Human-Centered Quantum Software Engineering: A Research Agenda

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Abstract

Quantum computing, grounded in principles such as superposition and entanglement, is revolutionising the design, testing, and understanding of software. While the community is working on its technical challenges, the human and collaborative aspects have received little attention. This vision paper outlines a research agenda for human-centred quantum software engineering (HC-QSE). Building on current QSE foundations, the agenda spans three interrelated themes: *understanding practice*, *designing support*, and *embedding responsibility*. The first calls for studying how interdisciplinary teams construct and share mental models of quantum behaviour, collaborate across disciplinary boundaries, and reason under uncertainty inherent in probabilistic computation. The second focuses on creating tools, workflows, and learning environments that enhance comprehension, interpretability, and shared accountability among practitioners, educators, and learners. The third integrates ethical reflection and equity considerations into the design and governance of quantum software ecosystems. By centering human experience within QSE, this agenda encourages cooperative, reflective, and ethically grounded approaches to building quantum software.

Keywords

quantum computing, quantum software engineering, artificial intelligence, ethics

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1 Introduction

Quantum computing has evolved from theoretical concepts to an applied technological frontier [28, 33]. As experimental platforms and software toolchains mature, research has begun to outline principles for *Quantum Software Engineering* (QSE) [3–5]. Much of this work extends classical methods, requirements analysis, modelling, testing, and verification, into the quantum domain. Yet such analogies overlook a deeper shift in understanding: quantum programs do not conform to deterministic reasoning or modular decomposition. Phenomena such as superposition and entanglement yield probabilistic outcomes, dissolve component boundaries, and render verification and reproducibility uncertain [12, 48, 49]. As experimental platforms and software toolchains mature, research has begun to outline principles for *Quantum Software Engineering* (QSE) [3–5].

Efforts to stabilise development through statistical verification, runtime monitoring, and hybrid testing frameworks [2, 18, 21, 26] reveal both technical ingenuity and conceptual strain. Assurance in QSE ultimately depends on different types of abstractions needed for testing and verifying quantum programs, akin to the different abstractions used for their development [39]. For the software engineering (SE) community, this shift highlights that quantum development challenges not only the epistemic foundations of engineering but also the human and cooperative dimensions through which software work achieves meaning and accountability.

Quantum software development brings together diverse multidisciplinary domain experts who must collaborate under uncertainty, scarce hardware access, and probabilistic outcomes. As observation alters program state and results resist reproducibility, traditional models of design, testing, and coordination begin to strain. Effective practice, therefore, depends not only on algorithms and tools but on how people communicate, share understanding, and build trust across disciplinary and organisational boundaries. These are inherently human challenges, highlighting the need for new forms of teamwork, interpretability, and reflective practice at the core of QSE.

Parallel debates in computing ethics reveal similar transformations. Classical professional codes, such as those of the ACM[1] and IEEE[2], assume that people remain clearly in control of systems and that cause and effect in technology are predictable and traceable. In emerging domains like artificial intelligence, scholars have questioned these assumptions [6], arguing that ethical responsibility should be shared and collaborative, involving diverse people in

[1] https://www.acm.org/code-of-ethics
[2] https://www.ieee.org/about/corporate/governance/p7-8

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decision-making about how technologies are designed and used [9]. Quantum technologies further complicate accountability, not only by distributing agency across physical phenomena, algorithms, and socio-organisational networks, but also by requiring collaboration among experts who speak different disciplinary languages, making shared understanding and anticipation of design consequences especially challenging [11, 32]. Ethical guidance in this context must therefore become iterative, situated, and co-designed with practice [4, 40, 41].

Despite these converging challenges, QSE and quantum ethics have evolved along largely separate paths. Ethics studies focus on governance and philosophical reflection [6, 11, 32, 41], while QSE research emphasises technical methods and tool development [3, 5]. This separation matters: when ethical reflection is detached from engineering practice, opportunities to address human collaboration, interpretation, and responsibility within development processes are easily missed. As shown in recent work on the socio-technical well-being of quantum software communities [19], social and organisational issues already shape how quantum projects function in practice. Treating design and ethics as distinct domains risks reinforcing a false divide between technical innovation and moral accountability, the very divide that quantum technologies make increasingly untenable [4, 30].

To address this gap, this paper advances a vision for *Human-Centred Quantum Software Engineering* (HC-QSE), which situates people, their understanding, collaboration, and values at the core of quantum software practice. Human-centred perspectives in SE emphasise empathy, collaboration, and interpretability as foundations of effective engineering [15]. Extending these ideas to QSE means recognising that quantum development is not only a technical endeavour but also a social one: it depends on how practitioners form mental models of probabilistic behaviour, communicate across disciplines, and design for shared accountability.

This paper proposes a research agenda for HC-QSE built on two complementary aims. The first is *understanding human experience in quantum software development*; how developers and teams form, communicate, and refine mental models of quantum behaviour, and how collaboration unfolds under uncertainty. The second is *designing human-centred tools and environments*; tools, workflows, and educational approaches that promote comprehension, accountability, and inclusion in quantum software practice.

2 Background and Motivation

Quantum software engineering (QSE) has advanced rapidly, with significant progress in testing, verification, modelling, and tooling. Verification research extends classical formalisms to quantum behaviour through Hoare logics and related reasoning frameworks [12, 48, 49]. Testing spans statistical assertions and runtime checks [18, 21, 23, 26], property-based and metamorphic techniques [1, 16], mutation and search-based generation [8, 43, 44, 46], and combinatorial approaches [45]. Surveys consolidate these developments and identify open challenges across the lifecycle [3, 5, 10, 27]. Meanwhile, languages, toolchains, and simulators continue to mature [14, 20, 47]. Collectively, this body of work provides a strong technical foundation for QSE while acknowledging persistent issues of hardware noise, limited observability of computations, hardware scarcity, and the probabilistic nature of correctness [12, 28, 33].

Despite this progress, the human and socio-technical dimensions of QSE remain underexplored. Most studies emphasise algorithmic accuracy, formal assurance, or tool performance, with limited attention to how developers conceptualise quantum behaviour, collaborate across disciplines, or interpret probabilistic evidence in practice. Recent mapping studies explicitly note the scarcity of developer-centred and socio-technical investigations [3–5, 27]. Where human concerns are mentioned, they tend to appear tangentially, often as usability remarks in tooling papers rather than as primary research questions.

Recent work begins to address this gap by examining the socio-technical aspects of quantum software communities. Lambiase et al. [19] show that open-source quantum projects already exhibit "community smells", patterns of coordination breakdown and communication imbalance that threaten collaboration and project sustainability. Their findings highlight that even in technically sophisticated projects, social and organisational fragility emerges early, reinforcing the need to study quantum software development not only as a technical process but as a complex human ecosystem.

Emerging work in ethics, governance, and responsible innovation addresses responsibility and equity at the ecosystem level [11, 24, 32, 40, 41], yet few studies examine everyday software practices, how interdisciplinary teams coordinate, negotiate accountability, and reason about uncertainty under constraint. Human-centred approaches, well established in software engineering and human–computer interaction, provide the conceptual and methodological foundations to address this gap [7, 13, 31, 34, 36].

This gap matters for several reasons. QSE inherently brings together a multidisciplinary team that must coordinate under uncertainty and incomplete observability. Furthermore, as governance debates emphasise, access, inclusion, and ethics must accompany technical innovation [11, 24, 40, 41]. The QSE field is thus technically vibrant but socio-technically weak [4]. Building on established research in verification, testing, and modelling [3, 5, 10, 12, 27], this paper advances a preliminary complementary agenda that places human experience, collaboration, and ethics at the core of QSE, ensuring that emerging methods are not only technically sound but also usable, trustworthy, and socially responsible.

3 Human-Centred Quantum Software Engineering

Building on current foundations in QSE, this section presents a research agenda for advancing human-centred quantum software engineering (HC-QSE). The agenda spans three cross-cutting themes: *understanding practice, designing support,* and *embedding responsibility.* Together, these directions aim to propel QSE towards empirical insights for designing socio-technical systems that are intelligible, inclusive, and accountable.

3.1 Understanding Practice

Quantum software development introduces cognitive and organisational challenges that differ fundamentally from classical software engineering. Developers must reason about systems governed by the laws of quantum mechanics (involving abstractions from linear algebra, complex numbers, and probabilities), complex logic of the algorithms, different abstractions, limited observability, and complicating debugging, validation, and coordination across disciplinary boundaries [3, 5]. Understanding how people navigate these challenges is essential for building human-centred methods and tools.

Research should explore how individuals and teams construct and share *mental models* of quantum behaviour, how they conceptualise superposition, entanglement, and measurement when designing, testing, and interpreting program outputs. Cognitive studies of programming show that developers rely on conceptual metaphors, mental simulation, and social explanation to make code intelligible [35]. Extending such inquiries to QSE can highlight how probabilistic reasoning and uncertainty shape comprehension, trust, and collaboration.

Because QSE projects often involve physicists, algorithm designers, and software engineers, collaboration depends on negotiation across disciplinary and knowledge boundaries. Prior socio-technical research demonstrates that coordination in uncertain and high-complexity domains relies on shared artefacts, communicative alignment, and negotiated accountability [39]. Empirical work, through in-depth studies (e.g., using ethnographic observations, interviews, surveys) and repository mining, can reveal how these mechanisms operate in QSE and where friction emerges.

Some HC-QSE research questions include:

- *How do practitioners form and communicate mental models of quantum program behaviour under uncertainty?*
- *How do interdisciplinary teams coordinate, negotiate meaning, and sustain trust across disciplinary boundaries?*
- *What artefacts and documentation practices (e.g., notebooks, logs, visualisations) enable shared understanding and decision-making?*
- *How can insights from cognitive and collaborative practices inform the design of human-centred tools and processes for QSE?*
- *How different are the perspectives and contributions of the different disciplines in the development process of quantum software?*

3.2 Designing Support

Advancing QSE also requires designing tools, workflows, and learning environments that support human reasoning, trust, and ethical awareness. Because quantum programs are probabilistic and partially observable, traditional debugging and verification tools offer limited support for interpretability or confidence [12, 26]. Human-centred design can address this gap by developing *visualisations*, *interaction techniques*, and *documentation tools* that help practitioners comprehend and explain quantum program behaviour.

Here, interpretability goes beyond "explainability" in a computational sense; it refers to the human capacity to understand, communicate, and reflect on how and why a quantum system behaves as it does. Building on work in AI interpretability and human–computer interaction [17, 25], QSE research can investigate how interface cues, uncertainty visualisation, and provenance tracking enhance collaborative reasoning and decision-making. Making reasoning processes visible also promotes accountability, enabling teams to share and justify design decisions in probabilistic settings [31].

Education and onboarding environments represent another critical frontier. Quantum programming requires conceptual fluency in both physics and computation, creating steep learning curves [5, 24]. Participatory and reflective design approaches can inform curricula and interactive tutorials that use analogy, visual scaffolding, and immediate feedback to build understanding. Participatory design workshops, UX evaluations, and field deployments can iteratively refine tools and pedagogical resources that align with developers' cognitive and ethical needs.

Some HC-QSE research questions include:

- *What visualisation and feedback mechanisms best support reasoning about quantum behaviour and uncertainty?*
- *How can tools communicate probabilistic evidence transparently without overwhelming or misleading users?*
- *What pedagogical designs foster incremental learning, confidence, and inclusiveness for diverse learners?*
- *How can QSE tools and workflows promote ethical awareness, trust, and reflective practice in quantum programming environments?*

This research stream emphasises the use of multi- and mixed methods [38], e.g., combining ethnography and design research with user experience evaluation and quantitative analysis, to ensure that QSE tools and workflows remain interpretable, usable, and equitable.

3.3 Embedding Responsibility

Human-centred QSE must also address socio-ethical dimensions of access, inclusion, and governance. Quantum computing remains resource-intensive and institutionally concentrated, raising concerns about equity and representation [11, 24, 41]. Embedding responsibility means ensuring that ethical reflection and value alignment are integral to quantum software practice rather than external constraints.

Research should examine how existing ethical frameworks, governance models, and professional codes can possibly translate into quantum contexts. Drawing from value-sensitive design [9], participatory ethics [40], and responsible innovation [11], HC-QSE can prototype reflective practices, such as ethics checkpoints, participatory review processes, and transparency, that embed responsibility in daily work.

Some HC-QSE research questions include:

- *How can ethical reflection be integrated into QSE tools, processes, and education?*
- *What participatory mechanisms ensure equitable access to quantum hardware and expertise?*
- *How can governance structures balance openness, accountability, and innovation in emerging quantum ecosystems?*
- *How can reflective and participatory practices be designed to embed ethical responsibility in day-to-day quantum software development?*

By embedding responsibility within QSE research and practice, the field can evolve toward systems that are not only technically robust but also ethically grounded and socially legitimate.

3.4 Implications for Software Engineering Research

For the software engineering community, this agenda extends classical concerns with quality and assurance into probabilistic, interdisciplinary domains. QSE provides an opportunity to expand socio-technical theories of cognition, collaboration, and trust while rethinking methodological boundaries between engineering, ethics, and human–computer interaction. Engaging with QSE as a socio-technical domain will enable researchers to develop frameworks that support reflective, participatory, and ethically responsible innovation, ensuring that the quantum future of software engineering remains both comprehensible, reliable, and humane.

4 Discussion

HC-QSE is not merely an adaptation of classical methods; it is an invitation to reimagine what engineering means when certainty, control, and complete understanding are no longer achievable. Quantum computation exposes a fundamental paradox: the more precisely we measure, the more we disturb the very phenomena we seek to understand [29]. This dynamic unsettles long-held assumptions in software engineering about transparency, determinism, and the traceability of cause and effect. In this light, HC-QSE is less a purely *technical* discipline than a new mode of *socio-technical* inquiry into how people reason, collaborate, and take responsibility when the ground truth of computation itself becomes probabilistic.

Rather than a deficit, uncertainty becomes a design material to be worked with and negotiated. As quantum software challenges reproducibility, establishing trusted, transparent, and ethically grounded practices becomes central [22, 42]. Reliable results arise from collaboration built on communication, interpretation, and clarity amid uncertainty.

As quantum technologies mature, the most enduring challenge will not be building machines that can compute what we cannot, but nurturing communities that can live responsibly with what we cannot predict. In embracing this challenge, software engineering can rediscover its human core: the craft of making systems that are as accountable to society as they are powerful in computation. Recent work in adjacent domains echoes this human-centred imperative. Spiegler et al. [37] argue that the future of AI depends on sustaining human control and ensuring positive societal impact, a perspective that resonates strongly with the emerging characteristics of QSE, where technical innovation must remain anchored in human values and responsibility.

These shifts also open provocative questions for the software engineering community such as: *If accountability is distributed across physicists, software engineers, and algorithm designers, what new ethics of shared responsibility emerge? If interpretability becomes a human–machine co-construction, how do we ensure that the stories we tell about quantum systems remain faithful to their realities rather than illusions of control?* Addressing these questions requires expanding our methodological imagination, combining empirical inquiry with reflective, participatory, and speculative approaches that take uncertainty seriously as both a technical and ethical condition.

HC-QSE thus offers a lens for examining not only quantum systems but the human infrastructure of engineering itself. Every design decision, how to visualise a qubit state, when to trust an algorithm, who gains access to hardware, encodes values and assumptions about knowledge, fairness, and agency. A human-centred approach makes these values visible and debatable, enabling engineering to become a site of ethical reflection rather than moral afterthought. In this sense, QSE is a microcosm of broader transformations across computing, where probabilistic reasoning, automation, and distributed responsibility challenge the very notion of control that once defined the profession.

5 Conclusion and Future Directions

Quantum computing redefines how software is reasoned about, developed, and governed. This paper argues that a human-centred approach is essential for ensuring that quantum software remains intelligible, inclusive, and ethically grounded. By combining insights from socio-technical systems, human–computer interaction, and responsible innovation, HC-QSE reframes development as a cooperative and reflective practice rather than a purely technical task. Looking forward, HC-QSE calls for reconfiguring how we conduct research and education. It urges interdisciplinary collaborations that bring social scientists, ethicists, and designers into quantum labs; participatory approaches that include learners and practitioners in shaping new tools; and infrastructures that support open, inclusive access to quantum computing resources. The success of this agenda will be measured not only in technical breakthroughs but in the cultivation of a research culture that values empathy, reflexivity, and diversity of expertise as forms of engineering competence.

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