Epistemic aims and values of quantum computation in foundational research papers and implications for education

Sara Satanassi[1] and Sibel Erduran[2]

[1]*Department of Physics and Astronomy, "A. Righi", University of Bologna, 40126 Bologna, Italy*
[2]*Department of Education, University of Oxford, Oxford OX1 2JD, United Kingdom*

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As quantum technologies gain importance across scientific and societal domains, understanding the foundational principles driving their development is increasingly crucial. While much work has been devoted to defining essential knowledge and curriculum content for quantum technologies at various educational levels, less attention has been paid to how the Second Quantum Revolution is shaping the nature of quantum computation in terms of its foundational epistemic aims and values. The paper presents a conceptual account of the nature of quantum computation through document analysis of foundational research papers. Using the lens of the Family Resemblance Approach to the nature of science, it uncovers the core epistemic aims and values characterizing the domain of quantum computation. By applying this analytical framework, the study identifies both predetermined epistemic aims and values (e.g., objectivity and accuracy) and emergent subcategories (e.g., materiality of information and efficiency) relevant to quantum computation. The document analysis contributes to the literature on the nature of science in general and to the characterization of quantum computation as a domain in particular. Furthermore, the analysis brings to light implicit epistemic aims and values that guide practitioners in a scientific domain to the foreground, which often remain unarticulated in educational contexts. The findings include 17 instances of epistemic aims and values of quantum computation generated from an analysis of significant research papers in the field. By systematically generating these epistemic aims and values, the study provides a nuanced and explicit approach to characterizing the nature of quantum computation, enabling educators to incorporate these themes into curriculum design, teaching, and learning. Some implications for quantum technologies education are discussed.

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I. INTRODUCTION

Quantum technologies have swiftly gained significant attention, becoming a focal point in strategic initiatives across multiple countries. Examples include the Quantum Flagship in Europe, the National Quantum Initiative in the United States, the 14th Five-Year Plan in China, and the National Quantum Technologies Programme in the United Kingdom. In 1999, for the first time, Milburn and Leggett [1] described the transition from understanding and applying the principles of quantum mechanics to a new era in which we can directly manipulate and control quantum systems, enabling transformative technologies known as the Second Quantum Revolution. This revolution follows the first one, which began in the early 20th century as scientists sought to provide theoretical explanations for phenomena such as blackbody radiation. This period introduced foundational quantum concepts such as uncertainty and complementarity, unravelling the initial mysteries of quantum mechanics [2]. It established new principles that govern physical reality and gave rise to transformative technologies, including transistors and lasers, which are the cornerstones of modern society.

The Second Quantum Revolution is giving rise to technologies that encompass quantum communication, which uses individual quantum particles to ensure secure data transmission [3]; quantum sensors, leveraging quantum phenomena such as the interaction of single quantum particles with magnetic fields for highly accurate measurements [4]; quantum computing, expected to transform problem-solving capabilities once a sufficient number of logical qubits is achieved, enabling accelerated solutions in areas such as optimization [5], machine learning [6], and large-number factorization [7]; and quantum simulation, which specializes in the simulation of complex molecular structures, significantly advancing quantum chemistry [8]. The rising interest in and expanding role of quantum technology across various industries underscore its strategic significance [9].

In the face of technological advancement, science education and science education research have been pursuing three main goals. First, science education needs to foster ecosystems to educate students about the Second Quantum Revolution by promoting collaboration among universities, enterprises, and schools [10]. Second, science education is now expected to address labor market needs by expanding workforce development through programs that serve both physics and nonphysics students. Finally, science education can inspire future quantum experts and foster quantum literacy (e.g., Quantum World Day) [11]. At the European level, QTEdu [12], a Coordination and Support Action (CSA) project supporting the European Quantum Flagship, has played a pivotal role in establishing a network of experts from different backgrounds and learning ecosystems, aimed at preparing a society ready for quantum technologies and building a skilled quantum workforce and a quantum-literate citizenship [11].

In this paper, we aim to highlight that, despite the significant efforts in tailoring the concepts and content of the Second Quantum Revolution to different educational levels and training objectives, the dynamic nature of scientific knowledge and its evolution in the context of quantum technologies has not yet been sufficiently addressed. Moreover, the profound impacts of the Second Quantum Revolution are reshaping the relationship between science and society. This shift warrants deeper reflection and consideration in both scientific and educational discourse. Nature of science (NOS) is an area of research that draws from both philosophy of science and science education research [13]. The philosophy of science provides deep insights into scientific reasoning and the nature of theories, laws, and models, as well as the role of values in science.

While NOS research has long examined how scientific knowledge is constructed and communicated, the rapid advancements of the Second Quantum Revolution introduce new challenges in understanding and teaching the evolving nature of science. We have chosen to focus on quantum computation because it is a research field that originated in the early 1980s and has reshaped traditional views on information, measurement, and determinism, reflecting broader epistemological shifts in science. These changes not only affect how knowledge is produced in quantum science but also raise critical questions about how science education can effectively reflect and communicate this evolving landscape. In light of these transformations, what is the nature of quantum computation that underpins many developments in the Second Quantum Revolution? What are the major aims and values of quantum computation that drive the generation of new scientific knowledge? What do such aims and values about knowledge imply for science education?

This paper addresses these questions through a conceptual and analytical investigation of the epistemic aims and values of quantum computation. Our study does not aim to provide an empirical classroom investigation but instead offers a document-based analysis of foundational papers in quantum computation, using the Family Resemblance Approach (FRA) to the Nature of Science as a theoretical lens. This framework has the potential to individuate the specific features that characterize the domain and explain why it is worth tackling from an educational perspective. Our goal is to contribute a foundational conceptual framework that can inform curriculum development, teacher education, and future empirical research in quantum technologies education. In doing so, we aim to highlight epistemic aspects often left implicit in science education, supporting a more meaningful integration of quantum technologies into science learning.

After a review of selected literature on quantum technologies education (Sec. II A), we present what we mean by the epistemological and cultural value of the Second Quantum Revolution (Sec. II B). We then introduce the specific account of NOS that we find particularly suitable for unpacking the Second Quantum Revolution (Sec. II C): the FRA. This account frames quantum technologies as a comprehensive effort that encompasses cognitive, epistemic, social, and institutional aspects. Finally, we present a conceptual analysis based on document analysis of foundational research papers related to the Second Quantum Revolution. Using ChatGPT and the FRA lens, we systematically analyze 16 seminal papers to explore the epistemic nature of quantum computation. We conclude with practical insights on how these epistemic goals and values can guide science education research and practice.

II. BACKGROUND OF THE STUDY

A. Literature review on quantum technologies and competence framework

As noted in the Introduction, the research and development of quantum technologies are increasingly becoming a priority not only for academia but also for industry as their applications expand beyond theoretical exploration to practical, commercial use. The most recent data from McKinsey [13] reveal that the talent gap in quantum technologies, although narrowing, remains a significant challenge. In 2022, approximately two-thirds of quantum technology job openings were filled by master's-level graduates.

In response to the growing demand for experts, substantial resources have been and will be allocated at the institutional level to develop doctoral programs, master's, and bachelor's courses for students from both physics and nonphysics backgrounds, as well as master's degree professionals, that is, courses aimed at the occupational market [14,15]. Projects are proliferating, such as DigiQ and QUCATS, which aim to expand and enhance training for a quantum-aware workforce at both European and international levels.

The essential skills and knowledge required for quantum technology have been identified to support the development of standards and guide the design of educational and training programs [16,17]. In particular, the Quantum Technologies Competence Framework [18] is a structured guideline that outlines the key concepts, knowledge areas, and topics to be introduced at different educational levels, aiming to support the development of quantum literacy and a specialized understanding of various roles and profiles in quantum technologies. It presents a list of concepts that encompasses eight domains: concepts and foundations (1), physical foundations of quantum technologies (2), enabling technologies and techniques (3), quantum hardware (4), quantum computing and simulation (5), quantum sensors and imaging systems (6), quantum communication and networks (7), valorization (8). Each domain is composed of topics and subtopics. In this version, the authors add three main (I, II, III) proficiency levels, each containing two sublevels: the first sublevel is includes A1 (awareness) and A2 (literacy), the second includes B1 (utilization) and B2 (investigation), the third one includes C1 (specialization) and to C2 (innovation). For each sub-level and proficiency level, the authors present the topics that have to be learned and one skill. Finally, they present nine profiles, which were developed through interviews with industry representatives, and explain how these profiles can be built from the proficiency levels [19].

While this document provides an overview of the topics necessary for preparing various forms of "quantum expertise" and guides the creation of a standard profile, it does not fully capture the broader epistemic and cultural impact of the Second Quantum Revolution and emerging technologies. For example, it does not articulate a framework for a systematic approach to the aims and values of the domain of quantum computation, putting the objectives of quantum technologies education in focus, and justifying why scientists do what they do in this domain. Aligning with Organization for Economic Co-operation and Development (OECD) reports that define competence as a combination of knowledge, skills, and attitudes, this paper primarily emphasizes content and technical skills, risking falling short of reflecting the more nuanced and complex understanding of competence as outlined in the widely accepted definition [20].

The problem of expanding the QT workforce necessitates that we consider the foundational aims and values of the domain in education to support novices in understanding how quantum mechanics works. Existing initiatives represent a leap, bridging the gap between foundational learning and deeper, more advanced comprehension of quantum concepts. Regarding teaching, Meyer *et al.* [21] conducted a study with instructors to investigate the gap between the interdisciplinary knowledge required in quantum information science courses and the instructors' mainly discipline-based experiences. Asfaw *et al.* [22] outlined a roadmap for integrating quantum technologies into engineering education. They propose accessible courses for quantum-aware students to equip engineers with the necessary skills for the growing quantum industry. Similarly, Dzurak *et al.* [23] present the development of the first undergraduate degree in quantum engineering that integrates quantum mechanics into engineering curricula.

Some efforts have also been made at the secondary school level regarding student and pre- and in-service teacher education. For example, Satanassi *et al.* [24–28] developed an approach and a module on the Second Quantum Revolution, targeting both students and preservice and in-service teachers, to recognize it as a cultural revolution, which we discuss in detail in the next section. Bondani *et al.* [29] describe an online extracurricular course on quantum physics concepts that successfully engaged about 300 high school students through interactive lectures, demonstrating the potential for innovative curriculum designs to improve student engagement and understanding of quantum technologies. Building on Ref. [24], Sutrini *et al.* [30] developed a teaching and learning sequence comparing experiments and circuits to introduce the Deutsch algorithm. Zuccarini *et al.* [31] discuss creating integrated secondary school courses in quantum information science, providing students with foundational knowledge through hands-on experiences. Pospiech [32] proposes incorporating quantum cryptography into a teaching-learning sequence on quantum physics based on two-state systems. This approach aims to teach basic quantum concepts such as nondeterminism, superposition, and uncertainty, while also exposing students to contemporary physics research.

These studies have thus examined quantum technologies education from various perspectives: from understanding the basic concepts to introducing quantum mechanics to novices [24,25,30,32] to developing new teaching strategies for both school [24,25,31,32] and university levels [21–23]. Furthermore, the different proposals emphasize the importance of engaging with quantum technologies today, not only because these technologies offer a new constructive perspective on quantum mechanics that the traditional teaching approach based on the "old quantum physics" usually does not provide, but also because they could serve as a potential bridge between school and society. A major gap in emerging literature is the lack of reflection on the nature of the field itself in relation to quantum computation. This area has the potential to offer new insights worth considering and could influence education. In the next section, we provide context for the epistemological and cultural aspects of the Second Quantum Revolution, with a focus on the epistemological issues related to quantum computation.

B. Epistemological and cultural aspects of the Second Quantum Revolution

The research group at the University of Bologna in Italy has examined the epistemological and cultural aspects of the Second Quantum Revolution within the education context. The team has developed an approach and a teaching module to highlight the Second Quantum Revolution as a cultural phenomenon in recent years [24–28]. In response to rapid technological growth driven by the Second Quantum Revolution, researchers, including the first author, aimed to understand this phenomenon from epistemological and cultural perspectives, analyzing media outlets that frequently discuss these new technologies for their ability to manage and process large amounts of data, perform numerous calculations simultaneously, and solve problems that traditional computers cannot handle efficiently. However, the scale and speed of these technological advances have prompted profound changes that, as Gisin states, constitute a revolution that is, above all, conceptual, of the same cultural scope as the Newtonian revolution. This revolution is transforming the relationships among humans, society, science, and technology.

> "We are living in an extraordinary age. […] Missing out on this revolution without giving it further attention would be as much a shame as remaining ignorant of the Newtonian revolution or the Darwinian revolution had we been their contemporaries. For the conceptual revolution taking place today is of no lesser importance. It completely overturns our previous pictures of nature and will doubtless give rise of new technologies that will simply look like magic. […] Had we lived at the time of the Newtonian revolution, would we have wished to understand what was going on? Today quantum physics gives us the opportunity to live through a conceptual revolution of similar importance." [33] (p. xi)

In light of this, how do these emerging concepts and technologies reshape our understanding of knowledge, human nature, and the world around us? What are the groundbreaking conceptual, experimental, and technological elements introduced by these innovations? In previous work [27,28], starting from this big question, we adopted a compare and contrast approach between the First and the Second Quantum Revolutions, particularly regarding the conceptual, epistemological, and experimental challenges. The two major quantum revolutions are anchored in distinct concepts: complementarity and entanglement [34]. These ideas initially posed significant conceptual challenges, which were primarily explored through thought experiments. Complementarity emerged as a core theme in the discussion at the 1927 Solvay Conference on Electrons and Photons, particularly in the Bohr-Einstein debate concerning the nature of quantum objects. Entanglement took center stage in the famous 1935 Bohr-Einstein exchange, where the completeness of quantum theory and its potential nonlocal characteristics were intensely discussed [35,36].

What began as theoretical puzzles soon transitioned into experimental challenges. Theoretical constructs previously confined to the "laboratory of the mind" were eventually reframed for empirical testing. Two pivotal experiments illustrate this shift: the double-slit experiment, which epitomized the wave-particle duality inherent in quantum objects, realized for the first time by Merli *et al.* [37], and Aspect's landmark experiment in 1982, which confirmed the violation of Bell's inequalities [38,39]. These experiments deepened our understanding of quantum mechanics and reinforced the conceptual rift between classical and quantum views of reality [40,41]. The compare and contrast principle was also applied to shed light on the different logic underlying the functioning between classical and quantum computers in terms of truth tables and logic gates [24,25]. Classical binary logic, which underpins the architecture of traditional computers, was contrasted with quantum logic, highlighting profound differences in how information is processed at the hardware level. Classical computers rely on binary states (0 and 1), whereas quantum computers leverage superposition and entanglement, enabling radically new computational possibilities [9].

The compare and contrast principle is employed to reconceptualize the three main phases of quantum experiments: state preparation, state evolution/manipulation, and measurement, respectively, in terms of input, processing, and output information. This framework was recently formalized in studies [24,25], aligning experimental procedures with the structure of quantum circuits. This reconceptualization builds on the foundational idea, first proposed by Landauer [42], that "Information is inevitably tied to a physical representation and therefore to restrictions and possibilities related to the laws of physics and the parts available in the universe." Similarly, Preskill [43] further elaborated on this notion, arguing "information, after all, is something that is encoded in the state of a physical system; a computation is something that can be carried out on an actual physically realizable device. So, the study of information and computation should be linked to the study of the underlying physical processes."

Finally, the "compare and contrast" approach enables the explanation of differences at a technological level. The first quantum revolution mainly produced technologies that relied on the bulk properties of quantum mechanics, such as wave-particle duality and energy level quantization. These insights led to innovations that laid the groundwork for modern technology, including lasers, transistors, and atomic clocks. These devices utilize quantum mechanics on a macroscopic scale, harnessing collective quantum phenomena without precise control over individual quantum entities. In fact, until the mid-20th century, manipulating a single quantum object was unthinkable. As Schrödinger said: "It is fair to state that we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo" [44]. The techniques developed in the late 1980s to control, isolate, and manipulate individual quantum systems (single photons, electrons, or ions), and thus exploit quantum phenomena like superposition and entanglement, are at the heart of the Second Quantum Revolution. They are enabling the development of this second era of quantum technologies [45].

Given these groundbreaking conceptual, experimental, and technological advances introduced by quantum technologies, what are the implications for education, especially secondary science teaching and learning? Which aspects of the Second Quantum Revolution need to be prioritized for educational purposes? The research group in Bologna began addressing these questions by designing and implementing a teaching module in secondary schools. The module was implemented 5 times as an extracurricular course for high school students and 2 times with preservice and in-service teachers [24–28]. Both implementations were conducted in collaboration with Piano Lauree Scientifiche (PLS), a project launched in 2004 by the Ministry of Education to address young people's growing disinterest in scientific disciplines. A significant finding from these efforts was that both students and teachers found it beneficial to understand how the Second Quantum Revolution is fundamentally shaping scientific development. In other words, students would gain from understanding the main goals and values driving the field of quantum technologies. This highlights the importance of teachers' and students' understanding of how science works and develops, necessitating the inclusion of metaperspectives on science in education, as represented in the line of research focusing on metaperspectives on science, namely NOS [46]. In the next section, we will review a specific perspective on NOS and explain how we plan to frame the paper's methodology using it.

C. Nature of quantum computation as a domain

In focusing on the epistemological aspects of the Second Quantum Revolution, we highlight the nature of quantum computation by exploring it as a domain of science. We use a particular framework for NOS called the FRA to characterize the domain. FRA was originally developed by philosophers Irzik and Nola [47,48] and later reinterpreted within science education by science education researchers Erduran and Dagher [46,49]. Building on Wittgenstein's family resemblance concept, Irzik and Nola [47] tackled the challenging methodological issue of defining science by considering the diversity of scientific disciplines and their mutual similarities that form the "science family." They argue that "there is no fixed set of necessary and sufficient conditions which determine the meaning of [science]" [47] (p. 594). Like family members, each discipline (beyond the metaphor) shares certain aspects with some disciplines and different aspects with others. The framework's strength lies in its avoidance of rigid definitions of science, offering instead a comprehensive overview of the various aspects that characterize the sciences [47,48]. The FRA approach characterizes scientific disciplines using broad categories that are both *domain-general* (i.e., characteristics common to all sciences and their activities) and *domain-specific* (i.e., features that make each discipline unique). For example, experimentation is common in chemistry and biology but is usually not prevalent in astronomy except within modeling contexts. Early explorations of the relevance of FRA in science curricula pointed to its relevance for science teaching and learning [49], and more recent curriculum investigations in numerous countries have highlighted that it is a lens that can shed light on trends in the coverage of NOS in science curricula at both secondary [50–53] and early childhood contexts [54].

FRA has been represented as a "wheel" of concentric circles by Erduran and Dagher (see Fig. 1). The wheel provides a shorthand for representing different aspects of NOS [46], such as the cognitive, epistemic, social, and institutional aspects, and points to the interactive and iterative nature of these various aspects. As illustrated in the wheel, the authors identified 11 categories that characterize the NOS.

At the wheel's core lies the cognitive-epistemic system, which is divided into four categories: aims and values, methods and methodological rules, practices, and scientific knowledge. The first category encompasses the values inherent in the scientific enterprise, such as objectivity, consistency, skepticism, rationality, simplicity, empirical adequacy, prediction, testability, and novelty. The second category pertains to the diverse cognitive, epistemic, and discursive practices that characterize scientific endeavors, including observation, classification, experimentation, argumentation, modeling, and reasoning. The third category involves the extensive array of observational, investigative, and analytical methods scientists employ in disciplinary inquiries, guided by specific methodological rules. Finally, the fourth category addresses knowledge as an interrelated network of theories, laws, and models (TLM) viewed as an outcome of a collective human

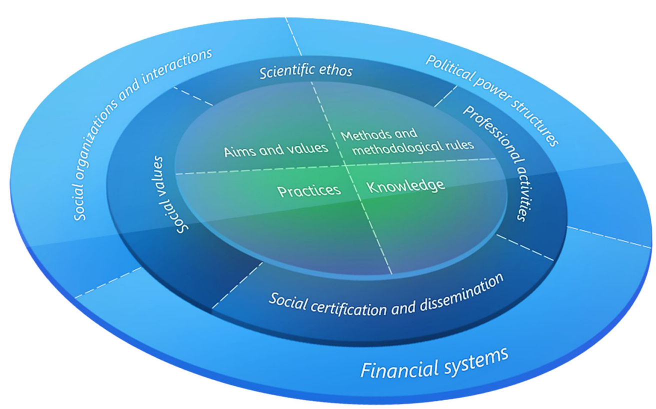

FIG. 1. FRA wheel by Erduran and Dagher [13] (p. 12).

endeavor, where individual scientists contribute their work, which is then refined and expanded through peer review, criticism, and collaborative intellectual effort. Scientific knowledge is holistic and relational; TLM is conceptualized as a coherent network rather than discrete and disconnected fragments of knowledge. The socio-institutional system, depicted by the two outer circular layers surrounding the core, emphasizes the socio-institutional aspects of NOS, which involve individual scientists working in social groups in social institutions, guided by social values and activities.

The 11 components of the framework depicted by the FRA wheel offer a portrayal of science as a holistic and dynamic system that visually illustrates the relationships among its components as parts of a larger whole. As Erduran and Dagher explain, “the boundaries (represented by dotted lines) between the two circles (or spaces) and their compartments are porous, allowing fluid movement across,” indicating that the categories influence each other regardless of their positions on the FRA wheel [46]. FRA has been applied in numerous ways in science education, as a recent review of the literature illustrates [55], including in teaching and learning and teacher education, and it has been adapted as an analytical tool. It has also been adopted as a framework to guide discussions on engineering education [56] and science, technology, engineering, and mathematics (STEM) education more broadly [56,57]. For example, Barak *et al.* [56] examined the aims and values of engineering, noting that generic epistemics such as objectivity, accuracy, and novelty are situated within engineering domains. In the context of engineering, objectivity refers to applying an objective and rational approach to the design process, using mathematics and scientific laws to solve engineering challenges, whereas accuracy refers to ensuring that the design and implementation processes are correct and precise. Novelty refers to generating creative ideas in an agile manner and turning them into practical and efficiently implementable solutions.

Although FRA has been used as a theoretical and analytical framework in science and engineering education, as well as in STEM education, it has not been applied to the investigation of the science of quantum technology. Given the literature on its adaptations and use in educational contexts, it is likely to prove useful for highlighting different aspects of the science of quantum technologies and their implications for teaching and learning in schools. Given the extensive nature of the FRA framework, it is beyond the scope of this article to cover all aspects of the FRA in relation to quantum technologies. Likewise, since the science of quantum technologies is very broad and diverse, we focus on quantum computation. Our objective is not to provide an exhaustive account of the nature of quantum technologies. Rather, our objective is to focus on the key aims and values of quantum computation, given that cognitive-epistemic aspect of the domain is foundational to any educational consideration. In other words, aims and values are essential guiding principles for understanding science in general because they offer a foundational perspective on what motivates scientific inquiry and how it is conducted. Understanding these aims and values is crucial because they influence the scientific practices and methodologies scientists adopt, as well as how they construct knowledge.

Focusing on the aims and values of quantum computation also helps us provide a nuanced account that can potentially inform educational decision making. For example, drawing on a set of epistemic aims of quantum computation can potentially enhance students’ meaning-making about why scientists in this field do what they do, and how their choices are affected by such aims. Clarifying the epistemic aims and values of quantum computation also ensures that curriculum designers and teachers have clear objectives for teaching and learning. Furthermore, recognizing the human and ethical dimensions embedded in these aims and values acknowledges that science is a collective human enterprise shaped by cultural influences and societal needs, shedding light on the intricacies and intertwined relationships between science, technology, and society. The emphasis on aims and values can also foster interdisciplinary connections by highlighting common goals and principles shared among different scientific fields.

In summary, given the recent developments in quantum technologies in the Second Quantum Revolution and their educational imperative, this paper highlights the importance of establishing a particular aspect, namely quantum computation, as a domain of science by using the FRA as a conceptual framework. FRA provides a lens through which this domain can be analyzed to draw out implications for education. The primary research question guiding the empirical study is as follows: *What epistemic aims and values characterize quantum computation?*

We are interested in this question primarily to guide us in characterizing the foundations of quantum computation for educational purposes. In other words, we aim to understand how professionals in quantum computation conceptualize the aims and values of the field and what we can thus draw out as potential learning objectives for students. Therefore, some implications will be drawn regarding how our analysis of the epistemic aims and values of quantum computation can inform educational approaches.

III. METHODOLOGY

A. Selecting papers

To address the research question, we conducted a document analysis of key foundational papers in quantum computation. The focus of the selection was on individual articles rather than journals, with journals serving primarily as search spaces for identifying candidate papers. The aim was to ensure that the corpus reflected contributions that played a formative role in establishing the theoretical foundations of the field. Several criteria were used to select the papers. These criteria included (i) the conceptual and historical significance of individual articles (e.g., In "Quantum theory, the Church–Turing principle, and the universal quantum computer," Deutsch provided the first formal demonstration of the possibility of a universal quantum computer); (ii) the introduction or formalization of key theoretical constructs (e.g., Grover's algorithm); (iii) their association with foundational authors in quantum computation (e.g., Feynman's "Simulating Physics with Computers: has been widely recognized as a key paper for quantum computation and simulation, as it established the fundamental insight that classical computers cannot efficiently simulate quantum systems); (iv) the role of publication venues during the formative years of the field (e.g., the *Proceedings of the Royal Society of London*, which, as a long-established generalist physics journal with high editorial standards, provided an institutional venue for the publication and early circulation of foundational quantum computation research at a time when the field had not yet developed specialized journals); (v) citation frequencies (e.g., Feynman's Simulating Physics with Computers has been chosen also because it has 15 246 citations), and (vi) journal impact factors (e.g., the inclusion of papers published in high-impact-factor journals such as *Science* and *Physical Review Letters*, reflecting the prominence and wide dissemination of selected contributions within the scientific community). All criteria were used alongside conceptual and historical considerations to inform the identification of influential contributions, without functioning as the sole determinants of inclusion. The criteria, while not resulting in an exhaustive pool of papers, were comprehensive enough to capture some major publications. The precise nature of the selection procedure is described in the following paragraphs.

The papers were identified through a stepwise process. The first step was to identify journals based on their impact factors and citation frequencies, employing these metrics as indicators of scholarly impact and recognition. This rigorous selection process yielded seven prominent journals in quantum computation: *Nature Physics*, *Nature*, *Nature Communications*, *Physical Review Letters*, *Physical Review A*, *Physical Review Research*, and *PRX Quantum*. Although not exhaustive, this list includes leading publication venues renowned for their stringent peer-review standards and for consistently disseminating cutting-edge research in an evolving field. It is noteworthy that several journals included in our selection—*Nature Communications* (established in 2010), *Physical Review Research* (2019), and *PRX Quantum* (2020)—were founded relatively recently.

The second step was to capture foundational contributions by scholars such as Benioff, Feynman, Deutsch, Grover, Shor, and Bennett. The rationale for including these authors lies in the fact that their work introduced theoretical models, algorithms, or principles that later became standard reference points in the field, often giving rise to eponymous concepts such as quantum Turing machines, the universal quantum computer, Shor's algorithm, Grover's algorithm, and related foundational criteria.

These papers were published before the establishment of the previously mentioned journals. Consequently, we incorporated seminal works published in earlier, historically significant platforms, including the *Mathematical and Physical Sciences; the Proceedings of the ACM Symposium on Theory of Computing; and the Proceedings of the IEEE Symposium on Foundations of Computer Science*. These journals have long served as authoritative outlets for pioneering research in the field.

The third step involved identifying journals that contributed to the formative years of quantum computation. In this case, we included articles from journals such as *Philosophical Transactions of the Royal Society A*, *Theoretical Computer Science*, *International Journal of Theoretical Physics*, and the *Journal of Statistical Physics*. When multiple quantum computation papers were available within the same journal, selection was guided by the extent to which a given article articulated a distinct foundational advance—such as the introduction of a new algorithm, a universality result, or a theoretical framework—rather than by representativeness or volume of publication. These journals offered rigorous peer review and played a vital role in the dissemination and legitimization of foundational theoretical developments.

As a consequence of the above procedure, 14 foundational papers were chosen, and they are included in the Appendix along with two additional contributions that are not properly foundational papers: "Quantum Technology: The Second Quantum Revolution" by Dowling and Milburn, and "Quantum Computing in the NISQ Era and Beyond' by Preskill. The first paper frames the technological advancements in quantum mechanics as a new revolution, emphasizing the transition from understanding quantum phenomena to harnessing them for practical applications. The second paper assesses the state of quantum computing, coining the term "NISQ era" to characterize current technologies. It sets expectations for what can be achieved with near-term quantum devices and guides researchers in identifying meaningful applications and necessary advancements.

B. Applying ChatGPT for document analysis

The principal objective of this study is to characterize quantum computation through the lens of its underlying aims and values. To this end, we employed a methodological framework combining both top-down and bottom-up strategies, informed by qualitative analysis methodologies. Specifically, the investigation sought, on the one hand, to examine the extent to which the subcategories of aims and values articulated by Erduran and Dagher [46] are manifest within seminal texts; and on the other hand, to identify emergent subcategories that may be distinctive to the domain of quantum computation.

The analysis involved a close reading of all papers to identify the epistemic aims and values of quantum computation. Drawing on prior domain expertise and familiarity with the literature, the first author conducted an initial qualitative familiarization with the corpus to establish conceptual orientation and inform the analytical framework. However, to ensure that the analysis could capture a broader set of examples, a generative AI tool was used to check and add any further examples triangulated by the first author. Generative-AI tools have been used for analyzing qualitative data [58–60] and have increasingly emerged as part of methodological approaches in educational research. Following the initial familiarization by the first author and triangulation with the second author, the identification of further examples relied on a generative AI tool. In other words, the identification of emergent epistemic subcategories was not carried out through independent human coding but rather through an AI tool that generates potential emergent subcategories, their descriptions, and exemplifying excerpts, which were subsequently subjected to systematic triangulation. Specifically, ChatGPT was used to identify both predefined and emergent subcategories of aims and values, propose general descriptions for each subcategory, and extract textual excerpts from the papers that exemplified them. All AI-generated outputs—including subcategory labels, descriptions, and examples—were manually reviewed and triangulated by the first author against the original papers to assess their epistemic validity, conceptual clarity, and alignment with the Family Resemblance Approach. Only outputs deemed accurate, meaningful, and theoretically coherent were retained in the final analysis.

The analysis was performed using generative AI—specifically, OpenAI's ChatGPT accessed via its API (Application Programming Interface)—customized through prompt engineering. This involved creating targeted instructions and example prompts to ensure the model's output aligned with the study's analytical framework. Structured API calls allow real-time generation of contextually appropriate responses. The customization process included three main steps: (i) setting up the GPT model's context and role, (ii) establishing guiding instructions to test the model's responsiveness, and (iii) iteratively refining prompts to improve the model's behavior through testing and adjustment. A chapter on epistemic aims and values [46] was incorporated as part of the contextual material provided to the model during this setup phase.

Prior to analysis, the Markdown format, a lightweight, human-readable, and machine-interpretable markup language, was selected as the optimal medium for interacting with the GPT model, consistent with best practices in structured data processing [61]. The 16 foundational papers were subsequently converted into Markdown and uploaded individually. The prompting strategy was designed to assess the presence of predefined subcategories of aims and values—objectivity, simplicity, accuracy, and novelty—and to identify potential emergent categories. The key prompts were structured as follows:

1. Briefly summarize the paper.
2. Identify any of the following subcategories of aims and values (objectivity, simplicity, accuracy, and novelty) and how they are addressed in the paper.
3. Identify emerging subcategories of aims and values not captured by the foundational subcategories.
4. For each subcategory, first write a general description and extrapolate sentences from the text that exemplify how the subcategories are addressed, both foundational and emergent.

By inputting each paper in Markdown format, the model was constrained to analyze the content strictly based on the provided material, ensuring that the analysis remained grounded in the original texts. Chain-of-thought prompting was employed to enhance the model's reasoning, following the techniques demonstrated by Kojima *et al.* [62], Wang *et al.* [63], and Wei *et al.* [64].

These key prompts, written above, were iteratively repeated across paper after paper. Starting from the second uploaded paper, a fifth prompt was introduced to support cross-paper synthesis: compare the description of each subcategory with that from the previous paper and refine them to elaborate a general description for each subcategory. Through this iterative process, ChatGPT progressively developed consolidated descriptions of the emergent subcategories across the corpus. The raw data obtained through this process are presented in Sec. IV B.

In summary, the study employed a qualitative research methodology to identify recurring themes and patterns across multiple foundational papers, aiming to characterize quantum computation in terms of its underlying aims and values, rather than attributing epistemic features to individual texts. While the generation of candidate categories and descriptions was delegated to the AI tool, epistemic responsibility for the analysis rested entirely with the authors. To ensure the reliability of findings, the model's outputs were cross-validated through manual review. During the analysis, cross-validation was implemented through an iterative process of checking model outputs against the original manuscripts. This involved returning to the source texts to verify that the excerpts identified by the model were present in the papers, that their interpretation was defensible in context, and that their association with specific epistemic subcategories was conceptually appropriate. When outputs were found to be insufficiently grounded in the text or ambiguous in their epistemic interpretation, prompts were adjusted and the analysis repeated. For example, when the paper "A Fast

Quantum Mechanical Algorithm for Database Search" by Grover was analyzed, ChatGPT initially did not recognize objectivity as a key subcategory, labeling it as implicit. However, under the provided definition, the paper makes objectivity explicit: it specifies the algorithm as a sequence of unitary operations grounded in the postulates of quantum mechanics; establishes correctness via a two-dimensional amplitude-rotation analysis; and derives the $O\sqrt{N}$ query bound through formal, reproducible arguments. There is no reliance on heuristics or subjective interpretation; the claims rest on logical consistency and established laws of quantum theory. On reconsideration, ChatGPT revised the classification to explicitly address, aligning with the paper's proof-theoretic presentation and its implementation grounding in the quantum postulates.

To support this process, the prompting strategy required the model to pair category descriptions with verbatim textual excerpts, enabling direct inspection of the relationship between proposed interpretations and the source material. This back-and-forth between model outputs and primary texts constituted the main mechanism through which analytic decisions were validated and refined.

While the use of generative AI tools in qualitative research is increasing, it is accompanied by ongoing methodological and ethical debates. A key concern is the limited transparency of large language models, whose internal processes remain opaque to users and may obscure how their analytic outputs are produced [65,66]. Relatedly, prior studies have noted that AI-assisted qualitative analysis may privilege surface-level thematic patterning over deeper conceptual interpretation, producing outputs that are linguistically plausible but epistemically thin—coherent or plausible, but they lack sufficient depth, justification, or theoretical grounding to count as robust knowledge—if not critically examined [65,67]. Further concerns address the potential displacement of researcher agency and ownership when AI tools are positioned as primary analytic actors [68]. In response to these concerns, ChatGPT was not treated as an autonomous analyst in this study but as a heuristic tool for generating subcategories and descriptions, and for extrapolating excerpts. Epistemic responsibility for interpretation and validation remained entirely with the authors, and all AI-generated outputs were systematically triangulated against the original texts using domain expertise and the theoretical commitments of the Family Resemblance Approach. This design choice was intended to mitigate risks associated with opacity, superficiality, and displaced authorship, while supporting a structured and transparent exploration of epistemic aims and values in quantum computation.

IV. RESULTS AND FINDINGS

A. Overview of results

A total of 17 subcategories were identified through the analysis, 4 of which were predetermined, while the remaining 13 emerged from the data. The four predetermined aims and values subcategories are objectivity, simplicity, accuracy, and novelty. These will be further discussed in the following sections pertaining to the research field. The generated subcategories are ethical principles, efficiency, scalability, optimization, feasibility, practicality, robustness, universality, epistemic flexibility and adaptability, explanatory and predictive power, materiality of information, control and utilization of natural laws, and harmony with natural laws. Figure 2 reports the frequency of subcategories in the foundational papers.

As Fig. 2 shows, objectivity, accuracy, novelty, control, and utilization of natural laws and harmony with natural laws were captured in every paper. Objectivity and accuracy are very foundational aims and values of science and, in the papers, are expressed, respectively, as rigorous formal reasoning and mathematical proofs rooted in the fundamental principles of quantum mechanics and as the precision of quantum operations by ensuring that quantum systems function correctly and produce reliable results. Novelty refers to the innovative nature of quantum research, focusing on the development of new theories, algorithms, and quantum technologies that enable applications in fields as diverse as cryptography, optimization, and material science. Natural laws and harmony with them, as well as the materiality of information, have a more ontological and epistemological character and can be linked to the cultural scope of the Second Quantum Revolution. "Materiality of information" is the name of the subcategory provided by ChatGPT and refers to the physical nature of the information that is tied to physical properties governed by quantum mechanical laws, as discussed above. Control and utilization of natural laws refers to what distinguishes the Second from the First Quantum Revolution: the potential of quantum technologies to harness and manipulate quantum phenomena, such as superposition and entanglement, to solve problems and perform computational tasks. Harmony with natural laws, instead, mirrors the alignment of quantum computation with the fundamental principles of quantum mechanics: Quantum computers operate within the constraints and possibilities offered by the microscopic world, ensuring that their operations mirror the behavior of natural quantum phenomena.

Efficiency, scalability, and optimization go hand in hand, highlighting quantum technologies as a technological and interdisciplinary challenge. The epistemic aim and value of efficiency concerns minimizing resource use, energy consumption, and overhead while maximizing performance and speed. Scalability refers to the ability of quantum systems to grow in size and complexity while maintaining functionality, precision, and reliability, whereas optimization refers to the ability to refine quantum systems to minimize resource usage while maximizing computational efficiency and performance. Feasibility,

	Aims and Values																
	Objectivity	Simplicity	Accuracy	Novelty	Ethical principles	Efficiency	Scalability	Optimisation	Feasibility	Practicality	Robustness	Universality	Epistemic Flexibility and Adaptability	Explanatory and Predictive Power	Materiality of Information	Control and Utilization	Harmony with Natural Laws
Benioff (1980)	✓	✓	✓	✓								✓			✓	✓	✓
Feynman (1982)	✓	✓	✓	✓						✓		✓	✓	✓	✓	✓	✓
Bennet & Brassard (1984)	✓		✓	✓	✓	✓			✓	✓			✓	✓	✓	✓	✓
Deutsch (1985)	✓	✓	✓	✓								✓		✓	✓	✓	✓
Dutsch & Joza (1992)	✓		✓	✓		✓								✓	✓	✓	
Berstein & Vizirani (1993)	✓		✓	✓		✓						✓				✓	✓
Shor (1994)	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓	
Lloyd (1995)	✓	✓	✓	✓		✓						✓		✓	✓	✓	✓
Barenco et al. (1995)	✓	✓	✓	✓		✓	✓	✓				✓				✓	
Shor (1995)	✓	✓	✓	✓		✓	✓	✓	✓		✓		✓	✓	✓	✓	
Di Vincenzo (1995)	✓	✓	✓	✓		✓						✓				✓	✓
Loyd (1996)	✓	✓	✓	✓		✓						✓		✓		✓	✓
Grover (1996)	✓	✓	✓	✓		✓		✓						✓	✓	✓	✓
Calderbank & Shor (1996)	✓	✓	✓	✓		✓	✓	✓	✓		✓		✓	✓	✓	✓	✓
Dowling & Milburne (2003)	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Preskill (2018)	✓		✓	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓

FIG. 2. Frequency of subcategories in the foundational papers.

practicality, robustness, epistemic flexibility, and adaptability go hand in hand and refer to the implementation and translation of quantum algorithms into the current or near-future quantum technologies into real-world applications that address practical problems. These aspects are deeply linked to the development of hardware and the experimental challenges of maintaining its performance and stability in the presence of external disturbances, decoherence, and noise or environmental factors.

As Fig. 2 shows, both these last subcategories, as well as the triplet efficiency, scalability, and optimization, were captured in just a few papers, due to the more theoretical nature of the foundational papers. Universality is another key aim and value captured, referring to the possibility of designing a quantum computer that can perform any computation or simulate any physical system. Simplicity, a predetermined subcategory, is often linked to universality. It is an aim and value to reduce the conceptual and operational complexity of quantum systems or algorithms while maintaining their full functionality. In particular, it is often associated with universality, as seen in papers such as Barenco *et al.* (1995) and Loyd (1995), which present a set of universal quantum gates capable of performing any computation. Explanatory and predictive power refers to quantum computation's capacity to explain and predict complex phenomena that are computationally intractable for classical systems. Finally, ethical principles, the least frequent subcategories (see Fig. 1), were captured as an aim and value in Bennet and Brassard (1984) regarding the development of a quantum cryptography protocol, in Shor (1994), which presents an algorithm that allows the factoring of large integers, intractable computational problem on which current cryptographic systems (RSA - Rivest, Shamir e Adleman) are based. It is also present in Dowling and Milburn (2003), who present quantum technologies and the Second Quantum Revolution more broadly, and discuss their implications at the economic, societal, and political levels.

In the following sections, we discuss in more detail only some of the 17 subcategories; in particular, we will discuss those most frequently identified, both predetermined and emerging, namely objectivity, simplicity, accuracy, novelty, efficiency, universality, materiality of information, control, and utilization of natural laws, and harmony with natural laws.

B. Epistemic aims and values of quantum computation

The descriptions of epistemic aims and values presented below are reproduced verbatim from the final synthesized outputs generated by ChatGPT at the conclusion of the analysis of the 16 foundational papers; apart from formatting and minor grammatical adjustments, they were not substantively edited by the authors. Using the FRA framework [13], this section presents the epistemic aims and values identified across the corpus of foundational papers. The analysis focuses on the epistemic "aims and values" category, drawing on both the predefined subcategories articulated by Erduran and Dagher—objectivity, simplicity, accuracy, and novelty—and the emergent subcategories generated through the analysis. In other words, the theoretical descriptions from the FRA framework guided the analysis because they highlighted some specific words that could be applied through ChatGPT. Likewise, the emergent subcategories (e.g., materiality of information) were identified if they pertained to specific aims and values of quantum computation.

For example, "objectivity" was described in context in the domain of quantum computation as follows:

> In quantum computation, objectivity refers to the commitment to rigorous, unbiased reasoning derived from the fundamental principles of quantum mechanics. Quantum systems, algorithms, and processes must be scientifically sound and avoid subjective interpretation, instead relying on formal proofs, logical consistency, and established laws of quantum theory. Objectivity ensures that quantum computational outcomes are consistently based on reliable, reproducible, and scientifically valid principles. The focus on objectivity ensures that quantum technologies are grounded in universal laws and maintain scientific integrity across different implementations.

Here, objectivity emerges through criteria such as logical consistency and coherence with universal laws. This account draws on the fundamental principles of quantum mechanics that underpin the domain. Likewise, the epistemic aim of "simplicity" is described in the following manner:

> Simplicity in quantum computation emphasizes reducing the conceptual and operational complexity of quantum systems or algorithms while maintaining their full functionality. It involves streamlining processes and minimizing the number of components, such as quantum gates or qubits. Simplicity is about distilling complex quantum phenomena into clearer, more straightforward models or operations that retain their effectiveness without unnecessary complications. This subcategory values clarity in both the design and interpretation of quantum systems, ensuring that the essential principles are represented in the most manageable and understandable forms possible.

In this case, the importance of reducing complexity is situated within quantum systems and algorithms while maintaining function. Furthermore, the criteria of manageability and comprehension of key principles are highlighted. "Accuracy" is another epistemic aim and value in science in general and in quantum computing in particular. The following description highlights the situations where information needs to be free of errors, including calculations, measurements, and quantum operations:

> Accuracy reflects the precision with which quantum operations (transformations) are carried out, ensuring that quantum systems function correctly and produce reliable results. It is a crucial aim in minimizing errors, maintaining the coherence of quantum states, and ensuring that results are as close to the true or expected outcome as possible. Accuracy ensures that calculations, measurements, and operations are performed with a high degree of correctness, enabling quantum systems to achieve reliable and valid outcomes, especially in the presence of noise or other disturbances. Accurate quantum operations are necessary for the robustness of quantum systems and for ensuring that the results of quantum computations are trustworthy and replicable.

The epistemic aim and value of "novelty" in science are contextualized here within quantum computation, illustrating how the boundaries of classical computing have been pushed and new breakthroughs have been achieved to solve problems.

> Novelty in quantum computation drives the field forward by introducing new principles, techniques, and algorithms that push the boundaries of what classical computing can achieve. Novelty is often associated with breakthroughs that extend quantum mechanics into new areas or solve problems previously considered intractable for classical systems. This subcategory captures the innovative ethos of quantum research, focusing on the development of new theories, algorithms, and quantum technologies that open up possibilities for applications in fields as diverse as cryptography, optimization, and material science. Additionally, novelty includes technological innovation—the practical advancement of quantum technologies that are not only theoretical but capable of influencing real-world industries.

> It emphasizes the creation of innovative tools, systems, and applications that leverage quantum principles to create breakthroughs in processing power, efficiency, and problem solving that classical technologies cannot match.

The analysis revealed not only the main subcategories (i.e., "objectivity," "simplicity," "accuracy," and "novelty") put forward by Erduran and Dagher [46] but also new ones. The analysis thus allowed us to identify such subcategories through the bottom-up approach used. For example, the epistemic aims and values of "efficiency" and "scalability" were noted as follows:

> Efficiency in quantum computation refers to the optimal use of quantum resources to solve problems faster and with fewer computational steps than classical systems. This subcategory focuses on minimizing resource use, energy consumption, and overhead while maximizing performance and speed. Efficiency is particularly important in scaling quantum technologies to handle larger, more complex problems. Quantum algorithms and systems that achieve efficiency use their resources in the most effective way possible, minimizing waste and optimizing both time and computational power.
>
> Scalability addresses the ability of quantum systems to grow in size and complexity while maintaining their functionality, precision, and reliability. As the number of qubits and the complexity of problems increase, quantum systems must continue to operate effectively without degradation in performance. Scalability ensures that quantum technologies can handle increasingly large datasets and more intricate algorithms without losing their accuracy or coherence. Research in fault-tolerant quantum computing and error correction techniques plays a crucial role in supporting the scalability of quantum systems.

While the examples of objectivity, simplicity, accuracy, and novelty were guided by a top-down approach generated from theoretical accounts of FRA based on Ref. [46], apart from efficiency and scalability, other categories also emerged in a bottom-up manner from the dataset. These include "explanatory and predictive power," "materiality of information," "control and utilization of natural laws," and "harmony with natural laws" as indicated below:

> Explanatory and predictive power refers to the capacity of quantum computation to both explain and predict complex phenomena that are computationally intractable for classical systems. This subcategory reflects how quantum computation enhances scientific understanding by (i) providing insights into how and why quantum systems behave in specific ways (explanatory power), (ii) enabling forecasts of future behavior or outcomes based on simulations of quantum systems (predictive power). By transforming intractable classical problems into tractable quantum solutions, quantum computation contributes to generating knowledge (explaining quantum phenomena) and to the practical application of this knowledge (predicting system behavior).
>
> Materiality of information emphasizes the inherently physical nature of information in quantum systems. Unlike classical information, which can be abstracted from its medium, quantum information is tied to the physical properties of qubits and is governed by quantum mechanical laws. This subcategory highlights the fact that quantum information is not purely conceptual but is linked to the physical states of quantum particles, giving it a tangible relationship to physical reality. Understanding the materiality of quantum information is essential for developing and controlling quantum technologies.
>
> Control and utilization of natural laws reflects the aim of quantum technologies: harnessing and manipulating quantum phenomena, such as superposition and entanglement, to perform computational tasks. This subcategory emphasizes scientific mastery over the natural principles of quantum mechanics, turning them into tools for solving complex computational problems. Quantum computation leverages the control of these fundamental phenomena to achieve breakthroughs in processing power and efficiency, making quantum technologies uniquely powerful compared to classical systems.
>
> Harmony with natural laws refers to the alignment of quantum computation with the fundamental principles of quantum mechanics. Quantum systems operate within the constraints and possibilities offered by quantum mechanics, ensuring that their operations mirror the behavior of natural quantum phenomena. This subcategory highlights how quantum computers are designed to work in harmony with the natural laws governing quantum systems, ensuring that their functionality is consistent with the underlying principles of quantum theory.

Overall, the epistemic aims and values of quantum computation have been identified, providing valuable insights into domain-specific reasoning in quantum computation that could be beneficial for inclusion in science education. Before exploring the implications of these themes in science education, we first contextualize them within the foundational papers to highlight how they are articulated therein. Our aim in doing so is to further showcase the importance of these themes for the scientists themselves and to situate how they were applied in the specific context of the research papers. Hence, in the next section, we review these findings in the published papers to illustrate how they are used in the accounts presented.

C. Contextualizing the results

1. Focusing on epistemic aims and values

The first subcategory captured is *objectivity*. In most papers, objectivity manifests as rigorous formal reasoning and mathematical proofs rooted in the fundamental principles of quantum mechanics. For example, in "A Fast Quantum Mechanical Algorithm for Database Search," Grover derived a quantum algorithm that enables the search of an unstructured database. His argument is built on rigorous mathematical proofs and logical consistency that demonstrate, by leveraging the laws and concepts of quantum mechanics, such as superposition and interference, the efficiency of his quantum search algorithm, whose aim is to examine several possibilities, N, to see which, if any, of them satisfy a given condition. He derives the speedup in database search using logical consistency and mathematical rigor, showing that a quantum system can perform the task in $O(\sqrt{N})$, time compared to $O(N)$ the time for classical systems.

Lloyd (1995), in the paper "Almost Any Quantum Logic Gate is Universal," formally and logically demonstrates that almost any two-qubit gate is universal for quantum computation when combined with arbitrary single-qubit operations. The paper outlines a step-by-step proof that these gates are universal, meaning that combining them can realize any arbitrary quantum computation. It carefully shows how unitary transformations can approximate desired operations over an arbitrarily large number of qubits and ensures that the results are mathematically consistent and grounded in quantum theory.

In "Good Quantum Error-Correcting Codes Exist," Calderbank and Shor showed that families of quantum error-correcting codes can be constructed that protect quantum information from noise while maintaining a nonzero rate of encoded information. Their work demonstrated that it is possible to design quantum codes that, like classical ones, are both efficient and robust, providing a foundation for fault-tolerant quantum computation. Through formal mathematical proofs, the authors ensure that their conclusions are firmly grounded in the established principles of quantum mechanics and error correction theory, thereby minimizing reliance on subjective interpretation.

In the three examples, the authors' logical and mathematical inferences, together with their foundation in quantum mechanics, suggest that the algorithm's outcomes are consistent and grounded in reliable, scientifically valid principles.

The second captured subcategory is *simplicity*, a value that plays a central role in scientific reasoning and theory construction. In the context of quantum computation, simplicity manifests in efforts to minimize the structural and operational complexity of quantum circuits while preserving their full computational capabilities. This value is especially prominent in foundational works that address the universality of quantum gates, where the goal is to identify a minimal set of building blocks from which any quantum operation can be composed. For instance, in *Elementary Gates for Quantum Computation*, Barenco *et al.* demonstrate that all unitary transformations, essential to quantum computation, can be decomposed into sequences of a limited number of elementary gates, specifically single-qubit and controlled-not gates.

In "Two-Bit Gates Are Universal for Quantum Computation," DiVincenzo (1995) shows that any unitary operation required for quantum computation can be constructed using only two-qubit gates. This result reflects the scientific value of simplicity, as it reduces the necessary components of quantum computation to a minimal and uniform gate type. By showing that interactions involving more than two qubits are not required, the paper simplifies the logical structure of quantum circuits. It supports a more streamlined approach to both their theoretical analysis and practical realization. The identification of two-qubit gates as a universal set thus provides a clearer, more economical framework for understanding and designing quantum algorithms while preserving the model's full computational power.

Similarly, in Lloyd's Almost Any Quantum Logic Gate is Universal (1995), simplicity is reflected in the reduction of computational complexity without any loss of functional completeness. Rather than relying on carefully constructed or highly specific two-qubit gates, Lloyd shows that almost any two-qubit gate, when combined with single-qubit operations, suffices for universal quantum computation. This result simplifies the structural assumptions underlying quantum circuits: it eliminates the need to search for or engineer special-purpose gates and instead reveals that a broad range of naturally occurring interactions can support universal computation. In this way, the paper reduces both the conceptual and operational demands of circuit design, showing that the essential requirements of quantum computation can be met with less restrictive, more general components.

The third aim and value is *accuracy*. It mainly refers to the precision of quantum operations by ensuring that quantum systems function correctly and produce reliable results. For example, in "Quantum Computing in the NISQ Era and Beyond," Preskill (2018) addresses the challenges posed by noise and error rates in NISQ devices, which directly affect the precision of quantum operations. He stresses the importance of performing quantum computations with precision to minimize errors and maintain the coherence of quantum states. In this sense, maintaining accuracy is essential for ensuring that quantum algorithms produce valid, reliable results, particularly in the face of external disturbances such as noise. This focus on precision aligns with the value of accuracy, ensuring that the computations are as close to the expected outcomes as possible.

Calderbank and Shor (1996), in their paper "Good Quantum Error-Correcting Codes Exist," aim to preserve the accuracy of quantum computation by developing error-correcting codes that can reduce the effects of decoherence and noise. They demonstrate that quantum information can be encoded in such a way that errors affecting individual qubits are detectable and correctable without directly disturbing the quantum state. This ensures that quantum computations can proceed reliably even in the presence of physical imperfections. The importance of accuracy is shown in their effort to preserve the fidelity of quantum operations, proving that reliable and precise computation is possible even in inherently unstable quantum environments.

Similarly, in the paper "Scheme for reducing decoherence in quantum computer memory," Shor proposes an error-correcting code designed to preserve the precision of quantum operations by minimizing errors introduced, for example, by decoherence. His scheme ensures that errors are corrected and quantum systems can operate with high accuracy in the presence of environmental disturbances, thereby enabling them to continue performing accurately, maintaining coherence, and producing reliable results.

Novelty pertains to the innovative aspect of quantum research, emphasizing the development of new theories, algorithms, and quantum technologies that enable applications in fields such as cryptography, optimization, and materials science. For example, in "Simulating Physics with Computers," Feynman paved the way to design a computer that "do[es] exactly the same as nature," namely by following the laws of quantum mechanics. The researcher introduces a groundbreaking idea: quantum computers could simulate physical processes that are intractable for classical computers. By leveraging quantum phenomena such as superposition and entanglement, quantum systems offer computational power that exceeds the limits of classical machines. This innovative approach redefines the boundaries of computation, suggesting that quantum computers could model any physical process and thereby enable significant advances in computational physics and beyond.

In "Quantum Theory, the Church-Turing Principle and the Universal Quantum Computer," *novelty* is a prominent aim and value throughout the paper. The paper addresses it primarily by exploring how quantum mechanics extends the limits of classical computation. The author introduces the concept of a universal quantum computer that can simulate any physical system, thereby surpassing classical Turing machines. This breakthrough proposes that quantum computers, leveraging principles such as superposition and entanglement, could solve problems deemed intractable for classical computers. Deutsch also paves the way for possible theoretical and practical advancements with implications for real-world applications.

In the paper *Scheme for reducing decoherence in quantum computer memory*, Shor introduces a groundbreaking approach to mitigate the issue of decoherence in quantum memory. His proposed scheme uses quantum error-correcting codes to protect quantum information from these environmental interactions. This innovation extends classical error correction into the quantum domain, addressing a unique challenge that classical systems do not face. By reducing the impact of decoherence, this work pushes the boundaries of what is possible in quantum computing, paving the way for more stable and scalable quantum memory systems. This contribution exemplifies *novelty* by solving a fundamental problem that directly enhances the feasibility of practical quantum computation.

Efficiency refers to minimizing resource use, energy consumption, and overhead while maximizing performance and speed. In "Rapid Solution of Problems by Quantum Computation," Deutsch and Jozsa present an algorithm designed to solve a specific class of oracle problems with remarkable efficiency. The task is to determine whether a given function is constant—producing the same output for all inputs—or balanced—returning 0 and 1 equally. Their quantum algorithm solves this with a single query to the oracle, whereas classical algorithms may require an exponential number of queries in the worst case. This efficiency is achieved through quantum superposition, which enables the simultaneous evaluation of multiple input states. By dramatically reducing the number of computational steps required, the algorithm illustrates how quantum resources can be used more effectively than classical ones. In this context, efficiency is not only a performance metric but also a guiding principle for algorithmic design, aiming to extract maximal computational power from minimal operations.

In "*Algorithms for Quantum Computation: Discrete Logarithms and Factoring*," Shor presents quantum algorithms that solve the integer factoring and discrete logarithm problems in polynomial time, offering exponential speedups over the best-known classical methods. These problems, which underpin much of modern cryptography, are known to be solvable in exponential or subexponential time. Shor's algorithm, by contrast, reduces these problems to the problem of finding periods, which it solves efficiently using quantum techniques such as the quantum Fourier transform. This significant improvement demonstrates the power of quantum computation, as the algorithm drastically reduces the number of computational steps by exploiting uniquely quantum features like superposition and interference. Rather than relying on brute-force classical methods, the algorithm shows how quantum systems can perform complex calculations with fewer operations, emphasizing efficiency not merely as a practical advantage but as a central goal in quantum algorithm design.

Similarly, in "*A Fast Quantum Mechanical Algorithm for Database Search*," Grover introduces a quantum algorithm that significantly improves the efficiency of searching an unsorted database. Classical algorithms require $O(N)$ queries to find a marked item, as each entry must be checked individually. Grover's algorithm, by contrast, reduces the number of queries to $O(\sqrt{N})$, offering a quadratic speedup. This gain is achieved by exploiting quantum superposition and interference, which allow multiple inputs to be processed simultaneously within a single computational step. By reducing both the time complexity and the number of operations, the algorithm exemplifies how quantum computation can optimize resource use and minimize effort, aligning directly with the value of efficiency in algorithm design.

Universality refers to the possibility of designing a quantum computer that performs any computation or simulates any physical system. In Deutsch's work (*Quantum Theory, the Church-Turing Principle, and the Universal Quantum Computer*), universality is a central aim and value. He formally derives the possibility of the existence of a universal quantum computer capable of simulating any physical process. The paper demonstrates that a quantum computer can perform any computation that a classical computer can, while also efficiently simulating quantum-mechanical systems, which classical computers cannot efficiently simulate. This highlights the quantum computer's broad applicability and ability to solve a wider range of problems, thus establishing it as a universal computational device.

In *Almost Any Quantum Logic Gate is Universal*, Lloyd (1995) shows that almost any quantum logic gate acting on two or more qubits is computationally universal. By repeatedly applying such gates to different combinations of quantum variables, it is possible to construct any unitary transformation on a quantum system. Since unitary transformations govern the evolution of closed quantum systems, this result implies that these gates can, in principle, be used to simulate any quantum process or perform any quantum computation. The paper demonstrates that a wide range of two-qubit gates is sufficient for universality, without requiring specially designed interactions. Through this result, Lloyd provides a foundational understanding of how universal quantum computation can be achieved using general entangling gates.

In "Two-Bit Gates are Universal for Quantum Computation," DiVincenzo discusses that any quantum computation can be constructed using two-bit quantum gates by proving that these gates are sufficient to generate any unitary transformation needed for quantum computation. By showing that a finite set of two-bit quantum gates can construct any quantum circuit, the paper establishes the universality of quantum gates in performing any quantum algorithm or operation, making them essential building blocks for quantum computation.

Explanatory and predictive power refers to quantum computation's capacity to explain and predict complex phenomena that are computationally intractable for classical systems. For example, in "Simulating Physics with Computers," Feynman proposes that quantum computers can simulate physical systems, particularly quantum mechanical ones, more efficiently than classical computers. Feynman emphasizes that classical computers are not well suited to model the complexities of quantum systems, while quantum computers, by nature, can replicate the exact behavior of these systems. This capacity to simulate quantum systems with exact precision allows quantum computers to model and explain physical processes with a precision unattainable by classical means.

In the paper "*Universal Quantum Simulators*," Lloyd discusses the possibility of a simulator replicating the dynamics of quantum systems, allowing scientists to understand how these systems evolve over time. It also demonstrates predictive power by enabling the simulation of future states of quantum systems, which classical computers cannot efficiently model. These capabilities reflect the role of quantum simulators in both explaining quantum phenomena and predicting their behavior in accordance with the principles of quantum mechanics.

In the paper "*Quantum technology: the Second Quantum Revolution*," Dowling and Milburn highlight how quantum computation can address computationally intractable problems for classical systems. The authors discuss the capacity to simulate and model complex quantum systems, offering insights into and explanations about the underlying behavior of quantum systems, such as the dynamics of many-body interactions. Similarly to Loyd's paper, the epistemic aim and value of predictive power rely on quantum computers' capability to model and simulate these systems, allowing researchers to predict outcomes and behaviors in quantum systems that classical methods cannot efficiently process.

Materiality of information underpins a central epistemic aim in quantum computation by foregrounding the physical nature of quantum information. In "*Simulating Physics with Computers*," Feynman's argument that classical computers cannot efficiently simulate quantum systems reflects more than a computational challenge—it signals that the information within quantum systems is inseparable from their physical behavior. The simulation must replicate not only the outputs, but also the physical processes themselves, because quantum information is realized in the actual dynamics of nature.

Deutsch further develops this insight in *Quantum Theory, the Church-Turing Principle, and the Universal Quantum Computer*, where he reframes computation as a physical process constrained by the laws of quantum mechanics. His call to extend the Church-Turing principle to quantum systems reinforces the notion that computation—and thus information—is defined by the behavior of physical systems. Importantly, Deutsch notes that the determinism of quantum evolution does not grant full epistemic access to the output states due to measurement constraints. This reinforces that quantum information is not fully abstractable; it is conditioned by material limits such as the no-cloning theorem and observer-dependent collapse.

Together, these foundational texts highlight that progress in quantum computation hinges on recognizing and harnessing the material constraints and possibilities of quantum systems. The goal of understanding and controlling information in this field cannot be separated from mastering the physical medium itself. Therefore, the materiality of information becomes not just a philosophical idea, but a practical and epistemological necessity in developing QT.

The *control and utilization of natural laws* emerge as a central epistemic driver in the development of quantum technologies, where fundamental quantum-mechanical phenomena are not merely observed or described but actively shaped into reliable mechanisms for performing information-processing tasks. In "Quantum Cryptography: Public Key Distribution and Coin Tossing," Bennett and Brassard show that security protocols can be constructed not on assumptions of computational difficulty—as in classical cryptography—but on the irreducible physical behavior of quantum systems. The protocol they propose uses quantum superposition to encode bits in nonorthogonal quantum states and exploits the no-cloning theorem to ensure that any eavesdropping attempt necessarily introduces a detectable disturbance. The key point here is that the unavoidable dynamics of quantum measurement guarantee security: a fundamental feature of quantum theory is turned into an operational tool. This represents a paradigmatic case of leveraging natural laws—not simply understanding them, but configuring them into a functioning communication protocol.

In the paper "Quantum Complexity Theory," Bernstein and Vazirani demonstrate how quantum algorithms harness fundamental principles of quantum mechanics, such as superposition and entanglement, to outperform classical algorithms on certain computational problems. The authors analyze the computational complexity of quantum systems and provide a rigorous framework for understanding how quantum mechanics can be used as a computational resource. The use of quantum parallelism—enabled by superposition and entanglement—reveals how control over quantum dynamics can be structured into algorithmic advantage. Here, the value lies in formalizing the connection between natural physical behavior and computational power, illustrating how quantum laws are not external constraints but internal resources to be managed, optimized, and applied.

In the paper "Algorithms for Quantum Computation: Discrete Logarithms and Factoring," Shor leverages the fundamental quantum phenomena of superposition and entanglement to create algorithms that exponentially outperform classical counterparts for these problems. This directly reflects the mastery and manipulation of quantum mechanical principles, turning them into powerful tools for computational breakthroughs. By harnessing these quantum effects, Shor's algorithm demonstrates how quantum computation can solve complex problems more efficiently than classical systems, underscoring the control and utilization of quantum laws to achieve significant advancements in computational power.

Harmony with natural laws mirrors the alignment of quantum computation with the fundamental principles of quantum mechanics. For example, in "Simulating Physics with Computers," Feynman emphasizes that to simulate quantum systems accurately, computers must operate within the framework of quantum mechanics itself. He discusses how simulating the exact behavior of quantum systems requires computers that can mimic the underlying principles of quantum physics rather than relying on classical approximation methods. This also reflects that quantum computation and simulation can inherently follow the natural laws governing quantum systems to produce accurate results, ensuring that their operations mirror the natural behavior of quantum phenomena. Feynman stresses the limitations of classical systems in simulating quantum systems, shedding light on the need to simulate physics as it occurs in nature, not just approximate it.

In "Quantum Theory, the Church-Turing Principle, and the Universal Quantum Computer," Deutsch discusses how quantum computers operate according to the principles of quantum mechanics, in contrast to classical computers, which are fundamentally limited in simulating quantum systems because they rely on deterministic processes. The author sheds light on the potential of computers to align with the laws of quantum mechanics, enabling them to simulate quantum phenomena accurately.

In the paper Good Quantum Error-Correcting Codes Exist, Calderbank and Shor discuss quantum error-correcting codes, shedding light on their aim of counteracting decoherence and preserving quantum information integrity. The error-correction scheme, to function properly, relies on inherent principles and is specifically designed to operate within the framework of quantum mechanics, ensuring that quantum computations adhere to the natural laws governing quantum systems.

Overall, the document analysis based on foundational papers in quantum computation illustrates key epistemic aims and values of the domain. The analysis contributes to the literature on NOS in general and the characterization of quantum computation as a domain in particular. In other words, our analysis often brings to the forefront implicit epistemic aims and values that guide practitioners in a scientific domain, which are usually not made explicit in the education sector. By systematically generating these aims and values, we sought to provide a nuanced, explicit approach to characterizing the nature of quantum computation so that educationalists can then use these themes for curriculum design, teaching, and learning.

2. The interdisciplinary nature of quantum computation

The aims and values emerging from the document analysis shed light on quantum computation as a unique field, in particular, a highly interdisciplinary field, at the nexus of physics, mathematics, computer science, and engineering.

Physics, as a discipline, is historically and methodologically committed to understanding the natural world through the formulation of general laws, the development of explanatory frameworks, and the pursuit of predictive, often mathematically elegant models. Core epistemic aims, such as accuracy, objectivity, and simplicity, have traditionally guided inquiry across the subfields of physics [46], from classical mechanics to quantum theory.

The aims and values emerging from quantum computation research, such as control and utilization of natural laws, materiality of information, optimization, and scalability, are not isolated from these broader commitments but rather represent a contextual specialization or transformation of them.

For instance, the aim of control and utilization of natural laws, identified across foundational quantum computing papers, resonates with the traditional physical aim of predicting and manipulating natural systems [69]. Yet, quantum computation shifts this aim from the realm of theoretical or experimental descriptions to technological enactment, where quantum laws are not merely modeled but operationalized for specific computational ends that also serve purposes beyond those that led to their development. In this sense, quantum computation extends physics' historical aim of controlling and manipulating nature into a new epistemic register: the creation of technologies that not only embody quantum laws but also use them as active, designable resources, turning physical principles into programmable mechanisms that enable novel forms of computation and knowledge production.

Similarly, the value of materiality of information, which emphasizes that quantum information is inseparable from specific physical systems or devices, resonates with an epistemic tendency—especially in operational and experimentally driven contexts of physics—to assign meaning to theoretical constructs such as information, energy, or force based on their instantiation in or interaction with physical systems [70–72]. Yet it also reframes this principle through the lens of information theory, highlighting that the quantum domain requires a rethinking of information not merely as an abstract quantity but as a resource embedded in and constrained by physical laws. This underscores the persistent interplay between conceptual abstractions and their material embodiments that characterizes modern physics, but one that quantum computation renders especially explicit and operational by requiring that information be instantiated in physical systems.

Emerging values in quantum computing, such as efficiency, optimization, and scalability, can be understood as domain-specific articulations of broader epistemic values that have historically guided physics. Notably, values such as parsimony and empirical feasibility have played a central role in theory development and model selection, shaping preferences for approaches that are not only explanatory but also experimentally grounded and practically manageable [72,73]. In classical physics, the elegance of a theory often correlates with its generality and simplicity [72]. In quantum computing, however, efficiency takes on a computational form, centered on resource scaling, algorithmic performance, and the physical implementation limits (e.g., error correction and decoherence). These values reveal a convergence of epistemic and pragmatic concerns, suggesting that quantum computation is not a straightforward inheritance of physics' aims but a domain in which those aims are modified and reinterpreted in light of new scientific and technological frontiers.

The aims and values that emerge from our analysis also shed light on the profoundly interdisciplinary terrain in which QISE is situated. Some of the detected aims and values characterize or derive from further knowledge domains and are rearticulated within the quantum computation. Values such as efficiency, optimization, and scalability, for example, reflect core methodological orientations in computer science, where concerns about algorithmic performance, resource allocation, and computational complexity have historically structured both theoretical and applied inquiry [74].

Some of the aims and values emerging from our analysis also align with those that characterize mathematics. Values such as simplicity, accuracy, objectivity, and explanatory clarity have long guided mathematical reasoning, in which proofs, models, and representations are evaluated for conciseness, precision, and structural transparency [75,76]. Within quantum computation, however, these values acquire new meanings: simplicity becomes tied not only to elegant formulations but also to circuits and algorithms that minimize quantum resources; accuracy is no longer purely a matter of exact derivation but of maintaining fidelity under noise and decoherence [77]; explanatory clarity involves not only revealing structural relations among mathematical objects in a specific framework but also relating these structures to physically implementable operations.

Engineering likewise contributes a distinctive epistemic lens, and some aims and values identified in our analysis—such as optimization, scalability, feasibility, robustness, and practicality—are also central to engineering practice. In engineering, optimization concerns designing systems that perform effectively under physical and economic constraints; feasibility and practicality refer to the ability to construct and operate systems reliably; and robustness denotes resistance to disturbances or failures [78]. In quantum computation, these values are reinterpreted in light of the constraints of quantum hardware: optimization involves minimizing error rates and resource overhead; scalability concerns the expansion of qubit architectures without prohibitive cost or fidelity loss; and robustness refers to resilience against decoherence and control imprecision.

These aims align with long-standing engineering concerns about system scaling, as illustrated in classical computing by the focus on increasing device density and computational performance, exemplified by Moore's law [79].

In sum, the document analysis shows that quantum computation is an interdisciplinary field in which aims and values from different knowledge domains converge. While many of these aims resonate with long-standing commitments in physics, they are also shaped by methodological orientations from computer science, mathematics, and engineering. Within quantum computation, these aims and values are not merely inherited but acquire new and distinct meanings in response to emerging scientific and technological trends.

V. CONCLUSIONS AND IMPLICATIONS

Drawing on the experts' notions of the major features of the domain is a necessary first step in setting objectives for science education in order to facilitate students' understanding of how quantum computation works as a discipline beyond the learning of concepts and techniques of the discipline, as highlighted in the Quantum Technologies Competence Framework [18,19]. Within science education literature, there has been a longstanding argument and research tradition in teaching and learning of the nature of science [46–55]. This approach is about teaching the epistemology of science, and it involves more than learning the concepts, methods, and outcomes of a discipline. It concerns disciplinary orientations to the construction and evaluation of knowledge claims. The epistemic aims and values identified through key publications in the quantum technology domain are important to the discipline itself and can therefore be integrated into curriculum objectives to promote understanding of the nature of quantum technology. Indeed, the terminology of "nature of quantum technology" may be a fruitful placeholder in the curriculum to highlight its importance and various aspects, including the epistemic aims and values. The document-based analysis of foundational quantum computation papers provides some information to inform educational objectives. The set of specific epistemic aims and values identified is contextually rich and provides an account for informing curriculum design in quantum computation.

As previously highlighted, the current depictions of quantum technology education, spearheaded by the Quantum Technologies Competence Framework, focus primarily on key concepts, knowledge areas, and topics to be introduced at different educational levels, aiming to support the development of quantum literacy and a specialized understanding of the various roles and profiles in quantum technologies. It presents a list of concepts that encompass eight domains, such as the physical foundations of quantum technologies and quantum hardware. Each domain is composed of topics and subtopics. None of these topics explicitly refers to the epistemic aims and values of quantum technology identified in this paper. Hence, the present study's outcomes provide a potential new addition to the framework and recommend that future curriculum frameworks include the nature of quantum technology in general and epistemic aims and values in particular.

The study raises questions for the curriculum as well as teaching and learning. For example, the following questions are implied by the study: *What is the benefit of students' understanding of the epistemic aims and values of quantum computation? How can the epistemic aims and values of quantum computation be taught effectively? How can teachers be supported in learning to teach the epistemic aims and values of quantum computation?*

In addressing the first question, it is essential to acknowledge the vast body of educational research demonstrating that students often perceive science as lacking purpose and meaning in the way it is taught, and that it is therefore crucial for students to understand the key aims of scientific investigations [80]. Without understanding *why* they are doing *what* they are doing in science lessons, students are often left demotivated from pursuing scientific investigations. There is also substantial research evidence suggesting that the epistemic components of science are often challenging for teachers to teach, given the lack of preparation in these aspects [81]. Effective teaching of novel content requires changes in teachers' practice [82]. Such partnerships can be established between teachers and researchers. However, numerous constraints need to be taken into consideration. For example, teachers usually follow curricula that offer little space for innovation. Furthermore, teachers need continuous support in learning to teach new content. Approaches to teacher learning are limited when they are perceived as a linear process. Educational change does not happen as "a natural consequence of receiving well-written and comprehensive instructional materials" [82] (p. 3)

When preservice teachers were asked to rate whether they believed the epistemic aims and values were important to science students, science teachers, or scientists, they stated them to be important in most cases [81]. Furthermore, preservice teachers identified teacher behavior as important in making the aims and values of science known. They also argued that epistemic aims and values of science could be highlighted more in teaching. Among the different epistemic aims and values, *objectivity* was considered highly important to develop in science lessons [81].

According to one teacher, objectivity is fundamental to the whole idea of doing an experiment. Teachers also suggested pedagogical strategies to support the teaching and learning of the epistemic aims and values of science, including inquiry-based approaches and the use of the history of science in science lessons. Drawing on such existing research on teachers' perceptions and views of epistemic aims and values of science may help situate the types of support that teachers may need in contextualizing these aims and values in quantum computation.

Such considerations from the existing educational literature need to be taken into account when implementing the recommendations provided in this paper. For example, given the familiarity of teachers with objectivity, this particular aim can be brought to the foreground in building up teachers' understanding of the various aims and values of quantum computation. In other words, it will be beneficial for teachers' learning if they begin with the aims and values of quantum computation with a familiar example they can subsequently build on. Furthermore, the emphasis on inquiry-based approaches suggests that teachers will benefit from interactive approaches in their own learning. Hence, teacher education interventions can include examples reported in the investigated papers and actively engage the teachers in mapping the aims and values of these examples. Group discussions can be organized around such mapping activities, such that teachers actively engage in evaluating what aims and values correspond to the various examples. Such pedagogical approaches have been used with preservice teachers. Researchers have employed such strategies, illustrating through reflective drawing analyses how participants' understanding of the aims and values of science has improved, given explicit teaching and use of visual representations to support their learning [83].

Overall, the paper frames quantum computation as a domain that possesses epistemic aims and values. It uses a theoretical framework [57] to characterize the nature of science in general and the epistemic aims and values of science in particular. An empirical study focusing on some top journal articles in the field of quantum computation is conducted to identify significant examples of epistemic aims and values from both a top-down and a bottom-up approach. Hence, the discipline is framed using empirical data from published research papers. In this sense, the paper contributes to the field of quantum computing more broadly by illustrating disciplinary accounts based on research reported in journal articles. The study offers a methodological contribution by using document analysis to identify the epistemic aims and values of quantum computation. Here, the research papers are treated as data sources that can inform objectives for education about the nature of quantum computation. By identifying and applying the epistemic aims and values of the discipline, the intention is to ensure robust coherence between disciplinary content and educational outcomes grounded in these aims and values.

Given that science education research broadly seeks, among other goals, to bridge the gap between understanding the world we live in and learning in schools, the paper strives to shed light on what is meaningful to teach, helping young people develop tools and competencies to navigate the complexity of contemporary society and orient students toward a sustainable future both individually and collectively [84]. Recently, the OECD, through Programme for International Student Assessment (PISA), introduced the PISA 2025 Science Framework to assess students' competencies in applying scientific knowledge, evaluating evidence, and making informed decisions [85]. These competences align closely with research on the NOS, which has long emphasized science as a dynamic, socially embedded, and epistemically diverse enterprise [46–49]. Some science education research focuses on how students and teachers perceive science and its nature, how curricula and instructional methods can improve students' understanding of NOS, and how NOS contributes to a broader educational goal of scientific literacy [46].

In future work, the broader FRA framework can be applied to investigations of foundational research in quantum computation to further articulate other dimensions of the domain. For example, the nature of the knowledge itself in terms of theories, laws, and models, as well as the practices and methods, can be examined. The broader social-institutional aspects of quantum computation can be highlighted either through the published research or by tracing how the scientists authoring particular articles were situated socially, for example, in the sense of research groups and institutions, in order to understand how such social and institutional contexts might have influenced the nature of the domain. Understanding the social-institutional context of quantum computation is significant as such understanding will help structure science learning environments to model to students how scientists work and what social dynamics influence their research. The social-institutional dimensions of science are often ignored in international science curricula [86]. Focusing on these dimensions of quantum computation can potentially contribute to the research and development efforts in quantum technologies education and motivate learners to take up quantum computation as a career.

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DATA AVAILABILITY

The data supporting this study's findings are available in the Appendix.

APPENDIX: ANALYZED PAPERS

	Authors	Year of publication	Title	Journal
1	P. Benioff	1980	The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines.	*Journal of Statistical Physics*, 22, 563–591, DOI: https://doi.org/10.1007/BF01011339.
2	R. P. Feynman	1982	Simulating physics with computers.	*International Journal of Theoretical Physics*, *21*, 467–488, DOI: https://doi.org/10.1007/BF02650179.
3	C. H. Bennett and G. Brassard	1984	Quantum cryptography: Public key distribution and coin tossing.	*Theoretical Computer Science*, *560*, 7–11, DOI: https://doi.org/10.1016/j.tcs.2014.05.025.
4	D. Deutsch	1985	Quantum theory, the Church–Turing principle, and the universal quantum computer.	*Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*, *400* (1818), 97–117, DOI: https://doi.org/10.1098/rspa.1985.0070.
5	D. Deutsch and R. Jozsa	1992	Rapid solution of problems by quantum computation.	*Proceedings of the Royal Society of London. Series A: Mathematical and Physical Sciences*, *439* (1907), 553–558, DOI: https://doi.org/10.1098/rspa.1992.0167.
6	E. Bernstein and U. Vazirani	1993	Quantum complexity theory.	*Proceedings of the Twenty-Fifth Annual ACM Symposium on Theory of Computing* (pp. 11–20), DOI: https://doi.org/10.1145/167088.167097.
7	P. W. Shor	1994	Algorithms for quantum computation: Discrete logarithms and factoring.	*Proceedings 35th Annual Symposium on Foundations of Computer Science* (pp. 124–134). IEEE, DOI: https://doi.org/10.1109/SFCS.1994.365700.
8	S. Lloyd	1995	Almost any quantum logic gate is universal.	*Physical Review Letters*, *75* (2), 346, DOI: https://doi.org/10.1103/PhysRevLett.75.346.
9	A. Barenco *et al.*	1995	Elementary gates for quantum computation.	*Physical Review A*, *52* (5), 3457, DOI: https://doi.org/10.1103/PhysRevA.52.3457.
10	P. W. Shor	1995	Scheme for reducing decoherence in quantum computer memory.	*Physical Review A*, *52* (4), R2493, DOI: https://doi.org/10.1103/PhysRevA.52.R2493.
11	D. P. DiVincenzo	1995	Two-bit gates are universal for quantum computation.	*Physical Review A*, *51* (2), 1015, DOI: https://doi.org/10.1103/PhysRevA.51.1015.
12	S. Lloyd	1996	Universal quantum simulators.	*Science*, *273* (5278), 1073–1078, DOI: https://doi.org/10.1126/science.273.5278.1073.
13	L. K. Grover	1996	A fast quantum mechanical algorithm for database search.	In *Proceedings of the Twenty-Eighth Annual ACM Symposium on Theory of Computing* (pp. 212–219), DOI: https://doi.org/10.1145/237814.237866.

(Table continued)

	Authors	Year of publication	Title	Journal
14	A. R. Calderbank and P. W. Shor	1996	Good quantum error-correcting codes exist.	*Physical Review A*, *54* (2), 1098, DOI: https://doi.org/10.1103/PhysRevA.54.1098.
15	J. P. Dowling and G. J. Milburn	2003	Quantum technology: The Second Quantum Revolution.	*Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, *361* (1809), 1655–1674, DOI: https://doi.org/10.1098/rsta.2003.1227.
16	J. Preskill	2018	Quantum computing in the NISQ era and beyond.	*Quantum*, *2*, 79, DOI: https://doi.org/10.22331/q-2018-08-06-79.

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