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Is everything quantum 'spooky and weird'? An exploration of popular communication about quantum science and technology in TEDx talks

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Abstract

Previous studies have identified four potential issues related to the popularisation of quantum science and technology. These include framing quantum science and technology as spooky and enigmatic, a lack of explaining underlying quantum concepts of quantum 2.0 technology, framing quantum technology narrowly in terms of public good and having a strong focus on quantum computing. Before assessing the effect of these potential issues on public perceptions, it is important to first determine whether these issues are actually present in popular communication. To this end, we conducted a content analysis in which we investigated how quantum science and technology are framed in a corpus of 501 TEDx talks. We also examined to what extent quantum experts, such as quantum scientists and leaders at organisations in quantum science and technology, communicate about quantum science and technology differently from non-experts, such as scientists from other disciplines and artists. Results showed that: (1) about a quarter of the talks framed quantum science and technology as spooky/enigmatic; (2) about half of the talks explained at least one underlying quantum concept (superposition, entanglement or contextuality) of quantum 2.0 technology; (3) quantum technology is narrowly framed in terms of public good as we found six times more talks mentioning benefits than risks; and (4) the main focus is on quantum computing at the expense of other quantum technologies. In addition, experts and non-experts differ on three out of four issues (only the fourth issue is similar for both). Our findings thus show that these potential issues related to the popularisation of quantum science and technology are present but not predominant in TEDx talks. Further research should explore their effect on public perceptions of quantum science and technology.

1. Introduction

In the 20th century, the first quantum revolution took off. Scientists started to understand and apply the laws of quantum physics, which led to ground-breaking technologies such as lasers and transistors (quantum 1.0 technology). The current second quantum revolution is expected to have an even bigger impact: by actively manipulating quantum effects in systems and materials, scientists are developing quantum technologies (quantum 2.0 technology) that might impact society at large (Vermaas *et al* 2019, European Quantum Flagship 2020, Stichting Quantumdelta NL 2020). Most of these quantum 2.0 technology based devices have not been realised commercially yet, but are developed in a research setting. This makes it hard to predict the exact impact these quantum 2.0 technologies will have on society, although some benefits have been envisioned. One of these benefits is that quantum computers can impact drug discovery through the simulation of chemical systems (Mohseni *et al* 2017, Outeiral *et al* 2021). Moreover, the vision of the quantum internet is to enable quantum communication between any two points on earth enabling secure communication, among other things (Wehner *et al* 2018). Thirdly, quantum sensors are expected to be useful devices in the development of transport and energy infrastructures, since these devices can measure very accurately what is happening underground and therefore identify risks to ground conditions (Stray *et al* 2022).

Besides potential benefits, these new quantum technologies could also pose risks for our society. For example, an envisioned risk is that governments will lose their grip on criminal organisations that communicate via quantum networks (Vermaas *et al* 2019). Unequal access to quantum computing between countries is another potential risk, making it unlikely that the benefits of the technology will be shared equally (Holter *et al* 2022). Also, large enough quantum computers—although still very challenging to build—pose the risk of '*breaking the Internet*': running a specific type of quantum algorithm, Shor's algorithm, enables large enough quantum computers to break current encryption methods (e.g. Vermaas *et al* 2019, Inglesant *et al* 2021).

To maximise the societal benefits of quantum technology while minimising the risks it may pose, societal engagement could be key. One of the reasons for this is that societal engagement might lead to more socially robust solutions as a result of gaining a wider view on the impact of the technology on different social settings (Roberson *et al* 2021). Several studies, however, expect problems due to potential issues in popularising quantum science and technology (Grinbaum 2017, Vermaas 2017, Roberson 2021, Roberson *et al* 2021). To date, their occurrence has not been quantified. Therefore, the goal of our research was to investigate whether these problems are present in the context of a specific type of popular communication: TEDx talks. In these talks, speakers share their research and ideas in order to spark conversations within local communities. Given that TEDx events invite a variety of speakers (TED n.d.-a), we have also compared the communication of quantum experts to that of non-experts. The next section presents our theoretical framework that includes the relevant literature on which our study is based.

2. Theory

2.1. The importance of connecting with societal actors in the development of emergent technologies

Science communication scholars agree that it is important to connect to the public in an early stage of a technology's development (i.e. upstream engagement; Kurath and Gisler 2009, Mooney 2010, Priest 2010). Arguments include that: (1) engaging societal actors could allow for more social contexts to shape an emergent technology (Roberson 2021); (2) engagement could lead to more public support and less public resistance (Kurath and Gisler 2009, Mooney 2010, Roberson *et al* 2021); and (3) public engagement fits a democratic point of view (van Dam *et al* 2020). This section briefly highlights each of these arguments.

First of all, according to Roberson (2021), engaging societal actors could allow for more social contexts to shape an emergent technology as well as give a broader overview of the technology's impact on different social settings. Upon designing an emergent technology, the scientists, who operate in social contexts themselves, mainly imagine the use and impact of the technology they are building. Their social contexts therefore have a great influence. If different societal actors would engage in an emergent technology's development, more social contexts could shape these imaginations.

Secondly, involving society can lead to more support and less public resistance (Kurath and Gisler 2009, Mooney 2010, Roberson *et al* 2021). The history of science communication of emergent technologies reveals that some of the previous emergent technologies have had to deal with public resistance (Kurath and Gisler 2009) and did not always lead to public benefit (Roberson *et al* 2021). For instance, Roberson *et al* (2021) describe an example of a new technology in agriculture, developed in the 1950s in the United States, that caused more than 80% of tomato-growing businesses to go into bankruptcy within 5 years of the technology's adoption. Businesses without adequate amounts of land were not able to benefit from the new technology. This prompted a public debate with civil society organisations about whose needs and desires the researchers were addressing and whose were not.

The third argument is normative in nature. From a democratic point of view, citizens should be allowed to express their opinions and concerns about developments that largely impact their lives. Since science and technology developments can have a great impact on citizens' lives, they should be allowed to participate in the decision-making process (van Dam *et al* 2020).

According to Reincke *et al* (2020), experts have a number of responsibilities in engaging the public in science, which include sharing input. Experts should share information in a meaningful way, such that the public feels empowered to participate in further engagement. This includes the fact that not merely the risks and benefits of a technology should be discussed, but also its potential for personal relevance and public good (Busby *et al* 2017, Reincke *et al* 2020). Ensuring that the public has access to meaningful information is a first step toward high-quality public engagement, even though it is not sufficient in and of itself (Priest 2010). In this study, we focus on the sharing of input by analysing how information about quantum science and technology is communicated in TEDx talks. The TEDx platform is a very suitable source as it aims to spark conversation within local communities across the world through knowledge sharing (TED n.d.-a.).

2.2. Science popularisation in TEDx talks

The process of science popularisation often involves a re-contextualisation of scientific knowledge by 'making the vocabulary plainer and more intelligible and adapting the content to the public's prior knowledge and immediate information needs' (Mattiello 2017, p 78). Popular communication about quantum science and technology has already been explored in different contexts, such as in popular science books (Dihal 2017), documentary films (Gaunkar *et al* 2022) and games (Seskir *et al* 2022). One specific form that to our knowledge has not yet been investigated is the TEDx platform.

In TEDx events, speakers from the community with different backgrounds and expertise are invited to present their research and ideas in under 18 min to the local community (TED n.d.-b.). This platform thereby allows speakers to talk directly to their local audience without a mediator in between. The events are very similar to TED events (Technology, Entertainment and Design), but a difference is that TEDx events are always locally organised. In addition to taking place in a local venue, the talks are freely accessible to web users (TED's secondary participants; Mattiello 2017) via the TEDx channel on YouTube.

2.3. Potential issues in popularising quantum science and technology

In this work, we analysed the framing of quantum science and technology in popular science communication. 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). Highlighting particular parts while neglecting other parts of some information can have a big effect on how the audience perceives and understands this information (Entman 1993).

We base our research on four potential issues that previous (theoretical) research has suggested to occur in the popularisation of quantum science and technology. These are: (1) framing quantum science and technology as spooky and enigmatic (Vermaas 2017); (2) the use of a pragmatic approach when explaining quantum 2.0 technology (Grinbaum 2017); (3) the use of a narrow public good frame in relation to quantum technology (Roberson *et al* 2021); and (4) the strong focus on quantum computing (Roberson 2021).

2.3.1. Spooky and enigmatic frame

The first potential issue in popular communication about quantum science and technology is the framing of quantum science as enigmatic (Vermaas 2017, Coenen *et al* 2022) and spooky. An example of the latter is a phrase coined by Einstein, who referred to the quantum mechanical concept of entanglement as 'spooky action at a distance' (translated from German *spukhafte Fernwirkung*) in one of his letters to Max Born (Einstein *et al* 1971).

According to Vermaas (2017), a possible consequence of framing quantum science as enigmatic is that it can hinder societal actors to join in on public debates. He supports moving away from enigmatic metaphors like Schrödinger's cat (i.e. a hypothetical cat that is in a combined state of being dead and alive to depict the concept of superposition) and from saying that quantum theory is counterintuitive in nature. Instead, it should be introduced as a novel information theory and the technological effects it might have should be presented (Vermaas 2017, Coenen *et al* 2022). The question arises whether the spooky and enigmatic frame is indeed widely present in popular communication about quantum science and technology.

2.3.2. Using a pragmatic approach for explaining quantum 2.0 technology

A second potential issue is how quantum 2.0 technology is explained in popular communication. We use the following definition of what constitutes an explanation: 'Explanatory discourse, (…), is premised on the assumption that readers are aware of some phenomenon such as light or language dialects but do not fully understand that phenomenon's nature. Thus explanatory discourse tries to promote or create understanding for lay readers of some phenomenon' (Rowan 1988, p 16).

Grinbaum (2017) states that popular and semi-popular accounts of quantum science and technology currently use a 'pragmatic approach' when explaining quantum 2.0 technology. Such an approach skips over the explanation of underlying quantum concepts, but instead focuses on protocols and how these are building blocks for quantum 2.0 technology. While such a pragmatic approach is an efficient short-cut, there are some drawbacks associated with it as well. For example, it does not allow the public to experience the beauty of quantum theory (something that quantum physicists experience when working with the mathematics of it), while Grinbaum (2017) argues this experience is necessary for the public to gain trust in quantum technology. Grinbaum (2017) proposes that narratives could be a solution and states that 'constructing a narrative that conveys scientific content as well as provoking a feeling of beauty is the hard problem in the relations between science and society' (p 304).

To our knowledge, no research has been performed yet to establish whether popular and semi-popular accounts indeed skip over the explanation of underlying quantum concepts when explaining quantum 2.0 technology. For physics in general, Kristensen *et al* (2021) found that in Dutch news articles physics is explained in many different ways. For example, sometimes the focus is on the causal factors, sometimes it is about what the function or application of a concept is, and analogy is another type of explanation. The question arises if the fundamental quantum concepts on which quantum 2.0 technology is based are explained in popular and semi-popular accounts.

2.3.3. Narrow vs wider public good frame, benefit vs risk frame

A rhetorical analysis of the national quantum strategies of the US, the UK and Canada points out a third potential issue where a dominant frame about 'winning the quantum race' and realising economic development (the economic development/competitiveness frame) was found (Roberson *et al* 2021). The Canadian national quantum strategy, for example, emphasises that nations are 'racing to develop technologies that can deliver incredible capabilities which will far exceed those of conventional technologies' (Roberson *et al* 2021, p 5). Roberson *et al* (2021) argue that such a frame is narrow in the sense that the uses and implications of quantum technology in and on society are not reflected upon more widely.

Roberson *et al* (2021) encourage quantum physicists to use a wider 'public good' frame, i.e. a wider reflection of how quantum research could benefit and harm society. Examples of a wider public good frame have been found in the rhetoric of quantum physicists during the conference *Project Q* in 2019 that focused on political implications of quantum technology. Quantum physicists have said to be mainly 'driven by goals of improving the society we live in' and are 'trying to solve problems in health, energy, [and] climate change' (Roberson 2021, p 109), thereby framing their motivation in terms of social progress.

Both the economic development/competitiveness frame as well as the social progress frame are frames that have consistently recurred in science and technology debates (Nisbet 2009), for example in artificial intelligence (AI). Cave and ÓhÉigeartaigh (2018) have assessed the risks of using the competitiveness frame (i.e. 'winning the AI race') and argue the frame is not beneficial for an inclusive, multi-stakeholder discussion on how AI can provide societal benefits while minimising risks. The social progress frame is presented as one of the alternatives that could counteract the risks the competitiveness frame poses (Cave and ÓhÉigeartaigh 2018).

Besides focusing on the benefits for society, a wider public good frame also includes a broader reflection on the risks. Many studies have already investigated how new technologies are framed in terms of benefits and risks (e.g. Gurr and Metag 2023), as these frames can influence the perception of societal actors towards a new technology (e.g. Cobb 2005, Druckman and Bolsen 2011, Achterberg 2014). Gurr and Metag (2023) found that the use of the benefit and risk frame vary depending on the technology, time period and media being analysed. For example, the frames most prominent in news media about nanotechnology are medical, scientific and economic benefits; carbon capture and storage is frequently framed in terms of political/legal and economic risks and benefits; and for synthetic biology, energy benefits are often mentioned (Gurr and Metag 2023). To our knowledge, it has not yet been explored how quantum technology is framed in terms of benefits and risks.

2.3.4. A focus on quantum computing

To realise a wider public good frame, Roberson *et al* (2021) suggest to focus on a wider range of quantum technology applications. This is in contrast to only focusing on the quantum computing applications of national security risks (e.g. decrypting public key cryptography) and realising economic development (e.g. big data in finance, to help calculate investment risks). In semi-structured interviews with four quantum physicists, who played important roles in designing visions for the national strategies of their countries, a focus on quantum computing got mentioned as well. One of them said that 'our field is broader than quantum computing: quantum tech is much broader' (Roberson *et al* 2021, p 5). Whether or not there is a focus on quantum computing in TEDx talks is an open question.

2.3.5. Differences in the use of frames between science experts and non-experts
Experts and non-experts might differ in how they frame and approach their communication about emergent technologies towards a general audience (Priest 2010, Droog *et al* 2020). In a study on cyberinfrastructure for big data, a specific emergent information technology, Droog *et al* (2020) analysed the metaphorical framing of that technology by experts involved in cyberinfrastructure development (e.g. technological developers and supercomputing centre administrators) and non-expert journalists. They analysed the use of metaphors in 15 US news texts (journalists) and 147 interviews with experts and found profound differences between both groups. An example of a difference is that most experts use precise metaphorical frames (e.g. a precise metaphorical frame that contains the word 'tool' specifies the type of tool, e.g. a hammer or a Swiss army knife), while the frames used by most journalists tend to be unprecise (e.g. an unprecise metaphorical frame that contains the word 'tool' does not specify which tool is referred to).

To examine whether differences between quantum experts and non-experts occur in popular scientific communication about quantum science and technology, we examine how often they use the four potential issues presented in sections 2.3.1–2.3.4.

3. Methods

The primary research question our study addresses is: How are quantum science and technology popularised in TEDx talks?

We investigated the following sub-questions:

(1) How often are quantum science and technology framed in terms of being spooky and enigmatic?
(2) When quantum 2.0 technology is mentioned, how often are the underlying quantum concepts explained on which the technology is based?
(3) How often are quantum science and technology framed in terms of economic development/competitiveness and social progress?
(4) How often are quantum science and technology framed in terms of benefits and risks?
(5) Which quantum technologies are mentioned most often?
(6) How does the popular communication about quantum science and technology of quantum experts and non-experts compare?

Because we are interested in analysing the different frames used to describe quantum science and technology in popular communication, we performed a content analysis on TEDx talks that cover quantum science or technology. This research method allows for a 'systematic, objective, quantitative analysis of message characteristics' (Neuendorf 2017, p 1). By following a standardized procedure which includes a codebook design and reliability testing, this research technique is expected to produce both replicable and valid results that are independent of the researcher (Krippendorff 2019, p 24).

3.1. Data selection

Figure 1 shows the sequence of our data collection. On 18 May 2021, we searched for videos containing the keyword 'quantum' in the TEDx channel on YouTube by making use of the YouTube Data Application Programming Interface (API) v3 (Google Developers n.d.). Since this API returns at most 500 videos per search, we performed individual searches per year. With 12 individual searches between 2009 (the year TEDx launched) and 2021, we acquired a total number of 4427 TEDx talks.

We downloaded all the transcripts of the collected TEDx talks and checked whether each transcript contained our keyword 'quantum'. Whenever the keyword could not be found, we deleted the transcript. This resulted in a total of 1002 transcripts.

Some of the talks had a transcribed or reviewed translated transcript which we refer to as 'manually transcribed'. Other transcripts had either been automatically generated by YouTube and therefore lacked punctuation, or had no English transcription available. We discarded those transcripts without an English transcription, leaving 796 automatically and 184 manually transcribed talks.

In the final step, we manually checked the transcripts for relevance to our study. When the transcript included enough substantive content about quantum science or technology, we included it in our final dataset. For example, when 'quantum' was used in 'quantum leap' or 'quantum jump' (to denote a sudden

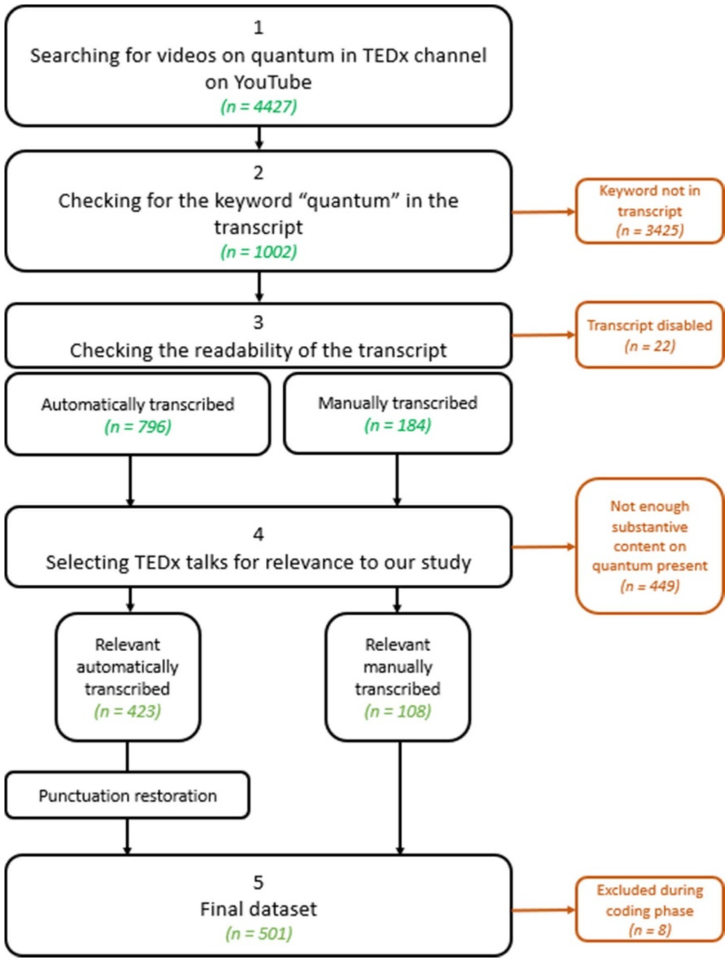

Figure 1. Data collection method.

change or step forward) but with no reference to quantum physics or quantum technology, we deleted the transcript from our dataset. Table A1 in the appendix gives an overview of the reasons to discard transcripts. A second coder went through 10% of the data to check for relevance of the transcripts to our study, which resulted in an acceptable agreement ($\alpha = 0.79$, 89.8%) between the two coders (Krippendorff 2004).

As a result of the final step, we retained 531 talks, of which the 423 automatically generated transcriptions from YouTube lacked punctuation. We improved the readability of the automatically transcribed talks by automatically restoring the punctuation (Tilk and Alumäe 2016). During the coding phases, we excluded another 7 transcripts for having a bad transcript and/or audio quality and one transcript for having appeared in the pilot already. Our final dataset thus consisted of 501 transcripts.

3.2. Coding

The coding consisted of two phases based on predefined codebooks. Phase 1 focussed on obtaining the descriptive data of the TEDx talk and identifying the quantum expertise of the speaker at the time of the talk, for which the YouTube descriptions were consulted. We defined quantum experts as scientists (undergraduates and graduates excluded) and leaders (e.g. founders, directors, CEO's, etc) at an organisation who are working in or have worked in the field of quantum nanotechnology or another field in which quantum science plays a role. Examples of non-experts include scientists from other disciplines, artists and high school students. For a complete list of the various professions that were classified as quantum experts and non-experts, we refer to the codebook in the appendix. If the speaker's quantum expertise could not be determined based on the YouTube description we categorized them as 'quantum expertise unknown'.

Phase 2 focussed on the content of the talks, based on the YouTube transcriptions. We first identified whether quantum science and/or technology was the talk's main focus, whether the talk included a holistic viewpoint (i.e. mystical ideas related to quantum physics, often pointing out that quantum physics tells us that everything is interconnected) and if a quantum 2.0 technology indicator (i.e. a term related to quantum technology of the second quantum revolution, for example quantum computer) was present in the transcript.

Secondly, for each talk we identified the occurrence of quantum applications. Specifically, we identified five quantum 1.0 technologies and three quantum 2.0 technologies. Whenever an application did not fall into one of the categories or remained unclear based on the text, the application was coded as other/unidentified. Subsequently, the specific frames that form the focus of our study were identified (i.e. the spooky and enigmatic frame, the social progress frame, the economic development/competitiveness frame, the benefit frame and the risk frame), and the accompanying quote was registered in the coding scheme.

Finally, we identified the presence of specific quantum science explanations, namely those mentioned by Grinbaum (2017) as theoretical notions underlying quantum technology[5]. These are (1) superposition, which means that a particle can be in a linear combination of states, e.g. an electron in a superposition state can simultaneously exist in spin states up and down; (2) entanglement, which means that two particles can share a strong connection with each other such that it no longer makes sense to talk about these two particles as being separate; and (3) contextuality, which means that performing a measurement on a quantum state irreversibly affects the state. The content of the explanations was based on definitions taught in physics education (Nielsen and Chuang 2010, Griffiths 2014) and coded by two physicists. The full codebook is available in the appendix. To test and improve the initial codebooks, TEDx talks from 2021 ($n = 22$) and 20 TED talks with quantum science and technology content that were not part of our final dataset were used for a pilot study.

3.2.1. Intercoder reliability

Inherent in doing content analyses is a degree of subjectivity, which we tried to overcome as best as we could by using a second coder. To determine the reliability of our final codebooks, two coders (the first and second authors of this paper) independently went through 15% of the final dataset (76 YouTube descriptions and transcripts). In phase 1, we found an acceptable agreement between the two coders ($\alpha = 0.78$, 88.6%) for identifying speakers' quantum expertise and profession. Because reliability remained relatively low in the pilot study for phase 2, the first and second coder discussed their independent codings of the final dataset to reach agreement. Before the discussion, percent agreements between 80% and 100% were achieved, except for the codes on establishing if the TEDx talk had a 'quantum' focus (78%) and determining the use of the benefit frame (61%). Even though most codes achieved high percent agreements, Krippendorff's α remained low for some of them. We think this is caused by the low number of times that those codes appeared in talks (see table A2 in the appendix), meaning that a slight difference in interpretation between the first and second coder is already detrimental for α. By further refining the codes and with the discussion in mind, the first coder went through the remaining 85% of the transcripts.

4. Results

4.1. Descriptive data

The 501 TEDx talks in our dataset were performed at TEDx events all over the world with a total of 55 different countries present in our dataset. Most talks were given in North America ($n = 222$ talks, 44%) and Europe ($n = 173$ talks, 35%) (see figure A1 in the appendix). The talks lasted between 3:49 min and 33:19 min and included the word 'quantum' eight times on average (the median is 3). Almost half ($n = 236$, 47%) of the 501 TEDx talks had quantum science and/or technology as their main focus. Furthermore, 73 talks (15%) included a holistic or mystical viewpoint. For example, one of the speakers mentioned that quantum physics is related to mental telepathy (TEDx Talks 2016a, 12:11):

> '[..] over the years I've been exposed to things like quantum physics, something known as the Morphogenic field, the field of our mind, expanding far beyond our brains, a kind of mental telepathy that says there could be a tipping point that if just one more person on the planet picks up a peaceful practice, and that person could be here in this room today, that there would be an instantaneous shift in everyone's awareness and the peace from our individual hearts would be communicated directly from mind to mind to mind spontaneously to everyone, everywhere on the planet'.

Additionally, we identified the profession and the quantum expertise of the speakers at the time they presented the talk. In total, 23 speakers gave 2 or more TEDx talks, and expertise was coded by talk. Generally, the talks were given by one speaker ($n = 490$, 98%), but 11 talks (2%) were given by two speakers

[5] Grinbaum (2017) also mentions discord and steering as theoretical notions, but we decided to exclude these concepts from our final codebook for the following reasons: (1) the coders found no reference to or explanation of these concepts in the pilot study; and (2) when performing a search through the final dataset for the words 'discord' and 'steering', discord yielded 0 hits and only 2 hits for steering which—upon closer inspection—showed to be unrelated to quantum steering.

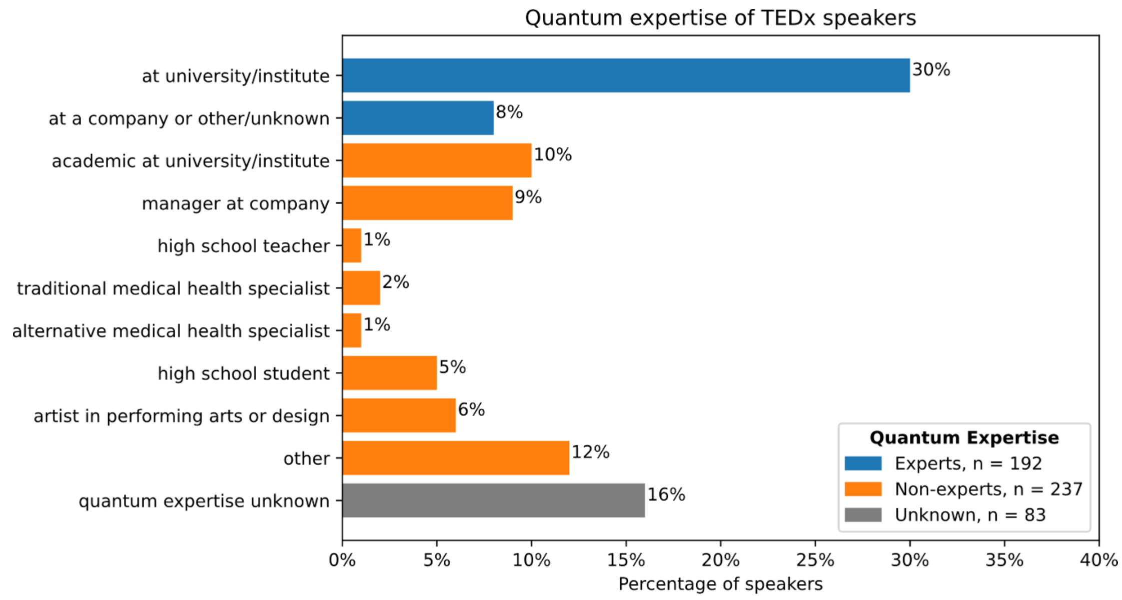

Figure 2. The percentage of TEDx speakers per profession and related quantum expertise.

(expertise was coded for each speaker). As a result, we identified the expertise of 512 speakers. The majority of speakers were non-experts ($n = 237$, 46%), followed by quantum experts ($n = 192$, 38%). There were also relatively many speakers whose expertise we were not able to identify ('unknown', $n = 83$, 16%). Figure 2 shows the professions of the speakers and their related quantum expertise category in more detail. Most quantum experts ($n = 153$, 30%) worked at a university, institute or (inter)national research organisation. Non-quantum experts had a main expertise domain outside quantum science, for example an academic working in a different research field than quantum science. Perhaps somewhat unexpectedly, one of the non-quantum experts was even a shepherd from Pashmina, India.

4.2. The spooky and enigmatic frame

The first frame that we analysed is the spooky and enigmatic frame. We found that the frame is apparent but not dominant in our dataset: 115 talks (23%) framed quantum science (applications) as spooky or enigmatic or as a synonym of these terms. Synonyms of spooky and enigmatic that occurred frequently are 'strange', 'weird' and 'crazy', such as in the following examples: 'Now the quantum world is a really strange place' (TEDx Talks 2013, 3:49), 'Everything "quantum" is spooky and weird' (TEDx Talks 2017, 8:06) and 'I will try to introduce you in a crazy way to this crazy world of quantum computers and of quantum properties' (TEDx Talks 2018, 2:32). Also, Einstein's well-known phrase came up, such as 'Einstein, he called this spooky action at a distance' (TEDx Talks 2012, 3:06).

4.3. Explanation of underlying quantum concepts when mentioning quantum 2.0 technology

We established whether talks included a reference to quantum 2.0 technology, i.e. applications from the second quantum revolution such as quantum computers and quantum networks ($n = 127$). If so, we checked whether an underlying quantum concept (superposition, entanglement or contextuality) was explained. In more than half of the quantum 2.0 technology talks we found an explanation of at least one underlying quantum concept ($n = 69$, 54% of the quantum 2.0 talks).

Out of the three quantum concepts that we studied, superposition was explained most often ($n = 57$, 45% of the quantum 2.0 talks) followed by entanglement ($n = 32$, 25% of the quantum 2.0 talks) and contextuality ($n = 31$, 24% of the quantum 2.0 talks). An example of a superposition explanation is 'If I make this ball quantum, […], my quantum ball can be red or it could be blue or it can be red and blue at the same time. […] it is a little weird, but we call it the superposition' (TEDx Talks, 2019, 5:10). Secondly, an example of an entanglement explanation is 'What happens if I take two of these quantum balls and I put them in a special kind of superposition state that I am going to call an entangled state. Well, this leads to some very strong correlations between the two balls, so strong, in fact, that it no longer makes sense to talk about them as separate objects' (TEDx Talks 2019, 5:54). Thirdly, an example of a contextuality explanation is 'But what happens if I try to look at this quantum ball? Well, it turns out that I, as a classical observer,

Table 1. Frequency table of the talks that include the economic development/competitiveness frame, social progress frame, benefit frame, and risk frame.

Frame	Total number of talks	Percentage of relevant dataset
Economic development/competitiveness	23	5%
Social progress	31	7%
Benefit	146	34%
Risk	22	5%

Note: Multiple frames can appear in a talk. The percentages provided are with respect to the hereby relevant dataset (total dataset with the holistic talks excluded, $n = 428$ talks).

cannot actually view the superposition, but very actively trying to look at the ball forces it to be either red or blue' (TEDx Talks 2019, 5:37).

4.4. The economic development/competitiveness vs social progress frame, and benefits vs risks frame

Besides the spooky and enigmatic frame, we analysed four more frames: the economic development/competitiveness frame, the social progress frame, the benefit frame, and the risk frame. Although holistic talks ($n = 73$, 15%) were found to frame quantum science and technology in terms of benefits, social progress and risks, they were unrelated to our research question. We therefore excluded the holistic talks from this part of the analysis. Consequently, the percentages presented in this section are with respect to the therefore relevant dataset ($n = 428$ talks). Table 1 gives an overview.

In our dataset, the amount of talks that mention the economic development/competitiveness frame ($n = 23$, 5%) was slightly lower to that of the talks with the social progress frame ($n = 31$, 7%). Of those, three talks included both frames simultaneously (1%). Examples of the economic development/competitiveness frame include 'quantum mechanics based products and services represent about more than one fifth of our gross national product' (TEDx Talks 2009, 15:20) and 'there is a massive race toward building a new technology called quantum computing' (TEDx Talks 2015, 3:19). An example of the social progress frame is 'I am going to tell you about how to make the world a better place with quantum mechanics' (TEDx Talks 2016b, 00:09).

A difference is more apparent between the benefit and risk frames: over six times more talks included the benefit frame ($n = 146$, 34%) compared to the risk frame ($n = 22$, 5%). A balanced view was provided (i.e. both frames present simultaneously) in 15 talks (4%). Benefits were most often mentioned in the life sciences & health field ($n = 52$, 12%), followed by energy & climate ($n = 46$, 11%). The security & privacy field was mentioned most often ($n = 16$, 4%) when a speaker highlighted a risk. In the appendix, figure A2 shows an overview of the percentage of talks with the benefit and risk frame in specific fields.

4.5. Technology applications of quantum science

In our total dataset, 197 talks (39%) mentioned at least one technology application of quantum science. Quantum computers and simulators were mentioned most often as technology applications of quantum science ($n = 120$, 24%), followed by quantum networks and cryptography ($n = 30$, 6%), and classical computers ($n = 25$, 5%). An overview is presented in figure 3, where quantum 1.0 refers to applications from the first quantum revolution, such as lasers and smartphones, and quantum 2.0 refers to applications from the second quantum revolution (quantum 2.0 technology). The other/unknown category ($n = 82$, 16%) contains technologies with a link to quantum science that we identified qualitatively. The top 3 applications that we identified in this category are transistors ($n = 18$, 4%), the scanning tunnelling microscope ($n = 10$, 2%) and solar cells ($n = 6$, 1%).

4.6. Comparison between quantum experts and non-experts

To establish whether there are any differences between popular communication by quantum experts ($n = 192$) and non-experts ($n = 237$), we did a comparative analysis. The group for which we were not able to determine the speaker's expertise was excluded from this comparison. The differences between the groups are tested for significance with a chi-square test. Note that this analysis only gives an exploratory view since there is a dependence between the data points.

First of all, experts ($n = 58$, 30% of the experts) framed quantum as spooky or enigmatic more often than non-experts ($n = 39$, 16% of the non-experts) ($\chi^2(1) = 11.456$, $p =< 0.001$).

Secondly, there is a difference between the expert and non-expert group in explaining underlying quantum concepts when mentioning quantum 2.0 technology. Although 70% of the experts ($n = 52$ out of

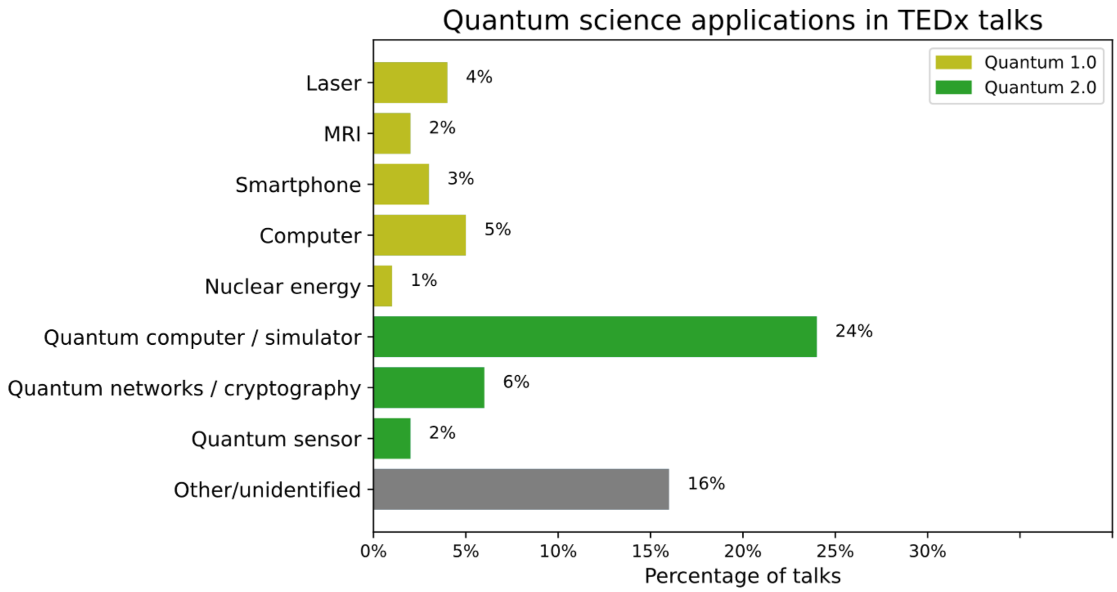

Figure 3. The percentage of quantum science applications mentioned in TEDx talks.

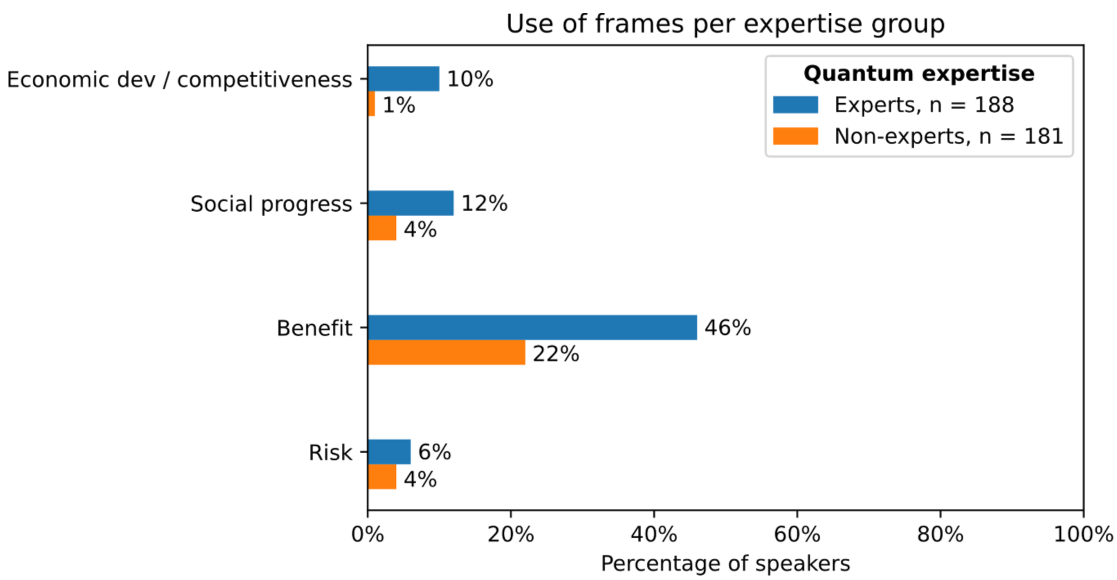

Figure 4. The percentage of speakers per expertise group that use the economic development/competitiveness frame, the social progress frame, the benefit frame and the risk frame. Speakers that expressed holistic views in their talks are excluded from this comparison.

72) that mention quantum 2.0 technology provided an explanation of at least one of the quantum concepts that we researched, only 28% of the non-experts ($n = 13$ out of 47) that mention quantum 2.0 technology did so. This difference between the groups is statistically significant, as confirmed by a chi-square test ($\chi^2(1) = 20.992$, $p =< 0.001$). Figure A3 in the appendix provides a comparison between the groups per quantum concept explanation (superposition, entanglement and contextuality).

We furthermore analysed whether experts and non-experts used the economic development/competitiveness, social progress, benefit and risk frames in relation to quantum science and technology. In this comparison, we again excluded the speakers that expressed holistic views in their talk (4 experts and 56 non-experts) resulting in a total of 188 experts and 181 non-experts to compare. Figure 4 shows that experts used all these frames more often than non-experts did[6].

[6] We performed a chi-square test to test for significance for the data in figure 4 (with mutually exclusive categories), but these test results are less reliable due to multiple cells having expected counts less than five.

Finally, the quantum computer/simulator was the most often mentioned quantum science application for both experts ($n = 71$, 37% of their talks) and non-experts ($n = 43$, 18% of their talks). For both groups, there is a big gap to the second most often mentioned application ($n = 24$, 13% of the experts and $n = 5$, 2% of the non-experts mentioned quantum networks/cryptography).

5. Discussion

In this study, we explored the occurrence of potential popularisation issues with quantum science and technology in TEDx talks. To the best of our knowledge, this is the first study that quantitatively assessed whether the four potential issues suggested in the literature are present in a type of popular communication towards a broader audience.

5.1. Spooky and enigmatic frame: apparent but not dominant

The spooky and enigmatic frame is apparent but not dominant. It was the second most frequently occurring frame in our study, with almost a quarter of all TEDx talks in our corpus framing quantum science (applications) as spooky or enigmatic or a synonym of these terms. As such, this finding can be considered to provide some support for Vermaas' (2017) claim that quantum science is typically framed as enigmatic. At the same time, however, this frame did not occur in the majority of the analysed TEDx talks, and is therefore not dominant. From this perspective, our findings line up with those of Busby *et al* (2017), who found that participants in a UK public dialogue exercise did not describe quantum science or technology as spooky or weird.

Our findings show that experts use the spooky and enigmatic frame statistically more often than non-experts. In order to explain this result, we looked for a link with Albert Einstein's well-known framing of quantum entanglement as 'spooky action at a distance' which experts might be more familiar with than non-experts. The specific phrase, however, was only used in 18 of the 115 talks that referred to the spooky and enigmatic frame (11 experts, 5 non-experts and 2 unknown). Therefore, we cannot identify this phrase as the main cause of the difference. Future research could delve deeper into this framing difference between experts and non-experts.

A first step to gain further insights into the prevalence of the spooky and enigmatic frame is to include an analysis of frames that can be seen as the positive counterparts of spooky and enigmatic, such as quantum science as an ordinary, comprehensible theory. Such an additional analysis could show whether experts and non-experts really present a different (i.e. more negative vs more positive) view on quantum science and technology. Furthermore, the research method that we chose can only describe what the 'product' (i.e. TEDx talks that cover quantum science and technology) looks like. We cannot draw conclusions about the speaker's motivations for using certain frames, nor can we discuss how these frames affect the audience's perceptions of, and actual engagement with, quantum science and technology. Therefore, future research could also investigate experts' and non-experts' motivations for using the spooky and enigmatic frame, as well as the public's reactions to it.

5.2. Explanations of underlying quantum concepts: mostly given by experts

Over half of the talks included an explanation of at least one underlying quantum concept (superposition, entanglement or contextuality) when quantum 2.0 technology was mentioned. On the one hand, this percentage is higher than expected given Grinbaum's (2017) claim that popular and semi-popular accounts of quantum science and technology skip over explaining underlying quantum concepts when explaining quantum 2.0 technology. This conclusion is consistent with the fact that TED speakers re-contextualise scientific knowledge by explaining concepts in understandable language to their audience (Mattiello 2017). The amount of time available could also play a role: TEDx talks generally last around 18 min, which gives speakers quite some time to delve into a topic. On the other hand, a substantial amount of the TEDx talks that mention quantum 2.0 technology did not provide an explanation of underlying quantum concepts. Perhaps, providing these explanations is too technical after all and therefore less relevant for TEDx talks, especially when quantum concepts are not the main topic.

The comparison between quantum experts and non-experts sheds further light on this finding: while Grinbaum's (2017) claim holds true for non-experts, it does not hold true for experts. The question arises whether non-experts make use of different explanatory tools when mentioning quantum 2.0 technology, as physics tends to be explained in many different ways (Kristensen *et al* 2021). This is a limitation of our approach: we only looked for three pre-defined quantum concepts, while undoubtedly, other interesting quantum concepts are explained as well in communication about quantum science and technology. This calls for a qualitative bottom-up analysis of all explanations that are provided by both experts and non-experts to go beyond the three pre-defined quantum topics.

5.3. Narrow vs wider public good frame: over six times more benefits than risks

The social progress frame (a wider public good frame) occurred slightly more often (7%) than the economic development/competitiveness frame (a narrow public good frame; 5%). Despite the fact that both of these frames are listed by Nisbet (2009) as ones that frequently appear in science and technology debates, neither of them appear particularly frequently in our dataset. This is unfortunate, since putting science in a broader and societal perspective, makes information more meaningful to the public and can guide them in discussions about science (Reincke *et al* 2020). One methodological explanation for our finding that the social progress frame and economic development/competitiveness frame were relatively uncommon in our corpus, is that we applied rather strict guidelines in our codebook. Only explicit references to social progress or economic development/competitiveness were coded, which may have worked as a limiting factor in identifying these frames. Future research might therefore want to consider taking a somewhat more lenient approach and formulate a broader identification criterion to capture these frames.

In addition, benefits of quantum technology were mentioned in over six times more talks than risks. Only 4% of the talks provided a balanced view (including both a benefit and risk frame), which Cobb (2005) showed eliminates framing effects in the case of nanotechnology. The predominant evaluation of quantum technology in TEDx talks is thus a positive one. This is similar to nanotechnology (a field closely related to quantum technology) as news media coverage mainly framed nanotechnology in terms of benefits (Gurr and Metag 2023). Due to the fact that risks are hardly mentioned in TEDx talks, we conclude that a narrow public good frame is present in that sense.

Our results showed that, although not statistically substantiated, these four frames (i.e. the economic development/competitiveness, social progress, benefit and risk frame) were used more often by experts than non-experts. Perhaps, this is an indication that experts do try to share input around quantum science and technology in a meaningful way (Reincke *et al* 2020), although the fact that experts hardly mention risks of quantum technology supports Roberson *et al*'s (2021) advice (i.e. that experts should reflect wider on how quantum research could benefit and harm society). From our analysis it remains unclear what the input of non-experts is. Given that the majority of speakers in our dataset are non-experts who are likely not actively involved in the quantum science and technology field, future research should characterize their input and analyse if it contributes in a meaningful way to sharing input around quantum science and technology.

5.4. Quantum science applications: a focus on quantum computing

Finally, quantum computer/simulator was the most often mentioned quantum science application. Both experts as well as non-experts focused on quantum computing. Based on these findings, we concur with Roberson *et al*'s (2021) recommendation to experts to pay attention to a wider range of quantum 2.0 technologies.

Of the three quantum 2.0 technologies identified, quantum sensors were mentioned the least, even though specific quantum sensors could very well have societal implications before quantum computing (European Quantum Flagship 2020). The complaint by one of the quantum physicists interviewed by Roberson *et al* (2021) who said that there is a focus on quantum computing is consistent with our results.

6. Conclusion

We performed a content analysis on 501 TEDx talks that cover quantum science and technology. Findings indicate that only some of the potential issues related to the popular communication of quantum science and technology are common in TEDx talks, and that there are differences in experts' and non-experts' references to these issues. For instance, the spooky and enigmatic frame is apparent but not dominant, and an explanation of underlying quantum concepts is relatively often accompanied by the mention of quantum 2.0 technology. This implies that some of the concerns among researchers about potential issues that may hinder public engagement with quantum technology are not as prevalent in popular communication as assumed; at least not in TEDx talks.

It should be noted that the Global South was underrepresented in our study: almost 80% of the TEDx talks in our dataset are from Europe and North America. To gain a more global perspective, additional research should analyse TEDx talks in languages other than English. Moreover, additional research is needed to make empirically based claims about both the choices speakers make when communicating about quantum science and technology and the effects of different frames on general audiences. In this undertaking, such future studies should also take the origins of the actual publics that the TEDx talks reach into consideration. Future research should reveal whether the patterns we have seen in TEDx talks also occur in other forms of popular communication about quantum science and technology, such as popular science books, documentaries and games. The findings in this study can serve as a starting point for such studies.

Finally, we already encourage quantum experts to reflect on these findings, especially in giving a more balanced view on the impact of quantum technology when talking to a broader audience, to enhance an open societal discussion on the future impact of quantum technology.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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