Introduction to Quantum Computing for Everyone

Experience Report

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ABSTRACT

Quantum computing presents a paradigmatic shift in the field of computation, in which unintuitive properties of quantum mechanics can be harnessed to change the way we approach a wide range of problems. However, due to the mathematics and physics perspective through which quantum computing is traditionally presented, most resources are inaccessible to many undergraduate students, let alone the general public. It is thus imperative to develop resources and best-practices for quantum computing instruction accessible to students at all levels.

In this paper, we describe the development and results of our Massive Open Online Course (MOOC) "Introduction to Quantum Computing for Everyone." This course presents an introduction to quantum computing with few technical prerequisites. In the first half of the course, quantum computing concepts are introduced with a unique, purely visual representation, allowing students to develop conceptual understanding without the burden of learning new mathematical notation. In the second half, students are taught the formal notation for concepts and objects already introduced, reinforcing student understanding of these concepts and providing an applicable context for the technical material. Most notably, we find that introducing the math content in the curriculum's second stage led to no drops in engagement or student performance, suggesting that our curriculum's spiral structure eased the technical burden.

CCS CONCEPTS

• **Social and professional topics → Computing education**.

KEYWORDS

MOOC, quantum computing education, visual representation, curriculum design

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1 INTRODUCTION

Quantum computing is an emerging field with the potential to revolutionize the way we use computers to solve problems. Quantum computers differ from classical computers in both their data storage and computation. While classical computers store data in binary electrical states, quantum computers store data in quantum (atomic or subatomic) particles. At this scale, the laws of quantum mechanics present unique ways to interact with stored information.

Theoretical advantages have been proven in the ability of quantum computers to solve many important and currently intractable problems, especially in the modeling of complex systems. However, quantum computers also have fundamental limitations, including high error rates and the inability to copy information. It is thus expected that quantum computers will not replace classical computers and will instead accelerate specific computational tasks.

Quantum computers are currently at the cusp of being able to perform computations faster than classical computers. By the time today's early teenagers graduate from college, it is anticipated that quantum computers will be in wide operation. Unfortunately, less than a dozen algorithmic kernels exist, and few people know how to take those kernels and write practical programs that apply them. A basic understanding of quantum computation is useful to contribute to quantum algorithms, software, compilers, and architecture, the demand for all of which will grow as quantum computers progress. Massive Open Online Courses (MOOCs) have the potential to advance this effort by making material accessible to a broader range of students, but MOOCs suffer from poor retention [11] and student diversity [5], especially in technical subjects.

In this paper, we present our MOOC "Introduction to Quantum Computing for Everyone," developed to serve a broad audience while requiring no more than basic algebra. We describe explicit, research-motivated design choices that tackle the challenges presented by the technical nature of the material and the low retention rate of MOOCs. We then present data from our first offering of the course to reflect on these choices. We find encouraging evidence that the design successfully mitigated the barrier and hope our study informs the development of related research and curriculum.

2 RELATED WORK

2.1 Massive Open Online Courses (MOOCs)

Though MOOCs promised a revolution in accessible education [16], they have generally failed to reach a broader audience and close equity gaps. Studies have shown that MOOC enrollees tend to be young white males with college degrees from developed countries [5]. MOOCs also tend to have low retention and completion rates [11], and those who do complete courses tend to fall into the aforementioned demographics [12].

Many studies have investigated the contributing factors to MOOC student dropout. A literature review finds that poor course design is a major contributing factor to high dropout rates, especially when courses are too complex [6]. Additionally, students often cite unmet mathematics prerequisites as a barrier to MOOC completion [3].

2.2 Spiral Curriculum

To address the above problems, we used a spiral curriculum, a theory-backed approach that teaches a complex topic by beginning with a simplistic, approachable exposition, then revisiting the topic multiple times, adding complexity and reinforcing understanding with each iteration [10]. Spiral curricula have been used for introductory [20] and advanced topics [2] in Computer Science.

2.3 Quantum Computing Instruction

Though the popularity of quantum computing has risen in recent years, the development of accessible curricula has been slow to follow. Traditionally, quantum computing has been taught at a graduate student level to students well-versed in quantum physics, information theory, and/or hardware design. More recently, undergraduate courses requiring computing and linear algebra have been introduced (e.g., [1, 13, 15]).

We are developing a full introductory curriculum accessible to students with only basic algebra as a prerequisite. A limited number of programs (e.g., [19]) and material (e.g., [4, 7, 17]) have been developed to introduce secondary school students to important concepts, and there are a couple of resources available online for the general public as well (e.g., [18, 21]). To our knowledge, no research has been published evaluating quantum computing curricula at this level, and no full introduction courses have been developed other than the one presented in this paper.

3 QUANTUM COMPUTING OVERVIEW

In this section, we provide a brief overview of quantum computing, enough to understand the design choices and analysis in this paper.

3.1 Qubits

Quantum computation is defined by the use of quantum bits - *qubits* - as the basic unit of information. A quantum computer harnesses the laws of quantum mechanics to act on these qubits and perform computation, though the physics is beyond the scope of this paper.

3.2 Superposition and Measurement

Much like classical bits, qubits can be in one of two *base* states, 0 and 1. A qubit can also be in both states simultaneously, a state known as *superposition*. However, this state can not be observed. Instead, when the state of a qubit is read, or *measured*, the qubit state collapses into one of the two base states, each with some probability. This resulting base state is output, but the superposition state has been lost. [1] This process is depicted in Figure 1. One helpful metaphor is a coin perpetually spinning midair - the coin can be viewed as both heads and tails while midair, but determining which side is on top requires us to stop the spinning.

[1]This state and measurement explanation is simplified but sufficient for this paper.

This has significant implications for quantum computing. A qubit can encode exponentially more information than a classical bit, as quantum operations can be used to adjust the superposition's probabilities. However, measuring the qubit collapses the superposition into a single base state, so it is difficult to extract this information.

3.3 Notation

Bra-ket notation is used to represent a superposition state. The two base states are represented by the *kets* $|0\rangle$ and $|1\rangle$. A superposition state is a linear combination of the two kets, $\alpha|0\rangle + \beta|1\rangle$, where α^2 and β^2 represent the probability of the qubit being in the corresponding state when measured. Below are two examples: a) an equal 50/50 state and b) a state skewed 75/25 towards measuring 0.

$$a) \quad \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle \qquad b) \quad \frac{\sqrt{3}}{2}|0\rangle + \frac{1}{2}|1\rangle$$

Two-qubit systems can be represented in a similar way. Given two qubits, the state $|01\rangle$ denotes the case where the first qubit is in state $|0\rangle$ and the second qubit is in state $|1\rangle$. The full state of two qubits is represented as $\alpha|00\rangle + \beta|01\rangle + \delta|10\rangle + \gamma|11\rangle$, where β^2 is the probability measuring 0 for the first and 1 for the second qubit.

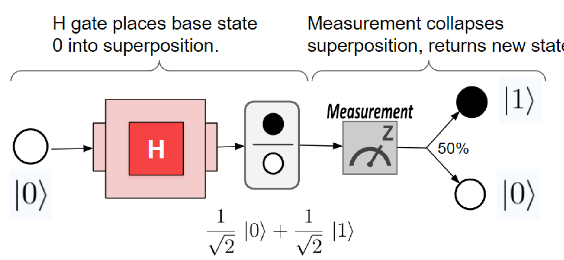
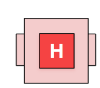
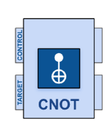


Figure 1: Circuit illustrating superposition and measurement

3.4 Quantum Operations

Quantum operations manipulate various properties of the qubit state, including the probability of measuring 0 vs. 1. Computation on a quantum computer can be depicted by a "quantum circuit" consisting of qubits and gates acting on those qubits. The gates represent *operations*, so a circuit should be viewed as the depiction of a program rather than a hardware diagram (more akin to a data flow graph than a circuit). Figure 1 contains an example of a simple circuit. In Table 1, we introduce two gates that are both foundational and unique to Quantum Computing.

Table 1: Two important quantum computing gates

Name	Description	Symbol
Hadamard (H)	Places a base state qubit into superposition with an equal chance of each state and vice versa.	
Controlled Not (CNOT)	Flips the state of the target (bottom) bit if the control (top) bit is $|1\rangle$.	

Quantum circuits can also be evaluated mathematically. An n-qubit state can be represented as a vector of 2^n coefficients – one for each combination of basis states – and gates can each be represented by matrices acting on these vectors. This is helpful for introductory courses, as it allows students a formal method to evaluate small circuits. This also demonstrates the potential for quantum supremacy: a quantum circuit on IBM's 2021 Eagle (127 qubits) would require a vector of size $2^{127} \approx 10^{38}$ to evaluate classically, and it is estimated that quantum computers will need at least thousands of qubits to begin tackling meaningful applications [9].

3.5 Entanglement

Qubits in superposition can also have their measurement outcomes be correlated, or *entangled*, with other qubits.

Consider the expected behavior of two qubits in superposition. Using the coin flip example, if we decide to measure two coins spinning in the air, we can calculate the probability of each of the four possible outcomes of heads (H) and tails (T): HH, HT, TH, and TT. There is an equal probability (1/4) of each outcome. If we represent H as 0 and T as 1, this scenario could be expressed:

$$|\psi\rangle = \frac{1}{2}|00\rangle + \frac{1}{2}|01\rangle + \frac{1}{2}|10\rangle + \frac{1}{2}|11\rangle .$$

In this scenario, the coins are not correlated - their outcomes are independent of each other, and measuring one coin will tell us nothing about the other coin's outcome.

Table 2 gives an example of a circuit in which the output is a dependent, or *entangled*, state. The starting state is $|00\rangle$ (both qubits in a classical 0 state). The Hadamard gate puts the first qubit into superposition, so the new state is a superposition of $|00\rangle$ and $|10\rangle$. Then, the two bits are put through a CNOT gate, which flips the second bit for only the state in which the first bit is 1. As a result, the final state is

$$|\psi'\rangle = \frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle ,$$

an equal split between $|00\rangle$ and $|11\rangle$.

This final entangled state is significant - prior to measurement, each qubit has a 50/50 chance of measuring 0 or 1, just like the two independently spinning coins. In $|\psi'\rangle$, however, if we measure the first qubit to be $|0\rangle$, then we conclude that the two-qubit state is $|00\rangle$, so the second qubit must be $|0\rangle$ as well. *Measuring one qubit collapsed the superposition of both qubits.* To represent this state with the coin metaphor, the coins would remain spinning, but stopping one coin would result in the other coin stopping on the same side. The two qubits in $|\psi'\rangle$ are *dependent* on one another, while the qubits in $|\psi\rangle$ are *independent*.

This dependence is known as entanglement, and its existence has significant and counterintuitive physical implications. It has been experimentally confirmed in qubits regardless of the physical separation between the qubits, and seems to violate our understanding of how objects interact with each other in our universe. Entanglement is a critical way in which qubits differ from classical bits, and is key to the development of meaningful quantum algorithms.

4 COURSE DESIGN

The guiding principle in our course design was to increase the material's accessibility by lowering the technical barrier that more traditional expositions of Quantum Computing place on students. We do so by introducing a visual representation alongside a spiral curriculum, both of which are best-practices that help ease students into the nonintuitive concepts.

4.1 Visual Representation

In the first half of the course, students learn about qubits and circuits with a purely visual representation that we developed, inspired by the representation from the book *Q is for Quantum*[21]. Visual representations help students, especially novices, develop a more accurate mental model of phenomena [14]. This representation also allows students to develop interest and understanding of the subject without the potential barrier of technical details.

The visual representation replaces bra-ket notation with balls of two possible colors – a white ball represents $|0\rangle$, and a black ball represents $|1\rangle$. Superposition is also depicted in a more intuitive visual format, with probabilities proportional to the number of balls, like the superposition in Figure 1 and Table 2.

Circuits are depicted as a middle-ground between the representation in *Q is for Quantum* and the traditional representation. Gates are represented as input/output boxes to guide evaluation, and the horizontal orientation and gate names mirror standard circuits to ease transfer between representations. Table 2 gives a side-by-side comparison of the three representations.[2]

Our goal was to build intuition and confidence through the visual representation, though the math is still necessary to discuss calculations and more specific states. As such, after we cover the core concepts that can be entirely understood through the visual representation, we introduce vector and bra-ket notation.

4.2 Curriculum Structure

The course material is divided into 7 distinct self-guided modules. Each module consists of approximately 2-3 hours of instruction and work. Table 3 provides a list of the modules in the course, with the transition between visual and mathematical notation indicated. Each module has video lectures, practice questions, and a set of homework questions at the end. There is also a cumulative final exam at the end of the course.

The modules follow a spiral curriculum. They are split into three stages (see Table 3), where each stage allows students to build a new layer of understanding. The foundational topics - qubits, gates, superposition, measurement - are all introduced using visual representation in Stage 1, allowing students to develop a primary understanding of the concepts. In Stage 2, students revisit these topics with bra-ket and vector notation, reinforcing their understanding through a new approach to the same concepts. For students with no background in linear algebra, this also takes a constructivist approach by teaching linear algebra in the context of the quantum objects they have already been introduced to. Finally, in Stage 3, more complex core topics like entanglement and algorithms are introduced. Each topic in this stage is first introduced visually to provide intuition and accessibility, followed by a mathematical exposition to provide formalism. This section introduces new concepts while bolstering the connection between the two representations.

[2]Standard representation generated with IBM's Quantum Composer: https://quantum-computing.ibm.com/composer.

Table 2: A comparison of an entanglement circuit with different notations

Q is for Quantum	Visual	Standard

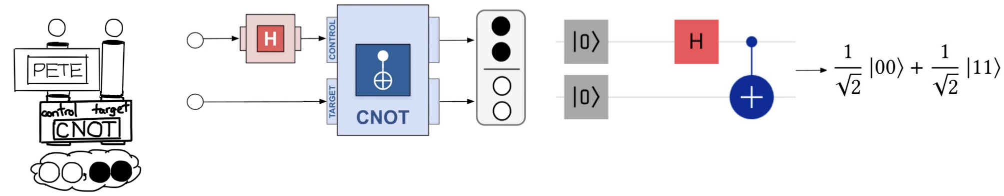


Table 3: Course content and ordering

#	Module Name	
1	The Power of Quantum Computing and Quantum Operations	Stage 1
2	Quantum Operations: Part 2	Stage 1
3	Probability, Measurement, and Superposition	Stage 1
4	Quantum Notation	Stage 2
5	Working with Single Qubits	Stage 2
6	Working with Multiple Qubits	Stage 3
7	Algorithms	Stage 3

Table 4: Enrollee self-reported demographics

Education	% of Total	Gender	% of Total
Unreported	52.5%	Unreported	50.5%
Advanced Degree	19.4%	Male	40.0 %
College Degree	14.5%	Female	8.7 %
Secondary or less	13.6 %	Other	0.8%

4.3 Videos

Alongside these curriculum-level decisions, we also adjusted the presentation of content to best retain students. Video lectures are split into digestible segments, most less than 6 minutes, which helps students remain focused and permits more flexibility. Videos also vary in focus - most are standard lectures on the course material, but some look more broadly at potential applications or state-of-the-art technology, and others work through example problems. Finally, each lecture video shows a talking head narrating, as opposed to simply words on a slide. All of these decisions have been associated with increased student retention in MOOCs [8].

5 METHODS

In this IRB-approved study, anonymous course data was examined to evaluate specific design decisions and identify challenges.

5.1 Data Collection

The course was offered on EdX between June 28, 2021, and September 5, 2021. Enrollment was free, but students had the option to pay to be a "Verified" student. Verified students submit their work to be checked and receive an official certificate upon course completion. EdX provides data about user enrollment numbers, video view rates, student self-reported demographics, and submission results.

5.2 Population

There were a total of 1302 students enrolled in the course when it ended. Of these, 44 were Verified. The enrolled students' self-reported education level and gender are summarized in Table 4, but most students opted not to report. Furthermore, many enrolled students never engaged with any of the course material. Of the enrolled students, only 525 students started watching the first module's first video. Only the 44 verified students could submit their answers, so we focus specifically on these students when analyzing student understanding. Unfortunately, we did not have access to demographic data that distinguished between verified and non-verified users.

6 RESULTS

In this section, we examine data about video view rates and student performance, followed by notably difficult problems. In doing so, we evaluate the extent to which our course design retained and taught students, especially with regard to the math notation.

Each result in this section is accompanied by a short discussion of its implications. In Section 7, we discuss holistic takeaways and lessons from a synthesis of the results.

6.1 Retention

Student engagement was measured as the number of unique viewers of each video in the course. This includes both auditing and verified users. Views were further categorized as "complete" or "incomplete" depending on the timestamp at which they stopped the video. We averaged these counts within each module and further computed the percentage difference in the number of viewers between modules. The results are shown in Figure 2.

Discussion. While the course suffers from a steady drop in engagement as expected, **there is no indication that the introduction of math notation in Module 4 caused students to leave the course.** In fact, the average number of viewers marginally grows between Module 4 (201.5 viewers) and Module 5 (203 viewers). This is a promising sign of the course design effectiveness.

6.2 Difficulty by Module

Next, we focus on how verified students performed on the questions in each module (because auditing students are not able to answer questions). Every question was multiple choice, with no partial credit given. The results are shown in Figure 3. The bars indicate the percentage correct, and the line depicts the percentage of verified students who answered each question. The average performance

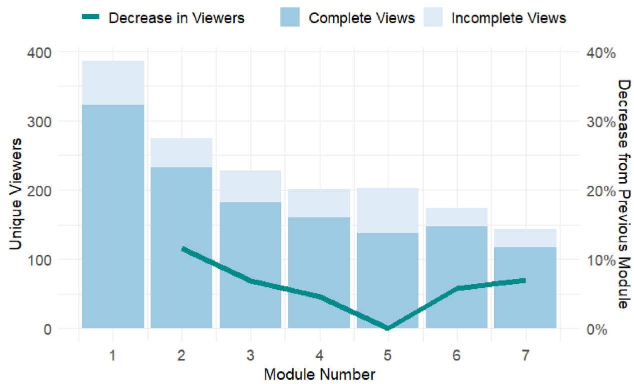


Figure 2: Video Engagement by Module

was at least 86% in each of Modules 1-6, and there was a steady but very gradual decrease in attempts.

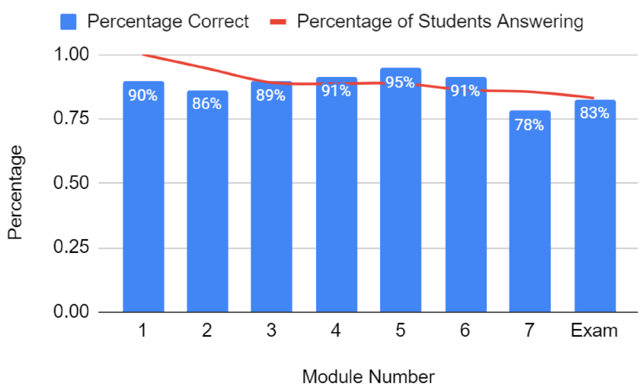


Figure 3: Problem Difficulty by Module (Verified Students)

Discussion. These results bolster the finding that students did not struggle with mathematical notation because **the verified students successfully learned the math notation and did not drop the course when it was introduced.** In fact, the emphasis of math in Modules 4 and 5 was accompanied with a slight increase in performance and no notable drop in answers per question.

6.3 Difficulty by Problem Type

For a more direct comparison between problems with the two types of notation, we focused on how students answered circuit evaluation questions. These problems appeared in nearly every module, and each problem could have been translated into an equivalent problem with the other notation, making them a natural choice for comparison. Figure 4 shows the results by module, as well as the final exam and course average. Recall that the first 5 modules only used one type of notation, whereas modules 6 and 7 used both.

Discussion. Students performed slightly better on circuit evaluation questions using math notation than on those using visual notation. It should not be deduced that the math was inherently

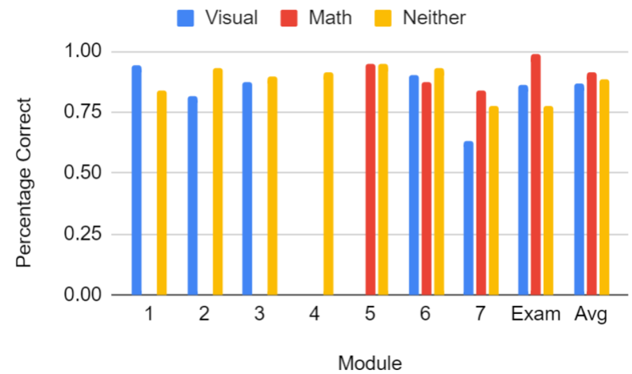


Figure 4: Problem Difficulty by Category (Verified Students)

easier for the students - our aim was to ensure that the math section was approachable, so questions with math notation were written to be more straightforward and contain similar conceptual ideas to questions they had previously seen in visual notation. **We conclude that our course successfully introduces math notation without increasing the difficulty for students.** We also see a slight drop in student performance in Module 7, which we attribute to the fact that it was the most conceptually challenging module, and that many of the most difficult questions were asked with visual notation.

6.4 Difficult Problems

Though students performed well overall, we identified some sets of questions with poor results and analyzed incorrect answer patterns.

6.4.1 Measuring Superposition. Module 3 introduces students to superposition, measurement, and the H gate. In Module 3's homework, students were asked about many variations of circuits involving these concepts. For example, students were asked to select **all** possible outcomes of the circuit in Figure 5. Notice this resembles the circuit from Figure 1. The outcome after the first measurement is a base state, which the second H gate sends into a superposition, so the result of the second measurement can be either base state.

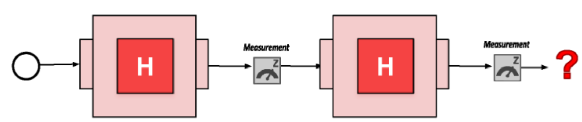


Figure 5: Question about Measuring Superposition

Only 54.7% of students answered this question correctly, and most (73.6%) of the incorrect students believed that the only possible outcome was a white qubit. White would be the only correct outcome if there had not been a measurement in between the two H gates since H gates are their own inverse. In two other questions testing similar ideas, only 65.9% and 61.9% of students answered correctly. The most common incorrect answers in all three questions demonstrate a belief that sending a qubit through an H-gate and then measuring it results in the original state, rather than an arbitrary base state. Interestingly, in earlier questions in the same module, 95.1% of students properly identified the superposition outcome when sending a qubit through an H-gate, and 97.7% of students understood that measuring this output has an equal chance of resulting in either base state.

6.4.2 Discussion. **Students appear to have trouble specifically with concatenating the H gate with measurement**, despite understanding the behavior of each piece individually. A qubit sent through two H gates always returns to its original state, so perhaps students confused that idea with the idea here. We recommend that instructors explicitly discuss this interaction to preempt misunderstanding.

6.4.3 Identifying Entanglement. In the final exam, four questions were of the following format, with varying coefficients:

Choose the correct option. The following 2 qubit state is:

$$-0.6\,|00\rangle + 0.8\,|11\rangle$$

- invalid,
- valid and not entangled,
- valid and entangled.

To answer this question, students should realize that the state is valid because the squares of the coefficients sum up to one and the state is entangled because the measurement of one qubit tells us the state of both qubits.

This question was conceptually challenging because it required students to apply their knowledge of entanglement in a novel mathematical setting, and the results reflected this difficulty: these four questions had an average score of 50.7%, whereas students averaged 82.6% on the exam as a whole. Interestingly, prior questions in the exam asked students to determine whether given bra-ket two-qubit states were valid (average score: 96.1%) and questions earlier in the course asked students to identify whether visual two-qubit states were entangled (average score: 93.4%). This indicates that students had the conceptual background required to solve the problem.

6.4.4 Discussion. Despite demonstrating the ability to differentiate entangled states from independent states, students struggled to do so with math notation. We believe students were unsuccessful in transferring their problem-solving ability to the less tangible math setting. We conclude from these results that the **visual representation properly develops intuition for difficult concepts, but more scaffolding is needed to line the visual intuition up with mathematical presentations of ideas.**

7 DISCUSSION

7.1 Curriculum Design

It is encouraging that the introduction of math notation was not accompanied by any drop in student engagement or performance. In fact, we see a slight growth in both of these metrics amidst this transition. This suggests that our curriculum successfully mitigated the perceived technical hurdle of the math notation. As such, **we encourage future designers of quantum computing curricula to incorporate a spiral structure with a visual representation to introduce quantum concepts.** We believe that doing so increases the accessibility of the material, especially for students without a linear algebra background. The course content is utilized successfully in an undergraduate Introduction to Quantum Computing course at our institution, indicating a transferability beyond the MOOC format.

7.2 Content

The difficult questions suggest a pattern of students having trouble piecing together known information when applying them to a new situation. We suspect that the unintuitive nature of quantum mechanics makes students likely to develop inaccurate and incomplete mental models of phenomena. As a result, even though they seem to process the material being taught, they struggle with applying it to new scenarios. **To address this, future curriculum should bolster an accurate mental model by presenting a more diverse set of examples in both instruction and practice problems.**

7.3 Limitations

It is important to note that this course was designed with best principles for students, which often came at the cost of analysis validity. Decisions like writing easier math questions and segmenting the curriculum into stages made it difficult to find meaningful comparisons to measure the design's success. Furthermore, we hesitate to draw sweeping conclusions from student performance rates given the small sample size and lack of demographics. Nonetheless, we hope that our results indicate promise, and inform future research directions as well as the development of a more accessible quantum computing curriculum.

8 CONCLUSION

In this report, we present the design and rationale for our curriculum in the EdX course "Introduction to Quantum Computing for Everyone." Our major contribution is a spiral curriculum that begins with a novel visual notation, allowing students to focus on the unintuitive nature of the subject before learning the math that traditionally accompanies it. To evaluate the success of our design, we split student engagement and performance data by the curriculum's usage of visual and math notation. We are pleased to find that students are retained upon the introduction of the math, and that students perform equally well on questions in each category, indicating that our course structure mitigates the burden that technical subjects often present to students, especially in MOOCs. We hope our experience contributes to the development of more accessible curriculum, both in quantum computing and broadly in technical subjects.

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