Designing a K-12 Course in Quantum Information Science

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Evolution of our project:

- **Quantum in Your Classroom:** 2022-2024
  Professional learning workshops with K-12 teachers,
- **Building Quantum into Your Classroom:** 2023-24
  Curriculum Development with K-12 teachers
- **Quantum is Elementary:** 2023-present
- **Quantum Information Science Course Development:**
  Fall 2024 - present

Building Quantum into Your Classroom

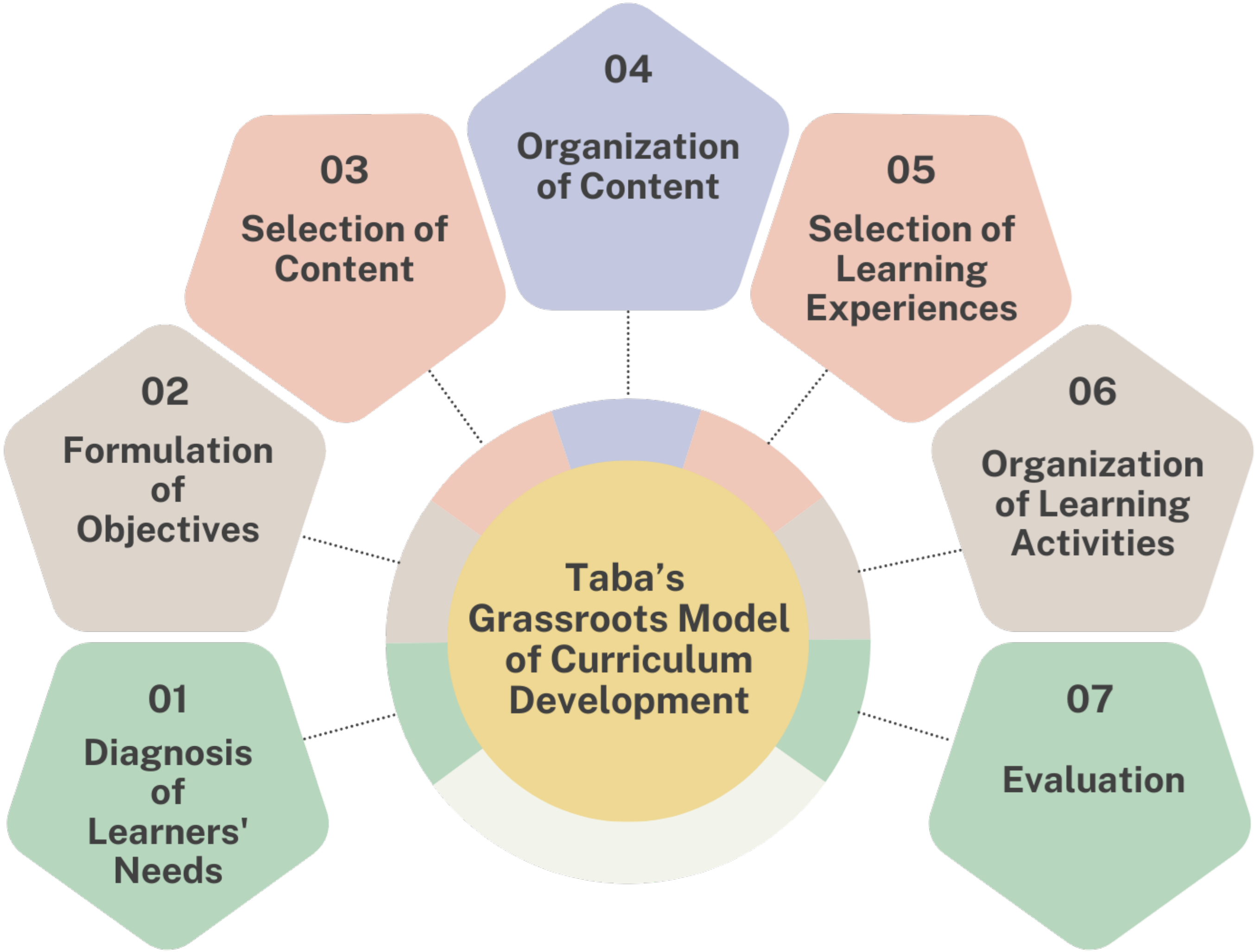
- In Summer 20024, we recruited 14 chemistry, physics, and computer science computer science teachers from across the DC-MD-VA region
- We led teachers in face-to-face and virtual professional learning around quantum concepts and applications
- Teachers then worked in disciplinary groups to develop curricular resources to use in their teaching

K-12 Teachers: Quantum in Your Classroom

Quantum Information Science Course Development

- **Our teacher team has been working on developing a high school course on Quantum Information Science (QIS):**
    - Emily Owens (FCPS chemistry), Erline Germain (MCPS computer science), & Brandon Harvey (FCPS physics)
    - Mark Hannum (FCPS physics) has also worked with the team
- Course development is ongoing, today we'll share a bit about the process and what the teachers have developed so far

Our curriculum development model is student-focused and teacher-led



Diagnosis of Learners' Needs:

Teachers identify what students need to learn, considering their background, interests, and academic requirements.

- Elective course that a student in any high school grade could take.
- Little-to-no math should be required
- Aiming to spark student interest in STEM and computer science
- Introduce students to quantum concepts and applications

Teacher team decided:

- To counter the abstract nature of quantum, course should focus on specific applications of quantum – a Case Study approach

Quantum Case Studies

Case Study #1 - Solar Power:

How does light become electricity? (5 weeks)

Case Study #2 - Astronomy

Why do nebulae appear as different colors? (6 weeks)

Case Study #3 - Quantum Microscopes

How can we see smaller & smaller things? (5 weeks)

Case Study #4 - MRI machines

How does an MRI machine work? (4 weeks)

Quantum Case Studies

Case Study #5 - Quantum Sensing

How does quantum help us build better sensors? (4 weeks)

Case Study #6 - Quantum Computers

How does quantum help us compute faster? (5 weeks)

Case Study #7 - Quantum Cryptography

How does quantum help keep our information secure? (4 weeks)

QISE 1:

The student will investigate and understand that **light exhibits behavior that cannot fully be described by classical physics. The model of quantum mechanics addresses light's observed particle-like and wave-like behaviors.**

QISE 2:

The student will investigate and understand that **fundamental particles such as electrons exhibit behavior that cannot fully be described by classical mechanics. The model of quantum mechanics addresses these fundamental particles' observed particle-like and wave-like behaviors.**

QISE 3:

The student will investigate and understand that **quantum systems (e.g., an atom, a pair of electrons, etc.) can exist as superpositions of mutually exclusive states**, and that the **states of quantum particles in a system can be entangled with one another**.

QISE 4:

The student will investigate and understand that **quantum principles can be applied in modern sensors that measure time, temperature, distance, gravity, and other quantities**.

QISE 5:

The student will investigate and understand that **many modern developments in scientific technologies** **utilize the principles of quantum mechanics**, including in the realms of astronomy, energy, medicine, and other research areas.

QISE 6:

The student will investigate and understand that **quantum systems are applied in** **modern quantum computing** **to optimize computational capabilities in select real-world scenarios**.

QISE 7:

The student will investigate and understand that **quantum cryptography is applied in information security, data manipulation, and real-world simulations**.

Focusing in on one standard: QISE 2 - *slide 1*

QISE 2:

The student will investigate and understand that fundamental particles such as electrons exhibit behavior that cannot fully be described by classical mechanics. The model of quantum mechanics addresses these fundamental particles' observed particle-like and wave-like behaviors.

In exploring this key idea, students will be able to:

- describe the theoretical classical mechanical outcomes of treating electrons as only particles
- explain evidence of electrons behaving as both a particle and as a wave.
- broadly explain how classical mechanics does not match observed behavior of electrons in atoms.

Focusing in on one standard: QISE 2 - *slide 2*

QISE 2:

The student will investigate and understand that fundamental particles such as electrons exhibit behavior that cannot fully be described by classical mechanics. The model of quantum mechanics addresses these fundamental particles' observed particle-like and wave-like behaviors.

In exploring this key idea, students will be able to:

- describe **momentum in the context of both particles and waves** in relation to mass and velocity (particle perspective) and wavelength/energy (wave perspective)
- describe the process of **photon absorption and emission** from an electron moving between energy states (ground and excited)

Focusing in on one standard: QISE 2 - *slide 3*

QISE 2:

The student will investigate and understand that fundamental particles such as electrons exhibit behavior that cannot fully be described by classical mechanics. The model of quantum mechanics addresses these fundamental particles' observed particle-like and wave-like behaviors.

In exploring this key idea, students will be able to:

- describe the difference between **discrete and continuous line spectra** and why that matters regarding the model of the atom
- explain how the **emission spectrum of hydrogen** provides support for quantized energy levels

Current & Next Steps

- Teacher team is finalizing the crosswalk between case studies, Q-12 key ideas, existing VA SOL & NGSS standards, and the team's newly created QIS standards
- They are also identifying and organizing learning activities and assessments
  - Teachers are currently developing a pacing and resources document, including videos, hands-on activities, and other materials

Discussion Questions

- What qualifications will teachers need to teach this course?
- Do you think teachers will want to teach the course?
- Do you think students will be interested in taking this course?
- How should student knowledge be assessed in a course like this one?

The following slides include the full QISE Standards

QISE 1

The student will investigate and understand that **light exhibits behavior that cannot fully be described by classical physics**. **The model of quantum mechanics addresses light's observed particle-like and wave-like behaviors.**

In exploring this key idea, students will be able to:

a. describe the characteristics of waves, including: wavelength, amplitude, frequency, and intensity
b. identify regions of the electromagnetic spectrum based on relative energy, wavelength, and frequency
c. describe the theoretical classical outcomes of treating light only as a wave
d. explain evidence of light behaving as ***both*** a particle (photon) and as a wave using supporting evidence from investigations of the photoelectric effect and the double-slit experiment.
e. broadly explain how classical physics does not match observed behavior of light
f. describe the photovoltaic effect with respect to the role of photons, electrons, and semiconductors

QISE 2

The student will investigate and understand that **fundamental particles such as electrons exhibit behavior that cannot fully be described by classical mechanics**. **The model of quantum mechanics addresses these fundamental particles' observed particle-like and wave-like behaviors.**

In exploring this key idea, students will be able to:

a. describe the theoretical classical mechanical outcomes of treating electrons as only particles
b. explain evidence of electrons behaving as ***both*** a particle and as a wave.
c. broadly explain how classical mechanics does not match observed behavior of electrons in atoms.
d. describe momentum in the context of both particles and waves in relation to mass and velocity (particle perspective) and wavelength/energy (wave perspective)
e. describe the process of photon absorption and emission from an electron moving between energy states (ground and excited)
f. describe the difference between discrete and continuous line spectra and why that matters regarding the model of the atom
g. explain how the emission spectrum of hydrogen provides support for quantized energy levels

QISE 3

The student will investigate and understand that **quantum systems (e.g., an atom, a pair of electrons, etc.) can exist as superpositions of mutually exclusive states**, and that the **states of quantum particles in a system can be entangled with one another**.

In exploring this key idea, students will be able to:

a. explain that atomic orbital “shapes” are probability densities of where electrons are most likely to be found when measured
b. explain that until an electron is measured, it is in all locations outlined by its probability density (a weighted superposition)
c. explain that measuring the electron is what makes the electron’s wave function collapse and have the electron be observed in one location
d. explain that until an electron is measured, its spin (up or down) is undetermined (superposition)
e. explain that measuring the electron is what then determines its spin, and that the other electron in the orbital has the opposite spin, as they are entangled
f. apply their knowledge of superposition and entanglement to other quantum particles, such as photons
g. describe the impact of a magnet/magnetic field on charged particles, like protons, and on the probabilities of their spin orientations when measured
h. describe the process of radiofrequency pulse absorption and emission from a proton changing the spin alignment probability, or a "spin flip

QISE 4

The student will investigate and understand that **quantum principles can be applied in modern sensors that measure time, temperature, distance, gravity, and other quantities**.

In exploring this key idea, students will be able to:

a. describe different types of quantum sensors, imaging techniques, and their applications including atomic clocks, magnetometers, gravitometers, interferometers, thermometers, chemical sensors, and/or imaging sensors
b. explain fundamental magnetic field sensing principles used in quantum sensors
c. describe the generation of a signal (a current) by a changing magnetic field used in quantum sensors
d. investigate the performance, accuracy, and limitation of quantum sensors
e. describe environmental monitoring applications of quantum sensors in management of pollution, hazardous waste, and industrial worker safety

QISE 5

The student will investigate and understand that **many modern developments in scientific technologies utilize the principles of quantum mechanics**, including in the realms of astronomy, energy, medicine, and other research areas.

In exploring this key idea, students will be able to:

a. apply their knowledge of light's particle behavior to the modern technology of solar cells and panels.
b. define blackbody and blackbody radiation, and explain how the continuous thermal emission spectrum (and perceived color of light) of a blackbody relates to the object's temperature
c. describe how various forms of spectroscopy are used to analyze nebulae and stars (absorption and emission spectra), planetary surfaces (reflectance spectra), and atmospheres (transmission spectra).
d. explain how the expansion of the universe causes stretches in light (redshift) and how it must be accounted for in the Webb Telescope's images of the first galaxies.
e. summarize the connections of superposition, entanglement, and momentum as they relate to quantum microscopes
f. describe the use of hydrogen (protons) in magnetic resonance imaging (MRI) in the medical field given the abundance of water in the human body
g. apply the concept of MRI (or NMR) to other atoms and scientific research scenarios
h. explain the fundamentals of global positioning system (GPS) architecture and design

QISE 6

The student will investigate and understand that **quantum systems are applied in modern quantum computing to optimize computational capabilities in select real-world scenarios**.

In exploring this key idea, students will be able to:

a. describe the foundational principles of quantum computing including the fundamental concepts of qubits, as well as applications to quantum computing of the concepts of superposition, entanglement, interference, and noise
b. explain the structure of a quantum circuit and its relationship to quantum computing
c. differentiate between the structure of wired and wireless networks
d. compare and contrast hardware vs software in quantum computing
e. describe the efficiency of quantum computers in computational problem solving
f. differentiate between Shor's algorithm and Grover's algorithm for programming various tasks

QISE 7

The student will investigate and understand that **quantum cryptography is applied in information security, data manipulation, and real-world simulations**.

In exploring this key idea, students will be able to:

a. define post-quantum cryptography (PQC) and how confidential data remains secure with the advancement of quantum capabilities
b. explain the impact quantum cryptography has on classical encryption and decryption
c. explain the utility of Quantum Key Distribution (QKD) protocols with regard to information security
d. explain how position-based cryptography offers new cryptographic methods for geographical positioning
e. differentiate the cryptographic protocols used in keeping information secure