The Quantum for All Project: Professional Development Model and Teacher Outcomes

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Abstract. The Quantum for All project has developed instructional materials and a professional development program to expand Quantum Information Science education in precollege education. In this paper, we discuss the background for Quantum Science education in the United States. We then discuss the design of the professional development plan and the development of the materials by the Leadership Team, and the workshops for teachers to learn and utilize this content. We will examine growth in teacher knowledge and confidence and examine the variation of these things across content domains as represented by the instructional modules.

1. Why teach Quantum Information Science?

Quantum Information Science (QIS) will play a critical role in security and economic prosperity throughout society in the future. QIS will play an increasingly important role in the workplace even among non-STEM careers [1]. The United States passed the National Quantum Initiative Act in January 2019 as a means to expand the nation's commitment to QIS by investing in the development of QIS and technology workforce pipelines. Many relevant documents about this effort are available at the National Quantum Initiative website [2]. An important aspect of this initiative is the need to expand education on QIS topics in precollege education and provide students with appropriate knowledge about content and applications of QIS, since currently there is no clearly defined set of career paths for the Science, Technology, Engineering, and Math (STEM) workforce pipeline to pursue that contains specific QIS connections.

Schools generally do not incorporate QIS-related instruction for several reasons. First, many teachers (and school systems) do not understand how the "abstract" quantum concepts are relevant to their classrooms, student careers, or the economy in general. Teachers themselves lack preparation or background in quantum mechanics as well as pedagogical models to teach these concepts to K-12 students. In addition, there is a general lack of age-appropriate resources that have been specifically designed to incorporate content, pedagogy, technology, and other disciplines (STEM), and which are also affordable given the equipment necessary to provide hands on learning experiences for students in the classroom. Finally, teachers are unclear how to connect QIS instruction to the various state and national science education standards that guide education in the US. Consequently, QIS has been largely ignored by precollege educators.

The Quantum for All Students (QAS) is a project funded by the US National Science Foundation (#2048691) to address the need for QIS education in High Schools. The targeted audience comprise secondary STEM educators and students, specifically grades 9-12. The content of QIS was taught using fully integrated STEM lessons that were based on existing materials as modified and adapted by the project Leadership Team (to be discussed in more detail below). The aim of the project was to set up and test a professional development model for teachers to incorporate QIS to into regular STEM classes.

2. State and National Education Standards

Education in the United States is extremely decentralized compared to that in other countries around the world. The basic administrative unit, the Local Education Agency (LEA), administers public schools within a particular area, which can vary widely is size depending on the state. Some LEAs constitute entire counties (such as in Maryland or Florida), while others can be very small, sometimes just a few schools (or even just one). For example, New Jersey, with a K-12 student population of almost 1.4 million students in 2024 has 697 LEAs, while Texas, with 5.9 million K-12 students, has about 1200 LEAs. However, in all cases the LEA is the basic unit for establishing the curriculum in the schools under its purview.

While LEAs are basically independent entities with great flexibility, they are responsible to the state for student progress as measured on state assessments, which in turn are based on state education standards. Traditionally, each state develops its own standards and assessments, as well as other requirements for students, such as number and type of different courses required for high school graduation. In the 1990's there was a movement to develop national documents to help guide this process, like the AAAS Project 2061 documents [3], but states still developed independent standards, with content sometimes rather different than what the AAAS documents suggested.

The National Governors Association decided that a more comprehensive and utilizable document was needed that built on previous documents like the AAAS Project 2061 documents. The US National Academy of Science was commissioned to develop a *Framework for Science Education* [4], which identified content students should know and when, following the most up to date research in science education. The *Framework* was turned over to a writing team (including author R. Lopez in the leadership team) to take the narrative and turn it into a set of standards that could be assessed. This document, the Next Generation Science Standards (NGSS), was released after a couple of years of work [5], and it was designed to be a set of standards that could be adopted wholesale by states. As of early 2025, 20 states plus the District of Columbia had adopted the NGSS, and a further 24 states had developed state science standards that are heavily influenced by the NGSS. The standards themselves are written as a set of performance expectations, combining Disciplinary Core Ideas, Science and Engineering Practices, and Cross-Cutting Concepts. More recently, there has been an unofficial effort to develop standards for QIS education [6], but for the time being, curriculum selected by LEAs will be driven by NGSS and state standards.

The NGSS were envisioned as a floor, identifying what all students should know and be able to do in science by the end of K-12 education. Since the NGSS are intended for all students, QIS concepts already in the NGSS would have the best chance of making their way into the classroom given the widespread influence of the document. The standards are labeled by grade band and topic. For example, HS-PS4-1, stands for High School, Physical Science, section 4 (waves), standard 1. The standards in the NGSS that have a direct connection to QIS, and which are the topics most likely to be integrated into High School instruction are listed below. It is worthwhile to note that these topics were not generally part of state standards previously, so inclusion in the NGSS represents an advance in getting QIS into the High School curriculum.

- Electromagnetic waves and Photons - HS-PS4-1, HS-PS4-3
- Using EM radiation for communication - HS-PS4-2, HS-PS4-5
- Spectra of atoms - HS-ESS1-2
- Radioactive decay - HS-PS1-8

Figure 1 presents an example of one of these standards, HS-PS4-1. The main, assessable, performance expectation is that students "*Evaluate the claims, evidence, and reasoning behind the idea* *that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other*." Example of phenomena include interference (wave model) and the photoelectric effect (particle model). The quantum hypothesis is a fundamental QIS concept, and although the Assessment Boundary places quantum theory (beyond photons) as being beyond the standard, the NGSS represents a floor, not a ceiling in science education. Providing teachers with a rationale for including QIS topics, which also contribute to meeting state standards was an important aspect of the professional development provided by the project.

Students who demonstrate understanding can:

HS-PS4-3. **Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.** [Clarification Statement: Emphasis is on how the experimental evidence supports the claim and how a theory is generally modified in light of new evidence. Examples of a phenomenon could include resonance, interference, diffraction, and photoelectric effect.] [*Assessment Boundary: Assessment does not include using quantum theory.*]

The performance expectation above was developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Engaging in Argument from Evidence Engaging in argument from evidence in 9–12 builds on K–8 experiences and progresses to using appropriate and sufficient evidence and scientific reasoning to defend and critique claims and explanations about natural and designed worlds. Arguments may also come from current scientific or historical episodes in science. • Evaluate the claims, evidence, and reasoning behind currently accepted explanations or solutions to determine the merits of arguments. - - - - - - - - - - - - - - - - - - ***Connections to Nature of Science*** **Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena** • A scientific theory is a substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment and the science community validates each theory before it is accepted. If new evidence is discovered that the theory does not accommodate, the theory is generally modified in light of this new evidence.	**PS4.A: Wave Properties** • [From the 3–5 grade band endpoints] Waves can add or cancel one another as they cross, depending on their relative phase (i.e., relative position of peaks and troughs of the waves), but they emerge unaffected by each other. (Boundary: The discussion at this grade level is qualitative only; it can be based on the fact that two different sounds can pass a location in different directions without getting mixed up.) **PS4.B: Electromagnetic Radiation** • Electromagnetic radiation (e.g., radio, microwaves, light) can be modeled as a wave of changing electric and magnetic fields or as particles called photons. The wave model is useful for explaining many features of electromagnetic radiation, and the particle model explains other features.	**Systems and System Models** • Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions—including energy, matter, and information flows—within and between systems at different scales.

Connections to other DCIs in this grade-band:
HS.PS3.D ; **HS.ESS1.A** ; **HS.ESS2.D**

Articulation of DCIs across grade-bands:
MS.PS4.B

Common Core State Standards Connections:
ELA/Literacy -

RST.9-10.8	Assess the extent to which the reasoning and evidence in a text support the author's claim or a recommendation for solving a scientific or technical problem. (HS-PS4-3)
RST.11-12.1	Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account. *(HS-PS4-3)*
RST.11-12.8	Evaluate the hypotheses, data, analysis, and conclusions in a science or technical text, verifying the data when possible and corroborating or challenging conclusions with other sources of information. (HS-PS4-3)

Mathematics -

MP.2	Reason abstractly and quantitatively. (HS-PS4-3)
HSA-SSE.A.1	Interpret expressions that represent a quantity in terms of its context. *(HS-PS4-3)*
HSA-SSE.B.3	Choose and produce an equivalent form of an expression to reveal and explain properties of the quantity represented by the expression. *(HS-PS4-3)*
HSA.CED.A.4	Rearrange formulas to highlight a quantity of interest, using the same reasoning as in solving equations. *(HS-PS4-3)*

Fig. 1 – A sample standard from the NGSS with a QIS connection

3. The Professional Development Model

The professional development model has two main components [7]. First, there is a 4-day workshop for teachers in which the teachers engage with the materials as students, learning both pedagogy and content in an active-learning teaching environment. The teachers can also become familiar with whatever technology particular activities may utilize so that they can integrate technological content knowledge along with the scientific and pedagogical content knowledge [8]. In the week following the workshop, there is a four-day summer science camp for students (grades 9-12) taught by the teachers using the knowledge and resources from the previous week. The idea is that by giving teachers an opportunity to practice using the materials with actual students, the teachers would be better prepared to take the resources back and integrate QIS into their classrooms.

The materials of instruction were developed by a Leadership Team that included professors of physics with a background in physics education research and classroom physics teachers. We began with existing materials from a variety of sources, which were configured into 5E learning cycles [9]. All materials were developed with an understanding of productive approaches identified in the research literature [10, 11, 12]. Many activities included concepts like energy, magnetic fields, forces, and conservation of momentum, all of which are also in the NGSS which broadens the opportunities for integration with more traditional content in High School science courses. For some activities, a historical storyline was used as a basis for the development of more complex ideas [13]. Activities were revised in response to teacher comments after the workshop, and again after the summer camp so that teachers could focus on what worked well with students and what need improvement. In the summers of 2023 and 2024, the topics for the modules were as follows (the first four being for 2023):

- Day 1: Maglev and Engineering Design - What is engineering? Understanding magnetic fields (currents, electromagnets, fields), Uses for magnetic fields such as MagLev Trains, Designing a model of a "maglev" train, quantum levitation and superconductors
- Day 2: Atomic Structure - Spectral lines/observations, electron transmissions, energy, photoelectric effect, Planck's constant, Bohr model and its limitations, properties of waves
- Day 3: Technology and Quantum - Classical vs quantum computers, superposition of states (polarization), quantum key distribution
- Day 4: Laser Cooling - Energy levels, conservation of momentum, Doppler effect, Magnetic fields and forces
- Day 1: Particles – This unit was an investigation of the properties of subatomic particles (hadrons, leptons), and the technologies used to study them (like cloud chambers and accelerators).
- Day 2: Radioactivity – This unit examined radioactive decay (α, β, γ), neutrinos, and Feynman diagrams.
- Day 3: Photoelectric – This unit examined Blackbody radiation, the UV Catastrophe, Planck's quantum hypothesis, the photoelectric effect, and the quantum model for atoms.
- Day 3: HEP – The unit discussed the Heisenberg Uncertainty Principle and how it arises from a wave description of particles with wave-particle duality.

Examining the topics listed below, some might feel that these activities are not really QIS topics but rather precursors, topics like the Photoelectric effect and the Heisenberg Uncertainty Principle. However, topics in QIS like quantum cryptography depend on understanding these basic ideas and so must be included in any attempt to incorporate QIS into broader instruction. Another point that is important to recognize is that the activities are not intended to represent long-term coherent instruction. Given the structure of US education as described in this paper, the best that we can hope for is to incorporate aspects of QIS in regular instruction. Teachers from different content domains (physics, chemistry, biology) need to determine where and how they can incorporate these materials to support core instruction aligned with state standards while also introducing QIS-related science. One last point is that this paper will not address implementation outcomes beyond what we have learned in professional development workshops.

4. Teacher outcomes

To measure teacher (and student) learning, the project developed content assessments for pre- and post-testing so that content gains could be determined. Teacher confidence in their content knowledge was also recorded using self-reporting on a 5-point Likert scale. Assessments were also given to students in the summer camps to determine their level of student understanding. In some cases, the pre- and post-items on the content assessments were identical, but in other cases the exact items were different, but covered the same content. An example of this is presented in Figure 2, which tests the concept of energy levels and transitions. The assessments for teachers were given before the workshop (which we refer to as "pre"), after the workshop but before the summer camp (which we refer to as "mid"), and after the summer camp (which we refer to as "post").

Table 1. Data on teacher content knowledge.

Unit	*N*	*Pre-test (stdev)*	*Mid-test (stdev), p-value*	*Post-test (stdev), p-value*
Particles (6 questions)	25	3.84 (1.46)	4.28 (0.84), 0.1977	5.16 (1.03), 0.0018
Radioactivity (7 questions)	27	5.33 (1.36)	6.33 (0.83), 0.0020	6.26 (1.20), 0.7927
Photoelectric (7 questions)	27	5.44 (1.19)	6.00 (0.92), 0.0582	6.11 (0.89), 0.6573
HEP (7 questions)	27	3.89 (1.12)	4.70 (1.23), 0.0147	4.59 (1.34), 0.7436

Table 1 shows the teacher assessment data from the summer 2024 workshop, and Figure 2 presents a sample assessment questions that measure the same content. The p-values are from a 2-tailed T-test comparing the column in question to the previous column. By and large, these results are similar to those from previous summers [7, 14]. There is generally a statistically significant increase in teacher content knowledge resulting from the workshops, but no statistically significant change resulting from the summer camp. However, there are exceptions to the pattern. For 2024, the increase in the scores for the Photoelectric module following from pre to mid just slightly failed to reach statistical significance (p=0.0582), however from pre to post there was a statistically significant increase (p=0.0229, not shown in Table 1), even though the increase from mid to post was not statistically significant. This module had the highest pre score, indicating that it was the content most familiar to the teachers before the workshop, and this helps to explain the relatively large p-value from pre to mid since there was not much dynamic range left for growth in the score. The Particles module was at the other end of the spectrum with the lowest pre score and the smallest relative score increase and largest p-value (0.1977) from pre to mid. However, the score did increase again after the summer camp so that the total increase in the assessment score was statistically significant. In this case, with rather unfamiliar content, it seems that teaching it to students solidified teacher knowledge. Teacher confidence in their content knowledge also increased by statistically significant values from "pre" to "post", even for the for the Particles module. Moreover, the scores on the assessments were well-correlated with teacher self-reported confidence values, indicating that the teacher know what they don't know, as has been shown in previous years [7, 14].

A key innovation in the professional development model is the summer camp that allows teachers to "test-drive" the materials with students, without having to worry about other issues, like alignment with standards or mandated curriculum. To evaluate teacher response to the PD model of workshop followed by summer camp, focus-group was held with the participating teachers in the summer 2024 who had attended the prior year to discuss factors related to implementation of the modules in their own classroom. Out of 13 teachers in the focus group, 8 identified the summer camp as a major factor in their decisions to use at least some activities in their own classroom during the 2023-24 school year. A sample comment was "*That second week allowed me to watch the students and have the questions on a student level presented…there is great value in actually, teaching the students in a second week to see what they're learning to see what you have to modify again to take it back with you*." Another teacher said "*I liked the second week now I agree. Two weeks is a long time, but I'm willing to do it because it helped me last summer. I learned so many things that I didn't understand, and I was so tentative on my understanding of it like you and I had the same conversation, but being able to present to the students and work them through their station that I was designed to help…it was like if you go to workshops in the summer and then you don't use it until you know October of November and you've kind of forgotten what you did*."

Teachers also expressed that they grew in confidence because of the interactions with other teachers and the instructors during the PD as they worked through the materials themselves. One comment was

"*I would say the more confidence I have in bouncing idea off of other science teachers…having a core of other teachers similar to what I teach being able to bounce those ideas. For me to feel more confident than to go back to teach. It was the best part*."

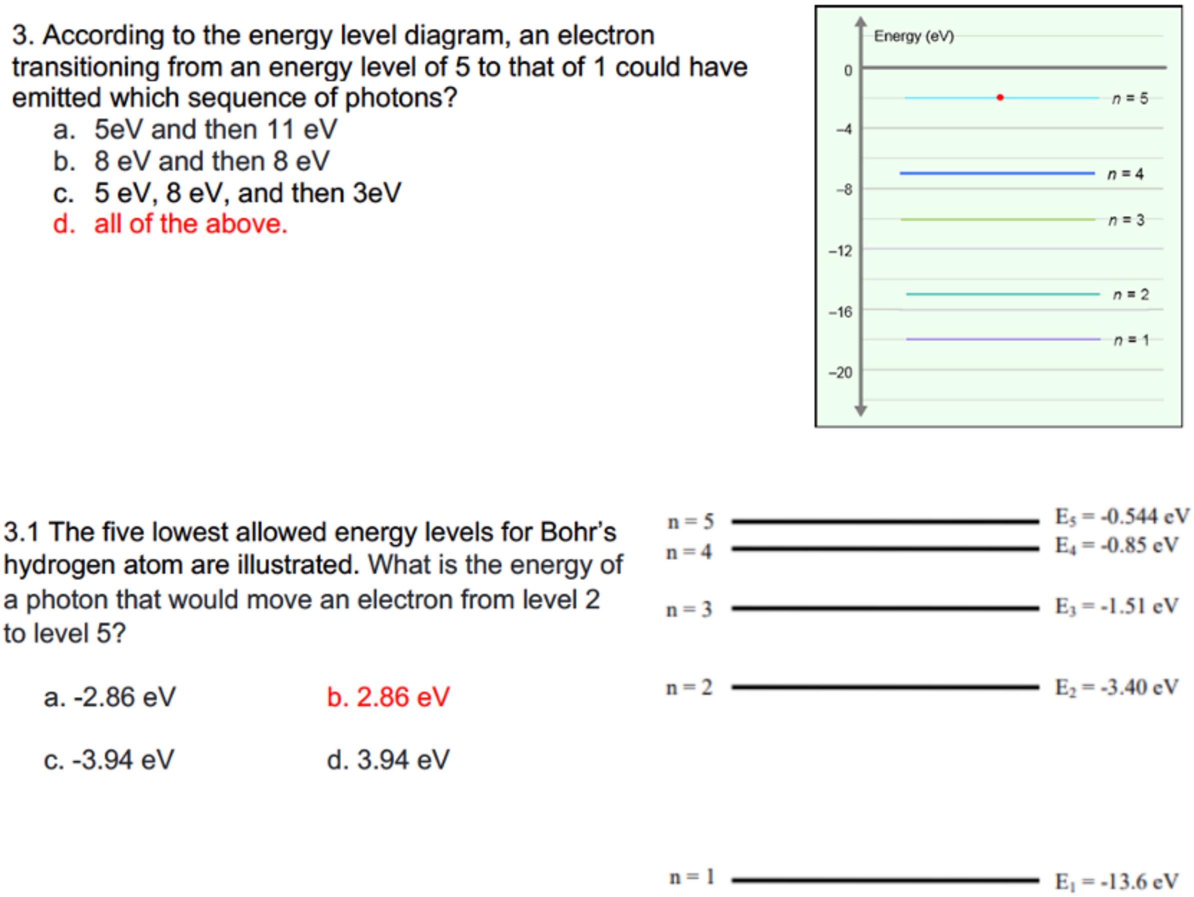

Fig. 2 – Two assessments that measure the same content knowledge.

The discussion among the teachers also indicates that there was a shift from a focus on the content during the PD to a focus on TPCK (Technological, Pedagogical, and Content Knowledge) during the summer camp [7]. This is probably why there was no change in the content knowledge after the summer camp, with the exception of the Particles module as described above. However, that module was an anomaly. In general, it seems that during the summer camp teachers were focused on pedagogy and the technology of the modules. For example, during the focus group one teacher said "*The opportunity to be persistent to get through the… like we were working on today with LED bulbs just trying to get that place constant and narrow down our percent error. I had the ability to really focus in and be given a little bit more room to be persistent and had people around me to help me. Understand what is it that I'm doing? … Um, and that gave me the courage to then do that with the kids because in a classroom you're going to see the same kind of problems, you know? Like, all right this connection wasn't working. So, if I fixed this…*"

5. Conclusions

The evidence is that the QAS professional development model was effective in producing statistically significant gains in teacher content knowledge. A key element was the hands-on, active learning in a collaborative setting where the teachers could support each other and develop a learning community.

The immediate follow-up with the opportunity to teach students was also seen by the teachers as crucial to their confidence and ability to implement the materials in their classrooms. However, at this point we do not have data on implantation to understand exactly how teachers are using these materials.

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