control over their own choices), competence (an individual’s sense that they have the knowledge and skills necessary to succeed), and relatedness (an individual's sense of community and belonging) [14]. While all three are important, we believe that competence and relatedness are particularly critical in teaching quantum to engineering students; commonly, we have heard from students that quantum is too hard for them (i.e., they lack a belief that they have the competency necessary to succeed in the field) or that it is irrelevant to a career as an engineer (i.e., it is insufficiently related to their communities and goals). As a result, many of the interventions we propose in the following sections will be focused on fostering students' senses of competency (for more, see, for example, [15]) and highlighting the many potential career paths in quantum engineering that can serve students' communities and advance their personal goals.

Motivation may also be described using Eccles' expectancy-value theory, an alternative framework for structuring specific activities in and out of the classroom for engineering students engaging with quantum. Expectancy-value theory posits that decisions to engage with specific tasks are informed jointly by competence and value beliefs [16]. As in self-determination theory, competence beliefs center on one's perception of their own ability to succeed in the task, whereas value beliefs address the importance of a given task. A task's value is dependent on many factors, including one's expected enjoyment of performing the task, perceived future importance of the task with respect to one's future goals, the cost of engaging with the activity, and alignment of performing the task with one's self-image [17]. When structuring coursework for engineering students in quantum (or, indeed, in any context), we should seek to make the activities aligned with students' goals and self-image, low-stakes, and, wherever possible, fun.

Case studies

The courses described in this paper are taught at a predominantly undergraduate institution of around 500 engineering students in a major metropolitan area. Currently, degrees are offered in mechanical, civil, electrical, & chemical engineering, as well as computer science. Of these, all students except for those in chemical engineering are required to take three physics courses (Mechanics, Electromagnetic Phenomena, and Modern Physics); the chemical engineers are not required to take Modern Physics. This unique instructional context has afforded us the opportunity to explore how engineering students approach quantum phenomena and the factors that lead them to continue to develop their quantum competency.

Quantum concepts in required courses

In required science and engineering coursework, there are rich opportunities to introduce quantum concepts to students in accessible and exciting ways. Introducing quantum in other courses may support students' senses of quantum competence, as it will demystify this field which so often is thought of as the alien domain of physicists. To that end, we suggest highlighting the role of quantum phenomena in scientific topics that are more familiar to students.

For example, in our electromagnetic phenomena course, we cover mechanical and electromagnetic waves. In this context, we may begin with a demonstration of a vibrating string, fixed at both ends, in a formal treatment of mechanical waves, where only certain resonant frequencies can persist as standing waves due to the perfect conditions of superposition. This is an opportune time to introduce the behavior of bound electrons, such as those in atoms or quantum dots, which are known to exist in discrete energy levels, providing physical intuition for the wave-like nature of quantum particles. Similarly, while treating electromagnetic waves, we characterize the waveform by frequency and wavelength, which form a close relationship to the speed at which the wave carries energy through space; this gives rise to a discussion of the quantized nature of light, where photons carry energy proportional to the frequency of light, according to Planck, and have momentum associated with the wavelength of light, as present by DeBroglie. This organically leads to the discussion of the photoelectric effect and Einstein's Nobel prize winning work. In both cases, we use phenomena that are more accessible to students as entryways into preliminary discussions of quantum concepts. Then, when faced later on with the opportunity to treat quantum more formally, students have a foundation upon which they can build. Developing some comfort with quantum phenomena early in their scientific education thereby facilitates student motivation to engage later on by supporting their competence belief.

The work of introducing quantum phenomena early in science education need not be confined to physics courses. Indeed, there are many potential avenues for inclusion in chemistry, biology, and other required engineering curricula as well. Chemistry instructors could offer quantized energy and angular momentum as an explanation for the systematic structure of atomic orbitals. This leaves room for instructors to even broach the topic of spin, the intrinsic angular momentum of quantum particles, to account for the pairs of electrons in each orbital, therefore illuminating the basis of Pauli Exclusion Principle. When teaching absorption and emission spectra, and the allowed transitions they represent, one can discuss the atom's ability to only absorb and emit whole photons of light whose energy matches that of the quantum jump. Similarly, biology instructors could highlight the quantum mechanical nature of many biological processes, including photosynthesis, cellular respiration, and many modes of sensing (e.g., olfaction, vision, magnetosensation). In a materials science course, a professor could discuss band gap structures as the basis of conductance, the behavior of fermions versus bosons as it relates to superconductivity, or quantum tunneling as it relates to semiconducting materials.

Perhaps most impactfully, engineering instructors may emphasize the existing and emerging applications of quantum mechanics to their own fields. In addition to supporting competence by presenting quantum through more familiar avenues, a treatment of quantum in an engineering context may be particularly important to student motivation given the clear relatedness this treatment would pose. In addition, students are often motivated by opportunities for societal impact and care deeply about ethical uses of emerging technologies. Indeed, if engineering students are driven by a sense of service to their communities rather than passion for science itself, an application-first presentation of quantum phenomena may be especially impactful. Faculty could draw on the many advances made possible by quantum mechanics to excite students to participate in a quantum future, including computing, sensing, communication, medical imaging, energy, pharmaceuticals, materials, and semiconductor devices, amongst many others. These need not be technical treatments, but rather opportunities to empower students with the knowledge of the technological advancements that apply to their own engineering practice and an understanding of where they belong in society.

Modern physics for engineers

In our modern physics course, which is required for and taught exclusively to engineering students, we focus on making the material immediately accessible to increase students' senses of competence. Indeed, opening up a traditional introductory quantum mechanics textbook can be daunting; the postulates and formalism of quantum mechanics can seem like ancient hieroglyphics. We therefore have developed hands-on mechanisms that build intuition for these concepts and are enjoyable to the students, while alluding to the accompanying quantum formalism.

For example, the following activity was developed to help students grasp the probabilistic nature of quantum particles. The activity begins with a straightforward exercise in observing the probability distribution of a six-sided die, modelled as our pretend quantum particle in a superposition state of six possible outcomes. Students perform 50 rolls in a cup and tally up the probability of getting an even number after 5, 10, 25, and 50 rolls, building a probability distribution for the various "states" of the dice roll. Intuitively and from their probability classes, students know that the probability of rolling an even number should be close to 50%. After rolling the die only five times, the probability is far from that prediction, but as the number of rolls increases, the probability typically converges toward this expected value. Many quantum analogies emerge which can elucidate otherwise complex concepts:

- Before lifting the cup and viewing the outcome of the roll, the dice is in a superposition state. We don't know what state it is in until we measure it.
- The probability of getting an even number or an odd number must sum to 1 (normalization condition).
- As we execute more rolls, the probability of it being even or odd approaches one half. Thus, an accurate expected value of the die emerges after more rolls. The true probability distribution would become known only upon an infinite number of rolls.

This activity also facilitates the introduction of other unique quantum phenomena. For instance, when a student's die accidentally flies out of the cup and off the desk, we may discuss quantum tunneling effects. When asked to consider what factors impacted the probability distribution of their "quantum particle", students identify current environmental conditions, like the temperature of the room or obstructions on their desk, and past actions, like how much coffee they drank that morning or how many hours of sleep they had; tracing these external conditions throughout time suggests concepts related to the interconnectedness of open quantum systems. Finally, we can consider what a roll of the die actually means. A roll is not a fundamental quality of the die; instead, it is purely a quantity defined by the way we measure it! This is the true nature of the quantum world and studying quantum mechanics uncovers the mathematical language needed to model this type of behavior. Thus, this simple intervention demystifies many central concepts relevant to quantum systems, building student confidence and intuition for the material.

Quantum electives

Given the motivational importance of alignment between one's personal goals and a given task, we designed a quantum elective for engineering majors focused on emerging applications of quantum technologies, Quantum Entanglement: Theory and Applications. An elective exploring these applications rather than complex derivations may be of particular appeal to engineering students who typically report a desire for practical skills [18]. Furthermore, the deemphasis on extensive formalism and unfamiliar mathematics may also support students' sense of competence in the field.

In this elective, we begin with the targeted goal of enabling students to study emerging quantum technologies that rely on the uniquely quantum resources, coherence and entanglement. We therefore narrow the scope of the full quantum formalism to solely two-level systems, often referred to as "qubits" for their attractive ability to store quantum bits of information. This approach allows us to cover the fundamentals in a mathematically tractable way and quickly equip students with the tools and confidence needed to read scientific journals on current applications.

For example, we studied the time-dependent Schrödinger equation for the case of spin precession of a qubit in a magnetic field, allowing us to visualize the changing phase of the qubit state on the Bloch sphere, and further making the connection to the gates of quantum computing. We seamlessly went from a simple two-state wavefunction to a 2x2 density operator, allowing us to shift focus to the ensemble state of a quantum particle and how to interpret coherence and our ability to store quantum information through controlled unitary evolutions, our quantum gates. However, when acting our gates on a density operator that has zero coherence, a straightforward exercise of matrix multiplication, the unitary evolution returns the same original state–we lose the ability to store or manipulate the quantum information once coherence is lost. This allowed us to quickly turn to what causes decoherence and focus the conversation on open quantum systems and the effects of environmental noise, a key challenge to many proposed quantum technologies. With fairly little time and effort, students were able to grasp the meaning of common quantum buzzwords, develop a basic understanding of current efforts in the field, and understand the relevance of these technologies.

Throughout the semester, students were also asked to study a specific application of quantum mechanics that was of interest to them. Students were encouraged to pick topics that were relevant to their field of engineering or broader society in order to foster both intrinsic motivation (as, in principle, they should particularly enjoy topics related to their field of study) and extrinsic motivation (as these are viable areas that can support their career ambitions); allowing students to choose their own areas of inquiry further supported student autonomy. This past year, one civil engineering major found that quantum sensors can detect pollutants in water at much lower concentrations than what is possible with traditional sensors. He went on to approach his professor in Civil Engineering, who had a shared interest in electrochemical sensing of water pollutants, and will now perform an independent study in quantum sensing versus electrochemical sensing in an interdisciplinary collaboration between the Physics and Civil Engineering departments. As a result, this student has widened his opportunities for innovation and career development, not only in his time as an undergraduate but potentially for years to come.

At the end of the semester, a project symposium was held for all students to present their researched applications in a poster session aimed at engaging all members of the institution, including the engineering, architecture, and art schools. Faculty and students across all disciplines attended, many commenting on how quantum mechanics felt more tangible. This intervention therefore supported all three pillars of self-determination theory, as students had ownership over their own learning processes (autonomy), the material was demystified to themselves and others during the symposium (competence), and the community came together in celebration of this work (relatedness). While the quantum symposium was very successful as part of this semester-long elective, the concept of peer-learning quantum technologies could easily be interwoven into existing course projects and even broader extracurricular clubs and events.

Conclusion

Motivation theory can support educators in effectively engaging with students on any topic, but careful consideration of what drives engineering students is of particular importance in advanced fields like quantum mechanics, where there can be some resistance to learning. By considering jointly the many factors that contribute to extrinsic and intrinsic motivation, we have identified some key components in attracting students to consider participating in a quantum future.

First, we note that the many exciting developments in the field of quantum engineering provide impetus for a renewed or novel push towards including quantum in engineering curricula, as well as rich inspiration for extrinsic motivation. Currently, there are more jobs in quantum engineering than qualified engineers, making this a secure career path for future engineers. As a result, we recommend highlighting the wide range of engineering related to quantum applications, including imaging, sensing, computing, computation, security, and materials, amongst others, in order to foster extrinsic motivation.

Second, basing our treatment primarily in self-determination theory, we find that feeling of competency and relatedness are key components in driving intrinsic motivation for quantum. Unfortunate stereotypes about quantum tend to suppress competence beliefs in students; the sense that quantum is prohibitively complicated and therefore inaccessible to engineering students or irrelevant to their engineering practice is prevalent and can keep students from opening themselves to the possibilities in this area. As a result, we have developed mechanisms of demystifying quantum early in students' academic careers (e.g., in introductory science and engineering courses). By broaching these topics early, we can prevent these stereotypes from taking hold of students and empower them to explore innovative ways of applying quantum applications in their own field. Furthermore, we provide avenues for the development of quantum intuition, such that students can maintain access to the material even as the mathematics becomes more advanced. We also note the potential links between relatedness as a driver for intrinsic motivation in self-determination theory and certain value beliefs in expectancy-value theory; students are more motivated to engage with work that they find enjoyable and that connect them to their communities. As a result, we recommend constructing activities and events that facilitate collaboration, engagement, and, wherever possible, fun.

Finally, we find that open-ended research projects are particularly beneficial in fostering intrinsic motivation as defined by the factors of self-determination theory. Open-ended projects allow students to take ownership over their learning, thereby increasing student autonomy. Further, they gain entry into the material through areas of their own interest, supporting their competency in the field; they enter with a sense of possibility, rather than opening a textbook to a page of rigorous mathematics and physics that is hard to relate to. Finally, avenues for collaboration or sharing their findings (e.g., symposia) provide opportunities to increase relatedness and community within the context of quantum mechanics. These projects can be fairly minimal interventions, allow for broad coverage of the current quantum landscape, and encourage peer-to-peer learning.

As quantum engineering blossoms in academia and beyond, it is more important than ever to equip students with the skills necessary to engage with quantum. We hope that the principles and interventions described in this work can support instructors who wish to usher students into this quantum future.

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