Quantum Computing As a Topic in Computer Science Education

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ABSTRACT

Quantum technologies are currently among the most promising technological developments, with quantum computing, in particular, playing a crucial role. This is accompanied by promising opportunities, but also new challenges for our society. However, quantum computing as a subject of computer science education is still at the very beginning. This paper aims to discuss quantum computing as a topic in computer science education and to make a first approach to central terms and ideas as well as their explanatory approaches. With the help of an explorative focus group interview with experts, five core ideas of quantum computer science are identified in this study. A literature review is then used to identify, categorize, and contrast different explanatory approaches for these ideas. The results thus contribute to making quantum computer science accessible for computing education and raise further questions for the computing education research community.

CCS CONCEPTS

• **Social and professional topics → K-12 education**.

KEYWORDS

quantum computing, quantum information science, focus group interview, core ideas, quantum computer science

ACM Reference Format:
Stefan Seegerer, Tilman Michaeli, and Ralf Romeike. 2021. Quantum Computing As a Topic in Computer Science Education. In *Woodstock '18: ACM Symposium on Neural Gaze Detection, June 03–05, 2018, Woodstock, NY*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION

With the digital transformation, computer technologies have found their way into almost all areas of life and people are encountering them in the form of increasingly numerous information technology innovations such as embedded ubiquitous systems, big data, or artificial intelligence. A major driving force of these advancements is computer science. Computer science education aims at making the corresponding fundamentals, applications, and implications of these technologies accessible and comprehensible to any target audience. Therefore, there is a consensus in computer science education research that teaching should emphasize concepts, ideas and principles that are fundamental to the subject and relevant in the long term, rather than short-term devices and technologies [2, 8, 30].

Quantum technologies are a rapidly emerging innovation at the intersection between physics, mathematics, and computer science. In the form of quantum computing, this new paradigm poses significant advances and challenges for computer science. Even though modern computer systems are already built on the principles of quantum physics, only more recent developments of the so-called "second quantum revolution" have the potential to influence our society. This leads to new opportunities and challenges. For example, future developments in quantum technologies may affect information security and privacy of citizens, governments, or companies. Sensitive data can already be tapped from networks without quantum-resistant encryption, stored, and potentially decrypted at a later time by quantum computers. At the same time, quantum cryptography creates new possibilities for tap-proof transmissions. Another important application area of quantum computing is simulation. Here, quantum computers promise increased efficiency, for example in drug research or meteorology. Thus, quantum technologies bring both great opportunities and risks for society that require an informed public debate.

Despite the increasing presence in the media and growing needs in science, economy, and society, quantum computing as a subject area of computer science education is still at an early stage – in contrast to the importance of quantum theory in physics. The aim of this paper is to present quantum computing as a topic and task of computer science education. To this end, it provides an initial approach to core terms, ideas, and suitable explanations based on a survey of experts and literature.

2 RELATED WORK

Information processing based on quantum physics differs from the conventional way of digital information processing in many ways: While a traditional computer represents information with bits valued either 0 or 1, a quantum computer uses so-called *qubits*. A qubit can also take the value 0 or the value 1. But in addition, it can be in a so-called *superposition*. In this case, the qubit has a certain probability to be measured as 0 or as 1. However, this measurement "destroys" the superposition – i. e. any further measurement would reveal the same result: If a qubit has a 50% chance to be measured as 0 and a 50% chance to be measured as 1 and the first measurement yields 0, the second measurement will also yield 0 100% of the time.

Moreover, qubits can be *entangled* – i. e., made dependent on each other – which enables the creation of arbitrary quantum states, and

WiPSCE '21, October 18-20, 2021,

ACM ISBN 978-1-4503-XXXX-X/18/06…$15.00
https://doi.org/10.1145/1122445.1122456

thus achieving quantum superiority. Taking advantage of superposition and entanglement, *quantum algorithms* attempt to solve certain problems such as prime factorization [31], database searching [15], or simulations [38] much faster than traditional supercomputers: While n traditional bits can only be in one of the 2^n possible states, n qubits can be used to represent 2^n states simultaneously, with each state assigned a specific probability: So while a traditional computer could only represent one state with 4 bits (e. g. 1001), a quantum computer can represent all 16 possible combinations of 0 and 1 with length 4, with each combination having a certain probability to be measured. Traditional computers use gates – primitive logical functions – such as AND, OR or NAND (not and) to process data stored in bits. Quantum algorithms manipulate qubits by applying special *quantum gates* in such a way that a correct result is measured at the end with high probability.

The three sciences directly involved, physics, mathematics, and computer science, can contribute to the understanding of quantum technologies, and each can serve as a perspective and entry point into the subject area. Thus, there are various educational concepts to address the basics of quantum physics in school, e. g., by starting with the double-slit experiment to illustrate central contents and questions of quantum physics [21], with light experiments [11] or by providing students the possibilities to experiment in different laboratory settings [12]. A physics education approach to quantum *computing* exists, for example, for high school students [28]. However, this approach requires in-depth mathematical knowledge.

If we consider quantum computing as a topic of computer science education, approaches are limited and there are only a handful of educational concepts. Quantum computing can be found in certain university courses in bachelor's (e. g., [20]) or master's computer science programs (e. g., [22, 33]). Billig [4] addresses quantum computing for secondary school students concerning their mathematics skills, e. g., by simplifying the central concepts and avoiding complex numbers. To illustrate the potentials of quantum computing, traditional computer systems and cryptographic methods are first described. Then, the special features, strengths, and challenges of quantum technology are highlighted. A first proposal for key concepts of quantum information science is presented by QISLearners [1]. Other secondary school curricula consider the STEM context [29], use problem-based learning and the IBM Quantum Circuit Designer [26], or propose quantum computing activities to support regular lessons [32]. Wootton [36] describes an approach to getting started using a brain game app that allows interested individuals ages 5 and up to learn about qubits and quantum gates in a playful manner. In addition, several videos explain quantum computing by teaching the basics of quantum technologies at different levels. To our knowledge, there are no scientific studies or research findings on the aforementioned approaches, which are primarily devoted to the preparation of content.

3 METHODOLOGY

In the following, an initial didactical analysis of the topic of quantum computing will be undertaken. For this purpose, we will first (1) identify central terms and concepts as well as relevant questions and needs for clarification based on relevant literature, (2) utilize a focus-group-interview with experts to determine candidates for core ideas of quantum computing, and (3) analyze and contrast existing explanatory approaches for the resulting core ideas to collect and discuss existing pedagogical approaches.

(1) Clarification and Analysis Of the Subject Area. In the first step, in an explorative literature analysis, relevant terms and concepts within literature were gathered. Furthermore, open questions and needs for further clarification were identified. The corpus comprises a total of 17 documents (children's books, textbooks, school curricula, and popular science books dealing with the topic of quantum computing), see table 1. This allows for an initial clarification and analysis of the subject area, providing the basis for the expert interviews.

Target audience	# Documents	Documents
Children	2	[13, 23]
Students	5	[4, 25, 26, 29, 35]
Professional audience	4	[5, 16, 17, 27]
Interested general public	6	[6, 10, 18, 19, 34, 37]

Table 1: Document corpus

(2) Focus group interview with experts. To discuss and evaluate the concepts and issues identified in the first step, an expert survey in the form of a focus group interview was conducted. Due to its exploratory and discursive character aiming at reaching a consensus, this survey method is particularly suitable for our research interest [14]. The experts were approached via the German Informatics Society's (GI) working group "quantum computing". They are characterized by both technical expertise in the research area of quantum computing as well as corresponding teaching experience. For the online workshop, 9 people could be recruited. As preparation, the experts were surveyed using a semi-structured questionnaire on central terms, possible applications, and social impact of quantum computing beforehand. The results of this written survey were then analyzed and summarized to provide the basis for the actual group discussions within the workshop. Thus, the structure of the questionnaire also served as an interview guide for the focus group. Within the workshop, those results were discussed. Based on the central terms of the field, the method of pile sorting was applied to develop and rate core ideas of quantum computing. In addition, follow-up interviews were conducted with selected participants.

(3) Explanatory approaches. In the third step, explanatory approaches for the previously-identified core ideas of quantum computing were elaborated, categorized, and contrasted with the help of a literature analysis. For this purpose, the corpus of step 1 (cf. table 1) was examined with the help of a structuring qualitative content analysis according to Mayring [24]. As a deductive category system, we used the resulting core ideas of step 2. This way, recurring patterns in the explanatory approaches for the corresponding ideas could be identified.

4 RESULTS

4.1 Clarification and Analysis Of the Subject Area

To identify the core ideas of quantum computing important to the context of computer science education, an initial overview of the relevant concepts is needed. This overview was first obtained with the help of an exploratory analysis of relevant literature for different target groups. The results show that there seems to be a certain consensus regarding topics and terms relevant to the subject area, which is reflected in a group of recurring terms used similarly in all analyzed documents (cf. the terms mentioned by experts in Tab. 2). Furthermore, the terms were largely independent of the literature's target group. Due to their prominence in the literature, it can be assumed that the terms are also central from the perspective of computer science education and thus for the understanding of quantum computing and can be used as a basis for identifying core ideas.

Furthermore, it has proven to be purposeful to consider not only the technological perspective but also the application-oriented and socio-cultural perspective [7]. However, in literature, statements almost exclusively came from a technological perspective. Possible applications and also societal implications of quantum computing were only hinted at, so that this question was also taken to the expert panel.

4.2 Focus Group Interview With Experts

Central Terms. Terms can help define, specify, and prioritize learning content in a subject area. With this goal in mind, the questionnaire asked participants to name what they considered to be the seven most important terms regarding quantum computing that everyone should know (see Tab. 2). These terms corresponded with the term identified in the exploratory literature analysis. In the focus group interview, these terms were initially grouped or combined together. For example, the terms quantum parallelism, quantum speed up, and quantum advantage were combined into one concept. When multiple terms were combined into a single concept, particular care was taken to ensure a similar level of abstraction for all involved terms. In addition, the terms were prioritized: Terms that contribute to a basic understanding and thus allow for access to the field were selected. For example, quantum internet and quantum communication or quantum simulation, which focus mainly on specific applications, were considered less relevant.

Core Ideas. Following the interviews, the concepts essential for understanding were formulated in the form of ideas and validated with follow-up interviews. The final 5 candidates for these ideas are as follows:

(1) Superposition: Qubits in a superposition of 0 and 1 have a certain probability of being measured as 0 and as 1, respectively.
(2) Entanglement: The state of multiple entangled qubits cannot be described by specifying an individual quantum state for each qubit.
(3) Quantum computer: Quantum computers can solve certain – but not all – problems more efficiently than traditional computers.
(4) Quantum algorithm: In a quantum algorithm, quantum gates are used to influence the state of the qubits in such a way that the probability of measuring a correct solution increases.
(5) Quantum cryptography: Quantum cryptography uses the fragility of qubits to enable tap-proof communication.

Application-oriented and Socio-cultural Perspective. . Three key application or societal implications emerge from the experts' responses. In the area of *cryptography*, on the one hand, there is a threat to traditional methods such as RSA, but on the other hand, there are opportunities for new, secure methods. At the same time, the experts promise social implications in *optimization* problems, for example in the field of artificial intelligence, which could be solved better or faster in the future. Finally, *quantum simulations* promise societal progress in biological, chemical, or physical research and can thus help, for example, to develop new vaccines. Nevertheless, with a few exceptions, such as the generation of random numbers on smartphones, quantum information applications have hardly been used in everyday life.

4.3 Explanatory approaches

In the following, the result of the literature analysis on explanatory approaches is presented. The individual approaches do not necessarily appear in isolation: Within a document, different explanatory approaches were sometimes used for the same idea.

Superposition: Qubits in a superposition of 0 and 1 have a certain probability of being measured as 0 and as 1, respectively. A popular way to explain this idea is to use *analogies* such as the coin toss (or the spin of a coin), where the coin in the air (or spin) is interpreted as a superposition of heads and tails (cf. Fig. 1). Another approach is represented by a *physical explanation approach*, in which concrete realizations of qubits by photons or electron spins are used, as well as experiments such as Stern-Gerlach. Furthermore, qubits in the corpus are also explained *mathematically-symbolically*: the state of one or more qubits is then represented by a vector. *graphical representations* are also used for explanation, for example geometrically via the Bloch sphere or unit circle, and schematically via partially filled circles or squares for each state of a qubit in a system. Moreover, qubits are introduced based on the bit notion with the help of probabilistic bits and subsequently generalized to qubits, i.e., building on *traditional topics of computer science education.*

Entanglement: The state of multiple entangled qubits cannot be described by specifying individual quantum states for each qubit. Similarly to the first idea, entanglement is often explained by *analogies.* For example, two entangled coins always land both on heads or always both on tails (cf. fig. 2). In another analogy, two colored balls are packed in different boxes: even if it is not known which color is in the boxes, both balls will have the same color. In addition, a *mathematical-symbolic* approach to the explanation is often taken, in which it is proved computationally that an entangled two-qubit state cannot be represented as two individual one-qubit states. Moreover, entanglement is also explained via *measurement of quantum circuits* when Hadamard and CNOT gates are combined, or again starting from *traditional topics of computer science education* via introducing probabilistic bits as an intermediate step.

Begriff	#	Begriff	#	Begriff	#
Qubit	8	State	2	Quantum Information processing	1
Entanglement	8	Measurement	2	Quantum communication	1
Quantum circuit / -gate	5	Quantum simulation	2	Quantum speed up	1
Superposition	5	Decoherence	2	Bloch sphere	1
Quantum cryptography	5	Teleportation	2	Supremacy	1
Quantum computer	4	Quantum internet	2	Quantum Advantage	1
Quantum algorithm	2	Error-prone	2	Photon	1
Quantum parallelism	2	Quantum information	1		

Table 2: Core terms and number of responses by experts.

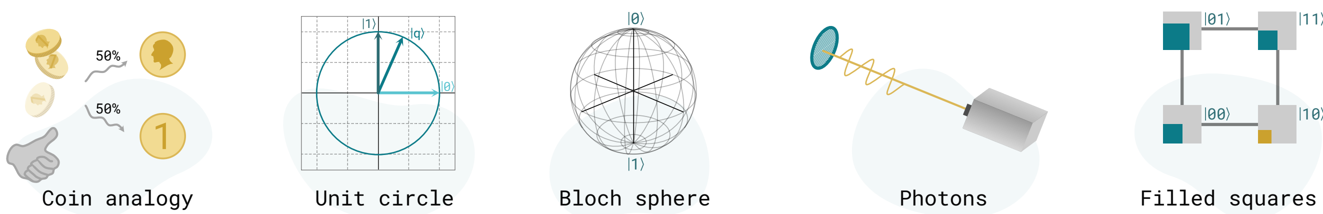

Figure 1: Examples for explainaing qubits and superposition

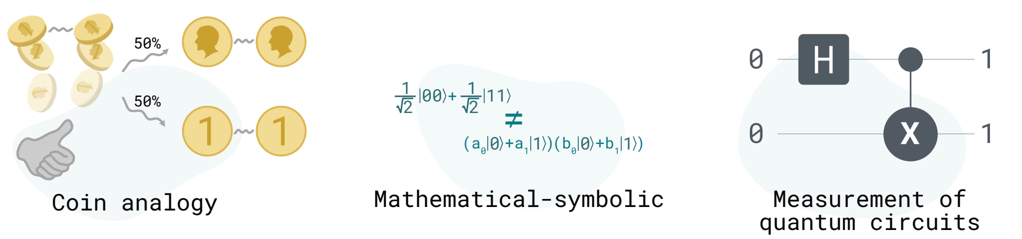

Figure 2: Examples for explaining quantum entanglement in the context of quantum computing

Quantum computers: Quantum computers can solve certain – but not all – problems more efficiently than traditional computers. Again, the *analogy* approach is often taken, describing quantum computers as operating in a highly parallel fashion. Another explanatory approach uses *set of states* – often using concrete examples and orders of magnitude: For example, 300 qubits can already represent more states (about 10^{90}) than particles that exist in the universe. Another popular explanatory approach works with a *concrete example* such as the Deutsch-Josza algorithm [9]. This way, the number of steps necessary to solve the problem can be compared between a traditional and a quantum computer.

Quantum algorithm: In a quantum algorithm, quantum gates are used to influence the state of qubits in such a way that the probability of measuring a correct solution increases. For this concept, on the one hand, a *physical explanation* approach is used, which describes a concrete realization and manipulation of qubits (e.g. photons) (cf. fig. 4). To explain the effect of the different gates on the state of one (or more) qubits, sometimes a *graphical representation* is chosen. For example, a rotation is made on the Bloch sphere, a vector is mirrored at a certain axis on the unit circle, or filled areas are exchanged along certain edges of a cube in a schematic representation. In the *experimental explanation approach*, the effects of the gates are investigated by measurement – for this purpose, one usually works directly with appropriate tools (usually simulators for quantum computers). Lastly, in a *mathematical-symbolic explanatory approach*, the quantum gates are used in their matrix representation, where applying a gate corresponds to multiplying the matrix by a vector, or mapped to a state transition diagram.

Quantum cryptography: quantum cryptography exploits the fragility of qubits to enable tap-proof communication. A *concrete example* is often chosen as an explanatory approach for the way quantum

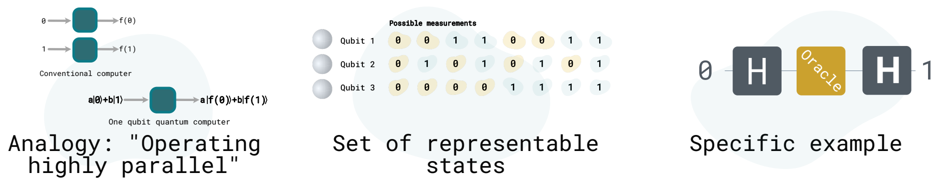

Figure 3: Examples for explaining why quantum computers can solve certain problems more efficiently than classical computers

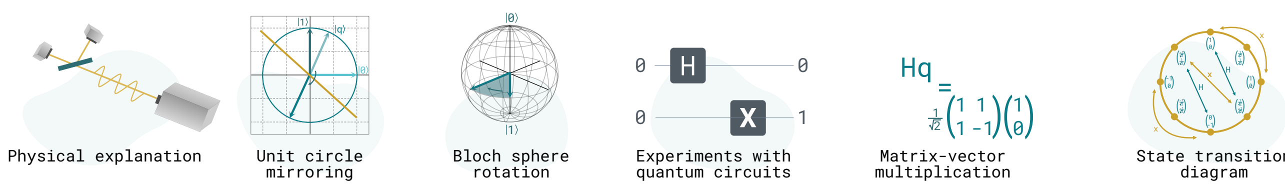

Figure 4: Examples for explaining gates

cryptography works, in the form of the BB84 key exchange protocol [3], since this does not require entangled states and is overall considered easy to understand. Furthermore, to illustrate the advantages of a quantum key exchange protocol, *traditional topics of computer science education* such as symmetric encryption and the one-time pad are also referenced.

5 DISCUSSION

Both the literature-based analysis and clarification of the subject area and the expert interview show that quantum computing can be made accessible via a core of central ideas. Similar to the beginnings of computer science, mathematical foundations, physical realization, and computational use of quantum computers are still very close to each other. This has an impact on existing foci and teaching approaches to quantum computing. The expert group agreed that a specific computer science perspective exists and is important. A particular challenge for computer science education is that there are – as of now – hardly any concrete applications of quantum computing. Therefore, applications and contexts used in teaching must be limited to simulation and future scenarios, for example. The same applies to the socio-cultural perspective: The potential effects of quantum technologies already motivate several research directions, such as (post-)quantum cryptography, but are not yet noticeable in everyday life. However, since they are considered to have the potential to change society, educational approaches that are comprehensible to the general public are necessary for an informed public discourse.

Looking at the analyzed explanatory approaches, it can be seen that mathematical and physical views and approaches to quantum technologies have dominated so far. Thus, in the corpus studied, physical experiments were often described in the context of an introduction to quantum computing. Furthermore, complex numbers or matrices were introduced to describe states and gates. The corpus shows, however, that explanations of the ideas are possible even without a corresponding foundation in physics or elaborate knowledge of mathematics.

Furthermore, our data indicates that quantum computer science ideas are often explained starting from traditional concepts of computer science – or are contrasted to them. Thus, traditional contents of computer science education, such as the representation of information by bits or the realization of information processing by computers with the help of logic gates, represent an important basis for the teaching of quantum computing.

Beyond that, the results show that – as usual in computer science education – analogies are often used. Analogies can help, according to a constructivist learning understanding, to clarify facts vividly, but mostly reduce the idea to a single aspect. This results in special challenges concerning misconceptions. For example, the analogy of a coin toss for qubits in superposition has only limited validity, since objects like coins do not behave according to quantum mechanical laws: The result of a toss could be calculated if all parameters were known exactly. These laws are subject to those of traditional mechanics. A comparable problem appears with the analogy that quantum computers – similar to traditional multiprocessor systems – would operate in a highly parallel fashion. In fact, quantum computers alter the probabilities of a large number of potential solutions in such a way that a correct solution is very likely to be measured. Accordingly, it can be seen as a task of research in computer science education to explore which approaches and analogies are suitable to develop helpful conceptions, which misconceptions should be avoided, and which age-appropriate competencies students can and should acquire concerning quantum computing.

6 CONCLUSION

The investigation of quantum computing as a rather young subdiscipline of computer science shows that both the research field as well as its educational discussion are still in an early stage. In light of the expected enormous progress in the field of quantum computing and the resulting growing influence on our everyday life, quantum computing may become an increasingly important subject and research area of computer science education.

The aim of this study was to present an analysis of quantum computing as a topic in computer science education by providing an initial approach to core terms, ideas, and suitable explanations. To this end, we investigated literature and conducted a focus group interview with experts of the subject area. Overall, our study provides the following two major contributions:

Firstly, we identified 5 core ideas of quantum computing. Those ideas make quantum computer science accessible for computing education by structuring the field with a focus on underlying principles relevant in the long term. This provides the basis for preparing the topic for teaching or developing respective curricula.

Secondly, we categorize, contrast, and discuss different explanatory approaches used within the literature for those core ideas. These approaches make the core ideas and the respective applications, and implications of quantum computing comprehensible, constituting the foundation for teaching the subject area. Furthermore, they raise further tasks and questions for the computing education research community, for example regarding the suitability of certain approaches or the relation and connection to traditional topics of computer science education.

Even though quantum computing will not find its way into K12 curricula in the near future, students should be given the opportunity to understand these exciting developments in the context of extracurricular activities or within elective formats. This way, they have the opportunity to develop an interest and perhaps be enabled to help shape the future themselves.

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