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Supporting Computing-centred Intuitions for Quantum Computing through Play

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ABSTRACT

Quantum computing is an emerging technology with a burgeoning industry and growing workforce needs. The demand for computer scientists with quantum computing knowledge is increasing, as their skills are needed to make quantum computing a scalable and useful resource. However, few computer scientists are formally educated in quantum computing, with most education occurring in physics curricula. Although some open source learning resources and software tools for quantum computing are available, they employ a quantum mechanical, hardware-driven framing that poses accessibility challenges for computing-focused learners. Educational games have seen some success in quantum computing outreach initiatives, particularly in building intuition for quantum mechanical concepts, but rarely relate to computing practices. This submission outlines a doctoral research programme that seeks to develop computing-centred interactions with quantum computing systems, and to explore how play can be leveraged in these interactions as a means of building quantum intuitions in a computing context.

CCS CONCEPTS

• **Social and professional topics → Computing education**; *Computational thinking*; • **Hardware → Quantum computation**; • **Human-centered computing → HCI theory, concepts and models**; **User interface design**; *Interface design prototyping*.

KEYWORDS

Quantum computing, User interfaces, Computing education, Educational games, Intuition, Accessibility

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1 INTRODUCTION

Quantum computing is an emerging computing paradigm that utilises quantum mechanical principles to approach complex problems [41]. Its central promise is that of 'quantum advantage': efficiently solving problems that are highly challenging, or even intractable, using typical binary (referred to as 'classical') computers [46]. As the tangibility of this promise is growing, so too are industry investments and associated workforce needs [5, 10, 19, 22]. In particular, there is increasing demand for individuals with both computer science expertise and working knowledge of quantum computing systems [1, 26, 57], whose skills are required to make these systems scalable and practically useful [1, 2, 16]. However, finding such individuals is a difficult task: quantum computing education is by no means commonplace, and is delivered primarily in physics curricula [11, 17, 40, 44, 48]. Although the quantum computing community has created some open-source educational materials for technical audiences, they typically begin with a 'crash course' in quantum mechanics, positioning this knowledge as a prerequisite for programming [57, 59]. Such an approach prioritises understanding the *quantum* before—and sometimes even without–the *computing*: appropriate for physics curricula, but for other disciplines not necessarily so.

In response, computer science educators have begun to create their own materials and courses, using quantum computing software tools—including programming libraries and a limited range of graphical user interfaces (GUIs) [21]—as the primary mode of instruction [11, 40, 48, 49]. However, these software tools require users to perform computations at the level of individual quantum bits: a hardware-motivated approach that, for learners with a computing background, conflicts with common mental models of programming and computation [24, 33], and thus is challenging to integrate within the framework of their prior knowledge. Some educators have taken a different approach, exploring games as an educational medium for quantum computing [51]. Although there is as of yet little empirical assessment of these games' educational quality [51], games and play are a fairly well-established instructional modality in computer science education [20, 25, 27, 43]. They have been found to support learners in forming and refining mental models of computing [31, 47], in addition to developing computational thinking [7, 28, 56] and programming skills [29, 37, 38]—in other words, the competences needed to address the computing skills gap in the quantum computing industry. Despite this promise, there is a key obstacle: in quantum computing, some familiar computing concepts (information and errors, for example) take unfamiliar forms, whilst others (such as entanglement and superposition) are new altogether. As a result, what constitutes computational thinking and programming can be quite different, and the applicability of existing guidelines for games in computer science education is uncertain. This research programme therefore seeks to investigate what playful, computing-focused learning in the quantum computing context might look like: which concepts should be conveyed, what kinds of abstractions could embody them, and how games and play could help learners to integrate them within a broader mental model of computing.

2 RELATED WORK

2.1 Software and interfaces for quantum computing

There is currently a modest but growing range of software tools for quantum computing, including libraries, software development kits (SDKs) and a small number of graphical user interfaces (GUIs) [21]. Most of the available tools use a gate-based approach to quantum computing [21], in which a program is built by applying quantum logic gates to quantum bits (more commonly known as 'qubits'), which collectively are referred to as a circuit. Programs written in Qiskit, for example—a popular Python-based SDK—refer to each qubit in a circuit with an index number, and successively append individual gates to the specified qubit(s). Likewise, IBM's Quantum Composer GUI[1] visualises a Qiskit program using a circuit diagram: a series of parallel lines and boxes to represent qubits and gates respectively.

This circuit-gate model of computation is not unique to quantum computing; it is a fundamental concept in computer science and forms the basis of almost all digital systems. However, the widespread use of high-level programming languages means that, for most computing paradigms, working with individual bits and gates is uncommon in practice [23]. A computing-focused user, even with significant programming experience, will therefore likely find existing quantum computing tools challenging. Although some GUIs include features intended to reduce this challenge (such as drag-and drop circuit building, automatic code generation and qubit state visualisations [21]), the interactions they afford are limited and provide little indication of purpose or utility from a computing perspective. Given that programming is an active, goal-driven and task-oriented process [24], this is a particular point of concern.

2.2 Games and play in quantum computing education

In response to ongoing accessibility challenges in quantum computing (as described above), there are increasing efforts to develop more accessible and diverse educational resources [18, 51]. Within such initiatives, the use of games has become a favoured approach, informed by prior work in computer science and STEM education [51]. These games are often designed with the aim of building players' 'quantum intuition', such that they can draw upon quantum mechanical concepts when solving problems within the game space without extensive instruction [3, 42]. Both intuition-forming [52] and problem-solving [28, 50, 58] have been described as core elements of computational thinking: the development of "*the full set of mental tools necessary to effectively use computing to solve complex human problems*" [32], but "*without understanding [a computing system's] every detail*" [58]. Computational thinking is thus especially pertinent given the quantum computing labour gap (see Section 1), in which the ability to practically apply and implement aspects of quantum computing—as opposed to deep system knowledge—is increasingly desirable [1, 26, 57]. Games have been shown to effectively support computational thinking in computer science education [7, 28, 29, 53], whilst some play theorists argue that play is in fact the ideal means by which to learn and build intuitions about complex systems [14, 15], owing to its structured yet emergent nature [14]. Games and play have also been described as forms of constructivist learning [13, 36, 45], which itself has been proposed as an optimal approach to computing education [6, 8, 9, 34] and the development of computational thinking [54]. A games and play-focused approach therefore seems promising for supporting computing-centred learners in the quantum computing context.

However, almost all existing games for quantum computing education share similar issues to the software tools previously discussed (see Section 2.1), in that they operate solely at the level of individual qubits and gates [51]. Initially, this may not seem problematic—such games may well be effective for learning about the qubits and gates they depict (although empirical evidence on this matter is scarce [51]). But for computational thinking, learning concepts in isolation from a broader computing system is insufficient. Learners need to be supported in thinking about a computing system at multiple levels of complexity; not just (qu)bits and gates, but functional combinations thereof to create algorithmic structures [58]. In order to support such thinking, a game must therefore enable direct application of concepts through game-play, clearly relating them both to each other and the real-world context in which learners might apply them [29]. As such, these games' support for quantum computational thinking—for forming intuitions about quantum computing and applying them to problems—appears limited. To realise the educational potential of games and play in this field, multiple layers of abstraction (and associated representations) need to be developed, and their interrelation by the learner facilitated through playful, contextually relevant interactions.

3 RESEARCH GAP AND QUESTIONS

Existing educational resources and software for quantum computing frame it as a quantum mechanical endeavour, reducing accessibility for learners with a computing background. Games and playful interactions have proven effective in making aspects of quantum computing more accessible, but provide little support for the multiple levels of abstraction needed to develop computing-centred intuitions and skills. These factors lead to the core aspiration of my research: to ask *how playful interactions with quantum computing systems might be used to support computing-centred intuitions*. Within this goal I identify four main research questions:

- **RQ1**: Which concepts within quantum computing are relevant for computing-centred learners?
- **RQ2**: What are possible design guidelines for computing-centred abstractions of these concepts that afford playful interaction?
- **RQ3**: How might game mechanics be used to structure and interrelate such abstractions and interactions?

[1] https://quantum.ibm.com/composer

- **RQ4**: To what extent do the resulting abstractions and interactions support learners in developing computing-centred intuitions?

4 METHODS

We investigated RQ1 by conducting semi-structured interviews and sense-making sessions with quantum computing educators. Having asked them to prepare their own examples of quantum computing abstractions, we used their explanations of these examples to elicit key concepts of quantum computing. The experts were then asked to rank the key concepts in terms of perceived complexity and challenge level for learners. This was followed by a discussion of the concepts' relevance for computing-centred learners, which was grounded by the use of a persona we developed to represent one such learner. We then explored RQ2 through the collection and analysis of existing quantum computing abstractions. These were gathered from both semi-structured interviews with quantum computing experts and literature. Drawing upon Lakoff and Johnson's framework [30], we identified the metaphors employed in each abstraction to communicate a given concept. We subsequently gathered ratings from quantum computing experts, who assessed each abstraction on several dimensions of communicative quality. Finally, we used Barr et al.'s taxonomy of interface metaphors [4] to investigate how the abstractions, and the metaphors they contain, help or hinder computing-centred action and playful interactions, and thus formulated suggestions for developing abstractions that better support learners with a computing background. RQ3 and RQ4 are currently being investigated in a Research through Design (RtD) process [60], in which interactive prototypes are produced and iterated upon, based on feedback from both quantum computing experts and novices with a computing background.

5 RESULTS AND DISCUSSION

Regarding RQ1, my first study yielded seven key concepts for quantum computing education, the most challenging (as perceived by our expert participants) of which being *entanglement*, *measurement* and *algorithms*. Through our persona discussions, the participants reflected critically on their own didactic approaches, and agreed that a more computing-centred approach would be valuable. Some made suggestions for developing such an approach, including focusing on algorithms and programming, creating higher-level abstractions, and supporting exploratory interactions.

Regarding RQ2, the results of my second study highlight the scarcity and limitations of existing abstractions for quantum computing. Thirteen distinct abstractions were compiled, the majority of which relate to quantum mechanical concepts. Our analysis and expert ratings indicate that few afford any form of interaction, and in fact misrepresent quantum information as unknowable or unalterable, discouraging exploration or play. Additionally, the abstractions do not clearly indicate the computational role of the concepts they represent, nor their relation to each other within a computing system. Consequently, I have proposed the following design guidelines for computing centred-abstractions of quantum computing: **(1)** the metaphorical basis of an abstraction should be derived from the computational process(es) in which it is applied; **(2)** abstractions should convey the probabilistic nature of information in quantum computing; **(3)** they should afford multiple interactions that communicate the extent and end to which a user can interact with such probabilities; **(4)** interactions should illustrate how timing and sequencing affect probabilities, and how this manifests in algorithmic structures.

6 LIMITATIONS

In both of my completed studies, the majority of participants are experimental or theoretical physicists, and as such the perspectives of algorithm specialists, or other more software-focused experts, has been comparatively limited. Although this is partially a reflection of the quantum computing community's demographics, I am pursuing a more diverse participant sample for my current and future work. Additionally, there is very little existing literature regarding quantum computing abstractions or interactions, and even less regarding these topics in the human-computer interaction research community [3]. As such, the design guidelines and prototypes I produce are a first foray into this area, and further work is needed to establish any form of best practice.

7 FUTURE WORK AND CONCLUSION

As mentioned in Section 4, my present and future work is structured as a RtD process, where I develop and iterate upon prototypes to investigate RQ3 and RQ4. I am currently exploring how a turn-based game format might support intuitions for the programmatic implementation of variational quantum algorithms (an algorithm type with near-term feasibility and industrial applicability [12, 39, 55]). In this work, I am developing audiovisual abstractions of the key concepts identified in my first study, implementing the guidelines developed in my second study (see Section 5), and applying turn-based game mechanics to provide structure for these abstractions, opportunities for their interrelation, and context for their use in (computational) problem-solving. I aim to test my prototypes with novice quantum computing users who have either academic or professional experience in computing. This will likely take the form of task-based cognitive walk-throughs [35], ideally in addition to co-creation sessions with quantum algorithm experts. It is my hope that these activities will demonstrate the validity and value of a playful approach to interacting with quantum computers, and encourage further dedicated HCI work in the quantum computing field.

REFERENCES

[1] Clarice D Aiello, David D Awschalom, Hannes Bernien, Tina Brower, Kenneth R Brown, Todd A Brun, Justin R Caram, Eric Chitambar, Rosa Di Felice, Karina Montilla Edmonds, et al. 2021. Achieving a quantum smart workforce. *Quantum Science and Technology* 6, 3 (2021), 030501.
[2] Shaukat Ali, Tao Yue, and Rui Abreu. 2022. When software engineering meets quantum computing. *Commun. ACM* 65, 4 (2022), 84–88.
[3] Zahra Ashktorab, Justin D Weisz, and Maryam Ashoori. 2019. Thinking too classically: research topics in human-quantum computer interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12.
[4] Pippin Barr, Robert Biddle, and James Noble. 2002. A taxonomy of user-interface metaphors. In *Proceedings of the SIGCHI-NZ Symposium on Computer-Human Interaction*. 25–30.
[5] Andreas Bayerstadler, Guillaume Becquin, Julia Binder, Thierry Botter, Hans Ehm, Thomas Ehmer, Marvin Erdmann, Norbert Gaus, Philipp Harbach, Maximilian Hess, et al. 2021. Industry quantum computing applications. *EPJ Quantum Technology* 8, 1 (2021), 25.
[6] Mordechai Ben-Ari. 2001. Constructivism in computer science education. *Journal of computers in Mathematics and Science Teaching* 20, 1 (2001), 45–73.

[7] Matthew Berland and Victor R Lee. 2011. Collaborative strategic board games as a site for distributed computational thinking. *International Journal of Game-Based Learning (IJGBL)* 1, 2 (2011), 65–81.
[8] Meurig Beynon. 2009. Constructivist computer science education reconstructed. *Innovation in Teaching and Learning in Information and Computer Sciences* 8, 2 (2009), 73–90.
[9] Shirley Booth. 2001. Learning computer science and engineering in context. *Computer Science Education* 11, 3 (2001), 169–188.
[10] Deborah Carberry, Amirhossein Nourbakhsh, Jay Karon, Mark N Jones, Mojgan Jadidi, Kyarash Shahriari, Christian Beenfeldt, Martin Peter Andersson, and Seyed Soheil Mansouri. 2021. Building knowledge capacity for quantum computing in engineering education. In *Computer Aided Chemical Engineering*. Vol. 50. Elsevier, 2065–2070.
[11] Ginés Carrascal, Alberto A Del Barrio, and Guillermo Botella. 2021. First experiences of teaching quantum computing. *The Journal of Supercomputing* 77, 3 (2021), 2770–2799.
[12] Marco Cerezo, Andrew Arrasmith, Ryan Babbush, Simon C Benjamin, Suguru Endo, Keisuke Fujii, Jarrod R McClean, Kosuke Mitarai, Xiao Yuan, Lukasz Cincio, et al. 2021. Variational quantum algorithms. *Nature Reviews Physics* 3, 9 (2021), 625–644.
[13] Andrew Csizmadia, Bernhard Standl, and Jane Waite. 2019. Integrating the constructionist learning theory with computational thinking classroom activities. *Informatics in Education* 18, 1 (2019), 41–67.
[14] Scott G Eberle. 2014. The elements of play: Toward a philosophy and a definition of play. *American journal of play* 6, 2 (2014), 214–233.
[15] Klaus Elle. 2011. *Metaphorical management: Using intuition and creativity as a guiding mechanism for complex systems.* Springer Science & Business Media.
[16] Mark Fingerhuth, Tomáš Babej, and Peter Wittek. 2018. Open source software in quantum computing. *PloS one* 13, 12 (2018), e0208561.
[17] Douglas Finke. 2018. Quantum computing report. https://quantumcomputingreport.com/players/universities/. Accessed: 17/05/24..
[18] Caterina Foti, Daria Anttila, Sabrina Maniscalco, and Maria Luisa Chiofalo. 2021. Quantum physics literacy aimed at K12 and the general public. *Universe* 7, 4 (2021), 86.
[19] Michael FJ Fox, Benjamin M Zwickl, and HJ Lewandowski. 2020. Preparing for the quantum revolution: What is the role of higher education? *Physical Review Physics Education Research* 16, 2 (2020), 020131.
[20] Ben Gibson and Tim Bell. 2013. Evaluation of games for teaching computer science. In *Proceedings of the 8th Workshop in Primary and Secondary Computing Education*. 51–60.
[21] Sukhpal Singh Gill, Adarsh Kumar, Harvinder Singh, Manmeet Singh, Kamalpreet Kaur, Muhammad Usman, and Rajkumar Buyya. 2022. Quantum computing: A taxonomy, systematic review and future directions. *Software: Practice and Experience* 52, 1 (2022), 66–114.
[22] Franziska Greinert, Rainer Müller, Philipp Bitzenbauer, Malte S Ubben, and Kim-Alessandro Weber. 2023. Future quantum workforce: Competences, requirements, and forecasts. *Physical Review Physics Education Research* 19, 1 (2023), 010137.
[23] Jan Friso Groote, Rolf Morel, Julien Schmaltz, and Adam Watkins. 2021. *Logic Gates, Circuits, Processors, Compilers and Computers.* Springer.
[24] Ava Heinonen, Bettina Lehtelä, Arto Hellas, and Fabian Fagerholm. 2023. Synthesizing research on programmers' mental models of programs, tasks and concepts—A systematic literature review. *Information and Software Technology* (2023), 107300.
[25] Hadi Hosseini, Maxwell Hartt, and Mehrnaz Mostafapour. 2019. Learning is child's play: Game-based learning in computer science education. *ACM Transactions on Computing Education (TOCE)* 19, 3 (2019), 1–18.
[26] Ciaran Hughes, Doug Finke, Dan-Adrian German, Celia Merzbacher, Patrick M Vora, and HJ Lewandowski. 2022. Assessing the needs of the quantum industry. *IEEE Transactions on Education* 65, 4 (2022), 592–601.
[27] Chris Johnson, Monica McGill, Durell Bouchard, Michael K Bradshaw, Víctor A Bucheli, Laurence D Merkle, Michael James Scott, Z Sweedyk, J Àngel Velàzquez-Iturbide, Zhiping Xiao, et al. 2016. Game development for computer science education. In *Proceedings of the 2016 iticse working group reports*. 23–44.
[28] Cagin Kazimoglu, Mary Kiernan, Liz Bacon, and Lachlan MacKinnon. 2011. Understanding computational thinking before programming: developing guidelines for the design of games to learn introductory programming through game-play. *International Journal of Game-Based Learning (IJGBL)* 1, 3 (2011), 30–52.
[29] Cagin Kazimoglu, Mary Kiernan, Liz Bacon, and Lachlan MacKinnon. 2012. Learning programming at the computational thinking level via digital game-play. *Procedia Computer Science* 9 (2012), 522–531.
[30] George Lakoff and Mark Johnson. 2008. *Metaphors we live by.* University of Chicago press.
[31] Lieve Laporte and Bieke Zaman. 2016. Informing content-driven design of computer programming games: a problems analysis and a game review. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. 1–10.
[32] James J Lu and George HL Fletcher. 2009. Thinking about computational thinking. In *Proceedings of the 40th ACM technical symposium on Computer science education*. 260–264.
[33] Linxiao Ma, John Ferguson, Marc Roper, and Murray Wood. 2007. Investigating the viability of mental models held by novice programmers. In *Proceedings of the 38th SIGCSE technical symposium on computer science education*. 499–503.
[34] Philip Machanick. 2007. A social construction approach to computer science education. *Computer Science Education* 17, 1 (2007), 1–20.
[35] Thomas Mahatody, Mouldi Sagar, and Christophe Kolski. 2010. State of the art on the cognitive walkthrough method, its variants and evolutions. *Intl. Journal of Human–Computer Interaction* 26, 8 (2010), 741–785.
[36] Vittorio Marone. 2016. Playful constructivism: Making sense of digital games for learning and creativity through play, design, and participation. *Journal For Virtual Worlds Research* 9, 3 (2016).
[37] Anuradha Mathrani, Shelly Christian, and Agate Ponder-Sutton. 2016. PlayIT: Game based learning approach for teaching programming concepts. *Journal of Educational Technology & Society* 19, 2 (2016), 5–17.
[38] Tamotsu Mitamura, Yasuhiro Suzuki, and Takahumi Oohori. 2012. Serious games for learning programming languages. In *2012 IEEE international conference on systems, man, and cybernetics (SMC)*. IEEE, 1812–1817.
[39] Nikolaj Moll, Panagiotis Barkoutsos, Lev S Bishop, Jerry M Chow, Andrew Cross, Daniel J Egger, Stefan Filipp, Andreas Fuhrer, Jay M Gambetta, Marc Ganzhorn, et al. 2018. Quantum optimization using variational algorithms on near-term quantum devices. *Quantum Science and Technology* 3, 3 (2018), 030503.
[40] Mariia Mykhailova and Krysta M Svore. 2020. Teaching quantum computing through a practical software-driven approach: Experience report. In *Proceedings of the 51st ACM technical symposium on computer science education*. 1019–1025.
[41] Michael A Nielsen and Isaac L Chuang. 2010. *Quantum computation and quantum information.* Cambridge university press.
[42] Laurentiu Nita, Nicholas Chancellor, Laura Mazzoli Smith, Helen Cramman, and Gulsah Dost. 2021. Inclusive learning for quantum computing: supporting the aims of quantum literacy using the puzzle game Quantum Odyssey. *arXiv preprint arXiv:2106.07077* (2021).
[43] Marina Papastergiou. 2009. Digital game-based learning in high school computer science education: Impact on educational effectiveness and student motivation. *Computers & education* 52, 1 (2009), 1–12.
[44] Thomas Plunkett, Terrill L Frantz, Hamida Khatri, Praveen Rajendran, and Sunny Midha. 2020. A survey of educational efforts to accelerate a growing quantum workforce. In *2020 IEEE International Conference on Quantum Computing and Engineering (QCE)*. IEEE, 330–336.
[45] Linda G Polin. 2018. A constructivist perspective on games in education. *Constructivist education in an age of accountability* (2018), 163–188.
[46] John Preskill. 2018. Quantum computing in the NISQ era and beyond. *Quantum* 2 (2018), 79.
[47] Jože Rugelj. 2015. Serious computer games in computer science education. *EAI Endorsed Transactions on Serious Games* 2, 6 (2015).
[48] Özlem Salehi, Zeki Seskir, and Ilknur Tepe. 2021. A computer science-oriented approach to introduce quantum computing to a new audience. *IEEE Transactions on Education* 65, 1 (2021), 1–8.
[49] Stefan Seegerer, Tilman Michaeli, and Ralf Romeike. 2021. Quantum computing as a topic in computer science education. In *Proceedings of the 16th Workshop in Primary and Secondary Computing Education*. 1–6.
[50] Cynthia Selby and John Woollard. 2013. Computational thinking: the developing definition. (2013).
[51] Zeki C Seskir, Piotr Migdał, Carrie Weidner, Aditya Anupam, Nicky Case, Noah Davis, Chiara Decaroli, İlke Ercan, Caterina Foti, Paweł Gora, et al. 2022. Quantum games and interactive tools for quantum technologies outreach and education. *Optical Engineering* 61, 8 (2022), 081809–081809.
[52] Amber Settle, Baker Franke, Ruth Hansen, Frances Spaltro, Cynthia Jurisson, Colin Rennert-May, and Brian Wildeman. 2012. Infusing computational thinking into the middle-and high-school curriculum. In *Proceedings of the 17th ACM annual conference on Innovation and technology in computer science education*. 22–27.
[53] Lihui Sun, Zhen Guo, and Linlin Hu. 2023. Educational games promote the development of students' computational thinking: a meta-analytic review. *Interactive Learning Environments* 31, 6 (2023), 3476–3490.
[54] Xin Pei Voon, Su Luan Wong, Lung Hsiang Wong, Mas Nida Md Khambari, and Sharifah Intan Sharina Syed Abdullah. 2022. Developing computational thinking competencies through constructivist argumentation learning: A problem-solving perspective. *International Journal of Information and Education Technology* (2022).
[55] Dave Wecker, Matthew B Hastings, and Matthias Troyer. 2015. Progress towards practical quantum variational algorithms. *Physical Review A* 92, 4 (2015), 042303.
[56] David Weintrop, Nathan Holbert, Michael S Horn, and Uri Wilensky. 2016. Computational thinking in constructionist video games. *International Journal of Game-Based Learning (IJGBL)* 6, 1 (2016), 1–17.
[57] Lewis Westfall and Avery Leider. 2019. Teaching quantum computing. In *Proceedings of the Future Technologies Conference (FTC) 2018: Volume 2*. Springer, 63–80.

[58] Jeannette M Wing. 2006. Computational thinking. *Commun. ACM* 49, 3 (2006), 33–35.
[59] James R Wootton, Francis Harkins, Nicholas T Bronn, Almudena Carrera Vazquez, Anna Phan, and Abraham T Asfaw. 2021. Teaching quantum computing with an interactive textbook. In *2021 IEEE International Conference on Quantum Computing and Engineering (QCE)*. IEEE, 385–391.
[60] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through design as a method for interaction design research in HCI. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 493–502.