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Incorporating Quantum Technologies into Engineering Curriculum

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Abstract: This paper first reviews the present status of quantum technologies that are rapidly making inroads to various fields of science and engineering. The author then suggests, in light of these developments, how one may incorporate the key principles, ideas, and topics of new quantum technologies into undergraduate quantum mechanics courses and laboratories to prepare and equip future engineers. Concrete examples of curriculum changes in modern physics, quantum mechanics, and advanced quantum mechanics courses are presented based on three years of experimentation of a new curriculum. The author finds that these changes have an additional benefit to engineering students as the topics bring together a number of once disparate areas of science and technologies such as electronics, optics, atomic physics, and computer and information sciences.

Introduction

Quantum mechanics, first formulated about 90 years ago, has not only revolutionized our scientific understanding of the world but also changed completely our technological landscapes by ushering in the age of electronics and information. Behind these technological achievements, often typified by the remarkable success of Moor's Law for the last five decades, are relentless engineering efforts that have driven these advances.

Far from plateauing at the current technological height, we are observing another wave of technological advances based on what some call the Second Quantum Revolution. [1] These quantum technologies are often referred to as a class of technologies that directly create, manipulate, and make use of the quantum properties of matter at the level of individual photons, atoms, electron spins, and exploit collective and entanglement quantum properties of matter.

For the last 30 years or so, the research in these areas have moved from theoretical explorations to experimental confirmations to realizations of prototype applications in diverse areas of technologies. These include, but are not limited to, quantum cryptography, quantum sensing and imaging, high-capacity communication, quantum computing, photonics and spintronics, nanomechanical devices, materials engineering, precision measurements, and energy and space savings in designs. Some of these quantum technologies have already entered the commercialization stage.

Many national and intergovernmental institutions [2]; US government agencies such as NSA, NASA, DOE, DOD, NIST, NSF; leading technology firms such as Microsoft, Google, Intel, IBM, Lockheed Martin, and many others; and research institutions around the world [3] are taking serious initiatives in engineering quantum technologies as they expect that these new technologies will revolutionize the landscape of 21st century technologies with their superior characteristics and capabilities. [4] It is very appropriate and timely, therefore, that a recent cover story of ASEE's PRISM magazine featured *Quantum Leap*. The article captured some of the transformational developments in new quantum information science and rightly recognized the needs to prepare engineers for these rapid advances. The article concludes with the quote; "As universities, government agencies, industry giants, and new start-ups explore quantum technologies, 'the future looks very bright for quantum engineers'. 'The sky's the limit.'" [5]

Wanted: Quantum Engineers

Are we adequately preparing our engineering students for this future? The author believes that typical quantum physics courses we offer to engineering students are not even adequate for the *existing* technologies that have brought us the Information Age, much less in preparing our students for another big transformation we are currently witnessing.

As it will be clear in the next sections summarizing key developments and identifying relevant areas of knowledge, these new quantum technologies often require an interdisciplinary and integrative understanding of quantum physics and related engineering disciplines. Students in the fields of Engineering Physics, Electrical and Electronics Engineering, Materials Engineering, Systems Engineering, Optical and Communication Engineering, and Computer Science and Engineering are expected to face these changes in the very near future.

For this reason, some universities have started to offer comprehensive Ph.D. programs in quantum engineering. [6] As University of Bristol's doctoral program in quantum engineering states, "Quantum Engineering encompasses both fundamental physics and the broad engineering skill-set necessary to meet the practical challenges of the future …A quantum engineer will be fluent in quantum mechanics, electrical and electronic engineering, systems engineering and computer science as well as other physical sciences." [7]

Some undergraduate physics programs now offer, in addition to the traditional quantum mechanics, key interdisciplinary topics related to quantum physics as well. One such topic is Physics of Quantum Information in which students are introduced to such topics as quantum computation, quantum cryptography, entanglement-based precision measurements, and high-capacity communications. They also offer tools to undergraduate students that are necessary to understand these relatively new topics. Some of the more recently published undergraduate textbooks in quantum mechanics rightly adopt such topics. [8]

Overview of the Current Frontlines in Quantum Technologies

In some sense, quantum technologies are not new. The remarkable developments we had for the last several decades in the areas of computer chip manufacturing, medical equipment such as Magnetic Resonance Imaging (MRI), precision scientific tools such as the Scanning Tunneling Microscope (STM), the Atomic Force Microscope (AFM), SQUID magnetometers, optical tweezers, lasers, electronics, and modern communications technology wouldn't have been there without exploiting the remarkable nature of quantum mechanics. On the other hand, we came a long way to understand some of the puzzling -- even to Einstein -- but fundamental aspects of physics such as quantum entanglement and "macroscopic" collective quantum phenomena. These new understandings combined with the technological advances that enable us to manipulate matter at the level of individual atoms or artificial "atoms," electrons and photons have opened the door to whole new opportunities. While we do not know where this new knowledge and technology will eventually take us, it became clear even at this rather early stage of development that some very important areas of applications are already making inroads to key areas of technologies thanks to the rapid advances made in these fields in the last 30 years or so. [9]

Quantum Physics and Computer & Communications Engineering

The success of Moor's Law for the last five decades has been the driving force for many technological advances we have experienced. [10] Intel's recent decision to build a $7 billion new 7 *nm* chip manufacturing facility in Arizona will help continue the Moor's Law's remarkable feat. [11] As we push Moor's Law to the limit, quantum mechanical properties become more and more dominant. Engineers need to overcome various quantum limits in their pursuit of the fabrications of materials in ever finer scales. The current frontiers include, but are not limited to, the use of new technologies involving quantum dots, quantum well lasers, atom optics, extreme ultraviolet (EUV) lithography, etc. Entanglement-enhanced lithography is also in sight.

Knowledge of quantum physics is essential in modern communication technologies. Quantum well (QW) devices provide such an example. QW devices feature very thin epitaxial layers of semiconductor materials that are grown using techniques like molecular beam epitaxy. These devices can be integrated with various optoelectronic devices to provide photonic integrated circuits with increased functionality. They are widely used in lasers, photodetectors, modulators, and switches. QW also operates much faster with much less manufacturing costs. These advantages are of great importance to the telecommunication and computer industry. QW semiconductor lasers have also become the key to many optoelectronic applications including material processing, medical therapy, single-mode, single-frequency sources for telecommunications, among many others. [12]

Among the most critical engineering problems we are faced with in this information age is what is often cited as "the Big Data problem." Three big questions are involved in it. Firstly, how can we meet the rapid demands of communication capacity? Secondly, how do we choose the information we need from the information deluge? Thirdly, how may we protect our private information? Each of these problems are a major issue by themselves and are still related to many other issues. For instance, large data storage and increased communication capacity require a rapid increase in energy use. According to the Natural Resources Defense Council, "US data center electricity consumption is projected to increase to roughly 140 billion kilowatt-hours annually by 2020, the equivalent annual output of 50 power plants, costing American businesses $13 billion annually in electricity bills and emitting nearly 100 million metric tons of carbon pollution per year." [13] How may we reduce electric consumption while increasing capacity in storage and communication? Finding the right data involves not only increased search capacity but also involves advanced artificial intelligence (AI). Can we find a more effective and powerful AI scheme than traditional computing can offer? Shor's algorithm has shown that quantum computers can break cryptographic protocols like RSA that are commonly used today in bank transactions and national security systems. How may we then protect our data from potential codebreakers?

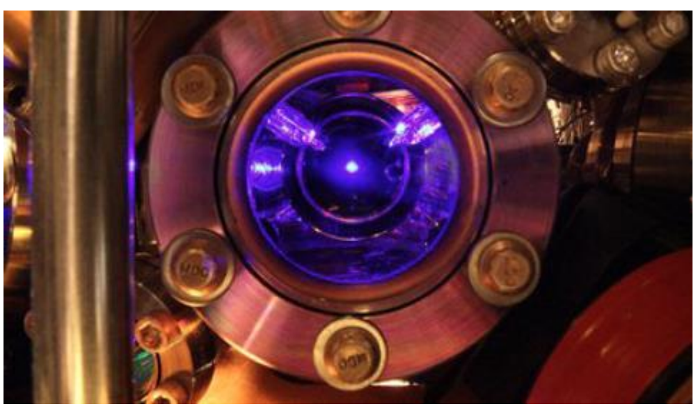
Quantum Entanglement

At the heart of many breakthrough applications of quantum information science lies the phenomenon called quantum entanglement. It is a feature of some many-body quantum systems which Einstein once considered too “spooky” to be real. Since the discovery of Bell’s theorem, many experiments confirmed this remarkable feature of quantum mechanics. Soon after, people like David Deutsch, Charles Bennett, and other pioneers have come up with ideas for how this property may be used in a number of important applications. [14] Now it is known to be a powerful means to make super-sensing devices, produce totally secure public key distribution, and achieve rapid and dense communications. As these technologies are expected to produce more secure, faster, smaller, cheaper alternatives to the present technologies, we are expected to be a big step closer to resolving the three major issues of the Big Data problem stated above. Quantum technologies will allow significant savings in energy and space through engineering designs.

Quantum entanglements of particles and their behaviors are well explored theoretically. Now, physicists and engineers experimentally have come up with varieties of entangled states. Multi-particle entanglements were realized among atoms and photons in a microwave cavity, among trapped ions, and among artificial-atoms. It is also achieved in integrated circuits. [15]

The power of quantum entanglement is being harnessed for many different technological developments. Here we are presenting three major areas of applications: quantum sensing and imaging, quantum communications and cryptography, and quantum information processing and computing.

1. Quantum Sensing and Imaging



A strontium clock, unveiled by NIST and JILA in January 2014, keeps accurate time for the next 5 billion years. (The Ye group and Brad Baxley, JILA)

Earlier, we have discussed the use of quantum mechanics in precision measurements and imaging such as MRI, STM, AFM, SQUID, etc. Entanglement systems can significantly enhance the precision of many measuring schemes and devices.

Currently, the most precise atomic clocks monitor the specific radiation frequency needed for electrons to jump between energy levels. The strontium clock at the U.S. National Institute of Standards and Technology (NIST) in Colorado revealed in 2014 is accurate up to 1 second in 5 billion years. The problem that remains is that the atomic clock depends on where it is located.

This could be a source of problems for GPS navigation, telecommunications and large-scale surveying. Entanglement can solve this problem, as it will effectively bring together different atoms as a single clock, allowing the system to measure the passage of time independently of locations. [16]

In 2014, Ono et al. from Hokkaido University developed the world's first entanglement-enhanced microscope. The microscope made use of two entangled beams of photons aimed at a substance and measure the interference pattern in the reflected beams. The use of entanglement significantly increases the information content gathered as the measurement of one photon will give you information about the other. This technology has a great potential in medical use where non-invasive, real-time imaging of a living organism is desirable. [17] Similar techniques in astronomy are expected to improve the performance of interferometers in astronomy. For instance, while LIGO finally detected gravitational waves from colliding black holes in 2015 using Michelson interferometers, entanglement enhanced interferometry can help detect weaker gravitational waves. [18]

2. Quantum Communications & Cryptography

Entanglement is known to improve substantially the quality and quantity of the transmission of information through new technological schemes that use the characteristics of quantum mechanics such as super-dense coding, quantum teleportation, and high-capacity optical communications using hyper-entanglements. [19] The current record for the distance of teleportation in open air is 143 km. It is now being tested over the satellites between Beijing and Vienna. [20]

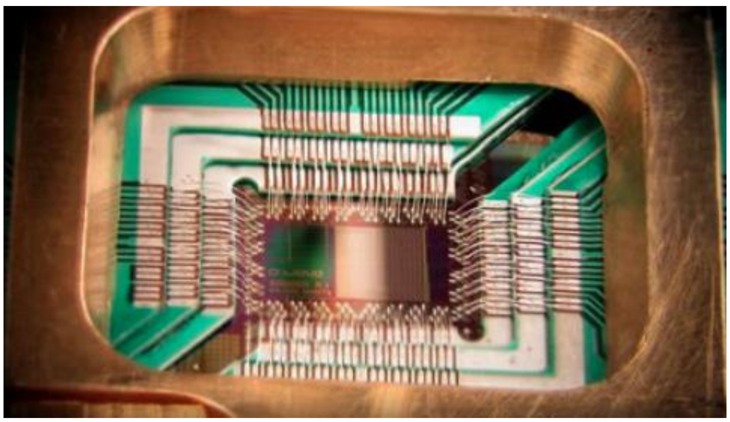
Classical encryption schemes may be broken in principle for two major reasons: Firstly, it makes use of pseudo random numbers rather than true random numbers. All pseudo random number generations rely on hard-to-crack schemes. However, it has been shown that quantum computers can crack such schemes. Secondly, classical bits can be cloned. Therefore, the interception of an eavesdropper can go, in principle, undetected. Entanglement based QKD can potentially provide a perfectly secure transmission of information as it makes use of both true random numbers and the "no-cloning" property of quantum systems. [21]

Companies like Toshiba and BBN Technologies have built their secure networks using QKD technology. The first bank transfer was made using QKD in Austria in 2004. Switzerland tried QKD to provide a tamper-proof voting system in 2007. As the photon pairs used in QKD are entangled, any interception made to one of the pair would be immediately apparent to the key-holder who is observing the system.

3. Quantum Information Processing and Computing

Ever since Feynman alluded to the future possibility of a quantum simulation of a complex many-body problem exploiting the quantum nature of atoms and particles, skepticism has abounded concerning the possibility of actually building a quantum computer. This is due to the very fragile nature of quantum coherence due to its interaction with the environment. This phenomenon of decoherence is still the number one enemy of processing quantum information and building quantum computers. However, researchers in the field have overcome the problem significantly with the discovery of effective schemes of quantum error correction and fault-tolerant quantum computation. Along with many other parallel technological developments relevant to quantum computing, now the realization of this powerful quantum computer is in sight.

Quantum algorithms have an ability to address computational complexity superior to that of classical algorithms. Shor's integer factorization algorithm is one such powerful example. It has shown that quantum computers can break a class of classical coding schemes such as RSA. Grover's search algorithm is another such example which shows that quantum computers can give us a quadratic speed-up over the best possible algorithm classical computers can offer.



A close-up of a D-Wave One computer chip. (D-Wave Systems, Inc.)

This field is still in development, but the developments are speeding up. In 2011, D-Wave Systems produced the world's first commercially available quantum computers: D-Wave One. NASA and Google have recently teamed up to form the Quantum Artificial Intelligence Lab based on a D-Wave Two. In March 2016, MIT and the University of Innsbruck in Austria realized Shor's algorithm to carry out factoring. [22] In mid-2016, the first fully programmable and reconfigurable computer using trapped ions was developed at the Quantum Engineering Center at University of Maryland, College Park team. [23] One can even now play with 5 qubits quantum computing online at IBM's Quantum Experience website. [24]

Many experts in the field believe that we will very soon have few tens of qubits, probably not with all of them individually under control yet, but with which one could make quantum simulations or work on dedicated quantum algorithms. Until we find a suitable material platform for more stable quantum information processes, the realization of a universal quantum computer may still be some distance away. However, with recent technological advances in fabrication and trapping, key candidate platforms seem to be emerging. Among them are superconducting qubits, ion trapped qubits, and hybrid systems that make use of chip-based atomic physics. [25]

Implications of New Developments in Quantum Technologies for Engineering Curriculum

The explosive new developments in quantum technologies described above force us to rethink the present quantum mechanics courses for engineering students. As there are a number of good graduate programs that educate and train the future leaders in quantum technologies, in the discussion that follows, we will limit our discussions to undergraduate courses in quantum physics for students in the fields of Engineering Physics, Electrical and Electronics Engineering, Materials Engineering, Systems Engineering, Optical and Communication Engineering, and Computer Science and Engineering.

A few important observations may be made before we jump into a more detailed discussion of potential curriculum and/or course revision. First of all, given the non-intuitive nature of quantum mechanics, it would be best to introduce students to quantum mechanics as early as possible. Secondly, priorities must be established as there are too many interesting quantum phenomena to be learned. The priorities should be given to broader areas of quantum physics and quantum technology which students are more likely to encounter in their near future. Thirdly, quantum mechanics needs to be taught in a broader context. New quantum technologies often require interdisciplinary and integrative understanding of physics and related disciplines such as computer sciences and electrical and materials engineering.

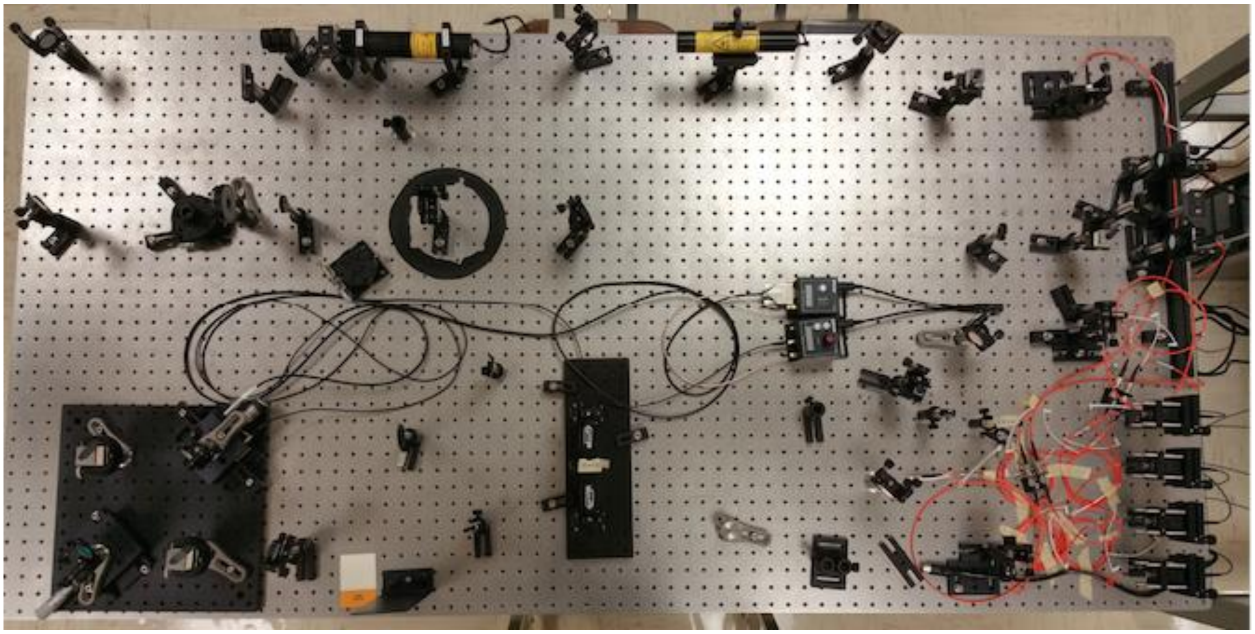
Curriculum Revision

In light of these considerations, we determined that our traditional quantum mechanics curriculum presented to engineering students is not sufficient and that major changes are required. We have redesigned the teaching sequence and contents of quantum mechanics courses following the observations made above. In general, any new topics in the curriculum are introduced with three elements: (1) a brief introduction to the topic in connection with what they have already learned, (2) the main body of the topic, and (3) a brief mention of how the topic may be potentially related to what students will encounter in the future courses or in their future careers.

To support our new curriculum in quantum mechanics, we have set up the Quantum Information Lab (QIL) to complement our traditional quantum mechanics experiments. There are three major reasons to choose quantum optics as a pedagogical tool for quantum technologies: Firstly, the scale of experiments and instruments are large enough for students to see what is going on. The polarizations of photons are also easier for mental visualization. Secondly, as we have listed them in this paper, a relatively simple set up, with only minor variations, allows different types of experiments. Finally, it is relatively affordable. We took advantage of the recent significant drop in prices of instruments that are necessary to build the system. The initial installation of the lab from scratch – with almost all new equipment – cost us less than $50K. This is largely due to a big drop in prices of single-photon detectors and solid-state lasers. We particularly would like to acknowledge the efforts made by the Advanced Laboratory Physics Association (ALPhA) in negotiating with Exclitas, a manufacturer of high quality single-photon detectors. ALPhA also supports the Laboratory Immersions program that provides university instructors with two to three days of intensive hands-on work that helps them to “learn new advanced experiments well enough to teach them.” The immersions program often offers low-cost, creative alternatives to very high-cost lab equipment. [26]

The QIL was initially equipped with an optics table, a 405*nm* laser, a He-Ne laser, BBO crystals for Type-I parametric down conversion, key optical elements, 4 single-photon detectors, a DE2 control board, and a LabVIEW program. We later added another optics table to accommodate active research by upper-level students. The lab turned out to be a big success in helping students

(1) understand the nature of quantum mechanics better in the introduction stage and (2) have hands-on experiments in quantum information systems in the advanced stage.



Quantum random number generation experiment set up (the upper and right sections) in our Quantum Information Lab

Introduction to Quantum Mechanics

Because of the non-intuitive nature of quantum mechanics, we started to introduce quantum mechanical formalism early in the third semester when students are first introduced to the topics of modern physics in University Physics III. By that time, students have studied a few key topics relevant to the introduction to quantum physics: the introductory physics based on the idea of particles (i.e., Newtonian physics in University Physics I), the introductory physics based on the idea of waves (i.e., Electricity and Magnetism in University Physics II), and some basics of computer programming (i.e., classical bits, universal logic gates, etc. in the Introduction to Engineering course).

When introducing quantum mechanics to students for the first time, instead of starting with rather detailed accounts of the historical introduction that begins with Planck's discovery of the quanta of radiation, we start directly with the idea of the particle-wave duality. The philosophy behind this decision to drop much of the historical account – while keeping a much shorter historical account of the early quantum revolution – is that when a discipline is mature and large enough, one needs to have a more systematic introduction to the discipline. For example, while the historical accounts of scientific revolution at the time of Copernicus, Kepler, Galileo, and Newton are very significant, we do not introduce these historical accounts in our physics text book. Rather, we directly begin the course with key physical concepts such as vectors, forces, and Newton's Laws. I think it is about time that we should take a similar approach to quantum mechanics. To me, it was a delight to see that some authors of more recent textbooks in quantum mechanics take such an approach. [27, 28]

In this revision, we have kept some of the key "historical" experiments that are also practically important -- such as the photoelectric effect, electron diffractions, etc. However, we skipped a number of historical discussions such as Frank-Hertz, Davisson-Germer experiments, etc. to have more time to introduce early on the Heisenberg-Dirac matrix formalism alongside Schrödinger's wave function formalism. It was, in our opinion, a necessary trade off. As students are just coming out of electricity and magnetism, which deals with light as a transverse wave, it is easy to introduce both Schrödinger's point of view *via* a single-photon version of the double-slit experiment and the matrix mechanics using the transverse nature of polarization of light. We also show how these two formalisms are conceptually "equivalent," lest they should think that they are two different *independent* approaches to quantum mechanics. The matrix formalism will later provide the natural connecting point with the intermediate quantum mechanics course where we begin with the analysis of various Stern-Gerlach experiments using Pauli matrices.

After introducing the basic quantum mechanical formalisms and the uncertainty principle through the dual "wave-particle" nature of matter, we introduce the subsequent topics in the following order: The Bohr atom, energy levels, atomic spectra, molecular bonding, structure of solids, band theories, semiconductors, quantum wells, wires and dots, superconductors, and their applications to various technological advancements, structure of an atom, nuclei and quarks, the strong and weak forces, radioactivity, nuclear fission and fusion, and brief mention of the standard model of particle physics. We add a brief, non-technical introduction to the Quantum Information and Quantum Computation to keep the excitement going (e.g. a conceptual introduction to the quantum bomb detector and the quantum eraser).

During this introduction, students perform the photoelectric effect experiment, Millikan's oil drop experiment, radiation analysis, spectral analysis of atoms and molecules, and observe the light quanta through the Grangier experiment, and start to use the matrix mechanics for single-photon Mach-Zehnder interferometer. In performing the last two experiments, we have benefitted significantly from the experimental designs and online resources provided by Mark Beck. [29]

Intermediate Quantum Mechanics

By the time students take the first serious Quantum Mechanics course, students have studied Linear Algebra and Electrical Circuits. This allows us to introduce the basic contents of Quantum Information systems as well. To go with the revised curriculum, we have adopted the textbook by John Townsend: *A Modern Approach to Quantum Mechanics*, 2^{nd} ed. as we have found that the contents of the textbook is very much in line with our new curriculum. [30] The text starts with an experiment-based introduction to the quantum state vector with Stern-Gerlach experiments. Then basic mathematical machinery of matrix mechanics is introduced through rotational and projection operators, matrix representations of operators, how to change representations and obtain expectation values.

The rest of the contents are introduced in the following order: angular momentum, eigenvalues and eigenstates of angular momentum, the harmonic oscillator, the raising and lowering operators, coherent states, eigenvalue problems of spin-1/2 and spin-1 particles, the time evolution of quantum systems, the precession of a spin-1/2 particle in a magnetic field, NMR, a system of two spin-1/2 particles, the addition of angular momenta for two spin-1/2 particles, the

Einstein-Podolsky-Rosen “Paradox,” quantum entanglement, quantum teleportation. We then reintroduce Schrödinger’s wave function as position eigenstates. It is followed by the discussion of position and momentum states, and their application to scattering problems. We have skipped some topics of more theoretical nature – for instance, the discussion of Path Integrals – to have more time for other topics such as Photon-Atom interactions and to introduce topics such as Lasers, Electron Gas models, and basic ideas of quantum information. We briefly introduce a density matrix formalism as it is essential to quantum information and quantum computation.

Besides our existing lab experiments on thin-film growing, STM analysis, NMR analysis, etc., we have added three experiments from our new QIL: (1) Quantum random number generator, (2) Coincidence measurements of entangled photons, and (3) Quantum eraser using entangled photons. Students usually find the entanglement–based quantum eraser to be the most striking.

Advanced Quantum Mechanics

Advanced Quantum Mechanics is required for physics and engineering physics students but is not required for general engineering students. However, we strongly recommend it to students who plan to work in the fields of materials and electrical engineering. The topics of this upper-level course should depend on the strength of each institution. Our focus is on quantum mechanical topics relevant to three major areas: condensed matter, quantum optics, and quantum information.

Rather than going through another layer of general foundations of quantum mechanics, we decided to explore some of the key state-of-the-art topics such as high-temperature superconductivity, quantum-mechatronics, laser cooling and atom optics, ion-trap qubits, superconducting qubits, hyper-entanglements and high-capacity communications, quantum teleportation and quantum computing. These include both theoretical explorations such as basic quantum circuits and many-body entanglements such as GHZ and W states [31] and basic manipulation of quantum information. The philosophy behind this choice is that (1) any of these advanced fields will require its own rigorous training at the graduate level anyway and that (2) we would like to prepare our students to be more interdisciplinary in light of our earlier assessment that future quantum technologies will be more and more interdisciplinary.

For the advanced labs, we offer research related to nanotech and quantum optics. For quantum information experiments, while it is not reality yet, with little tweaks, QIL can accommodate a number of advanced experiments such as building key quantum gates such as C-Not, square-root-of-not gate, entanglement swapping, hyper-entanglement, cryptography based on Ekert91 protocol, and quantum teleportation. In teaching quantum information and computation, we have benefited from some new and fairly accessible introductory textbooks on the topics by Michel Le Bellac [27] and by Jones and Jaksch. [28]

Key Pedagogical Resources

While there are many good pedagogical resources out there, the author would like to point out two very practically helpful resources for developing hands-on quantum experiments. Setting up our Quantum Information Lab was only possible because of the available resources such as Mark Beck’s Modern Undergraduate Quantum Mechanics Experiments website. It contained almost all the information needed to run seven different quantum experiments, including parts lists and LabVIEW vi's. [32] The author found it relatively easy to tweak and upgrade some of these experiments to perform other very interesting experiments in quantum information such as quantum random number generator, quantum gates, hyper-entanglement, and entanglement swapping.

Another very helpful practical resource for pedagogy in advanced quantum technologies is the Advanced Laboratory Physics Association (ALPhA) mentioned earlier. [26] Their strength is two-fold. They not only provide individual hands-on experience at low cost, but also help people to build low-cost alternatives to otherwise expensive high-tech equipment. Some of the ALPhA lab immersion programs include: low-cost femto-second laser construction, multiphoton microscopy with a compact fiber laser, low cost ultrafast optics with a mode-locked erbium fiber laser, electrodynamic ion trapping, precision measurements using laser interferometry, diode laser spectroscopy, high-Tc superconductivity, and electron spin resonance.

Conclusion

It is the author's view that the second wave of quantum revolution is really upon us. While it is difficult to predict how far-reaching its impacts on society will be or to know which areas of quantum technologies will turn out to be most fruitful, the new body of knowledge in quantum technologies is increasing very rapidly. For the last three years, we have carried out a revised curriculum in undergraduate quantum mechanics that would better prepare our students in this new environment. As the course contents have become more interdisciplinary, we have strived to maintain coherence and tried to strike a balance between the breadth and the depth in the curriculum.

Our own initial assessment of this pedagogical revision was satisfactory. The majority of students who studied under the new curriculum moved on to some of the nation's top graduate programs in materials engineering, photonics, high-temp superconductors, electrical engineering, and physics. They understood quantum physics better than their predecessors. [33] However, that is no proof that our new curriculum is adequate in preparing students in engineering well enough to take on the challenges ahead of them. It is the author's hope that this paper will stimulate further discussions and collaborations so that we may provide better education to our engineering students.

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[3] Major research institutions around the world are racing toward the top in these new fields of research. There are too many of them to list here. One notable phenomenon is that some countries that were not traditionally at the top of scientific research are now leading the efforts in

these fields with strong supports from their governments and industries. Some of these examples are Center for Quantum Technologies in University of Singapore, China National University of Defense Technology in Changsha, China, University of Science and Technology of China, University of Waterloo and University of Calgary in Canada. University of Innsbruck in Austria, etc. Canada was the first in producing commercial quantum computers from *D-Wave*, China is working toward building "quantum Internet." There are many spin-offs from these leading institutes. The *ionQ*, a spin-off from University of Maryland, and *PsiCorp*, a spin-off from University of Bristol are among such examples.

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[31] The implications of these maximal many-particle entangled states are not fully understood yet. Greenberger, Horne, Zeilinger have discovered the GHZ states; Cirac, Vedral et al. have discovered the W states.

[32] http://people.whitman.edu/~beckmk/QM/

[33] This observation is from the simple fact that these students studied quantum physics and technologies at the level significantly higher than their predecessors did and have shown the mastery of the topics through exams, lab performances, and their senior honors theses.