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The societal implications of quantum technologies through the lens of quantum humanities illustrated by the case of quantum computing

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The societal implications of quantum technologies through the lens of quantum humanities illustrated by the case of quantum computing

Abstract

Quantum computing is a rapidly developing field in the second wave of quantum development, with the potential to revolutionise a wide range of industries and fields of study. As the capabilities of quantum computers continue to advance, they have the potential to significantly impact society and the way we live, work, and think. Whether the applications by the use of quantum computing have a significant impact must be further analysed. This makes it important for scholars from a variety of disciplines to come together and consider the possible implications of these technologies. To do this analysis we use the Quantum Humanities research programme and limit the research scope to quantum computing. The research programme is explained in a first step and what it offers for the elaboration of implications that may arise. Afterwards, selected applications are shown and their societal implications highlighted. In this way, we present the research programme of Quantum Humanities and subject it to a first attempt to work with the research programme. As Quantum Humanities is still in its early stages, the precise boundaries of the research program are actively being explored, while presenting a first endeavour on quantum computing and its implications.

1. Introduction

Quantum innovations in general, have emerged as an increasingly vital aspect of our reality, according to certain specialists. Therefore we will elaborate on this by analysing the possible implications of quantum computing in different areas of human knowledge and reflect upon them.

In the field of science and technology studies, there are a number of approaches that attempt to analyse the relationship between technology and society. Socio-technical integration research, for example, focuses on the integration of research and innovation with the contextual awareness of practitioners (Fisher, Schuurbiers 2013). In contrast, midstream modulation as an approach pursues a reflection of the researchers in the laboratories, which is called second-order reflection. It is about exploring science and its implications through the researchers themselves. However, the potential impact (implications) of quantum technologies on society through the exploration of their applications - and thus their implications - is currently represented by one approach in particular.

We use the Quantum Humanities Approach, which advocates for a holistic research program that considers the reciprocal relationship between quantum technologies and various societal bodies and human interactions (Bötticher et.al 2023). By emphasising the humanities as central to the exploration of the technical agenda of quantum innovation it offers a valuable perspective that goes beyond the limitations of a predominantly technological focus (Janda 2014). Firstly, this offers a more comprehensive, reflexive, and inclusive approach by multiple different foundational stances, as it challenges the assumption of quantum technologies' inevitable revolution and questions the authority and historical context of such claims within existing societal narratives and power structures (Bötticher et.al 2023). Quantum Humanities works with an image of a technological shell originally developed by Acatech, that can take up the multiperspective and map it on a large scale, so that the various possible nodes and connections are shown neutrally, in which changes in a network society can emerge, in which power relations can be critically worked through (Castells 2000). The overview does not insist on completeness in the sense that new nodes and new connections could not emerge with technology, through technology or through the technologised society -, it therefore does not work with predefined fields (Rammert 1997).

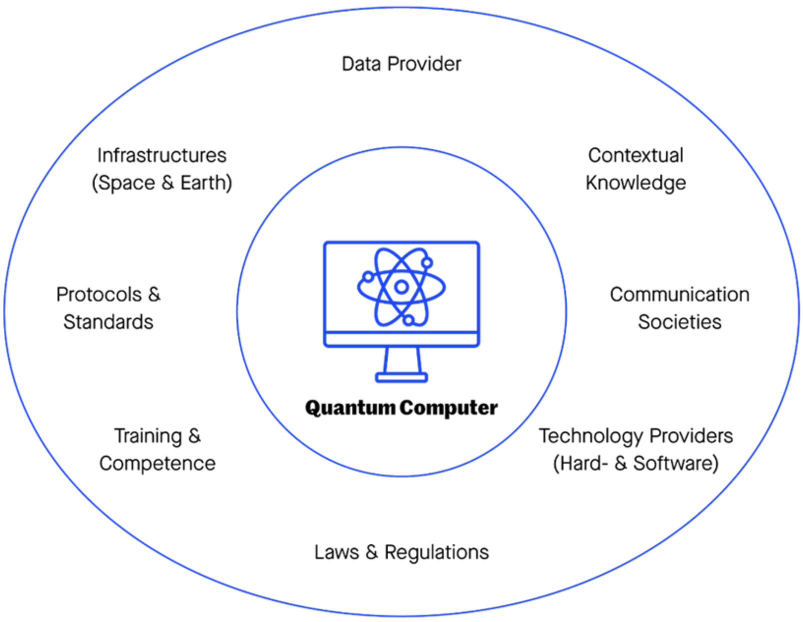

Fig. 1. Quantum Humanities. Design: Dark Horse GmbH. Original Design: Organisational shell using the example of PC. In: Intelligente Objekte. Acatech diskutiert. German Academy of Science and Engineering 2009.

Quantum Humanities (QH) aims to provide a more comprehensive understanding of the potential consequences of these possible changes by examining the applications of quantum technologies on society and considering the implications of these technologies and reflecting upon them. QH thus follows the approach of Rammert's pragmatic sociology of technology.

This article will apply the framework of Quantum Humanities to do a critical analysis of the possible societal consequences of the implementation of quantum computing in different fields. But the core challenges here discussed for quantum computing enable insights from other fields to be applied to quantum metrology, sensing, and communication, due to their similar nature.

The following analysis is structured according to the core elements of quantum humanities with a focus on quantum computing applications and its implications. These applications are centred around the topics: 1.Security, 2.Energy, 3.High-Performance Computing 4.Transportation, 5.Health, 6.Natural Language Processing. After an analysis of the applications, the possible innovations are examined for their significance for the humanities and social sciences. In a final step, we would like to at least briefly outline the theoretical Implications that accompany our findings and make them available for further discussion.

2. The Research Program of Quantum Humanities

2.1 Defining Quantum Humanities

Quantum Humanities as a concept and term originally grew from the field of digital humanities due to research applications. But in contrast to Digital Humanities, Quantum Humanities has a greater process oriented focus on the development, reflection and implications of quantum technology: Computations on quantum computers are significantly different, with questions and answers adapting to the nature of quantum algorithms (probability), distinguishing Quantum Humanities from Digital Humanities by a technical standard (Feynman, R. P. 1982). The difference lies in the object itself: a quantum computer, unlike a universal computer, employs quantum mechanics for calculations. This distinction justifies why Quantum Humanities are not merely Digital Humanities. Notably, computations on a quantum computer alter two essential functions. Firstly, the questions must adapt to the algorithm, posing a non-trivial challenge when working with atoms, whose calculations find a physical equivalent for our inquiries. Secondly, the answers change due to the probabilistic nature of quantum algorithms, leading to pattern recognition through constant iterations (Barzen, J., Leymann, F., Falkenthal, M.,et al 2021, Barzen, J. 2022). Yet, Quantum Humanities is an interdisciplinary field that brings together scholars from the humanities and the arts, to explore the intersection between quantum technology and topics within the humanities (Barzen, J. 2018, Coecke, B., 2022). It contains various research fields (see below) that have been defined, and which, in terms of form, go qualitatively beyond what the Digital Humanities offers.

The possible consequences of this novel computing paradigm on our humanities-related domains, remain a subject of contention. To designate these potential transformations, early endeavours have introduced the concept of Quantum Humanities, drawing inspiration from the Digital Humanities, yet mainly focussing on hermeneutics (Barzen, J.: Leymann, F. 2019, Barzen, J. 2022). We distinguish the conceptual toolkit used here from this concept, as focusing on hermeneutics hardly does justice to the broad field of the humanities, their theories and methods, and choose an approach that presents a research field that we can use to describe applications and reflect on their possible implications and possible reflections.

Quantum Humanities is defined as "a research programme based on the development of the second quantum wave that encompasses theories, concepts and reflections that may be based on quantum mechanics, but whose research focus is on the developments related to the second quantum wave, and the society that emerges with it. Therefore, Quantum Humanities includes those humanities researchers that utilise quantum technology among their methodological instruments or reflect on their usage, and those that examine the cultural-social implications related to devices of the second quantum wave, or their development." Bötticher, Hernandez, Bravo et al 2023)

Within this definition QH defines four main fields of interest for quantum humanities. These fields of research are comprised of: i) application of quantum computing for addressing questions from humanities and social science research or research that can have an impact on implications or reflections; (ii) reflection of the methods, techniques, and impact; and (iii) societal, cultural and social implications that are expected as a potential for upheaval; and (iv) looking at how development processes and ecology are structured and how developments will be driven forward with what emphasis. This results in a hybrid field of research, located between humanities and quantum computing.

2.2 A holistic qualitative research program

This article shall focus on the implications subfield exploring the implications of quantum computing applications. Quantum engineering and its various fields, such as quantum sensing, are again so comprehensive that the topic could not be covered.[1] The areas of applications were selected to cover different industries and sectors that have already seen change with quantum computing. Quantum computing has the potential to solve complex societal problems, such as optimising supply chains, developing new medicines or solving environmental problems. This shows the

[1] Specific aspects unique to individual quantum technology domains exist, yet they share fundamental issues and challenges akin to quantum technologies in general. Insights from diverse fields can thus be applied to quantum metrology, sensing, and communication. These disciplines all ground themselves in quantum mechanics principles and employ quantum phenomena for secure communication tasks. Quantum computing, like these disciplines, derives its foundation from these quantum mechanical principles, establishing a common basis. Analogous to Digital Humanities, where various digital devices fall under its purview, differences in quantum technologies emerge in their implications, applications, reflections, and developments, rather than in their overarching framework. To streamline research efforts, establishing a unified framework is advisable, aligning with parallel initiatives such as European standards development in quantum technologies (van Deventer et al., 2022, EPJ Quantum Technology, 9, 33).

versatility and potential of quantum computing applications and how they could be used in different fields - yet their consequences need to be explored. The selection of these research areas reflects an interdisciplinary approach in which quantum computing serves as an intersection between scientific and humanistic disciplines. Each of the selected research areas presents unique challenges and opportunities that stimulate discussion on how this technology might influence research and practice in the humanities, without contributing to the creation of a Western-centred technological imaginary.

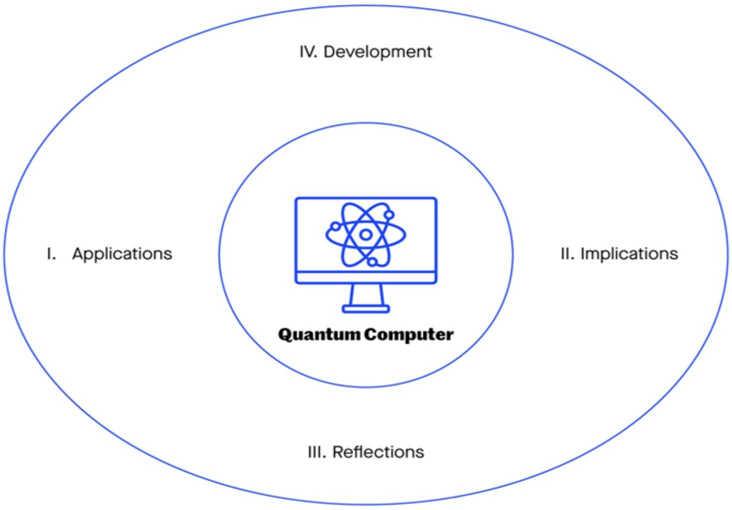

Fig. 2: Core elements of Quantum Humanities. Bötticher et al 2023. Design: Dark Horse GmbH.

3. Fields of interest

The applications we aim to discuss originate from diverse fields, not limited to the humanities. While they were not originally designed with a focus on advancing the humanities through quantum computing, they have the potential for transformative impact. The selection of these cases was not contingent on their immediate relevance to the humanities; rather, it was driven by the broader question of whether quantum computing could induce significant changes within their respective domains.

The utilisation of quantum computing has seen significant advancements across various domains, experts claim (De Touzalin, A. et al 2016). Our primary focus lies in exploring applications that offer a broader perspective on the associated implications. This approach differs from that of Miranda (2022). We abstain from delving into the intricacies of quantum gate calculations or the establishment of programming loops. Such technical specifics are more aptly addressed in dedicated research investigations rather than in a generalised overview as presented here. Our aim is to provide initial insights into the essence of quantum technology exemplified on QC, within the context of theories in the realms of humanities. It should be noted, however, that our capacity to encompass all innovations and developments is limited.

Nevertheless, our exposition here intends to offer a preliminary glimpse into potential research topics and the application of novel techniques and tools within our respective scientific disciplines.

In terms of structure, within each field we will state the potential changes that quantum could cause and then proceed to discuss the transformations. These transformations will be described among the lines of societal, cultural and social implications. The use of quantum computers has important implications for the realm of societal organisation e.g. vast infrastructure must be secured and replaced to be quantum safe. Hence, we discuss the implications of quantum computing research. In this section we link the applications and the associated transformation processes back to the scientific task and briefly outline the ways in which the humanities and social sciences might be affected. Here, however, it must be said restrictively that the effects on the specific sciences have not yet been systematically considered, and we can only give broad strokes of thought here (Vermaas 2017). We are so far at the beginning that we first have to sound out which innovations could have any significance at all - in order to then be considered systematically for the individual humanities and social science strands in a second step. Of course, this task is far too complex here - already using the example of political science, we can briefly outline how specialised the individual sciences are: In addition to the study of war and violence (and their termination), there are bureaucratic processes that are so highly differentiated that, for example, pension issues have to be considered separately from questions about long-term care insurance or social welfare. Nevertheless, all these specialisations are united by the fact that they depend on the processing of huge amounts of complex data (while changes can occur quickly) in order to be able to make any statements at all.

3.1 Security

3.1.1 Application

Quantum security (Harlow/Hayden 2013) is a central topic of security policy, which has increasingly addressed the concept of digital sovereignty in the context of (post)digitization (Capgemini 2022). In the field of technology, there is a desire for quantum sovereignty in hardware and software on the one hand, and an urgent need for security to safeguard central societal systems such as the military, the intelligence service, critical infrastructure like transport systems on the other (Wimmer/Moraes 2022).

Modern encryption technology is based on an asymmetry: it is very fast to multiply two prime numbers, but it takes an incogitable long time to decompose a very large whole number into its prime components (Bennett/Brassard 1984). The Shor algorithm (Shor 1997) to factorise whole numbers is used for prime number decomposition and is a quantum algorithm. RSA encryption (Rivest–Shamir–Adleman public-key cryptosystem) is based on this. For today's systems, RSA encryption is the gold standard, but previous work shows that the RSA standard, which is used to encrypt sensitive areas of communications, will not be able to withstand quantum computing (Gidney/Ekerå 2021). This is why the quantum computer poses a risk to the digital systems developed today (Vlachou/Rodriguez/Mateus/Paunković 2015). Therefore, for questions of security, the standardisation of quantum computer-resistant alternatives in particular is at the forefront of activities and migrational activities are the main activities of governments (NSA News 2020).

Risk analysis against quantum computers distinguishes different processes. These include (among others) the time in which existing systems must securely protect data stores or the time to migrate existing systems into a post-digital age (Mosca/Piani 2019). For migration purposes (among others) a distinction is made between post-quantum cryptography and quantum cryptography (BSI 2022). In 2016 NIST proposed a competition (NIST 2022) to develop quantum-safe cryptography and was looking for proposals for algorithms to proceed with migration processes for existing systems (Computer Security Resource Center 2022) or quantum cryptography, there is more effort is needed, as great technological infrastructural systems (like optical fibre deployment and satellite networks) need to be built (Chen/Zhang/Chen 2021) and today, we witness a geopolitically motivated race for the establishment of quantum supremacy, that is coined (among other) with the concept of crypto agility (Johnson et al 2019; Giles 2019). Another important development for security studies might be the transfer of social network monitoring analysis to quantum computing for terrorism detection purposes (Zahedinejad/Crawford/Adolphs 2019) or other community monitoring applications relevant to security (Bisconti/Corallo/De Maggio et al 2009). Since a very large amount of data often has to be collected here in real-time, and since this data must be determined as precisely as possible - also to protect civil rights - it could be an immense improvement to apply quantum computing to this type of use (Grover 1996).

3.2 implication

In terms of development and use, the quantum computer and its capability are woven into a web of (international) political relationships already set by digitization (Paul 2007), and the post-digital technology is thus given a specific political meaning (de Wolf 2017) and is dependent on institutions for its use and utility. Within the realm of security, the quantum computer is understood as a technology that poses a systemic risk to economies (Mosca/Piani 2019), and could trigger catastrophic cascading effects if used for conflict-oriented political purposes (Ekert/Renner 2014), and an urgent need for action on polycentric regulation (World Economic Forum n.d.) is indicated. This is especially important regarding the topic of blind computing, that becomes something like the new TOR in a much more fundamental sense, if you like (of course this analogy has central weakness) (Broadbent/Fitzsimoni/Kashefi 2009). In addition to being a gamechanger on the international geopolitical stage, quantum computing is a gamechanger for issues related to the security and stability of entire systems or their institutions and infrastructures. At the same time, the application of quantum computing to specific security contexts, such as the detection of terrorist entities in real time or the analysis of security-related data in disaster management, can become an important new tool for threat analysis. Yet could also become a threat provoking new security measures (Johnson et al 2019). In addition to these more traditional security applications for law enforcement and intelligence or the military, there are important advances coming for disaster response that should not be overlooked. These include the management of floods and also other issues related to global warming that pose a challenge to disaster management systems - not least new weather models (Oriel, A. 2020). What is largely missing in the literature is the protection of private communication and data storage and its connection to democracy and civil rights as outlined by jurisprudence.

3.1.3 Reflection

For security production in cyberspace, fundamental changes will occur in the dimension of the threat situation (from individual companies to the entire economy) and the protection actions (post-quantum cryptography and quantum cryptography) as well as the analysis options for assessing threat situations. This makes security research a lot more technical - quantum technical. In the next few years, security researchers will no longer be able to avoid using quantum computers or including them as a central factor in their calculations and analyses. This also applies in particular to the security-providing authorities. New questions will arise for security research that relate to the emergence of probabilistic algorithms as a side effect to the advantages that arise from the quantum computer in terms of speed and accuracy. Security research must be able to assess the hazards that arise from quantum computing, but in the future it will also need to draw on the technology as a tool to focus on those developments that previously required too much computing power, such as calculating the superposition of sentiments in the population toward actions and fault lines, or analysing emergent hazards just to name an example (NEASQ a, n.d.). Yet quantum security issues will also become a scope for research in jurisprudence.

3.2 Energy

3.2.1 Application

There are several ongoing and predicted application areas of quantum computers for the energy sector, such as materials research on batteries (Mitsubishi 2019) and fuel cells (DLR 2021), optimising power (Exxon Mobil 2019), and energy grids (Ajagekar/You 2019), simulation and reliability analyses (Giani et al 2021) and expanding reservoir production(Parney/Garcia/Womack 2019). Furthermore, there are expectations of quantum computers vastly outperforming supercomputers when it comes to energy efficiency (Villalonga 2020,) and studies on roughly estimating when this might happen are being conducted (Jaschke/Montangero 2022). This will be very important for those experts, studying climate change and transformational processes (Berger et al 2020). Companies like Mitsubishi Chemical, ExxonMobil, Gazprom Neft, and BP have been actively experimenting with one or more of these application areas. Therefore, in the energy sector, the use of quantum computing has the potential to be widely adopted if advantages over classical supercomputers can be shown.

3.2.2 implication

One relevant risk posed by quantum computers is enabling cyber attacks, rendering previously safe systems vulnerable. There are of course efforts being undertaken to prevent such attacks via transitioning these systems to either post-quantum cryptography algorithms or to quantum cryptography schemes. However, it is a race between quantum computers being developed and the critical cyber infrastructure being upgraded. Considering the timeline of the quantum threat (Mosca/Piani 2019), there is a chance that certain critical infrastructure, especially in regions with less available resources to spend on upgrading their existing systems, might be vulnerable to these kinds of attacks. Therefore, working on prevention and mitigation scenarios that don't rely on overhauling entire infrastructures is needed. The question of unequal access to quantum technology is pressing and will be a question to be answered in the humanities.

3.2.3 Reflection

Energy is a critical sector with multiple relevant dimensions for humanities. It is intrinsically connected to the utilities that allow everyday operations of any society. Energy security issues, such as vulnerabilities in critical infrastructure or access to regional or global energy markets, are important on national levels. Sustainability and cost of access to energy resources is an essential requirement for any industry. Furthermore, processes such as energy transition (Energiewende) require development of novel and innovative approaches compared to the established rules of the public energy infrastructure management strategies and industries. Considering all these, the risks and opportunities that quantum computers might present should be assessed and addressed. There will be plenty of room for research to be undertaken by humanities and social sciences.

3.3 High-Performance Computing (HPC)

3.3.1 Application

High-performance computing is a major area of impact for quantum computing due to the nature of HPC itself and to the possible applications that could leverage quantum computing for radical improvements, such as green aircraft design, flood prediction, and realistic models of protein interactions within human bodies (Möller/Vuik 2017. Perini 2021)."

Although the use of isolated quantum computers continues to be an area of research and progress, many expect that their integration to the High performance computing world will be in the form of Quantum processing units (QPU). The concept of HPC centres with quantum processing units (QPU) has been in circulation since at least 2017 (Britt/Mohiyaddin 2017). This train of thought relies on two main arguments: First, that quantum computers (or QPUs) themselves are expected to require considerable computational support systems, especially for error correction which is necessary for fault-tolerant quantum computation. These requirements make an HPC data centre a suitable environment for a quantum computer due to its pre existing infrastructure.

Second, it is a long-known fact that quantum computers only allow speed-ups for algorithms that can utilise certain mathematical structures. A very obvious example is multiplication. The multiplication process itself does not get any speed-up from quantum computers, but prime factorization (which is practically the reverse of multiplication) gets an exponential speed-up, hence enabling Shor's algorithm. This effectively creates two subsets of problems, ones that make sense to use quantum computers for and the ones that don't. However, complex algorithms with commercial value usually do not fit neatly into these subsets. Certain parts of the algorithms can get substantial speed-ups from quantum computers while the rest don't. In such cases, a hybrid approach that utilises different processing units for different purposes is usually adopted. A similar example of this is the division of labour between graphics processing units (GPUs), central processing units (CPUs), and recently tensor processing units (TPUs). Therefore, adding QPUs to this set of processing units seems like a logical next step for HPC data centres.

In addition to on-premise integration of quantum computers, there are already several cloud service providers experimenting with integrating quantum devices into their systems. IBM Quantum, Amazon Bracket, Microsoft Azure, and D-Wave's Hybrid Solvers are some early examples. This is expected to effectively equip HPC centres that employ QPUs with enhanced capabilities which in return will enable them to outperform their fully classical counterparts.

However, the current technology readiness levels of the quantum devices, sometimes referred to as QTRLs, developed by Michielsen & Lippert (2022), are not high enough for integration to occur throughout the entire HPC industry. Such a migration doesn't make sense for competitive purposes due that many applications remain theoretical or exaggerated(Singh Jattana 2020).

3.3.2 implication

The integration of quantum computing to the existing workflows of classical high-performance computing presents significant opportunities for applications in other fields that use HPC for their work such as chemistry modelling and defence industry. But HPC resources are also tools beyond their actual operational uses.

HPC centres and their raw computing power are frequently used as a show of force, where countries and companies demonstrate their computational capabilities. A good example of this is the TOP500 (Top 500 n.d.) list that ranks and details the 500 most powerful non-distributed computer systems in the world. A reflection of this can be seen in the race for quantum computers as well. In 2019 Google announced it has reached 'quantum supremacy' (Arute/Arya/Babush 2019), igniting a flurry of interest on the impact of quantum computing for technological supremacy discussions at the global socio political level. The following year a group of researchers at USTC in China announced they also achieved quantum computational advantage. And although there have been calls from researchers to keep quantum computing global and open (Biamonte/Dorozhkin/ Zacharov 2019), recent developments (such as the invasion of Ukraine) makes it practically not possible for countries to consider quantum computers as mere tools of scientific research.

3.3.3 Reflection

HPC resources are actively used in all fields of STEM research, however, they are costly both in terms of financial resources and carbon footprint (Allen 2022/Greene-Diniz 2022). Furthermore, supercomputers were not always the go-to tools of researchers and companies. Considerable effort went into making scientific computing a powerful tool and enabler of research. Now, with the oncoming of the quantum computing era, new opportunities arise for scientific computing. The promise of fully realised large scale fault-tolerant quantum computers that work hand in hand with classical supercomputers is to reduce both of these costs, and even further enable researchers to do novel research. This is, of course, not a straightforward step where research groups just re-write some parts of their simulations to make them run on these new devices. As mentioned above, quantum computers provide speed-ups for only a subset of algorithms, and even in this subset there are rank orders between the amount of speed-up quantum computing can provide. Therefore, much research and effort is needed to explore where a quantum assisted supercomputer can benefit research greatly and where it can't.

3.4 Transportation

3.4.1 Application

There have been studies in adapting quantum computers for advantage in four of the major areas of transportation; airlines (IBM Institute for Business Value 2022a), maritime logistics (IBM Institute for Business Value 2022a), railroads (Saran 2021), and the automotive industry (BMW Group Challenge 2022). Companies have been experimenting with quantum-enhanced solutions. Live testing for public transportation was implemented in 2019 with a collaboration between Volkswagen AG and the city of Lisbon to provide quantum computing-based traffic optimization (Yarkoni et al 2020).

Proposals in various fields are based on three key assumptions about quantum computing: Quantum computers are superior for optimisation, in particular through Quadratic Unconstrained Binary Optimisation (QUBO) algorithms. The emergence of Quantum Approximate Optimization Algorithms (QAOA) in the mid-2010s (Farhi, Goldstone, Gutmann, 2014) strengthened this assumption and established quantum computers as valuable tools for optimization tasks. Due to the exponential nature of Hilbert space, large-scale quantum computers are seen as promising tools for big data analytics. Extensive research over the past decade (Wiebe, Braun, Lloyd, 2012) has explored the efficient adaptation of data to quantum devices. However, the practical utility and feasibility with current smaller devices remains a subject of investigation. It has been suggested that there is an overlap between industrially relevant transport problems and mathematical structures that benefit from the exponential speedup of quantum computers. In particular, groups in the US, China and Canada (Arute, Arya, Babbush, 2019; Madsen, Laudenbach, Askarani, 2022; Zong, Wang, Deng, 2020) have demonstrated the significant speed-up of specific tasks using quantum computing devices. In the transport industry, the focus is now on identifying relevant problems that can effectively exploit these exponential speedups.

Quantum computers are suited for optimization purposes, can handle big data effectively, and can provide exponential speed-ups, making these devices really intriguing for many applications related to transportation. Traffic data, abundant and real-time, demands substantial computational power for optimization. A swift quantum algorithm, though potentially less precise than classical counterparts, could rapidly adapt to changing conditions, fostering broad adoption in these industries.

3.4.2 implication

Quantum computing has societal potential in the transport sector, particularly in autonomous vehicles and traffic management systems in the short to medium term. While initially perceived as a purely technical domain, this transition period offers opportunities with significant social implications, potentially reshaping public spaces. With the global adoption of concepts such as car-free city centres, the optimisation of limited resources for public transport is becoming increasingly important. Cities often face disruptions in their public transport and traffic flow. Quantum computers, with their potential to significantly reduce simulation times, could enable city authorities to respond and reallocate transport resources in real time. However, this will require staff retraining and significant infrastructure development. There are many other applications of quantum computing in transport. Prioritisation of concerns and parameters becomes critical as real-time optimisation capabilities expand. Choices may arise between prioritising traffic noise over commuting time, or between different elements within the transport system, as exemplified by Germany's recent prioritisation of freight trains carrying coal over passenger trains (Dezem, 2022). Quantum computers offer an opportunity for increased public participation in transport issues, which will require debates on the equitable allocation of resources in logistics and mobility systems.

3.4.3 Reflection

Quantum computing is particularly relevant to the analysis of public transport resources and infrastructure, and the study of complex transport systems. With the advancement of autonomous vehicles and smart city technologies, the management and allocation of public resources is becoming a data analysis challenge. By creating digital city twins and simulated environments, mobility researchers can explore numerous scenarios without actual implementation. Mobility systems are inherently complex. Although high performance computing (HPC) has enabled studies in this area (Fraunhofer, 2022), the increasing complexity at larger scales makes comprehensive simulations computationally prohibitive, necessitating simplifications and reductions in current models. With the development of large-scale, fault-tolerant quantum computers, certain aspects of this complexity could be offloaded onto quantum processing units (QPUs) within HPC systems. This could enable more detailed simulations, providing deeper insights into existing and potential mobility and transport systems.

3.5 Life Sciences / Health

3.5.1 Application

A report published by the IBM Institute for Business Value in 2020 titled "Exploring quantum computing use cases for healthcare" puts forward three use cases for quantum computers in the healthcare industry; (i) diagnostic assistance, (ii) precision medicine, and (iii) pricing. An early example of how quantum algorithms might be used for diagnostic assistance is a collaboration (Case Western Reserve University n.d.) between Microsoft and Case Western Reserve University in 2018, where they reported 30% more precise findings, and up to three times faster scans for Magnetic Resonance Fingerprinting (MRF) using quantum-inspired algorithms that work on existing machines.

Similarly, approaches like quantum network medicine (Maniscalco/Borrelli/Cavalcanti 2022) aim to explore efficient search mechanisms for new drugs and new drug combinations using quantum algorithms (Polarisqb 2021). Research on the molecular drug development that might later be utilised for personalised medicine has been a selling point to get pharmaceutical companies involved in quantum computing. However, current quantum computers are able to effectively simulate molecules such as H2O at best (Eddins/Motta/Gujarati 2022), while pharmaceutically relevant molecules and interactions of them with other types of molecules require much further capabilities than what is available today.

The concept of quantum risk analysis (Woerner/Egger 2019) has been around for some time, and there have been several applications of quantum computers for finance (Orùs/Mugel/Lizaso 2019). Therefore, adapting these applications to risk assessment for insurance purposes and pricing of health insurance is another potential application of quantum computers in the healthcare industry. Changes in health care and the impact of quantum computing on public health systems is not foreseeable today. However, the ability to develop medicine tailored to the patient or to better detect and target tumour cells is a potentially system-changing opportunity for the increasingly rampant cancer epidemic in the developed world (Abbott 2021;

Solenov et al 2018; Fraunhofer 2021). This gives rise to potentially important tasks for the sociology of medicine or questions of the sociology of technology, but also for political science, law and ethics.

3.5.2 Implication

Health is a fundamental part of human life and healthcare systems have been an essential element of any modern functioning society. With the advent of digitalization and artificial intelligence, these systems are expected to undergo severe changes. For example, in recent years there have been an increasing number of studies on whether A.I. systems can outperform doctors on diagnostics, which they sometimes do (McKinney/Sieniek/Godbole 2020). However, such discussions were held in 1970s and 1980s with the ‘expert systems’ approach to A.I. as well, and after much research, those models failed to deliver the expected performance. This time around, A.I. researchers and cloud computing companies (such as IBM with their Watson Health) are more confident in their models. Simultaneously, all these companies are also working on developing quantum computers. This might result in several societally relevant outcomes.

First, quantum computers, especially the ones that rely on superconducting qubits, are centrally operated machines. This means, they are operated at dedicated data centres (as discussed in the HPC subsection). As health data and diagnostics become integrated into these cloud computing based business models, sharing of data with these companies needs to become an industry norm. Although there are certain proposals, like blind computing (Broadbent/Fitzsimoni/Kashefi 2009) to circumvent this necessity, they require additional steps and constraints to be introduced, effectively raising both the cost and the level of expertise required to implement quantum enabled diagnostics systems. As measures such as GDPR and sectoral regulations for data management (especially in finance and health) are being developed, in parallel, there are technical systems being developed that require annulment of the protections brought forth by these regulations. Similar to the Chatcontrol (European Commission 2022) discussions, the proper amount of exceptions in data protection for access to automatized healthcare services might become a societally relevant issue as health applications that run on quantum computers gets further developed.

Second, as healthcare systems further get integrated with the computational way of providing services, there will be a need for new linkages to be formed and further skills to be blended into the existing networks. For example, ongoing discussions in the field of algorithmic decision-making in healthcare (Grote/Berens 2020) will only be exacerbated as methods developed for fair machine learning, such as explainability, can’t be used for quantum fair machine learning models (Elijah Perrier 2021). New methods of integrating non-medical technical expertise into healthcare systems, how to assess the fairness of ongoing operations, and how to effectively distribute resources for optimal outcomes are topics for social debate where the existence of quantum computers might have some role in.

3.5.3 Reflection

Health issues and medical technologies have been gaining popularity even before the emergence of COVID-19. There are proposals like the European Health Data Space (European Commission/Directorate Health Data Space n.d.) that is expected to generate huge amounts of data, which can enable research to identify the relations between socially relevant factors like education and socioeconomic status, and medical conditions(Emani et al . 2021) Quantum computers and quantum enabled applications can play an important role here, as they are expected to be used for: (i) diagnostic assistance, (ii) precision medicine, and (iii) pricing.

First, any researcher studying either the network of socio-technical relationships or the consequences of implementing these technologies would highly benefit from having a general understanding of what quantum computers can and can't do. Second, utilising quantum computers for performing scientific studies in humanities requires a level of expertise that, since no packaged software with GUI like VOSViewer or SPSS is expected to appear during the emerging years of quantum computing. There are many training programs and bootcamps on introduction to quantum programming, but the tools available for research using quantum computers don't exist and a particular set of expertise is required to develop those, especially for the tools that deal with sensitive data such as health and medical records.

3.6 Natural Language Processing

3.6.1 Application

Natural Language Processing (NLP) is a method that is relevant for many humanities and social science research, since it is used as a quantitative technique for the investigation of semantic networks, sentiment analysis, and other techniques for the investigation of social or humanistic questions. This makes NLP useful for computational linguistics, quantitative law, and relations analysis in the different social science fields. The central problem for the use and expansion of these methods is that they usually require large amounts of data and complex processes that are lengthy to calculate with the existing standards of computing. For some of these problems the research community has started exploring Quantum natural language processing (QNLP) (Villalpando et al 2021).

QNLP is a concept first appearing in the literature in 2016 (Zeng & Coecke) and whose first conference was organised in 2019. QNLP utilises quantum algorithms for quantum data encoding to facilitate the current research being done in natural language processing. This research field is slowly developing due to its emerging status but has produced theoretical works showing quadratic speedups for text classification tasks(Abbaszade et al 2021). This theoretical speedups do depend on the realisation of fault-tolerant quantum computing. Other work in QNLP has occurred in machine translation, sentiment analysis, relationship extraction, word sense disambiguation and automatic summary generation (NEASQ b. n.d.).

In addition there exists introductory avenues for QNLP work such as lambeq, a Python library (Kartsaklis, et al., 2021) accessible via Github (Cambridge Quantum's QNLP team 2021).One interesting relation of QNLP is with music composition, which is also highlighted in one of multiple conferences on the topic titled "1st International Symposium on Quantum Computing and Musical Creativity" organised in 2021 (Interdisciplinary Centre for Computer Music Research 2021).

3.6.2 implication

Natural Language Processing, that uses sentences as networks, is already widely used in the digital industry, in security and science (especially linguistics). Whether for advertising or the use by authorities (police, intelligence, military) or scientific usage such as surveys and conflict research - data analytics and its network applications today are mainly based on the idea that sentences are networks and their respective tools. The use of the quantum computer as a tool will help to undertake analysis at faster speeds and for heterogeneous data analysis in conjunction(Coecke/Genovese/Lewis 2018). As more precise results are achieved with quantum computers, a new field of legal science could emerge here for example (of course, only if the relevant algorithms are developed) that makes use of modern technology (Floridi/Sanders 2001). But there are no use cases today that we know of, though there are some practical works presented connected with QNLP (Rudolph/Bashige/Touissant/Katabarwa 2022).

3.6.3 Reflection

In particular, the humanities and social sciences depend on the analysis of communication, on the analysis of natural language. There are no contracts, no political trades or laws without language and every discussion, every historical fact is transmitted through language. Therefore, it could be that this field holds one of the most important transformations for our sciences. There are countless examples that could be given to show the potential impact on our sciences that the use of technology will have. These include all the tasks of systematisation, such as the construction of repositories or schema and network developments, but also the development of systematics based on existing data sets. QNLP is relevant for all sciences that rely on language analysis, from history, law, political science, sociology, and religious studies to criminology and other "minor" specialties. QNLP changes the way of NLP as it "treats language as a quantum process and interprets sentences as circuits by using categorical quantum mechanics" (Garcia Molina 2021). But even though progress has been made, it seems that QNLP applications are still waiting to be developed for larger scale research projects. This hesitancy in development may also be a symptom of increased attention in classical Large Language Models and other related advances in machine learning for NLP.

4. Assessing a Research Program

Quantum humanities, an interdisciplinary field encompassing quantum computing's intersection with the humanities, delves into the societal implications of quantum technologies. Notably, quantum computing applications poised to significantly impact the humanities and social sciences include security, energy, high-performance computing, transportation, healthcare, and natural language processing. Quantum security, for instance, harnesses quantum algorithms to bolster digital systems' security. In the energy sector, it holds potential for optimising renewable energy system design and chemical reaction efficiency (friis et al 2018). Transportation can benefit from quantum computing in logistics and supply chain management. Healthcare may utilise quantum computing for data analysis and personalised treatment. Natural language processing could experience enhanced accuracy and efficiency.

These quantum computing advancements transform our daily lives and pose profound questions for the humanities and social sciences. The impact of these applications on societal transformation becomes evident as quantum technology matures. Thus, exploring applications that may not immediately appear relevant to the humanities or social sciences is prudent, as they hold disruptive potential. While some of these scenarios remain futuristic, delving into their development and societal context is both timely and intriguing.

Further areas within Quantum Humanities Research warrant exploration, particularly as we enter a phase of scrutinising developments and their societal implications within the quantum realm. This critical examination is essential to understanding the conditions that drive quantum technological advancements.

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