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From Practice To Theory: Three Types of Influence of Quantum Technology on Quantum Mechanics and its Foundations

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Abstract
Although quantum reality is often discussed as notoriously difficult to comprehend, quantum mechanics is applied with increasing success in the development of quantum technologies. In this paper, we collect and organise views on the influence of quantum technology on quantum mechanics and the foundations of quantum mechanics. We distinguish three types of influence: quantum technology helps in (1) *understanding*, (2) *developing*, and (3) *evaluating* quantum mechanics and its foundations. We outline several illustrations of these types by introducing examples. By mapping the influence of research and engineering practices in quantum technology on quantum mechanics and its foundations, this paper illuminates the interaction between the two areas. This paper suggests both how technological practices can aid in long-standing theoretical debates on understanding quantum mechanics, and how investigating the relation between quantum technology and quantum mechanics can inform understanding in the philosophy of science on the interaction between science and technology in general.

Keywords Quantum mechanics · Quantum technology · Foundations of quantum mechanics · Science-technology interaction

> One of the goals of quantum computation and quantum information is to develop tools which sharpen our intuition about quantum mechanics, and make its predictions more transparent to human minds (Nielsen & Chuang, 2010, p. 2).

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1 Introduction

While there exists no consensus on how to interpret quantum mechanics (e.g., Adlam, 2021; Laloë, 2019, 2022; Myrvold, 2022; Nielsen & Chuang, 2010), the 'second quantum revolution' (Dowling & Milburn, 2003) is currently unfolding in practical domains: physicists and engineers are finding innovative ways to actively create, manipulate, and exploit the quantum behaviour of single quantum systems. So, while quantum reality is seen as notoriously difficult to comprehend (e.g., Feynman, 1985, p. 129; Universiteit van Nederland, 2022), quantum mechanics is applied in quantum technologies with increasing success. One must wonder: How does this technological development relate to the supposed difficulty in fundamental understanding? More specifically, does the development in quantum technologies influence quantum mechanics and the foundations of quantum mechanics? In this paper, we survey quantum mechanics literature and delineate three types of influence of development in quantum technology on quantum mechanics and its foundations.

Recently, scholars have emphasised the interplay between theoretical and technological aspects of science in scientific progress (Santo, 2024),[1] and it is increasingly argued that research and engineering practices in technology play a role in (scientific) knowledge creation (Boon, 2011; Russo, 2016, 2022). Despite these arguments highlighting the role of practices, and despite a host of historical examples, a broad mapping and organisation of *how* technologies influence theoretical development, including in the realm of quantum mechanics and quantum technology, remains underexplored. Muller (2023), for example, recently discussed the influence of quantum physics on philosophy, but the role of quantum technology has remained absent from such inquiry.[2] In this paper, we organise the influence of technology on theory in the quantum domain. We propose three types of influence: quantum technology helps in (1) *understanding*, (2) *developing*, and (3) *evaluating* quantum mechanics and the foundations of quantum mechanics. We will address several illustrations of these types, mapping the impact of quantum technology on quantum mechanics and illustrating *how* quantum technology influences quantum mechanics.

Studying the interaction between science and technology can be done on various levels. Ad hoc, one can distinguish three: the micro (studying the interaction between one specific (aspect of a) technology and one concept or theory), the meso (studying the interaction between a collection of technologies and a domain of science), and the macro (studying the interaction of science and technology in general).[3] Studies in the history and philosophy of science often analyse interactions on the macro level, referencing cases on the micro level to illustrate a larger point (e.g., how Gardner argues technological knowledge is necessary for the growth of science illustrated by how practical knowledge about copper displacement of German miners in the 17th century enabled scientific understanding of electrolytic refining; Gardner, 1997). The present study, however, maps meso interactions between, on the one hand, research and engineering practices in quantum technology (including experimentation) and, on the other hand, quantum mechanics and the foundations of quantum mechan-

[1] Del Santo describes these theoretical and technological aspects as the two souls of science, namely: understanding nature and controlling nature. See Santo (2024).

[2] Note that in this paper we focus in this paper on quantum mechanics, not quantum physics more broadly. We mention quantum physics here since we paraphrase Muller (2023), who explicitly discusses quantum physics.

[3] This can be seen as analogous to how historians study micro or macro history (e.g., Galtung, 1990).

ics, and utilises a collection of micro-interactions as illustrations of the types of influence. As this study aims to map influences on the meso level, this paper collects illustrations rather than working them out in elaborate detail.

A historically dominant view on the relation between science and technology, where knowledge follows a straightforward, sequential path from scientific discovery to technological application (e.g., Bush, 1945; Casimir, 2010),[4] has been challenged in a variety of ways (e.g., Boon, 2006; Cardwell, 1971; Cartwright, 1974, 1983; Douglas, 2014; Galison, 1997; Gardner, 1997; Kroes, 1992; Laudan, 1984; Layton, 1971). The idea that technology plays a substantive role in scientific knowledge creation is increasingly endorsed by philosophers of science (e.g., Boon, 2011; Russo, 2016, 2022). Besides its contribution to understanding the role of quantum technology in quantum mechanics specifically, this paper contributes to developing a more fine-grained understanding of the science-technology relation that those authors endorse and elaborates on the multifaceted character of technology in scientific development.

We start with a brief introduction to quantum technology and a discussion of the relations between quantum mechanics, its foundations and interpretations in Sect. 2.1.. Section 4. adds some methodological remarks. Sections 4.1., 5.1., and 6.1., respectively, present the three types of influence and the corresponding illustrations. In Sect. 8., we briefly address the interrelated character of these types and illustrations. Lastly, in Sect. 8, we summarise our findings and their implications and provide suggestions for future research.

2 The Research Fields

2.1 Quantum Technology

The dawn of quantum mechanics in the early 20th century advanced insights into core notions of the quantum world, resulting in a vast array of practical advancements that are vital today, such as lasers and transistors. This initial advancement in understanding the laws that govern quantum behaviour and the resulting technologies has been coined the first quantum revolution (Dowling & Milburn, 2003). In recent decades, however, control of quantum phenomena has developed so that physicists and engineers are increasing their control over single quantum systems: quantum behaviour can be created, manipulated, and exploited for practical benefit. In quantum computing, one of the ways in which quantum bits are physically realised is by trapping single electrons and using their spin as the qubit. In quantum sensing, information is extracted from single atoms to make exponentially more accurate and efficient devices. In quantum communication, entanglement is exploited to create secure communication protocols that transmit qubits between remote places. This active employment of quantum behaviour to alter the face of our physical world at the quantum scale has become known as the second quantum revolution (Dowling & Milburn, 2003).

It should be noted that despite impressive growth in the field of quantum technology recently, questions whether quantum algorithms can efficiently solve classically intractable problems and whether large-scale quantum computing can actually be realised are often

[4] This debate seems to go back to debates on the relation between pure and applied science. For historical accounts, see Bud (2012, 2014); Schauz (2014). Moreover, the linear account has also been prevalent in textbooks on science, see Gardner (1993).

still considered open questions (Cuffaro & Hagar, 2024). The technological advancements referred to in this paper happen largely in an experimental context. As the experimental goals are often oriented towards practical application in technology,[5] we prefer to speak of quantum technology in this paper.[6]

2.2 Quantum Mechanics, Foundations and Interpretations

On the theoretical side, a *prima facie* distinction can be made between quantum mechanics, the foundations of quantum mechanics, and the interpretations of quantum mechanics. While quantum mechanics concerns a specific physical theory that describes behaviour at the quantum scale, the foundations of quantum mechanics seek to understand and clarify the conceptual, physical, and mathematical underpinning of quantum mechanics. Foundational questions span a range of quantum phenomena, such as entanglement, non-locality, superposition, the status of the wave function (ontic or epistemic), the quantum-to-classical transition, and more (e.g., Norsen, 2017). Interpretations of quantum mechanics pursue the development of theoretical frameworks (i.e., interpretations) to explicate, in Bas van Fraassen's words, what quantum mechanics says the world is like when it is true (van Fraassen, 1991, p. 242).[7] The foundational issues mentioned are essential to the interpretations of quantum mechanics, and many topics, concepts, and questions overlap: the interpretations of quantum mechanics can be seen as a sub-field in the foundations of quantum mechanics, as various scholars imply (Hardy & Spekkens, 2010, p. 1; Laloë, 2019; Norsen, 2017). Interpretations of quantum mechanics, however, focus on making sense of these particular quantum phenomena in a broader theoretical framework (such as the many worlds interpretation (MWI), Copenhagen interpretation, or relational quantum mechanics). For the purpose of this paper, we refer to the influence of quantum technology on quantum mechanics and the foundations of quantum mechanics, the latter of which includes the interpretations of quantum mechanics.

3 Methodology

For the purpose of this research, we surveyed the literature on the influence of quantum technology on quantum mechanics and the foundations of quantum mechanics in the second quantum revolution.[8] This spans a timeframe from roughly the 1980s until the present:

[5] For example, the mission statement the research institute developing quantum technologies at TU Delft reads: 'At QuTech, we work on radically new technologies with world-changing potential. Our mission: to develop scalable prototypes of a quantum computer and a quantum internet by integrating world-class research and groundbreaking innovation.' (QuTech, n.d.)

[6] Another fitting term may be 'experimental technology.'

[7] Another way of phrasing quantum interpretations, would be to say that these debates aim at explaining what the empirical success of quantum mechanics tells us about the physical world (Myrvold, 2022).

[8] One exception to this timeframe is made for the debate on quantum non-demolition measurements in the 1970s, discussed in Sect. 6., due to the relevance of this debate to the topic of this paper and the close approximation to the scope of the second quantum revolution.

Richard Feynman's, 1982 paper on quantum computing can be taken as a seminal moment launching the second quantum revolution (Feynman, 1982).[9]

In this study, we organise the literature by delineating and explicating three types of influence of development in quantum technology on quantum mechanics and its foundations. Type 1: Quantum technology helps advance *understanding* of quantum mechanics and foundational issues by aiding the intelligibility and analysis of the theory (Sect. 4.1.). Type 2: Quantum technology helps in the *development* of quantum mechanics and its foundations by opening up physical domains for scientific inquiry, aiding the assessment of the boundaries of quantum mechanics, and informing development of concepts in quantum mechanics (Sect. 5.1.). Type 3: Quantum technology helps in the *evaluation* of quantum mechanics and foundational issues by providing both the tools and a practice for evaluating the theory and its foundations (Sect. 6.1.).

Some of the illustrations of these types of influence have naturally emerged from this inquiry because researchers make explicit a concrete example or case where the illustration comes into view (e.g., how quantum technology can illuminate the border between quantum and classical descriptions, as discussed in Sect. 5.3.). Other illustrations are developed by us to account for an implicit role of technology in quantum mechanics or the foundations of quantum mechanics that are present in the literature (e.g., how the illustration of the decoherence process can be seen as a tool for achieving understanding that aids in making quantum mechanics intelligible in Sect. 4.2.).[10]

This paper does not claim to present an exhaustive list of types and illustrations regarding the influence of quantum technology on quantum mechanics and the foundations of quantum mechanics – there are more illustrations and possibly more types of influence to be discerned. Neither should the three types of influence nor the illustrations be understood as independent categories – developments in quantum technology can influence (the foundations of) quantum mechanics in multiple ways (as will be outlined in more detail in Sect. 8). Instead of presenting an exhaustive list of independent, clearly demarcated categories, we present the types and illustrations in this paper as a useful organisational heuristic for future discussion and analysis of the role of quantum technology in quantum mechanics and its foundations. Future studies might build up and expand the framework outlined in the following.

[9] We do not imply practical or technological development has not made meaningful contributions to quantum mechanics and its foundations before this timeframe of the second quantum revolution. In fact, there have been many. Think, for example, about the practical desire to make better light-bulbs leading to Planck's discovery of the quantum (Kumar, 2008), or the role of cloud and bubble chambers in inquiring into the quantum scale (Galison, 1997).

[10] As important parts of the analysis happen implicitly in the literature, a strict literature review methodology, such as a systematic or scoping literature review, does not fit the objectives of this research. However, some further methodological notes can be provided: Papers included in this literature survey have been found through database searches or through reference assessment of the resulting papers. Databases used for search queries are the following: WorldCat Discovery, Scopus, Dimensions, and IEEE Xplore. A tool employed for reference assessment is ConnectedPapers. The criterium employed for selecting literature from search queries is that the paper either explicitly mentions a way in which (some aspect of) quantum technology influences (some aspect of) quantum mechanics or the foundations of quantum mechanics, or discusses a topic in which the implicit role of quantum technology influencing quantum mechanics or the foundations of quantum mechanics can be recognised.

4 Quantum Technology Helps in Developing Understanding of Quantum Mechanics and its Foundations

Development in quantum technology aids in developing the *understanding* of quantum mechanics and its foundations. This can be illustrated in at least two ways, namely that quantum technology helps make quantum mechanics intelligible by enriching the set of tools for understanding (Sect. 4.2.) and that quantum technology helps in the analysis of quantum mechanics and foundational issues (Sect. 5.). We will address both of these ways in which quantum technology aids in developing understanding, starting with increasing its intelligibility.

4.1 Quantum Technology Aids in Making Quantum Mechanics Intelligible

Quantum technology aids in making quantum mechanics intelligible by enriching the tools for understanding the theory. Henk de Regt's (2017) notion of scientific understanding in his book *Understanding Scientific Understanding*, hinges upon the notion of the intelligibility of scientific theories. For de Regt, a theory is intelligible to a scientist (in a given context) when that scientist can recognise qualitatively characteristic consequences of a theory without performing exact calculations.[11] A key characteristic of de Regt's account is that qualitative insight is contextual; there is no universal intelligibility standard. Rather, de Regt prefers to speak of possible tools for understanding. One of the most famous tools for understanding is the visualisability, as historically emphasised by physicists such as Ludwig Boltzmann (de Regt, 2017, pp. 200–205) and Erwin Schrödinger (de Regt, 2017, p. 87),[12] and it is precisely tools for understanding such as visualisability that quantum technology can contribute to.

Progress in the technological development visualising decoherence can illustrate this point. For example, in Serge Haroche's 2012 Nobel Prize lecture (shared with David Wineland), which he received 'for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems', he mentions the 'striking illustration of the transition from the quantum to the classical world', which they were able to produce (Haroche, 2013).[13] Drawing on several practical techniques, such as quantum non-demolition (QND) measurements, they conducted cavity QED experiments utilising the Rydberg atom Ramsey interferometer to perform state reconstructions (Deléglise et al., 2008; Haroche, 2013). They have been able to address aspects of the quantum-to-classical transition by, for example, non-destructively measuring the progressively field-state collapse

[11] For de Regt, a phenomenon is understood scientifically if and only if there is an explanation of that phenomenon that is based on an intelligible theory and conforms to the basic epistemic values of empirical adequacy and internal consistency – this is de Regt's *Criterion of Understanding Phenomena CUP* (de Regt, 2017, p. 92). This emphasis on an intelligible theory in scientific understanding requests de Regt to further formulate what it entails for a scientific theory to be intelligible to a scientist. Hence, de Regt presents a *Criterion for the Intelligibility of Theories* (CIT), which reads: A scientific theory T (in one or more of its representations) is intelligible for scientists (in context C), if they can recognise qualitatively characteristic consequences of T without performing exact calculations.

[12] Other tools discussed are unification (de Regt, 2017, p. 103), causality (de Regt, 2017, p. 113), mathematical intuition (de Regt, 2017, p. 103).

[13] For another example, see Verstraten et al. (2025).

(Guerlin et al., 2007) and have been able to reconstruct a snap-shot movie of the decoherence process (Fig. 1; Deléglise et al., 2008).

Such experimental work, enabled by technological development, one may argue, illustrates concepts such as decoherence – a concept that may otherwise be difficult to visualise. These empirically robust visualisations of quantum processes support the visualisability of quantum mechanics. If we understand visualisability as a tool for understanding, as de Regt does, these tools can allow scientists in different contexts to recognise qualitatively characteristic consequences of the theory (de Regt, 2017, p. 108), contributing to making the theory of quantum mechanics intelligible to the scientist. Quantum technology can, thus, influence the intelligibility of quantum mechanics by enriching this set of tools for understanding that scientists can utilise.[14]

4.2 Quantum Technology Aids in the Analysis of Quantum Mechanics and its Foundations

Technological development also aids in developing understanding of quantum mechanics and foundational concerns by aiding the analysis of quantum mechanics and its foundations in various ways, such as by providing open questions, making certain questions particularly pressing, and making apparent underlying assumptions.

Technological development can aid in analysing quantum mechanics and foundational issues by providing open questions. Gisin and Fröwis (2018), for example, argue that work on locality has proven extremely fruitful across theoretical, mathematical, experimental and applied physics and that work on this issue has suggested many open questions. Some of these open questions originate from technological or applied contexts. An example they mention is from applied quantum communication, where physicists and engineers work hard to develop quantum networks where multiple nodes are connected to several neighbours (Gisin & Fröwis, 2018, p. 4). They argue that this practical desire to develop and implement quantum networks raises novel questions on non-locality. While standard Bell scenarios deal with correlations from a single shared source between two parties, these quantum networks work with many independent sources and need to connect many nodes. So, an open question and a theoretical challenge that arises from these practical aims is what kinds of correlations can be simulated by such a local model in complex quantum networks with independent sources, particularly in networks with loops. Or what is the equivalence in such a setup to the standard Bell inequality? They write: '[…] in the case of (realistic) networks with loops, essentially nothing is known, not even for a mere triangle […] we feel we still do not understand non-locality' (Gisin & Fröwis, 2018, p. 4).

The analysis of quantum mechanics and foundational issues is not just aided by the novel open questions technological applications can provide, as is the case in the abovementioned quantum network example, but the promise of technological applications also makes certain standing open questions particularly pressing. One of the key open questions on quantum computation today is understanding why a quantum computer is faster than a classical com-

[14] For de Regt, the intelligibility of scientific theories is part of the condition for scientific understanding of phenomena (e.g., de Regt, 2017, p. 92 or 108), so the capacity for quantum technology to enrich the tools that scientists utilise to satisfy the intelligibility condition can potentially contribute to the scientists' understanding of quantum phenomena as well. In this paper, however, we highlight merely how these visualisations contribute to making the theory intelligible.

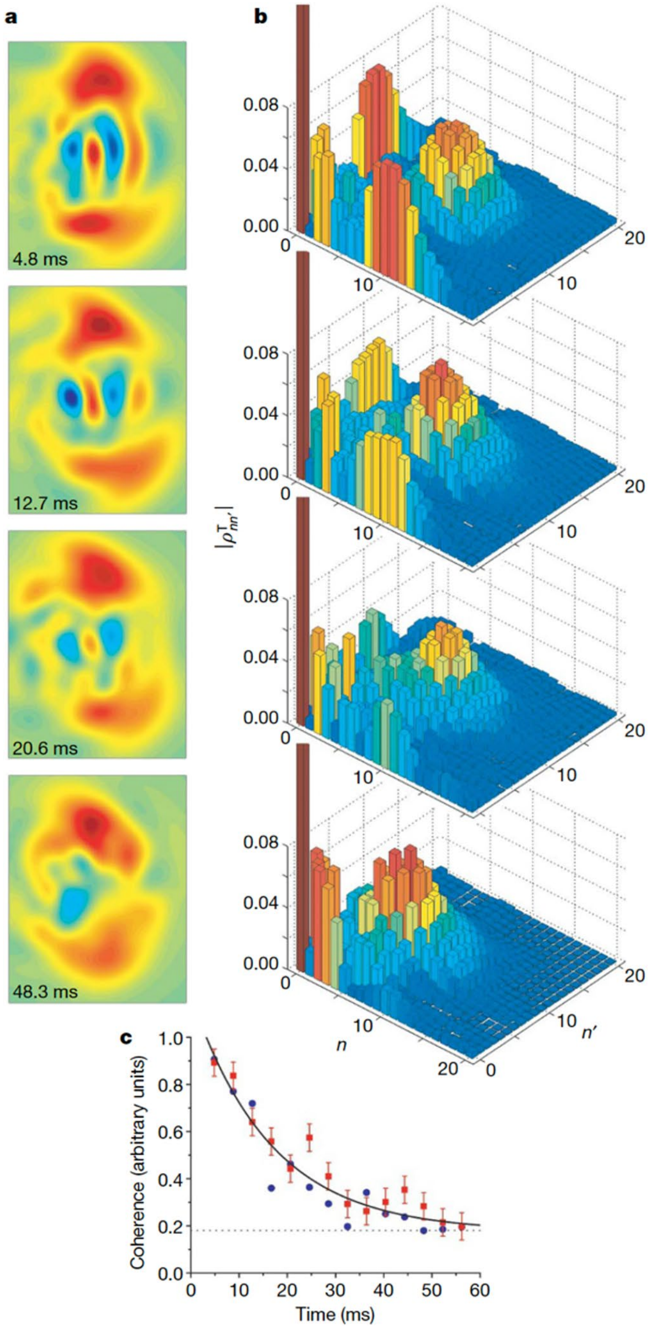

Fig. 1 **a**, Snapshots of the Wigner function of the odd Schrödinger cat state at four successive times after state preparation. **b**, Corresponding snapshots of the translated density matrix. Each of the 3D plots corresponds to a different time point, matching the Wigner functions in (a). Note that the off-diagonal bars change from high (indicating high coherence) to near zero (indicating decoherence) as time progresses. **c**, The quantum coherence of the Schrödinger cat states (Deléglise et al., 2008)

puter. The question on the quantum speedup did not originate from engineering or technological practices necessarily, as it was already sparked by the development of quantum algorithms, but it does become more pressing when the speedup is physically implemented. This debate on the quantum speedup directly relates the promise of practical applications to the interpretations of quantum mechanics. Although quantum computers are presumed to be significantly faster in specific tasks and can compute tasks that a classical computer cannot compute in a realistic time scale, it remains unclear why quantum computers are faster – i.e., what physical resources are responsible for the increased computational speed (Cuffaro & Hagar, 2024). This induces the need for reflection and analysis of theoretical and foundational concerns. For example, trying to answer the question of what resource a quantum computer utilises aids analysis of phenomena such as entanglement (e.g., Jozsa & Linden, 2003), T-gates (Bravyi & Kitaev, 2005) or interference (Fortnow, 2003). Moreover, various interpretational frameworks, or aspects of them, have been utilised to explain the quantum speedup, such as contextuality (Howard et al., 2014; Kupczynski, 2024) or time-symmetric and relational quantum mechanics (Castagnoli, 2016; Castagnoli et al., 2019). The interpretation that arises most often in this context is the many worlds interpretation (MWI) or some variation of it. David Deutsch famously argues that the parallelism found in quantum computing – also called the quantum parallelism thesis (Duwell, 2018, 2021) – should be explained through some version of the MWI (Deutsch, 1997). Others have argued similarly that the MWI provides a reasonable explanation of quantum computing (Hewitt-Horsman, 2009) at least for certain algorithms (Wallace, 2012). This use of the MWI to explain the quantum speedup is sometimes referred to as the many worlds explanation (MWX) of quantum computing (Cuffaro & Hagar, 2024). Various arguments have been levelled against the MWX, for example, by rejecting the quantum parallelism thesis as an explanation for the quantum speedup (e.g., Steane, 2003), or by accepting the quantum parallelism thesis but rejecting its supposed unique support for the MWI (Duwell, 2007, 2018).[15]

This application of interpretations of quantum mechanics to the question of the quantum speedup can aid analysis of the interpretations. For example, the question of the quantum speedup informs our understanding of the explanatory power of different interpretations, as some interpretations may be better equipped to explain the quantum speedup than others. More specific analysis is possible as well. For example, some argue that the preferred basis problem becomes especially problematic in the many-worlds explanation of quantum computing (e.g., Cuffaro, 2022, p. 134). The analysis of interpretations of quantum mechanics and their ability to address the open question of the speedup will become increasingly relevant as the technological applications develop. Rich discussions such as these display how open questions that are made increasingly relevant by the development of quantum technologies offer insightful avenues to analyse quantum mechanics and its interpretations.

Development in quantum technologies can, furthermore, aid in the analysis of quantum mechanics by displaying presuppositions. Michael Cuffaro mentions that reflecting on quantum computing emphasises that there are important differences in the methodological presuppositions in physics and computer science – which should be noted to prevent confusion (Cuffaro, 2022, pp. 109, 146). For example, Cuffaro argues that not all no-go results

[15] Moreover, some argue that there is a *prima facie* tension between the MWX and the MWI (Aaronson, 2013; Cuffaro, 2012, 2022), since MWI employs decoherence to distinguish macroscopic worlds from one another (so worlds are distinguishable through decoherence), while quantum algorithms utilise coherent superpositions before the state has decohered.

in a theoretical context must necessarily be assumed to be constraints in practical contexts (Cuffaro, 2022).

Ultimately, such practice-driven developments influence the understanding of quantum mechanics and its foundations by aiding their analysis.

5 Quantum Technology Helps in Developing Quantum Mechanics and its Foundations

Technological development in quantum technology aids not just in understanding and analysing existing theory and foundational issues, but also in the *development* of quantum mechanics. How research and engineering practices in quantum technology aid the development of quantum mechanics can be illustrated in at least three ways, namely by opening up physical domains for theoretical inquiry (Sect. 5.2.), providing insight into the limit of quantum mechanics (Sect. 5.3.), and informing the development of concepts in quantum mechanics and its foundations (Sect. 6.).

5.1 Quantum Technology Opens Up Physical Domains for (further) Theoretical Inquiry

The history of science encompasses many examples where technical and technological development made new physical domains accessible for theoretical reflection. To name a striking example, Antoni van Leeuwenhoek utilised his practical knowledge about magnifying glasses used for assessing cloth to create a powerful microscope, opening up the pathway towards microbiology (e.g., Wollman et al., 2015). Some authors argue similarly that quantum technology plays an important role in the inquiry into the quantum realm (Nielsen & Chuang, 2010). When arguing against the existence of quantum jumps, Erwin Schrödinger stressed in a 1952 paper that ‘we *never* experiment with just *one* electron or atom or (small) molecule. In thought experiments, we sometimes assume that we do; this invariably entails ridiculous consequences […]’ (Schrödinger, 1952, p. 239; italics in original). By virtue of improved technological capabilities, Schrödinger’s statement no longer holds true today, as physicists are now controlling and manipulating single-quantum systems. Technological development thus moved the status of experimentation on single quantum systems from thought experiment to actual experiment. In their quantum computation and information textbook, Nielsen and Chuang (2010) argue that the most profound scientific insights are enabled by creating methods to probe new research regimes. They maintain quantum computing and quantum information is an example situated in such a context. They argue that ‘[…] by obtaining complete control over single quantum systems, we are exploring untouched regimes of Nature in the hope of discovering new and unexpected phenomena’ (Nielsen & Chuang, 2010, p. 3).

Opening up new research regimes can be considered one of the original promises of quantum computing. Feynman famously argued that ‘[…] nature isn’t classical, dammit, and if you want to make a simulation of nature, you’d better make it quantum mechanical […]’ (Feynman, 1982, p. 486). Quantum simulation, it is often pointed out, opens up simulations of the quantum scale, potentially enabling inquiries into, for example, protein folds and photosynthesis (e.g., Boulebnane et al., 2023) – potentially resulting not only in major practical advances in medicine, biology and chemistry but also opening up these scales of single quantum systems for further scientific inquiry.

There are various examples where the opening up of research domains by experimental development in quantum technology is already useful in developing quantum mechanics and its foundations today. For example, increased experimental control can allow studying new effects and processes at the quantum scale. The technological realisation of the controlled interaction between superconducting circuits and microwave photons led to the creation of the field of circuit quantum electrodynamics (QED). According to Blais et al., circuit QED opened up the study of light-matter interaction and the study of new possibilities in quantum physics at an unprecedented scale (Blais et al., 2021). Technological development in circuit QED opened up 'regimes of strong, ultra-strong, and even deep-strong coupling' leading to the experimental exploration of many higher-order effects that are unusual in traditional cavity QED, such as 'giant Kerr effects, multi-photon processes, and single-atom induced bistability of microwave photons' (Gu et al., 2017, p. 1).[16]

There are numerous ways in which experimental advancements can aid in developing quantum mechanics and its foundations by enabling the study of new effects and processes. Trapping ions is one possible candidate to experimentally realise qubits for quantum computing (Bruzewicz et al., 2019) and this technological capability to trap individual ions is utilised in studying, for example, the quantum Zeno effect (Ozawa et al., 2018; Wunderlich et al., 2001). Superconducting circuits – another candidate for realising quantum computing – are utilised in studying the anti-Zeno effect (e.g., Harrington et al., 2017). Technological developments thus make the scale of single quantum systems accessible for studying processes such as the quantum (anti-) Zeno effect.

5.2 Quantum Technology Enables the Assessment of the Boundaries of Quantum Mechanics

A widely advocated argument suggests that development in quantum technology supports research into the limits of quantum mechanics, furthering the development of the theory. Quantum technologies, it has been argued, can help explore the boundaries to where the physical theory of quantum mechanics accurately provides descriptions and predictions of physical systems (Agnesi et al., 2018; Marchildon, 2006). However, quantum technology can also illuminate the 'border' between quantum and classical descriptions (Cuffaro & Hagar, 2024; Cuffaro, 2017, 2018; Pitowsky, 1994). With the rise of quantum technologies like quantum computing and the number of connected qubits increasing, the philosophical questions about at what point quantum mechanical descriptions stop being valid (and we should rather describe a system classically) have become an important practical concern. This quantum-to-classical transition and the limits of classical and quantum descriptions have been extensively sought after experimentally. Improved technological capabilities enable experimentalists to investigate the quantum-to-classical transition, for example, by gaining control over increasingly smaller quantum systems and conducting quantum experiments on increasingly larger collections of quantum systems. Quantum behaviour has been observed in larger and larger systems, with interference effects reported in systems of up to

[16] Gu et al. note that 'These developments may lead to improved understanding of the counterintuitive properties of quantum mechanics, and speed up applications ranging from microwave photonics to superconducting quantum information processing' (Gu et al., 2017, p. 1).

2000 atoms (Arndt et al., 1999; Fein et al., 2019; Shayeghi et al., 2020), interrogating the limits of quantum descriptions. Such experimental work that is enabled by improved technological capability, we argue, aids in the development of quantum mechanics by exploring the domain to which quantum mechanical laws can be effectively applied and, furthermore, can inform the development of philosophical notions in the foundations of quantum mechanics (such as the Heisenberg cut).

5.3 Quantum Technology Informs the Development of Concepts in Quantum Mechanics and its Foundations

Technological development can, according to some physicists and philosophers of physics in the quantum mechanics literature, inform concepts in quantum mechanics and the foundations of quantum mechanics, aiding its development. For instance, technological development informs the development of concepts such as quantum entanglement, as technological development enables and informs experimental studies of more diverse and complex forms of entanglement, such as high-dimensional quantum entanglement (Erhard et al., 2020) and asymmetric entanglement structures (Malik et al., 2016). According to Cuffaro and Hagar (2024), technological advancements may also shed light on matters of traditional epistemic and theoretical concern, such as causality (Allen et al., 2017; Costa & Shrapnel, 2016; Shrapnel, 2019) and the relation between mathematics and the physical world. Moreover, when considering quantum and classical mechanics as two alternative languages for describing physical systems, some scholars argue that interrogating the computing power inherent in such languages provides insight into the logical structure of quantum and classical mechanics (Janas et al., 2022). Moreover, some argue that development in quantum technology also offers new insights into some of the key concepts of quantum mechanics such as decoherence (Marchildon, 2006) or measurement (Cuffaro & Hagar, 2024), developing these concepts.

Development in quantum technologies may also inform concepts in fields that are close to physics (or may have grown closer as a result of quantum technology, such as computer science). Some examples include Cuffaro and Hagar, who suggest that the mathematical concepts of complexity and computability ‘may not only be translated into physics, but also *re-written* by physics’ (Cuffaro & Hagar, 2024).[17] Quantum computers, by virtue of the supposed capability to solve intractable problems, redescribe the abstract space of computational complexity (Bernstein & Vazirani, 1997; Cuffaro & Hagar, 2024). Cuffaro and Hagar, furthermore, mention that efficient quantum algorithms may serve as counterexamples to a-priori arguments against reductionism in the debate on functionalism and the physical character of types and properties in computer science (Cuffaro & Hagar, 2024; Pitowsky, 1996).

While technological development contributing to the development of concepts is often emphasised in the literature, as the number of above-mentioned sources demonstrate, it is not often discussed *how* this informing of concepts by technological development takes shape. To get a clearer picture of such processes, we will briefly discuss a historical example discussed in the literature that we surveyed, namely, how engineering challenges in designing instruments for repeated precision measurements contributed to conceptual development in quantum measurement. Outlining the origin of the concept of quantum non-demolition

[17] Italics in original article.

(QND) measurements – a concept that is essential in today's development of quantum technology[18] – is helpful here.

Precise measurements of quantum systems are not possible without introducing perturbations. Whenever one measures a property, say, of an electron, this measurement will disturb the system in a somewhat unpredictable way. Regarding Heisenberg's uncertainty relations, an accurate position measurement will disturb the momentum of the quantum system and vice versa, and hence, follow-up measurements after the initial measurement will show that the earlier disturbance has occurred (Braginsky et al., 1980, p. 547). The effects of measurements on macroscopic systems are typically very small and can usually be ignored. However, with the influx of technical capabilities of measurement precision, questions about the quantum mechanical effects of these precision measurements became relevant (Braginsky & Vorontsov, 1975). For example, the aluminium bars (suspended like a pendulum) in the gravitational wave detectors had to be measured so precisely that quantum mechanical effects had to be taken into account (Braginsky et al., 1980). The measurement perturbation seemed to demolish the possibility of making a second measurement with the same precision (Braginsky et al., 1980, p. 548), while one needed repeated precision measurements to detect gravitational waves in this setup. The laws of quantum mechanics (measurement perturbation) thus posed, first and foremost, an engineering challenge: Can we find a way to conduct repeated precision measurements in such a way that disturbance effects due to the initial measurement are circumvented? Practical options, such as making the aluminium bars much bigger, were not practically feasible (Braginsky et al., 1980). Some scholars took the engineering challenge of repeated precision measurement to theory. As a result, measurement schemes were devised in which back-action noise is kept entirely within unwanted observables,[19] allowing for repeated precision measurement (Braginsky & Vorontsov, 1975; Braginsky et al., 1980; Grangier et al., 1998; Thorne et al., 1978; Unruh, 1979). These measurement schemes were the first of a type of quantum measurements known as quantum non-demolition (QND) measurements.

The theoretical consideration of QND measurements is thus sparked by practical concerns of repeated precision measurements, such as in the design of gravitational wave detectors. In this case, an engineering challenge instigated theoretical reflection and opened up new ways of thinking about quantum measurements, developing quantum measurement theory by inspiring the development of QND measurements.[20] Moreover, the development of QND measurement schemes is also relevant to quantum foundations as it shows measurement disturbance can be controlled and directed. The development of quantum measurement theory through QND measurements informs the broader concept of quantum measurement and shows (together with other notions such as weak measurements) that quantum measure-

[18] Today, QND measurements are vital to emerging quantum technologies, QND measurements are of 'fundamental practical importance in overcoming detector inefficiencies' (Gambetta et al., 2007) and are, for example, 'needed to efficiently detect the state of a logical qubit without destroying it' (Xue et al., 2020).

[19] The term 'unwanted observables' here refers to those quantum variables of the system that are not of interest to the measurement, so those variables that do get disturbed by the measurement (due to quantum back-action) but do not matter for the quantity you want to measure.

[20] Note, here, that there are various examples of concepts that are developed to address practical problems in the development of quantum technologies rather than theoretical ones. For example, quantum error correcting codes is an example of theoretical developments arising from practical challenges of building a quantum computer – the practical needs of error correction drive these theoretical advancements. However, it is not always comprehensively explored how such protocols impact the development of quantum mechanics as a physical theory, or its foundations.

ment is not an all-or-nothing phenomenon – as was assumed in the early days of quantum mechanics.

These examples – how technological development in quantum technology opens up physical domains, enables assessment of the boundaries of quantum mechanics, and supports the development of concepts in quantum mechanics, are illustrations of ways in which quantum technology aids not just in understanding and analysing existing quantum mechanics and foundational issues, but also aids in developing quantum mechanics.

6 Quantum Technology Helps in Evaluating Quantum Mechanics and its Foundations

Aside from aiding the understanding and development of quantum mechanics and its foundations, quantum technology also helps evaluation. This can be illustrated vis-a-vis quantum technologies' provision of both the tools and a practice for assessing and evaluating quantum mechanics and its foundations. Research and engineering practices in quantum technology enable more sophisticated tests and experimentation (Sect. 6.2.) and provide a practice to explore the utility of theoretical notions and interpretations (Sect. 7.).

6.1 Quantum Technology Enables More Sophisticated Tests and Experimentation

Development in quantum technology influences, rather straightforwardly, the ability of scientists to evaluate its predictions – including in new domains (see Sect. 5.2.). Historically, experiments such as the Stern-Gerlach experiment, an experiment crucial in understanding spin and testing the quantisation of angular momentum, have played a key role in the development of quantum mechanics. Another famous example is that of the Bell tests, where technological development enabled experimentation on the violation of the Bell inequalities, as conducted in various experimental schemes (Aspect et al., 1981; Freedman & Clauser, 1972; Weihs et al., 1998). Such tests enabled the assessment of key notions, such as entanglement and non-locality, crucial to the evaluation of quantum mechanics. These tests and experimentation enabled by technological development concerns not just the predictions of quantum mechanics, but, according to some, also concerns quantum foundations – leading some to conclude this is a case of 'experimental metaphysics' (Shimony, 1989, p. 27). Assumptions on non-locality, traditionally considered as metaphysical assumptions in debates on entanglement, famously discussed in the Einstein-Podolsky-Rosen (EPR) paper (Einstein et al., 1935), became testable. These tests, initially executed by experimentalists such as Anton Zeilinger and Alain Aspect, require increasingly more advanced equipment to close the loopholes in each iteration. The most recent loop-hole free tests of the Bell inequalities display the role of quantum technology. For example, the 2015 tests at TU Delft were conducted using the electron spins of nitrogen-vacancy centres in diamonds, a technology that is developed as one of the contenders for realising qubits in quantum computers (Hensen et al., 2015). In 2023, a group in Zurich conducted a loop-hole free test using another contender for realising qubits in quantum computing, namely superconducting circuits (Storz et al., 2023). Enabled by improved experimental capabilities, more sophisticated empirical tests of Bell's theorem were developed and new loopholes closed, ultimately informing views about local realism and non-local correlations predicted by quantum mechanics. The experimental assessment of famously contested theoretical notions such as entanglement and non-locality constitute important milestones in the evaluation of such notions. Consequently, this empirical evaluation enabled by technological progress provides an important input to the assessment of these notions in both quantum mechanics and in discussions on the foundations of quantum mechanics.

Moreover, development in quantum technology enables the testing of some predictions of alternative quantum theories, such as objective collapse theories.[21] Collapse theories propose a modification of the Schrödinger equation. These theories provide differing predictions under circumstances where decoherence effects can be restrained (Bassi et al., 2005). Recently, there have been developments towards examining some testable aspects of objective collapse theories: Donadi et al. (2020) have shown that the natural parameter-free version of the Diósi-Penrose model – so a specific version of one particular objective collapse reformulation of quantum mechanics – must be ruled out. Cuffaro and Hagar argue that quantum computing has potentially much to offer in terms of testing collapse theories, since the main practical problem of testing these collapse theories coalesces with the problem quantum computing aims to overcome, namely, suppressing decoherence to create longer coherence times (Cuffaro & Hagar, 2024). Moreover, as these authors maintain, the capabilities to realise large-scale quantum computers relate to the capabilities needed to test what collapse entails.[22] As such, the development of these technologies has the potential to test conceptual questions in foundational debates, for instance, about true and false collapse (Pearle, 1998) – informing the long tradition of theoretical debates (Cuffaro & Hagar, 2024). As such, technological development enables the testing of alternative quantum theories, potentially influencing long-standing debates on, e.g., the interpretations of quantum mechanics.

6.2 Quantum Technology Provides a Practice To Explore the Utility of the Theoretical Notions and Interpretations

It has been argued that the practical utility of certain concepts or interpretations can inform the status of these positions in theoretical foundational debates. Let us discuss the example of how the utility of Bohmian mechanics may affect the status of Bohmian mechanics, according to some authors (Benseny et al., 2014).

Bohmian mechanics, or the pilot-wave interpretation, developed by Louis de Broglie in the 1920 s and David Bohm in the 1950 s, explains quantum phenomena through point-like particles guided by waves. Its practical usefulness has often been challenged, but recent decades have displayed an increased utility of the theory in addressing practical problems (Benseny et al., 2014). Late 1990 s, the chemistry community started investigating the utility of Bohmian trajectories (Lopreore & Wyatt, 1999; Wyatt, 2005), after which various applications developed in quantum physics. In their book *Applied Bohmian Mechanics*, Oriols & Mompart write about quantum computing: 'In some systems, the Bohmian equations might provide better computational tools than the ones obtained from the orthodox machinery, resulting in a reduction of the computational time, an increase in the number of degrees

[21] Cuffaro and Hagar see this as an example of experimental metaphysics (Cuffaro & Hagar, 2024).

[22] Cuffaro and Hagar (2024) stress that the computer does need to be of the right architecture, as dynamical collapse theories do not collapse large superpositions of photon polarisation or spin.

of freedom directly simulated, etc.' (Oriols & Mompart, 2019, p. 6).[23] In their review study, Benseny et al. depict Bohmian theory as a 'very enlightening route' to study nonlinear and nonunitary quantum evolutions. They highlight various examples where Bohmian trajectories can come in handy, such as obtaining insight into the adiabatic transport of single atoms, Bose-Einstein condensates, and holes in triple well potentials in ultra-cold atom physics (Benseny et al., 2010, 2012), making approximations to the many-body problem in electron-nuclei coupled dynamics (Benseny et al., 2014, pp. 6–8), and in the study of the interaction between intense light fields with matter.[24] Notably, the authors highlight that the field of quantum computation is a paradigmatic example of where Bohmian mechanics can be applied: Bohmian mechanics provides, according to the authors, no magical computational solutions, but it does display an alternative and 'fresh' route to tackle nonlinear and nonunitary evolution of quantum systems (Benseny et al., 2014, p. 36). Concerning applied Bohmian mechanics, Benseny et al. argue that they 'are convinced that the final status of the Bohmian theory among the scientific community will be greatly influenced by its potential success in those types of problems that present nonunitary and/or nonlinear quantum evolutions' (Benseny et al., 2014, p. 1). As such, the way in which applied Bohmian mechanics adds additional ways to make calculations in practical contexts such as quantum computing will, according to the authors, affect the status of Bohmian mechanics in foundational debates. Hence, the application of these theories in quantum technology has the potential to not just act as a measure for the success of the interpretational framework of Bohmian mechanics (reminiscent of arguments in the philosophy of science, where technology is seen as a marker of scientific progress (Douglas, 2014; Rescher, 1999, p. 39), but also informs the status of the framework in the interpretational debates.[25]

The authors do not explain *how* the practical utility of applied Bohmian mechanics would influence the status of Bohmian theory. This work on applied Bohmian mechanics does not add or modify postulates, equations, concepts, or predictions of Bohmian theory. So, this example in applied Bohmian mechanics seems to be a development of applications of the theory which does not by itself *develop* Bohmian mechanics in a way discussed in Sect. 5.1.. However, reflecting on the authors' statement in a different light, one could argue that the development of quantum technology can be seen to provide a practice for *evaluating* theoretical notions and concepts, such as Bohmian theory, on the basis of its practical utility.[26] From a pragmatist perspective, for example, truth can be defined in terms of utility, or truth can be understood as a function of the practices people engage in (Capps, 2023). One could argue quantum technology provides a space in which the utility of a theory can be explored. In light of the practical utility of applied Bohmian mechanics discussed above, one could argue that research and engineering practices in quantum technology expand the space for

[23] First edition was published in 2012.

[24] The authors of the review study discuss many more examples: see Benseny et al. (2014)

[25] Note, here, the break with the linear view on the science-technology interaction as noted in the introduction and conclusion of this paper: technology is here not just a marker of scientific progress – following scientific development – but also feeds back into the status of scientific theories or interpretations.

[26] It should be noted that the authors, by arguing that the application of Bohmian mechanics can influence the status of Bohmian theory, could be making a sociological argument about how the utility of a theory influences the community's perception of the theory. This sociological perspective raises many interesting questions: how and why is a certain idea or theory adopted, what socio-cultural conditions support this adaptation, how does the adoption of an idea or theory by a community influence the theory choice of other individuals or communities? For reasons of scope, we will not go into a detailed explanation of such sociological factors.

evaluating the utility (and hence the truth of the theory for this kind of pragmatist) of Bohmian theory. Technological development in quantum technology then helps evaluating theoretical notions and interpretations in light of their practical success.

A similar point may be put in realist terms. If views on the reality of theoretical entities should not be endorsed on the basis of theoretical justification (Hacking's 'representing'; Hacking, 1983), but should rather be informed by experimental practices (Hacking's 'intervening'), technological application provides the practices in which such assessment can take place. So, if we follow Hacking's famous slogan 'If you can spray them, then they are real' (Hacking, 1983), one could argue that development in experimental and technological contexts expands the set of practices in which you spray stuff, and thus expands the set of practices in which you can assess the reality of the entities postulated by the theory. Although there are various interpretations of quantum mechanics that are empirically equivalent to Bohmian mechanics, the ontology of these interpretations can differ, and hence the capacity of experimental practice to evaluate what entities can be sprayed can inform reflection on the ontologies of these interpretations. As such, quantum technology provides a practice in which Bohmian mechanics can be applied, informing our assessment of the ontological status of entities in quantum mechanics and thus aiding the evaluation the evaluation of the ontology of Bohmian mechanics.

This practice of testing the utility of an idea that quantum technology provides should, according to some authors, be more explicitly exploited in the evaluation interpretations of quantum mechanics (Vermaas, 2005). Vermaas (2004, 2005) argues research and engineering practices in technological development can provide conditions for theoretical debates in the interpretations of quantum mechanics. Motivated by the use of quantum mechanics in quantum technologies, Vermaas proposes two new conditions for selecting tenable interpretations, arguing that interpretations should accommodate engineering sketches and function ascriptions to technical artefacts (Vermaas, 2005).[27] Vermaas challenges philosophers of physics to provide rich enough interpretations for engineers to ascribe functions to artefacts, and challenges engineers to help select tenable interpretations – interpretations can be tested on the basis of conditions (next to other conditions such as empirical adequacy) about the ability to reproduce function ascriptions to the artefacts they design and accommodate engineering sketches (Vermaas, 2004, 2005).

7 Interrelated Types of Influence

This paper surveyed and organised literature to understand what role technological development in quantum technologies can play in quantum mechanics and its foundations. Besides the types and illustrations discussed in this paper, one could further delineate and adjust the

[27] First, Vermaas wants to accommodate the engineering intuition that artefacts have their function on the basis of their physical structure. Therefore, Vermaas formulates the condition that interpretations of quantum mechanics should accommodate the ascription of technical functions to technical artifacts described by quantum mechanics (Vermaas, 2005, p. 645). Second, Vermaas argues quantum mechanics poorly supports sketching practices in engineering. For example, in such sketches, trajectories of particles are typically included, but (standard) quantum mechanics does not ascribe definite positions to particles and thus does not yield the result that particles follow trajectories in space. As such, Vermaas proposes an engineering sketches condition which entails that the interpretations of quantum mechanics "should accommodate the sketching practice of engineers in the designing of technical artefacts described by quantum mechanics, by reproducing the properties these sketches ascribe to the artefacts" (Vermaas, 2005, p. 652).

scheme presented here. For instance, developments in one of these types and illustrations can influence developments captured in other of these types and illustrations: If the development of quantum mechanics fails in a particular domain (type 2, Sect. 5.1.), this can be input for (re)evaluating (parts of) the physical theory (type 3, Sect. 6.1.). As another example, the way in which technological development enables more sophisticated tests and experimentation is, first and foremost, an example of how quantum technology aids in evaluating predictions of quantum mechanics. However, more sophisticated tests and experimentation could clearly be important throughout the other types of influence as well. For example, more sophisticated tests and experimentation of quantum mechanics (type 3, Sect. 6.1.) can support further analysis of the theory – informing understanding of it (type 1, Sect. 4.1.). Similarly, better tests and experimentation (type 3, Sect. 6.1.) of quantum mechanics can enable further development of the theory (type 2, Sect. 5.1.) – and further development of quantum mechanics can reciprocally allow for new predictions to be evaluated (type 3, Sect. 6.1.). Moreover, the interrelated characters of different types of influence also seem to extend towards the illustrations within the specified types of influence. For example, the expanded toolkit for making theories intelligible (Sect. 4.2.) likely also contributes to the analysis of quantum mechanics and foundational issues (Sect. 5.), as development in the intelligibility of quantum mechanics reasonably informs the capacity of scientists and philosophers to analyse quantum mechanics (and vice versa). Here, a web of influences seems to emerge, as the interrelated character of these illustrations of the way quantum technology contributes to, for example, developing understanding of quantum mechanics (type 1, Sect. 4.1.) may then consequently aid, for example, in the development of quantum mechanics (type 2, Sect. 5.1.). Such influences between the illustrations or between the types of influence discussed in this paper hint at the interrelated nature of the examples given in this paper.

8 Conclusions

In this paper, we surveyed and organised literature on the influence of quantum technology on quantum mechanics and its foundations. We distinguished three types of influence of quantum technology on quantum mechanics and the foundations of quantum mechanics: quantum technology helps in *understanding*, *developing*, and *evaluating* quantum mechanics and its foundations.

- Quantum technology aids in developing *understanding* of quantum mechanics and its foundations by making quantum mechanics intelligible and aiding the analysis of the theory and its foundations (Sect. 4.1.).
- Quantum technology helps in the *development* of quantum mechanics and its foundations by opening up physical domains, aiding the assessment of boundaries of the theory, and informing concepts (Sect. 5.1.).
- Quantum technology helps in the *evaluation* of quantum mechanics and its foundations by enabling more sophisticated tests and experimentation and providing a practice to test the utility of ideas and concepts (Sect. 6.1.).

Several illustrations of these types and examples of these illustrations have been presented. Quantum technology aids in making quantum mechanics intelligible by enriching the set of tools for understanding through enabling, for example, empirically robust visualisations (Sect. 4.2.). Quantum technology aids in the analysis of quantum mechanics by providing novel open questions (Sect. 5.). Quantum technology aids in opening up physical domains by expanding control over single quantum systems (Sect. 5.2.). Quantum technology aids in the assessment of the boundaries of quantum mechanics by enabling investigation of the quantum-to-classical transition (Sect. 5.3.). Quantum technology informs concepts of quantum mechanics through novel insights arising from engineering challenges (Sect. 6.). Quantum technology enables more sophisticated tests and experimentation by enabling the practical realisation of tests (Sect. 6.2.). Quantum technology provides a practice to test the utility of ideas and concepts by providing a practice to explore the utility of theories (Sect. 7.). Lastly, we have noted that neither these types of influence nor the illustrations discussed should be seen as independent and strictly separated categories. Rather, the three types and illustrations appear to be interrelated.

This research has focussed particularly on the meso-level interactions between quantum technology and quantum mechanics and foundations. Hence, we must be prudent, refraining from making general claims about the macro-level interaction between science and technology as discussed in the philosophy of science and philosophy of technology. However, the diversity of ways in which quantum technology influences quantum mechanics and foundational issues seems to support what is increasingly emphasised about the macro-level interactions between science and technology (e.g., Boon, 2006; Li, 2024; Russo, 2016; Russo, 2022; Santo, 2024). The interaction between science and technology appears to be far more complex and multifaceted than the historically widespread linear view presupposes, where technology merely applies pre-existing theoretical notions and ideas. Moreover, research and engineering practices contribute in more complex ways to scientific development than via mere testing of scientific ideas and predictions. When looking into the field of quantum technology, as outlined in this paper, we find that technology plays a multifaceted role in theoretical inquiry and can influence scientific development in a multitude of ways.

We have outlined different types of influence, but did not explore a discussion of the *degree of influence* those types exert on theoretical development. Some authors go as far as to say that next to the concept-driven scientific revolutions introduced by Thomas Kuhn, there are tool-driven scientific revolutions that induce paradigm shifts, such as the Galilean revolution by way of using a telescope for astronomical research and the Crick-Watson revolution resulting from the use of X-ray diffraction to determine the structure of big molecules in biology (Dyson, 1998). It would be worthwhile for future research projects to consider whether the current development of quantum technologies – the second quantum revolution – can be considered a scientific revolution induced primarily by technology. Or, one could speculate whether this development may bring about a scientific revolution in the future – similar to how some argue the practical desire to make better light-bulbs was the driving force behind the black body research program, leading to Planck's discovery of the quantum (Kumar, 2008). Moreover, while our research primarily focussed on quantum technologies influencing quantum mechanics and its foundations, this does not mean that the influence of quantum technologies is restricted to quantum mechanics and its foundations; quantum technology likely affects many other fields in physics as well. Take, for example, the role of quantum technologies in gravitational wave astronomy in the Einstein telescope (Korobko, 2025; Schnabel & Korobko, 2022), the potential role of quantum sensing in the detection of single gravitons (Tobar et al., 2024), or the role of quantum error correcting codes (developed to address practical problems in building a quantum computer) in the context of research on quantum gravity, particularly AdS/CFT (e.g., Almheiri et al., 2015; Bain, 2020). Moreover, quantum technology potentially facilitates the bridging of different fields. Such as how the experimentation enabled by earth to satellite quantum communication that is being developed (e.g., Liao et al., 2018; Liao et al., 2017; Ren et al., 2017; Vedovato et al., 2017; Yin et al., 2017) may provide insight into phenomena where gravity affects quantum objects, testing the foundations of quantum theory in relativistic regimes (Agnesi et al., 2018; Bruschi et al., 2014; Rideout et al., 2012).

This paper started with the observation that while quantum mechanics is increasingly applied with great success, the quantum world appears to be notoriously difficult to comprehend. Given the results of this paper and looking at future work, we think that research and engineering practices in quantum technologies will continue to contribute to efforts to develop comprehension of quantum reality. Although it is not clear whether quantum technology could facilitate a breakthrough in, for example, the interpretations of quantum mechanics (Vermaas, 2005) or whether it further complicates matters of interpretation – this study shows that development in quantum technologies plays an important role in facilitating various insights in foundational discussions (from empirical insights to informing concepts). Moreover, quantum technology does not merely add perspectives, it also aids in critically evaluating theoretical considerations – playing a role in removing views and concepts. This research serves as a reminder that the relation between technology and foundations is not mono-directional.[28] It may be that fundamental breakthroughs also arise from application-driven research.

This emphasis on the role of technologies in foundational research does not imply that quantum technologies magically solve foundational issues. Rather, we argue that active cooperation and productive dialogue between research practices in quantum technology and researchers in the foundations of quantum mechanics bear the potential to yield a fruitful area of research, ultimately shaping our views on quantum reality.

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Declarations

Competing interests The authors declare no competing interests.

[28] This mono-directional character still seems to be implied in the basic science vs. applied science distinction (e.g., The Lancet, 2021).

References

Aaronson, S. (2013). Why Philosophers Should Care about Computational Complexity. In C. J. P. B. J. Copeland, & O. Shagrir (Ed.), *Computability: Turing, Gödel, Church, and Beyond,* 261–327. MIT Press.

Adlam, E. (2021). *Foundations of quantum mechanics*. Cambridge University Press. https://doi.org/10.1017/9781108885515

Agnesi, C., Vedovato, F., Schiavon, M., Dequal, D., Calderaro, L., Tomasin, M., Marangon, D. G., Stanco, A., Luceri, V., Bianco, G., Vallone, G., & Villoresi, P. (2018). Exploring the boundaries of quantum mechanics: Advances in satellite quantum communications. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,376*(2123), 20170461. https://doi.org/10.1098/rsta.2017.0461

Allen, J. M. A., Barrett, J., Horsman, D. C., Lee, C. M., & Spekkens, R. W. (2017). Quantum common causes and quantum causal models. *Physical Review X*. https://doi.org/10.1103/PhysRevX.7.031021

Almheiri, A., Dong, X., & Harlow, D. (2015). Bulk locality and quantum error correction in AdS/CFT. *Journal of High Energy Physics,2015*(4), 163. https://doi.org/10.1007/JHEP04(2015)163

Arndt, M., Nairz, O., Vos-Andreae, J., Keller, C., van der Zouw, G., & Zeilinger, A. (1999). Wave–particle duality of C60 molecules. *Nature*, *401*(6754), 680–682. https://doi.org/10.1038/44348

Aspect, A., Grangier, P., & Roger, G. (1981). Experimental tests of realistic local theories via bell's theorem. *Physical Review Letters*, *47*(7), 460–463. https://doi.org/10.1103/PhysRevLett.47.460

Bain, J. (2020). Spacetime as a quantum error-correcting code? *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, *71*, 26–36. https://doi.org/10.1016/j.shpsb.2020.04.002

Bassi, A., Ippoliti, E., & Adler, S. L. (2005). Towards quantum superpositions of a mirror: An exact open systems analysis. *Physical Review Letters*, *94*(3), 030401. https://doi.org/10.1103/PhysRevLett.94.030401

Benseny, A., Fernández-Vidal, S., Bagudà, J., Corbalán, R., Picón, A., Roso, L., Birkl, G., & Mompart, J. (2010). Atomtronics with holes: Coherent transport of an empty site in a triple-well potential. *Physical Review A*, *82*(1), 013604. https://doi.org/10.1103/PhysRevA.82.013604

Benseny, A., Bagudà, J., Oriols, X., & Mompart, J. (2012). Need for relativistic corrections in the analysis of spatial adiabatic passage of matter waves. *Physical Review A,85*(5), 053619. https://doi.org/10.1103/PhysRevA.85.053619

Benseny, A., Albareda, G., Sanz, Á. S., Mompart, J., & Oriols, X. (2014). Applied bohmian mechanics. *The European Physical Journal D*, *68*(10), 286. https://doi.org/10.1140/epjd/e2014-50222-4

Bernstein, E., & Vazirani, U. (1997). Quantum complexity theory. *SIAM Journal on Computing*, *26*(5), 1411–1473. https://doi.org/10.1137/s0097539796300921

Blais, A., Grimsmo, A. L., Girvin, S. M., & Wallraff, A. (2021). Circuit quantum electrodynamics. *Reviews of Modern Physics*, *93*(2), 025005. https://doi.org/10.1103/RevModPhys.93.025005

Boon, M. (2006). How science is applied in technology. *International Studies in the Philosophy of Science*, *20*(1), 27–47. https://doi.org/10.1080/02698590600640992

Boon, M. (2011). Defense of engineering sciences: On the epistemological relations between science and technology. *Techné*, *15*(1), 49–71.

Boulebnane, S., Lucas, X., Meyder, A., Adaszewski, S., & Montanaro, A. (2023). Peptide conformational sampling using the quantum approximate optimization algorithm. *Npj Quantum Information*, *9*(1), 70. https://doi.org/10.1038/s41534-023-00733-5

Braginsky, V. B., & Vorontsov, Y. I. (1975). Quantum-mechanical limitations in macroscopic experiments and modern experimental technique. *Soviet Physics Uspekhi*, *17*(5), 644. https://doi.org/10.1070/PU1975v017n05ABEH004362

Braginsky, V. B., Vorontsov, Y. I., & Thorne, K. S. (1980). Quantum nondemolition measurements. *Science*, *209*(4456), 547–557. https://doi.org/10.1126/science.209.4456.547

Bravyi, S., & Kitaev, A. (2005). Universal quantum computation with ideal Clifford gates and noisy ancillas. *Physical Review A,71*(2), 022316. https://doi.org/10.1103/PhysRevA.71.022316

Bruschi, D. E., Ralph, T. C., Fuentes, I., Jennewein, T., & Razavi, M. (2014). Spacetime effects on satellite-based quantum communications. *Physical Review D*, *90*(4), 045041. https://doi.org/10.1103/PhysRevD.90.045041

Bruzewicz, C. D., Chiaverini, J., McConnell, R., & Sage, J. M. (2019). Trapped-ion quantum computing: Progress and challenges. *Applied Physics Reviews*. https://doi.org/10.1063/1.5088164

Bud, R. (2012). Applied science: A phrase in search of a meaning. *Isis*, *103*(3), 537–545. https://doi.org/10.1086/667977

Bud, R. (2014). Applied science' in nineteenth-century britain: Public discourse and the creation of meaning. *History and Technology*, *30*(1–2), 1817–1876. https://doi.org/10.1080/07341512.2014.921416

Bush, V. (1945). *Science, the endless frontier: A report to the President*. National Science Foundation. Retrieved July 11 from https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm

Capps, J. (2023). The Pragmatic Theory of Truth. In E. N. Zalta & U. Nodelman (Eds.), *The Stanford encyclopedia of philosophy* (Summer 2023 Edition ed.).

Cardwell, D. S. L. (1971). *From Watt to Clausius: The rise of thermodynamics in the early industrial age*. Heinemann.

Cartwright, N. (1974). How do we apply science?? *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association*, *1974*, 713–719. http://www.jstor.org.tudelft.idm.oclc.org/stable/495834

Cartwright, N. (1983). *How the laws of physics lie*. Oxford University Press. https://doi.org/10.1093/0198247044.001.0001

Casimir, H. B. G. (2010). *Haphazard reality: Half a century of science*. Amsterdam University Press. (1983).

Castagnoli, G. (2016). Highlighting the mechanism of the quantum speedup by time-symmetric and relational quantum mechanics. *Foundations of Physics,46*(3), 360–381. https://doi.org/10.1007/s10701-015-9968-4

Castagnoli, G., Cohen, E., Ekert, A. K., & Elitzur, A. C. (2019). A relational time-symmetric framework for analyzing the quantum computational speedup. *Foundations of Physics,49*(10), 1200–1230. https://doi.org/10.1007/s10701-019-00300-z

Costa, F., & Shrapnel, S. (2016). Quantum causal modelling. *New Journal of Physics*. https://doi.org/10.1088/1367-2630/18/6/063032

Cuffaro, M. E. (2017). On the significance of the Gottesman–Knill theorem. *The British Journal for the Philosophy of Science*, *68*(1), 91–121. https://doi.org/10.1093/bjps/axv016

Cuffaro, M. E. (2018). Reconsidering no-go theorems from a practical perspective. *The British Journal for the Philosophy of Science,69*(3), 633–655. https://doi.org/10.1093/bjps/axw038

Cuffaro, M. E. (2022). The philosophy of quantum computing. In E. R. Miranda (Ed.), *Quantum computing in the arts and humanities: An introduction to core concepts, theory and applications* (pp. 107–152). Springer International Publishing. https://doi.org/10.1007/978-3-030-95538-0_3

Cuffaro, M., & Hagar, A. (2024). Quantum Computing. In E. N. Zalta & U. Nodelman (Eds.), *The Stanford encyclopedia of philosophy* (Spring 2024 Edition ed.).

de Regt, H. W. (2017). *Understanding scientific understanding*. Oxford University Press.

Deléglise, S., Dotsenko, I., Sayrin, C., Bernu, J., Brune, M., Raimond, J. M., & Haroche, S. (2008). Reconstruction of non-classical cavity field states with snapshots of their decoherence. *Nature,455*(7212), 510–514. https://doi.org/10.1038/nature07288

Deutsch, D. (1997). *The fabric of reality: The science of parallel universes– and its implications*. Penguin Books.

Donadi, S., Piscicchia, K., Curceanu, C., Diósi, L., Laubenstein, M., & Bassi, A. (2020). Underground test of gravity-related wave function collapse. *Nature Physics*, *17*(1), 74–78. https://doi.org/10.1038/s41567-020-1008-4

Douglas, H. (2014). Pure science and the problem of progress. *Studies in History and Philosophy of Science, Part A,46*, 55–63. https://doi.org/10.1016/j.shpsa.2014.02.001

Dowling, J. P., & Milburn, G. J. (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.

Duwell, A. (2007). The many-worlds interpretation and quantum computation. *Philosophy of Science,74*(5), 1007–1018.

Duwell, A. (2018). How to make orthogonal positions parallel: Revisiting the quantum parallelism thesis. In M. E. Cuffaro & S. C. Fletcher (Eds.), *Physical perspectives on computation, computational perspectives on physics* (pp. 83–102). Cambridge University Press. https://doi.org/10.1017/9781316759745.005

Duwell, A. (2021). *Physics and computation*. Cambridge University Press. https://doi.org/10.1017/9781009104975

Dyson, F. J. (1998). *Imagined worlds*. Harvard University Press.

Einstein, A., Podolsky, B., & Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete?? *Physical Review,47*(10), 777–780. https://doi.org/10.1103/PhysRev.47.777

Erhard, M., Krenn, M., & Zeilinger, A. (2020). Advances in high-dimensional quantum entanglement. *Nature Reviews Physics*, *2*(7), 365–381. https://doi.org/10.1038/s42254-020-0193-5

Fein, Y. Y., Geyer, P., Zwick, P., Kiałka, F., Pedalino, S., Mayor, M., Gerlich, S., & Arndt, M. (2019). Quantum superposition of molecules beyond 25 kDa. *Nature Physics,15*(12), 1242–1245. https://doi.org/10.1038/s41567-019-0663-9

Feynman, R. P. (1982). Simulating physics with computers. *International Journal of Theoretical Physics*, *21*(6–7), 467–488. https://doi.org/10.1007/BF02650179

Feynman, R. (1985). *The Character of physical law*. The MIT Press. (1965).

Fortnow, L. (2003). One complexity theorist's view of quantum computing. *Theoretical Computer Science,292*(3), 597–610. https://doi.org/10.1016/S0304-3975(01)00377-2

Freedman, S. J., & Clauser, J. F. (1972). Experimental test of local hidden-variable theories. *Physical Review Letters,28*(14), 938–941. https://doi.org/10.1103/PhysRevLett.28.938

Galison, P. (1997). *Image and logic: A material culture of microphysics*. University of Chicago Press. https://books.google.nl/books?id=6Gcu92U8CwYC

Galtung, J. (1990). Macro-History as metaphor for biography: An essay on macro and Micro history. *Biography*, *13*(4), 283–299. http://www.jstor.org/stable/23539870

Gambetta, J., Braff, W. A., Wallraff, A., Girvin, S. M., & Schoelkopf, R. J. (2007). Protocols for optimal readout of qubits using a continuous quantum nondemolition measurement. *Physical Review A*, *76*(1), 012325. https://doi.org/10.1103/PhysRevA.76.012325

Gardner, P. L. (1993). Textbook representations of science-technology relationships. *Research in Science Education*, *23*(1), 85–94. https://doi.org/10.1007/BF02357048

Gardner, P. L. (1997). The roots of technology and science: A philosophical and historical view. *International Journal of Technology and Design Education*, *7*(1), 13–20. https://doi.org/10.1023/A:1008892400827

Gisin, N., & Fröwis, F. (2018). From quantum foundations to applications and back. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,376*(2123), 20170326. https://doi.org/10.1098/rsta.2017.0326

Grangier, P., Levenson, J. A., & Poizat, J. P. (1998). Quantum non-demolition measurements in optics. *Nature*, *396*(6711), 537–542. https://doi.org/10.1038/25059

Gu, X., Kockum, A. F., Miranowicz, A., Liu, Y., & Nori, F. (2017). Microwave photonics with superconducting quantum circuits. *Physics Reports*, *718–719*, 1-102. https://doi.org/10.1016/j.physrep.2017.10.002

Guerlin, C., Bernu, J., Deléglise, S., Sayrin, C., Gleyzes, S., Kuhr, S., Brune, M., Raimond, J. M., & Haroche, S. (2007). Progressive field-state collapse and quantum non-demolition photon counting. *Nature*, *448*(7156), 889–893. https://doi.org/10.1038/nature06057

Hacking, I. (1983). *Representing and intervening: Introductory topics in the philosophy of natural science*. Cambridge University Press. https://doi.org/10.1017/CBO9780511814563

Hardy, L., & Spekkens, R. (2010). Why physics needs quantum foundations. *arXiv preprint arXiv:1003.5008*.

Haroche, S. (2013). Nobel lecture: Controlling photons in a box and exploring the quantum to classical boundary. *Reviews of Modern Physics*, *85*(3), 1083–1102. https://doi.org/10.1103/RevModPhys.85.1083

Harrington, P. M., Monroe, J. T., & Murch, K. W. (2017). Quantum Zeno effects from measurement controlled qubit-bath interactions. *Physical Review Letters,118*(24), 240401. https://doi.org/10.1103/PhysRevLett.118.240401

Hensen, B., Bernien, H., Dréau, A. E., Reiserer, A., Kalb, N., Blok, M. S., Ruitenberg, J., Vermeulen, R. F. L., Schouten, R. N., Abellán, C., Amaya, W., Pruneri, V., Mitchell, M. W., Markham, M., Twitchen, D. J., Elkouss, D., Wehner, S., Taminiau, T. H., & Hanson, R. (2015). Loophole-free bell inequality violation using electron spins separated by 1.3 kilometres. *Nature,526*(7575), 682–686. https://doi.org/10.1038/nature15759

Hewitt-Horsman, C. (2009). An [review]ntroduction to many [review]orlds [review]n quantum computation [Review]. *Foundations of Physics*, *39*(8), 869–902. https://doi.org/10.1007/s10701-009-9300-2

Howard, M., Wallman, J., Veitch, V., & Emerson, J. (2014). Contextuality supplies the 'magic' for quantum computation. *Nature*, *510*(7505), 351–355. https://doi.org/10.1038/nature13460

Janas, M., Cuffaro, M. E., & Janssen, M. (2022). *Understanding quantum raffles: Quantum mechanics on an informational approach: Structure and interpretation*. Springer International Publishing.

Jozsa, R., & Linden, N. (2003). On the role of entanglement in quantum-computational speed-up. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences,459*(2036), 2011–2032. https://doi.org/10.1098/rspa.2002.1097

Korobko, M. (2025). Quantum technologies for the Einstein telescope. *Galaxies*, *13*(1), 11. https://www.mdpi.com/2075-4434/13/1/11

Kroes, P. (1992). On the role of design in engineering theories: Pambour's theory of the steam engine. In P. Kroes, & M. Bakker (Eds.), *Technological development and science in the industrial age: New perspectives on the science-Technology relationship* (pp. 69–98). Springer Science.

Kumar, M. (2008). *Quantum: Einstein, Bohr and the great debate about the nature of reality*. Icon.

Kupczynski, M. (2024). My discussions of quantum foundations with John Stewart Bell. *Foundations of Science*. https://doi.org/10.1007/s10699-024-09946-z

Laloë, F. (2019). *Do we really understand quantum mechanics?* (2 ed.). Cambridge University Press. https://doi.org/10.1017/9781108569361

Laloë, F. (2022). Quantum mechanics is routinely used in laboratories with great success, but no consensus on its interpretation has emerged. In O. Freire Jr. (Ed.), *The Oxford handbook of the history of quantum interpretations* (pp. 7–52). Oxford University Press.

Laudan, R. (1984). *The nature of technological knowledge: Are models of scientific change relevant?* Springer.

Layton, E. (1971). Mirror-image twins: The communities of science and technology in 19th-century America. *Technology and Culture,12*(4), 562–580. https://doi.org/10.2307/3102571

Li, J. (2024). Understanding the interaction between the divergence of science and the convergence of technology based on Polanyi's thoughts on science. *Foundations of Science*. https://doi.org/10.1007/s10699-024-09961-0

Liao, S. K., Cai, W. Q., Liu, W. Y., Zhang, L., Li, Y., Ren, J. G., Yin, J., Shen, Q., Cao, Y., Li, Z. P., Li, F. Z., Chen, X. W., Sun, L. H., Jia, J. J., Wu, J. C., Jiang, X. J., Wang, J. F., Huang, Y. M., Wang, Q., & Pan, J. W. (2017). Satellite-to-ground quantum key distribution. *Nature*, *549*(7670), 43–47. https://doi.org/10.1038/nature23655

Liao, S. K., Cai, W. Q., Handsteiner, J., Liu, B., Yin, J., Zhang, L., Rauch, D., Fink, M., Ren, J. G., Liu, W. Y., Li, Y., Shen, Q., Cao, Y., Li, F. Z., Wang, J. F., Huang, Y. M., Deng, L., Xi, T., Ma, L., & Pan, J. W. (2018). Satellite-relayed intercontinental quantum network. *Physical Review Letters,120*(3), 030501. https://doi.org/10.1103/PhysRevLett.120.030501

Lopreore, C. L., & Wyatt, R. E. (1999). Quantum wave packet dynamics with trajectories. *Physical Review Letters*, *82*(26), 5190–5193. https://doi.org/10.1103/PhysRevLett.82.5190

Malik, M., Erhard, M., Huber, M., Krenn, M., Fickler, R., & Zeilinger, A. (2016). Multi-photon entanglement in high dimensions. *Nature Photonics*, *10*(4), 248–252. https://doi.org/10.1038/nphoton.2016.12

Marchildon, L. (2006). The epistemic view of quantum states and the ether. *Canadian Journal of Physics,84*(6–7), 523–529. https://doi.org/10.1139/p06-018

Muller, F. A. (2023). The influence of quantum physics on philosophy. *Foundations of Science*, *28*(1), 477–488. https://doi.org/10.1007/s10699-020-09725-6

Myrvold, W. (2022). Philosophical issues in quantum theory. In E. N. Zalta & U. Nodelman (Eds.), *The Stanford encyclopedia of philosophy* (Fall 2022 Edition ed.).

Nielsen, M. A., & Chuang, I. L. (2010). *Quantum computation and quantum information: 10th anniversary edition*. Cambridge University Press. https://doi.org/10.1017/CBO9780511976667

Norsen, T. (2017). *Foundations of quantum mechanics: An exploration of the physical meaning of quantum theory*. Springer International Publishing.

Oriols, X., & Mompart, J. (2019). *Applied Bohmian mechanics: From nanoscale systems to cosmology* (2nd ed.). Jenny Stanford Publishing. https://doi.org/10.1201/b12311

Ozawa, A., Davila-Rodriguez, J., Hänsch, T. W., & Udem, T. (2018). Quantum Zeno effect assisted spectroscopy of a single trapped ion. *Scientific Reports*, *8*(1), 10643. https://doi.org/10.1038/s41598-018-28824-w

Pearle, P. (1998). True collapse and false collapse. arXiv preprint quant-ph/9805049.

Pitowsky, I. (1994). George boole's 'conditions of possible experience' and the quantum puzzle. *The British Journal for the Philosophy of Science,45*(1), 95–125.

Pitowsky, I. (1996). Laplace's demon consults an oracle: The computational complexity of prediction. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics,27*(2), 161–180. https://doi.org/10.1016/1355-2198(96)85115-X

QuTech. (n.d.). *About us*. Retrieved 04-06-2025 from https://qutech.nl/about-us/

Ren, J. G., Xu, P., Yong, H. L., Zhang, L., Liao, S. K., Yin, J., Liu, W. Y., Cai, W. Q., Yang, M., Li, L., Yang, K. X., Han, X., Yao, Y. Q., Li, J., Wu, H. Y., Wan, S., Liu, L., Liu, D. Q., Kuang, Y. W., & Pan, J. W. (2017). Ground-to-satellite quantum teleportation. *Nature*, *549*(7670), 70–73. https://doi.org/10.1038/nature23675

Rescher, N. (1999). *The limits of science*. University of Pittsburgh Press. https://doi.org/10.2307/j.ctt9qh79p (1984).

Rideout, D., Jennewein, T., Amelino-Camelia, G., Demarie, T. F., Higgins, B. L., Kempf, A., Kent, A., Laflamme, R., Ma, X., Mann, R. B., Martín-Martínez, E., Menicucci, N. C., Moffat, J., Simon, C., Sorkin, R., Smolin, L., & Terno, D. R. (2012). Fundamental quantum optics experiments conceivable with satellites—reaching relativistic distances and velocities. *Classical and Quantum Gravity*, *29*(22), 224011. https://doi.org/10.1088/0264-9381/29/22/224011

Russo, F. (2016). On the poietic character of technology. *Humana Mente: Journal of Philosophical Studies*, *9*(30).

Russo, F. (2022). *Techno-scientific practices: An informational approach*. Rowman & Littlefield Publishers, Incorporated.

Santo, F. D. (2024). Between understanding and control: Science as a cultural product. *Foundations of Science*. https://doi.org/10.1007/s10699-024-09960-1

Schauz, D. (2014). What is basic research?? Insights from historical semantics. *Minerva*, *52*(3), 273–328. https://doi.org/10.1007/s11024-014-9255-0

Schnabel, R., & Korobko, M. (2022). Macroscopic quantum mechanics in gravitational-wave observatories and beyond. *AVS Quantum Science*. https://doi.org/10.1116/5.0077548

Schrödinger, E. (1952). Are there quantum jumps?? Part II. *The British Journal for the Philosophy of Science,3*(11), 233–242.

Shayeghi, A., Rieser, P., Richter, G., Sezer, U., Rodewald, J. H., Geyer, P., Martinez, T. J., & Arndt, M. (2020). Matter-wave interference of a native polypeptide. *Nature Communications*, *11*(1), 1447. https://doi.org/10.1038/s41467-020-15280-2

Shimony, A. (1989). Search for a worldview which can accommodate our knowledge of microphysics. In e. James T Cushing & Ernan McMullin (Ed.), *Philosophical consequences of quantum theory, Reflections on Bell's theorem*. Univesity of Notre Dame Press.

Shrapnel, S. (2019). Discovering quantum causal models. *The British Journal for the Philosophy of Science*, *70*(1), 1–25. https://doi.org/10.1093/bjps/axx044

Steane, A. M. (2003). A quantum computer only needs one universe. *Studies in History and Philosophy of Modern Physics,34*(3), 469–478. https://doi.org/10.1016/S1355-2198(03)00038-8

Storz, S., Schär, J., Kulikov, A., Magnard, P., Kurpiers, P., Lütolf, J., Walter, T., Copetudo, A., Reuer, K., Akin, A., Besse, J. C., Gabureac, M., Norris, G. J., Rosario, A., Martin, F., Martinez, J., Amaya, W., Mitchell, M. W., Abellan, C., & Wallraff, A. (2023). Loophole-free bell inequality violation with superconducting circuits. *Nature*, *617*(7960), 265–270. https://doi.org/10.1038/s41586-023-05885-0

The Lancet, M. (2021). Funding basic sciences: A solid structure is built from the ground up. *The Lancet Microbe*, *2*(2), e48. https://doi.org/10.1016/S2666-5247(21)00011-2

Thorne, K. S., Drever, R. W. P., Caves, C. M., Zimmermann, M., & Sandberg, V. D. (1978). Quantum nondemolition measurements of harmonic oscillators. *Physical Review Letters*, *40*(11), 667–671. https://doi.org/10.1103/PhysRevLett.40.667

Tobar, G., Manikandan, S. K., Beitel, T., & Pikovski, I. (2024). Detecting single gravitons with quantum sensing. *Nature Communications*, *15*(1), 7229. https://doi.org/10.1038/s41467-024-51420-8

Universiteit van Nederland. (2022). *Why does nobody understand quantum physics?* [Video]. YouTube. https://www.youtube.com/watch?v=CBGoX6WHJ58

Unruh, W. G. (1979). Quantum nondemolition and gravity-wave detection. *Physical Review D*, *19*(10), 2888–2896. https://doi.org/10.1103/PhysRevD.19.2888

van Fraassen, B. C. (1991). *Quantum mechanics: An empiricist view*. Clarendon Press.

Vedovato, F., Agnesi, C., Schiavon, M., Dequal, D., Calderaro, L., Tomasin, M., Marangon, D. G., Stanco, A., Luceri, V., Bianco, G., Vallone, G., & Villoresi, P. (2017). Extending wheeler's delayed-choice experiment to space. *Science Advances*, *3*(10), e1701180. https://doi.org/10.1126/sciadv.1701180

Vermaas, P. E. (2004). Nanoscale technology: A two-sided challenge for interpretations of quantum mechanics. In D. Baird, A. Nordmann, & J. Schummer (Eds.), *Discovering the nanoscale* (pp. 77–91). IOS Press.

Vermaas, P. E. (2005). Technology and the conditions on interpretations of quantum mechanics. *British Journal for the Philosophy of Science*, *56*(4), 635–661.

Verstraten, J., Dai, K., Dixmerias, M., Peaudecerf, B., de Jongh, T., & Yefsah, T. (2025). In situ imaging of a single-atom wave packet in continuous space. *Physical Review Letters,134*(8), Article 083403. https://doi.org/10.1103/PhysRevLett.134.083403

Wallace, D. (2012). *The emergent multiverse: Quantum theory according to the Everett interpretation* (1st ed.). Oxford University Press.

Weihs, G., Jennewein, T., Simon, C., Weinfurter, H., & Zeilinger, A. (1998). Violation of Bell's inequality under strict Einstein locality conditions. *Physical Review Letters,81*(23), 5039–5043. https://doi.org/10.1103/PhysRevLett.81.5039

Wollman, A. J. M., Nudd, R., Hedlund, E. G., & Leake, M. C. (2015). From animaculum to single molecules: 300 years of the light microscope. *Open Biology,5*(4), Article 150019. https://doi.org/10.1098/rsob.150019

Wunderlich, B., & Toschek, P. E. (2001). Evolution of an atom impeded by measurement: The quantum Zeno effect. *Zeitschrift Für Naturforschung A*, *56*(1–2), 160–164. https://doi.org/10.1515/zna-2001-0125

Wyatt, R. E. (2005). *Quantum dynamics with trajectories: Introduction to quantum hydrodynamics*. Springer. https://doi.org/10.1007/0-387-28145-2

Xue, X., D'Anjou, B., Watson, T. F., Ward, D. R., Savage, D. E., Lagally, M. G., Friesen, M., Coppersmith, S. N., Eriksson, M. A., Coish, W. A., & Vandersypen, L. (2020). Repetitive quantum nondemolition measurement and soft decoding of a silicon spin qubit. *Physical Review X*, *10*(2), 021006. https://doi.org/10.1103/PhysRevX.10.021006. M. K.

Yin, J., Cao, Y., Li, Y. H., Liao, S. K., Zhang, L., Ren, J. G., Cai, W. Q., Liu, W. Y., Li, B., Dai, H., Li, G. B., Lu, Q. M., Gong, Y. H., Xu, Y., Li, S. L., Li, F. Z., Yin, Y. Y., Jiang, Z. Q., Li, M., & Pan, J. W. (2017). Satellite-based entanglement distribution over 1200 kilometers. *Science,356*(6343), 1140–1144. https://doi.org/10.1126/science.aan3211

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