In a state of superposition: exploring (in)effective public communication about quantum technology

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CHAPTER 1

Introduction

In 2012, postdoctoral researcher Krister Shalm at the University of Waterloo's Institute for Quantum Computing gave a TEDx talk in which he said:

> If we were [. . .] to take ourselves and shrink all the way down to the smallest things, like atoms, you'd find that the rules are completely different.
> This is the quantum world, and this is what I study, and in particular what I study is a type of partner dance that happens at the quantum level.
> In my lab, what I do is, I take the smallest chunks of light, we call them photons and I bring them together and I entangle them.
> They become partners, and when I do this, they become connected in a powerful way.
> In fact, it's the strongest connection that physics allows, and what's incredible is they don't have to be next to each other to remain partners, I could take them to opposite ends of the universe and no matter what I did to this one or this one, they would still remain correlated.
> Einstein, he called this spooky action at a distance.
> I prefer to call it partner dancing at a distance.
>
> (TEDx Talks, 2012a)

In this quote, Shalm creatively describes quantum physics, which explains how nature works at the smallest scale. Being a dancer himself, he makes a comparison between partner dancing and a particular phenomenon in quantum physics, called quantum entanglement. The comparison does not only remain in linguistic form - at the end of Shalm's talk, six swing dancers on stage, and almost 500 dancers from 36 cities worldwide on video, illustrate the idea of quantum entanglement through dance. This is an example of a creative way to communicate quantum physics to a broader, non-expert audience.

The type of science communication illustrated above can potentially influence non-experts' attitudes of and engagement with a new technology: quantum technology. Scientists around the world are developing this emergent technology by manipulating quantum phenomena, such as quantum entanglement, to their own design (Dowling & Milburn, 2003). Quantum technology is expected to have a significant impact on society in the future (Stichting Quantumdelta NL, 2020). For example, the technology is expected to enable the simulation of new materials and medicines (Outeiral et al., 2021), to provide fundamentally secure communication, which could enable, for example, secure online voting (Wehner et al., 2018), and to improve the detection of small, underground objects (Crawford et al., 2021). At the same time, the technology could increase the digital divide between rich and poor countries (Ten Holter et al., 2022) and be exploited by criminals, for instance when they acquire unauthorized access to facilities such as energy plants or air traffic control systems (Vermaas et al., 2019).

Non-experts are likely not (yet) familiar with quantum science and technology. Therefore, in communication about quantum science and technology, the way information is formulated can be important. For example, through the sentence 'Einstein, he called this spooky action at a distance', Krister Shalm presents quantum entanglement as something spooky. Such information may make the field of quantum technology seem inaccessible to non-experts and thereby influence their engagement with the field (Coenen et al., 2022; Vermaas, 2017). When non-experts hear that even physicists like Albert Einstein believed quantum entanglement is spooky, they may consequently feel that they themselves cannot understand and engage with information about quantum technology (Coenen et al., 2022; Vermaas, 2017, see).

In addition, the sentence 'I prefer to call it partner dancing at a distance' may also influence non-experts' engagement with quantum technology. By comparing an abstract, counterintuitive phenomenon (quantum entanglement) with a more familiar and concrete image (a partner dance), such information not only explains the science, but could also elicit some sort of emotional response (Grinbaum, 2017). According to Grinbaum (2017), these sorts of comparisons are useful in helping non-expert audiences understand what quantum experts do on a daily basis, and at the same time, help them experience the beauty of quantum physics.

In the scientific literature, several concerns have been raised about the way quantum science and technology are currently communicated to broader, non-expert audiences (Coenen et al., 2022; Grinbaum, 2017; Roberson, 2021; Roberson et al., 2021;

Seskir et al., 2023; Vermaas, 2017). For example, there are concerns about public communication presenting quantum physics as something spooky or enigmatic (Coenen et al., 2022; Vermaas, 2017), and omitting quantum phenomena explanations (Grinbaum, 2017). In addition, possible opportunities for communication about quantum technology are also mentioned (Grinbaum, 2017; Roberson et al., 2021), such as the use of metaphors to explain counterintuitive quantum phenomena (Grinbaum, 2017). However, to date, it is unclear whether these concerns and opportunities will actually result in problems and benefits, because it is not yet clear what public communication about quantum science and technology exactly looks like, nor is it clear what effect certain communicative decisions have on the public.

This dissertation therefore focuses on the following 3 aims:

1. To investigate the occurrence of potential popularisation issues mentioned in the scientific literature around quantum science and technology in public communication.
2. To investigate the effect of these potential issues on public engagement with quantum technology.
3. To what extent metaphors make quantum phenomena more comprehensible, and whether that consequently influences people's attitudes towards quantum technology.

To set the stage of this dissertation, the remainder of this chapter will first introduce the field of quantum science and technology, followed by a discussion of the role that science communication can play in this type of science and technology. The chapter will conclude with an outline of this dissertation.

1.1 The field of quantum science and technology

Quantum physics plays a central role in our daily lives. Our understanding of quantum physics has led to many of the technologies we use today, such as computers, tablets and smartphones (in which the semiconductor chip is an integral part), lasers and MRI scanners (Dowling & Milburn, 2003). These technologies originate from what we call the *first quantum revolution* (Dowling & Milburn, 2003).

To understand the origins of the field, we have to return to the period when quantum physics was formulated. The first quantum revolution began at the start of the 20th century. A key moment early in this revolution was the fifth Solvay International

Conference, entitled ‘Electrons and Photons’, held in 1927 (Golub & Lamoreaux, 2023). The conference brought together 29 of the most prominent physicists of that time in Brussels, 17 of whom were, or would become, Nobel Prize winners (Wikipedia contributors, 2025b). To this day, it is viewed as one of the most important conferences in the history of physics (Golub & Lamoreaux, 2023). Some physicists at the conference raised objections to quantum theory which led to debates, for example by Albert Einstein who remained critical of the theory for the rest of his life (Golub & Lamoreaux, 2023). For instance, Einstein described entanglement as ‘spooky action at a distance’ (Einstein et al., 1971) and argued that quantum theory had therefore still to be incomplete (Einstein et al., 1935).

This first quantum revolution has led to the development of technology (such as smartphones, lasers and MRI scanners), because of *our understanding* of how nature works on the smallest scale. Currently we are in the *second quantum revolution*, which is about developing new technology by *manipulating* nature on the smallest scale (i.e., manipulating quantum effects to our own design; Dowling & Milburn, 2003). Three quantum effects that scientists are trying to manipulate to their own advantage in this second revolution are superposition, entanglement and contextuality (Grinbaum, 2017, but see Dowling & Milburn, 2003 for other key principles). Box 1 provides a brief overview of these three key quantum effects. By manipulating these effects, scientists are developing new technologies such as quantum computers, the quantum internet, and quantum sensors. These technologies will be briefly introduced in Section 1.1.1.

1.1.1 Technology of the second quantum revolution

The quantum computer

An expected technology of the second quantum revolution is the quantum computer. In contrast to the computers we use today (classical computers), which process information according to the rules of classical physics, quantum computers process information according to the rules of quantum physics. Instead of classical bits, which can take on the values of 0 or 1, quantum computers use the quantum version of bits: qubits. As a result, they are expected to outperform classical computers on certain tasks to a greater or lesser extent. For example, quantum computers are expected to help coordinate agendas (DiVincenzo, 2000) and develop new medicines (Outeiral et al., 2021), but they also have the potential to break our current encryption, which may enable criminals to access protected information (Vermaas et al., 2019).

At the time of writing, smaller quantum computers have already performed calcula-

Box 1: Superposition, Entanglement and Contextuality

Three quantum phenomena important in the development of quantum technology from the second quantum revolution are superposition, entanglement and contextuality. An explanation is provided below for each phenomenon, based on Nielsen and Chuang (2010) and G. Jaeger (2019).

- **Superposition:** A quantum particle that is in a superposition state can be in multiple states at the same time. For example, a quantum system can be in a superposition of states “0” and “1” at the same time. This contrasts with classical physics, where a system can only be in state 0 or state 1, but never both at the same time. Superposition is thus a quantum phenomenon with no counterpart in classical physics.

- **Entanglement:** Multiple entangled particles can share a superposition state. Measuring one of the particles instantly affects the state of the others, even when the particles are separated by a large distance. Quantum entanglement also has no counterpart in classical physics. In mathematical terms, particles can only be described by the quantum state for the entire system, and not by their individual quantum states.

- **Contextuality:** In quantum systems, the context of a measurement can influence its outcome. This means that the result of a measurement may depend on prior measurements performed on the quantum system. This contrasts with classical systems, where measuring one property - such as the width of a bicycle - always yields the same result, regardless of whether you first measured the length of the bicycle. Whereas measurements are thus non-contextual in classical systems, they are contextual in quantum systems. For physicist Niels Bohr, contextuality was a consequence of his principle of complementarity, which states that certain pairs of properties - such as position and momentum - cannot be simultaneously measured in a precise manner.

tions believed to be out of reach for current classical computers (see e.g., Acharya et al., 2025; Arute et al., 2019; Zhong et al., 2020, 2021). However, these calculations appear to be primarily of academic value, lacking practical applications (Roberson, 2021). Expectations for when quantum computers will have practical use vary. One estimate suggests that early quantum computers may already prove useful for tasks such as simulating certain materials or combining classical and quantum computers for optimization problems (Mohseni et al., 2017). In addition, the majority of experts surveyed by Mosca and Piani (2024) believe it is likely that a quantum computer will crack our current encryption method in the next 15 years.

The quantum internet

Another expected technology of the second quantum revolution is the quantum internet. In their vision paper, Wehner et al. (2018) describe the quantum internet as a new internet technology that should enable the transmission of qubits between any two places on the planet. The ultimate goal is a gradual move towards a network of large-scale quantum computers that can transmit an arbitrary number of qubits among each other. One of the main anticipated applications of the quantum internet is secure online communication - even in the presence of an eavesdropper or when the quantum device itself is considered untrustworthy. It could also eventually support applications such as online voting which is secure to malicious attacks. In addition, a risk includes law enforcement agencies losing their grip on terrorist organisations that use the technology to communicate, amongst other (see Vermaas et al., 2019).

At the time of writing, early quantum networks (i.e., trusted repeater networks) have already been tested in applications such as secure conferencing (Project UQCC, n.d.) and secure banking (Zhang, 2017). In the Netherlands, versions of these networks have been trialled in the Port of Rotterdam to securely exchange sensitive data between two places in the port (Port of Rotterdam, 2024). Progress has also been made toward more advanced stages of quantum networks (i.e., end-to-end networks) in lab-based settings. For instance, three quantum devices have been connected in a lab-based network (Pompili et al., 2021) and several research groups have connected two quantum devices over longer distances using existing underground optical fibers (Castelvecchi, 2024), such as over 25km across the Dutch cities Delft and The Hague (Stolk et al., 2024). One estimate from a Chinese research team is that, by 2030, they will be able to connect quantum devices over 1,000 km via optical fibers (Castelvecchi, 2024).

The quantum sensor

A third technology of the second quantum revolution is the quantum sensor. Quantum sensors can measure time, gravity or other physical quantities with, for instance, a quantum phenomenon such as entanglement (or with a quantum system or quantum property; C. L. Degen et al., 2017). This allows quantum sensors to outperform classical sensors, for instance in terms of accuracy of the measurement.

At the time of writing, commercial quantum sensors have already been shown to outperform classical sensors when measuring small, underground objects (Crawford et al., 2021; Stray et al., 2022). Stray et al. (2022), for instance, showed that their quantum sensor measured a 2-by-2 meter tunnel located about 0.5 meters underground more quickly and precisely than current classical sensors. They argued this finding is important for safety reasons, minimizing risks for unexpected ground conditions, when building energy and transportation infrastructure, amongst others. Furthermore, commercial quantum sensors have been developed for applications such as 3D terrain mapping, even underwater, and for monitoring greenhouse gas emissions (Crawford et al., 2021). In addition, quantum sensors may also raise ethical and privacy issues when used to monitor personal data, such as individuals' energy or water usage, or when large amounts of sensing data are not well protected (Chapman et al., 2024).

1.2 The field of science communication in quantum developments

1.2.1 Public engagement with quantum science and technology

Quantum technology from the second revolution is still largely in the early stages of development. Many of the applications that exist are still lab-based and have no real-world application yet. Although there are technological obstacles to the further development of quantum computers (Mohseni et al., 2017), quantum networks (Wehner et al., 2018), and quantum sensors (Kantsepolsky et al., 2023), the real-world applications are expected to have a significant impact on society in the future. Examples include new medicines (Outeiral et al., 2021), secure online voting (Wehner et al., 2018), and safer constructions of energy and transportation infrastructure (Stray et al., 2022), but also the breaking of our encryption that may enable data breaches (Vermaas et al., 2019), losing grip on criminal organisations (Vermaas et al., 2019) and ethical and privacy issues from large amounts of sensing data (Chapman et al., 2024).

While quantum technology is still in an early stage of development, the field of science communication provides several reasons to already engage societal actors. A contemporary definition of science communication is (Smeets et al., 2025, p 5):

> **Science communication** encompasses all the ways in which people outside of the scientific world could be engaged with scientific research. This could be listening to and looking at results of research, formulating research questions together or discussing the possible consequences of science. One can think of popular scientific lectures, TV shows, discussion panels or audience research.

The first reason to already involve a broader group of people early in the development of a new technology is that, according to Roberson et al. (2021), it can lead to more socially robust solutions to societal challenges. Although scientists often imagine the potential societal impact of the technologies they develop, involving a broader group of people allows for a broader perspective to be included in this imagination.

Second, involving society can result in greater support for, and less opposition towards, the technology. When compared with scientists, non-experts often have a different perception of risks and benefits and judge information based on other factors such as trust in the source, their own values and beliefs, and existing knowledge (Siegrist, 2010; Van Dam et al., 2020). For instance, in assessing the risk perception towards nanotechnology, laypeople were found to be more concerned about social risks such as job loss, whereas experts were more concerned about potential health and environmental risks (Siegrist, 2010). Furthermore, while scientists know the scientific facts, members of the public possess lay knowledge (Van der Sanden & Meijman, 2008). According to Van der Sanden and Meijman (2008), it is the task of science communication to clarify that lay knowledge. This would allow scientists to understand better if (and if yes, which) misconceptions form some of the starting points of the public's perceptions and expressions.

Third, public engagement is regarded as important for aligning new technology with societal values (Cath et al., 2018; Van Dam et al., 2020). This can be seen, for example, in the field of artificial intelligence (AI), where there is a call for greater public engagement (Cath et al., 2018). While transparency, such as disclosing information of source code and data use by AI developers, is the most commonly referenced value in reports and ethical guidance documents for AI (Jobin et al., 2019), in practice, private actors often keep such information to themselves. There are certainly examples about dialogue and deliberation with the public on AI, such as the Moral Machine experiment (Awad et al., 2018), but national agendas still primarily view the public as users of AI services or as members of a potential workforce – not as individuals who should be involved in aligning AI with societal values (Wilson, 2022). This example shows that, while developments in science and technology can have a major impact on people's lives, aligning new technology with societal values does not always appear to be a priority. To achieve such a proper alignment, public engagement is regarded as important (Cath et al., 2018).

To achieve meaningful public engagement, Reincke et al. (2020) have proposed three roles for experts, which can be extended to science communicators in general. The first role involves sharing information in a meaningful way. This means that senders should go beyond merely mentioning the benefits and risks of a technology, but they should also try to address its potential to personal relevance and the public good. The second role involves listening to and learning from others. This aligns with the notion that while scientists know the scientific facts, members of the public can possess valuable lay knowledge (Van der Sanden & Meijman, 2008). The third role is about investing in relationships with the public. To build trust, senders should try to show their expertise, but avoid becoming too scientific as this can create a sense of distance.

The information that is presented in public communication can thus contribute to creating a good connection between a new technology and society (see the first role proposed by Reincke et al., 2020). This dissertation focuses on this first role by specifically focusing on the role of two communication devices that can play a role in the process of engaging people with quantum technology: *frames* (section 1.2.2) and *metaphors* (section 1.2.3).

1.2.2 Frames

Framing refers to "select[ing] some aspects of a perceived reality and mak[ing] them more salient in a communicating context, in such a way to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation" (Entman, 1993, p 52). In this dissertation, we focus on emphasis frames which highlight various dimensions of an issue. For example, a 'benefit frame' focuses on the positive outcomes of a certain aspect, whereas a 'risk frame' emphasizes potential downsides. Such emphasis frames are seen as important in understanding how people form opinions based on the specific aspects of an issue they are confronted with (Brugman & Burgers, 2018).

Research on frames has shown that certain frames are common in topics related to science and technology, while others are issue-specific (Nisbet, 2009). An example of a frame that consistently appears in communication on science and technology is the economic development/competitiveness frame, which focuses on economic investment, market benefits or risks, and competitiveness at local, national, or global levels (Nisbet, 2009). In the context of new technologies, benefit and risk frames have been analysed frequently (Gurr & Metag, 2022). In contrast, an issue-specific frame is specific to a certain topic. For instance, in the context of quantum physics, an issue-specific frame is the enigmatic frame, which presents quantum physics or one of its applications as something mysterious (Coenen et al., 2022; Vermaas, 2017). Frames that are analysed frequently are useful to examine such that we can make comparisons between different topics over time, while issue-specific frames can provide deeper insights into the framing of a particular topic (Brugman & Burgers, 2018).

By highlighting certain aspects of information while omitting others, frames can shape how people perceive and understand that information (Entman, 1993). In the context of new technologies, exposure to certain frames has been shown to influence public attitudes toward these technologies (Achterberg, 2014; Bingaman et al., 2021; Cobb, 2005; Druckman & Bolsen, 2011). For example, an experimental study found that people expressed greater support for AI when they read about its benefits (increase safety, improve lives, and solve global problems), compared to when they read about its risks (poses dangers, disrupts lives, and could lead to humanity's downfall; Bingaman et al., 2021). The extent of a framing effect can, however, vary depending on several factors. Examples of factors include individual characteristics like trust in science and technology (Achterberg, 2014) and message characteristics such as whether a frame emphasizes specific risks or benefits versus broader ones (Cobb, 2005).

1.2.3 Metaphors

Metaphors are communicative tools that allow people to comprehend one concept (referred to as the target domain) in terms of a different one (referred to as the source domain; Lakoff & Johnson, 1980). Defined as 'cross-domain mappings' (Lakoff & Johnson, 1980), metaphors map information from a source domain onto a target domain. The source domain is usually more concrete, straightforward and familiar (such as a partner dance), while the target domain is generally more abstract and complex (such as entanglement). By choosing a particular source domain, metaphors make certain aspects more salient while automatically downplaying others. This illustrates that metaphors are also framing devices that can subsequently affect how concepts are perceived and understood.

In the context of science communication, metaphors generally function to make a scientific concept easier to understand (Beger & Smith, 2020; Smedinga et al., 2023), but metaphors may also lead to misinterpretation (Zook & Maier, 1994) and possible resistance from experts and non-experts (Brugman et al., 2022; Gibbs Jr & Siman, 2021). Resistance, for instance, occurs when experts feel that a metaphor does not sufficiently explain the scientific topic (Gibbs Jr & Siman, 2021). Gibbs Jr and Siman (2021) even put it that "one of the worst criticisms a scientist can make of a theory is that it is 'just metaphorical', which is tantamount to saying that the theory is false, unscientific, and of little practical value" (p 672). Non-experts may resist metaphors because the metaphor does not resonate with them (Brugman et al., 2022). While metaphors may thus be promising tools in science communication, there may also be limitations.

1.2.4 Call for research

The previous sections have highlighted the importance of creating a strong connection between quantum technology and society. This calls for research to improve our understanding of how to do so. There are concerns that the current communication around quantum technologies poses barriers for public engagement with quantum technology (Coenen et al., 2022; Grinbaum, 2017; Roberson, 2021; Roberson et al., 2021; Seskir et al., 2023; Vermaas, 2017). Examples of possible barriers include famous physicists calling quantum mechanics 'spooky' (Einstein et al., 1971) and 'incomprehensible' (Feynman, 1967), national quantum agendas focusing on winning the quantum race (Roberson et al., 2021), and a focus on quantum computing at the expense of other quantum technologies (Roberson et al., 2021).

However, we do not know whether the concerns about the communication of quantum technology to a broader audience (Coenen et al., 2022; Grinbaum, 2017; Roberson, 2021; Roberson et al., 2021; Seskir et al., 2023; Vermaas, 2017) are justified, because we have no insight into the occurrence of these possible barriers in public communication, nor do we know what the actual effect of these barriers is. For instance, it is unknown whether frames such as the spooky and enigmatic frame are common in communication about quantum technology targeted at a broader audience, nor do we know its effect on public engagement with quantum technology. The question furthermore arises whether certain communication devices can help to establish good connections between quantum and society – such as the use of metaphors in explaining quantum mechanics to make the topic more comprehensible. This dissertation addresses these issues.

1.3 Outline of the dissertation

This dissertation investigates the occurrence of two communication devices around quantum science and technology (frames and metaphors), and their influence on the public. It consists of the following chapters (see Figure 1.1 for a schematic overview):

- **Chapter 2** reports on a content analysis of 501 TEDx talks, focusing on four potential popularisation issues in quantum science and technology, as postulated in the literature. These issues are: 1) framing quantum science as spooky or enigmatic (Coenen et al., 2022; Vermaas, 2017), 2) skipping the underlying quantum phenomena when explaining what quantum technology entails (Grinbaum, 2017); 3) using a narrow instead of a wider public good frame (Roberson et al., 2021); 4) focusing on quantum computers at the expense of other quantum technologies, such as quantum networks and quantum sensors (Roberson et al., 2021). We begin by describing these potential issues in the popularisation of quantum science and technology and report on their frequency in TEDx talks. In addition, we examine differences between quantum experts and non-quantum experts. We discuss the implications of these findings for quantum experts when communicating their work to a broader audience.

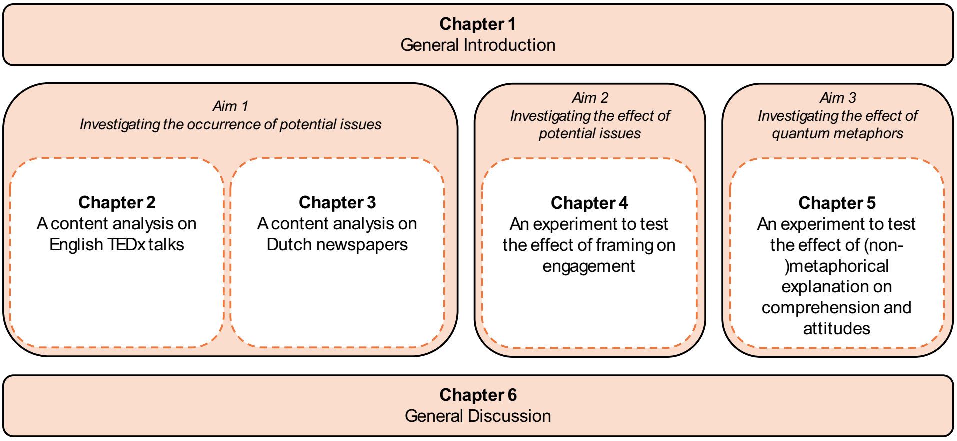
- **Chapter 3** further investigates the occurrence of potential popularisation issues in quantum science communication by analysing 385 Dutch newspaper articles. Implications for science communicators and journalists are discussed.

- After having quantified the occurrence of the potential issues in popular communication in the previous chapters, **Chapter 4** explores their effects on engagement with quantum technology. To keep the experimental design feasible, we concentrate on the first three potential issues: enigmatic framing, explaining quantum physics, and the balanced frame. Using an experiment involving $n = 637$ participants representative of the Dutch population, we examine how these communication characteristics influence public engagement with quantum technology. Practical advice is provided for science communicators in the field.

- **Chapter 5** explores how metaphorical and non-metaphorical explanations of superposition and entanglement in a news article affect comprehension and attitudes towards quantum technology. In an experiment involving $n =$ 1,176 participants, we investigate how two explanation types (metaphorical

Figure 1.1

Schematic overview of the dissertation.



and non-metaphorical explanations of a quantum phenomenon) influence perceived comprehension of the news article, actual comprehension of the quantum phenomena, affect-based attitudes towards quantum technology, and cognition-based attitudes towards quantum technology. We further investigate whether explanation types influence attitudes which is mediated by comprehension. We conclude with practical implications of the findings.

- **Chapter 6** provides a reflection on the work presented in this dissertation. We present an outlook on future research directions in the field, and offer recommendations for science communication researchers and science communicators based on the implications of this dissertation.