ABSTRACT

Title of Dissertation: THREE ESSAYS ON QUANTUM TECHNOLOGY APPLICATIONS

Amanda Stein, Doctor of Philosophy, 2024

Dissertation directed by: Dr. Ping Wang, College of Information, University of Maryland

This dissertation examines quantum technology applications in three essays. Essay 1 portrays how companies are beginning to innovate with quantum computing in four case studies. The cases employ and enrich the Diffusion of Innovations theory as a conceptual framework for quantum computing innovation adoption and management. Essay 2 follows the evolution of quantum sensing with two cases of how organizations currently use the technology and plan to use it in the future. These cases illustrate how people and organizations use their discourse to develop an organizing vision for adopting and applying quantum sensing. Essay 3 focuses on the relationships between quantum technology and artificial intelligence through a literature review using grounded theory. The essay provides examples on how the two technologies interact and recommendations to stakeholders for future advancement. In summary, while the science and engineering side of quantum technologies is still developing, understanding how quantum technologies are and will be applied can help inform business and public policies.

THREE ESSAYS ON QUANTUM TECHNOLOGIES APPLICATIONS

by

Amanda Stein

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2024

Advisory Committee:
Associate Professor Ping Wang, Chair
Professor Wayne Lutters
Professor Christopher Monroe
Professor Steve Rolston, Dean's Representative
Professor Mega Subramaniam

Dedication

To my family, friends and coworkers, who have had to listen to me talk about this for almost five years (or more)…

Acknowledgments

I am so incredibly grateful for the opportunity to pursue a Ph.D. at the College of Information (iSchool) at the University of Maryland, College Park. I am incredibly thankful and appreciative to all of those who have supported me on this journey, from the faculty and staff of the iSchool to my friends, family, and coworkers. I was able to do this degree thanks to their guidance, expertise, advice, and encouragement. While not easy, this process has been exciting and rewarding, and it was made possible through a network of incredible people.

First and foremost, I would like to express my ultimate gratitude to Professor Ping Wang, the Chair of my dissertation committee. Prof. Wang took a chance on an atypical Ph.D. applicant with grand ideas for quantum technology research, and for that, I will be forever grateful. It has been a pleasure getting to know and to work with Prof. Wang. He is an extraordinary researcher who has guided and challenged me over the last five years. I will always be appreciative and indebted to Prof. Wang for this opportunity and for believing in me. Second, thank you to Dean Keith Marzullo for his interest and desire to bring quantum research to the iSchool. The research assistantship I did with Dean Marzullo and Professor Susan Winter in Spring 2023, digging into quantum teaching and research at other iSchools and current happenings in quantum at UMD, was interesting, fun, and rewarding. Last, I want to express my sincerest thanks to the other members of my dissertation committee. Professor Chris Monroe has been with me at every milestone, including encouraging me to pursue the Ph.D. to begin with. Professor Wayne Lutters has been a wonderful sounding board and a complimentary mentor to Prof. Wang. Professor and Chairman of the Physics Department at UMD, Professor Steve Rolston has been extremely encouraging of my research and career. Last, Professor Mega Subramaniam has been a great guide, specifically for methodology and literature reviews.

In addition to my incredible committee and those who have helped me along the way in the iSchool, I would like to express my appreciation for my co-workers at Quantum Catalyzer. I have been so fortunate to live firsthand through my professional work what I have studied and written about in this dissertation. I work with some of the most amazing researchers in the field of quantum science. My co-workers have been extremely encouraging, patient, and helpful during this process. Specifically, they have explained technical terms, edited my work for technical correctness, and allowed me to discuss socio-technical topics. They have made this journey much more pleasant and gone out of their way to accommodate my schedule and studies. Thank you for your support and guidance.

A very special thank you goes to my good friend, Shana Hattis. Shana, who is a professional editor, has edited all my work, starting with my initial applications to Ph.D. programs. She has been a rock during this journey. Last but certainly not least, I want to acknowledge my incredibly supportive, loving, and patient family. When a mid-thirties mother decided to get a Ph.D., the whole family was getting that PhD with her! My husband, Jonathan, and children, Emma and Benny, have put up with many days where I have locked myself away to write or missed dinner time and bedtime to attend class or continue my research. Juggling school, work, and a family has not been easy. This degree could have only happened through the support and love of those three. In addition, I am so thankful to my wonderful in-laws, Chet and Rita Stein. They have been so helpful with our children and have taken on so much more for our family while I was working on this degree and working full time. Finally, I would like to thank my mother, Janet Fein. My mother’s passion and emphasis on education have guided me to this milestone. I hope I have made my family proud.

When I finished my master’s degree over sixteen years ago, I thought I was done with school, but sometimes life surprises you. As my life's “student” chapter ends (most likely!), I could have done this only through the support of those mentioned above and many others. Thank you to everyone who has touched my life and made this milestone possible.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AI	Artificial Intelligence
BCG	Boston Consulting Group
AWS	Amazon Web Services
DoI	Diffusion of Innovations
HPC	High Performance Computers/High Performance Computing
IP	Intellectual Property
IT	Information Technology/Information Technologies
MEG	Magnetoencephalography
ML	Machine Learning
NISQ	Noisy Intermediate-Scale Quantum
OPM	Optically Pumped Magnetometers
OV	Organizing Vision
QC	Quantum Computers/Quantum Computing
QKD	Quantum Key Distribution
QML	Quantum Machine Learning
QS	Quantum Sensing/Quantum Sensors
QT	Quantum Technology/Quantum Technologies
SQUID	Superconducting Quantum Interference Device
SVM	Support Vector Machines

Introduction

Quantum mechanics, established in the early 20th century, is a fundamental theory of modern physics that describes the properties and behavior of energy and matter at the atomic and subatomic levels. The advancement of quantum physics has catalyzed discoveries in materials science, chemistry, biology, and astronomy. The innovations that stem from these discoveries have led to some of the most important technologies in the latter part of the 20th century, such as lasers and semiconductors (Cohen, 2003). The 21st century has brought further advancements in quantum physics research and technology, allowing current innovations to harness the full capabilities of quantum mechanics. This has led to the development of a vast number of powerful new technologies, ranging from new materials to next-generation sensors and computers, called quantum technologies (used interchangeably between technology/technologies in this dissertation as “QT”). The emerging field of QT both presents novel possibilities and poses challenges for society (Coenen et al., 2022).

One of these innovations, the quantum computer, utilizes quantum phenomena such as superposition and entanglement to perform information processing in ways that are anticipated to be exponentially faster and possibly better for specific problem classes. This is in direct contrast to the best “classical” (i.e., modern electronic) computers, which process information using binary logic (IBM, 2024). The idea of harnessing quantum physics to build such a computer was proposed by prominent physicist Richard Feynman nearly half a century ago. Feynman’s vision has been built upon by many others ever since, and these new ideas include the exploration of potential applications for quantum computing. Research and development of quantum computers are thus now at the core of 21st-century science and its emerging technology landscape (Preskill, 2021). Further, harnessing the power of quantum physics for other technologies, such as devices with extreme precision, next-generation materials, and cryptography, also opens new possibilities and opportunities for products and businesses. The idea of these transformational QT has excited researchers as well as governments, businesses, and investors. Therefore, as research in quantum physics has advanced over the last decade, the commercialization of new QT has accelerated. As of 2023, there were more than 350 startup companies in the QT ecosystem. In addition to these startup companies, major corporations such as IBM, Google, NVIDIA, Microsoft, Bosch, Thales, Intel, and Amazon have utilized quantum research programs to supplement and advance their current businesses (Mohr et al., 2023). Furthermore, 30 governments have committed more than $40 billion in public funding for QT research over the next decade, in addition to what has already been spent (IQM, 2024). Similarly, private investors have invested more than $2 billion in over 90 QT companies worldwide, primarily in quantum computing (Blank, 2022). With this type of investment, many worldwide are betting on QT's success.

Though promising, most QTs are still in their infancy and have a long path in development and engineering before realizing their full potential (Dargan, 2024). However, end users in industry, academia, and government are putting more focus on taking advantage of the short-term benefits of QT. Due to this new focus, QT hardware and software advancement are happening in tandem with application development. For example, some startup companies have developed quantum-inspired algorithms for the banking and finance sectors. Large banks are now conducting research projects with these algorithms to demonstrate if they can solve complex computational problems, optimize trading portfolios, and provide better results than those achievable by current high-performance computers (HPC) (Bova et al., 2021). Another example is the United States military's work with large companies to research and develop quantum sensors for better navigation in environments without access to ranging signals from the global positioning system (GPS) or other such networks (Swayne, 2024). This joint development effort will further advance these sensors for military and possible commercial use. These examples underscore how many early users of QT are conducting research and development activities to push the technology beyond the current state of the art, and, if successful, to explore how QT can be further deployed. Early-use cases like these examples also build relationships and confidence in QT amongst large companies, startups, government, academia, and even those using other emerging technologies such as artificial intelligence (AI). The initial uses of QT and the transformational opportunity these technologies pose is essential to maintaining the momentum behind the QT ecosystem, which, in its turn, is necessary for commercialization and sustained public and private funding for QT research, development, and use-case exploration.

With technological advancement, application development, and early-use cases currently happening in tandem, a unique opportunity has formed to analyze the applications and relationships surrounding QT. There is also room for investigation since the long-term consequences (positive or negative) of QT in society are largely unknown (Roberson, 2021). Understanding how the technologies are currently being used can help identify the early successes needed for the continued advancement of QT into broader applications and can help justify the "bets" (public and private) funders have made on QT. As value for QT is found in commercial and government sectors, there will be continued research, development, and refinement of applications, along with (likely) additional public and private funding. This co-evolution of QT and the commercial ecosystem can eventually lead to societal diffusion of QT applications that can have major long-term impact. Contributing to that understanding, for this dissertation, three areas of QT will be studied, with an emphasis on emerging applications and relationships. Through three essays, examples of current end users of QT will be assessed, and these results will help analyze how the technologies are being deployed and might be used in the future.

The first essay, *Early Diffusion of Innovations with Quantum Computing,* examines how quantum computing is beginning to spread in society through the lenses of the *Diffusion of Innovations* theory (Rogers, 2023) and the follow-on insights by Geoffrey Moore (Moore, 1991). The essay has four case studies of how the earliest users on an S-curve of an innovation's adoption, called innovators by Rogers and Moore, have explored quantum computing applications, with examples of key elements of early quantum computing in the pharmaceuticals, finance, automotive, and energy industries. The second essay, *The Organizing Vision for Quantum Sensing: Case Studies in Neuroscience and Geophysical Surveying,* outlines the development of an organizing vision around the quantum sensing ecosystem. The essay has two case studies on how quantum sensors are currently being used in the fields of neuroscience research and geophysical surveying and speculates how they might be used in the future. Finally, the third essay, *Understanding the Relationship Between Quantum Technologies and Artificial Intelligence,* discusses how QT is advancing artificial intelligence (AI), how AI is advancing QT, and the challenges of the relationship. The essay provides key examples of this symbiotic relationship and makes suggestions as to how stakeholders can advance the relationship for continued research, development, and investment.

A primary conclusion from the above three areas of study (and associated essays) is that the promise of QT can have significant implications on social shaping (Roberson, 2021). In the short term, and as this dissertation will demonstrate, QT can impact research, such as new ways to conduct functional brain imaging or improved efficiency in the development of pharmaceuticals. In the long term, the contributions of QT at scale could be significant, touching everything from cybersecurity to human health and renewable energy (Crawford, 2021; Bova, 2021). The examples of early uses of QT in the following three essays are a start to understanding where the value of QT currently lies, the beginnings of the ecosystem advancement, and if the investments made in QT will come to fruition**.** The relationships between the technologies, users, and researchers will be critical for long-term advancement through the ongoing application research needed for technological development. While it will likely be a long journey to move QT from research projects to systems used consistently and reliably in diverse societal contexts, the cumulation of the three essays in this dissertation will show that studying these relationships can offer insights into how the adoption of QT in the future by various entities might be achieved and how best to further encourage development and funding.

Essay 1: Early Diffusion of Innovations with Quantum Computing*

Abstract

Quantum Computing (QC) is an emerging technology with a long development road for mass adoption. Nonetheless, there is excitement around the potential for QC to add business value. Through a literature review and interviews with key stakeholders currently using QC, informed by the literature, we conducted four case studies of major corporations adopting QC in various industries. The case studies show that companies are beginning to innovate with quantum computing, adding value to their current high-performance computing systems. The findings from the case studies illustrate and enrich the Diffusion of Innovations (DoI) theory as a framework for adopting and managing technological innovations, along with Crossing the Chasm as a follow-on to DoI. Specifically, the paper identifies the current adopters that have actively engaged in developing QC applications with other players and analyzes the four elements of innovation diffusion led by these innovators.

* This paper was published in the 2023 conference proceedings of the Australasian Conference on Information Systems (ACIS). Amanda Stein was the lead author.

Stein, A., Wang, P., & Lutters, W. (2023). Early diffusion of innovations with quantum computing. Australasian Conference on Information Systems, Wellington, New Zealand, 87.

1.0 Introduction

In January 2023, Forbes online featured an article entitled “Quantum Computing Is Coming, and It’s Reinventing the Tech Industry” (Q.Ai, 2023). Articles like this demonstrate the early adoption of quantum computing (QC) and convey a palpable sense of excitement about its promise and potential benefits once at scale.

The present reality of QC is that achieving "quantum advantage" (sometimes called quantum supremacy), defined as the ability of a quantum computing device to solve problems faster or better than a high-performance computer (HPC), is difficult to achieve consistently, although quantum supremacy has infrequently been attained (Terhal, 2018). In addition, today's quantum computers are considered “noisy intermediate-scale quantum” (NISQ) era, meaning the processors are very susceptible to their environment, making it hard for computations to scale. The research needed for quantum computers to scale is very difficult and will require much more research funding and years of development. Whether quantum computers can ever be used efficiently is left to be proven (Preskill, 2018). However, in the short term, quantum algorithms promise more efficient machine learning. In the longer term, quantum computing hardware could surpass the best HPC in computational time and power (Bayerstadler et al., 2021).

Despite these technological challenges, scientific refutations, and the immaturity of QC systems, as the headline states, the technology industry is beginning to innovate with QC (Q.Ai, 2023). The companies creating the earliest quantum computers are partnering with other organizations and governments to find applications in which quantum computers can complement or outperform HPC, driving the value of QC (MacQuarrie et al., 2020). Large companies, such as those in the financial, energy, and automotive industries, actively seek out problems for which they believe QC can provide an advantage over HPC, mainly through algorithmic development.

While QC is still nascent, the introduction of QC for real-world applications follows a similar trajectory to the commercialization of other technologies with hard engineering problems, called “deep tech.” Deep tech often makes the leap from research labs to commercialization slowly and over time, with a progression highly influenced by the technology’s early acceptance or rejection (Kirchberger & Pohl, 2016). This idea is at the core of Everett M. Rogers’ Diffusion of Innovations (DoI) theory, which explains how innovations (including technologies) are adopted and spread. DoI is the “process in which an innovation is communicated through certain channels over time among the members of a social system.” The elements of DoI (innovation, communication, time, and social system) help delineate trends and enable technology developers to assess the chances of adoption, with adaptations accordingly (Rogers, 2003).

Admittedly, there is a long road to the mass adoption of QC by organizations with many challenges to overcome. Understanding how and why some technologies diffuse early will be important to inform future technology design and lead to successful adoption over the longer term, as the development of deep tech is very dynamic and ever-changing. Through looking at specific case studies of organizations adopting early QC, conclusions can be made about how QC adoption follows the parameters set out by DoI theory and how the theory can inform the future of QC. Further, evaluating early successes of companies innovating with QC and how they communicate helps advance the field, providing scientific rigor and legitimacy to the emerging technology for the researchers and those who invest in QC. Hence, this paper addresses the following research question: *How do organizations innovate with quantum computing (QC), and how do QC innovations diffuse?*

2.0 Background

While the principles of quantum mechanics date to the early 20th century, the creation of technologies able to take advantage of these principles only began in the mid-20th century (Dowling & Milburn, 2003). Similarly, the DoI theory was first published in the 1962 book Diffusion of Innovations (Rogers, 2003). This section summarizes the history of QC and provides an overview of DoI and its follow-on theory – Crossing the Chasm (Moore, 1991).

2.1 History of Quantum Computing

Through the first half of the 20th century, physicists created a body of knowledge on how particles interact, including quantum mechanics. Their breakthroughs brought understanding through mathematics to the chaos that is observing the physical universe (Cohen, 2003). In a paper titled Quantum Technology, the Second Quantum Revolution, physicists Jonathan Dowling and Gerard Milburn described the technological developments made possible by research in quantum mechanics and called this period the “first quantum revolution” (Dowling & Milburn, 2003). The way matter sometimes behaves like a wave, as well as the way light waves sometimes interact like particles in quantum mechanics is the basis for many technologies in the modern era, including semiconductors, imaging, and nuclear technologies. In the 21st century, physicists and engineers have used concepts such as superposition (the ability for matter to be in two states until measured) and quantum entanglement (how distant objects can affect one another) to create innovations for the field of quantum information processing (Cohen, 2003). The emerging field uses quantum mechanics to develop hardware and software that holds the potential to process information faster than ever before. Dowling & Milburn (2003) call this the “second quantum revolution.” This new phase in technology development has allowed for the creation of quantum computers that use the effects of quantum mechanics to create innovative computing technologies (IBM, 2024). Other areas of using quantum mechanics include quantum sensing for precision measurements; quantum materials, which manipulate materials at subatomic levels; and quantum communications, which allows for unhackable encryption (Seskir et al., 2022). These technologies manipulate the quantum mechanical properties of atomic and optical particle systems to achieve advantages over technologies that only use classical phenomena, such as HPC (Cohen, 2003).

Stemming from the "second quantum revolution," advancements in the quantum bit (qubit), the basic unit of information in quantum processing, the quantum gate (qgates), how the qubits interact with each other mathematically, and the design of the first quantum algorithms paved the way for the commercialization of QC technology by startups and large companies (Deutsch, 2021). Though all research is related to building and manipulating qubits for computing, many academic groups have developed various QC approaches due to the properties of the qubits and how they are manipulated to process information through gates (Cohen, 2003). Today, the most advanced approaches are annealing, superconducting qubits, ion traps, and neutral atoms, which companies of various sizes commercialize. Each of these provides different advantages for QC. However, no one approach has proven to be superior.

Canadian startup D-Wave was the first to create and sell a product demonstrating large-scale quantum behavior. D-Wave uses a quantum annealing approach, which uses energy in the quantum state for information processing (Gibney, 2017). However, this technique is controversial in the research community due to how annealing achieves quantum effects using many qubits (Shin et al., 2014). In 2011, D-Wave sold a first-generation quantum computer to Lockheed Martin for $11M. Lockheed Martin was interested in using QC to integrate software with environmental sensors, becoming one of the first-known applications of QC. The companies also created a research agreement to develop the product further and explore other applications (Merali, 2011).

Since 2011, there has been an influx in the commercialization of QC, specifically in hardware, algorithmic development, and cloud platforms (Bova et al., 2021). New companies emerged, and large corporations like Amazon Web Service (AWS) and Microsoft took up QC research and development. For example, in 2019, Google claimed “quantum supremacy” with its superconducting computing platform, which uses superconducting electronic circuits as artificial atoms to create quantum processing units. The programmable quantum computer could solve specific problems in minutes, whereas the best HPC would take days (Arute et al., 2019). In the “NISQ era,” QC continues to advance, specifically in algorithmic development that can be run on quantum computers and HPC (Preskill, 2018). As of early 2023, three QC startups developing hardware and software have been listed on the New York Stock Exchange. As a result, McKinsey suggests that by 2035, QC has the potential to capture over $700B in value through partnerships and the development of use cases (Biondi et al., 2021).

2.2 Theoretical Background: Diffusion of Innovation and Crossing the Chasm

DoI theory explains how populations of individuals and organizations adopt innovations. The theory has been applied to various technologies as they have cycled through perception for new audiences; therefore, DoI theory is foundational to understanding and shaping how innovations are adopted. As a more recent follow-on of DoI, Crossing the Chasm theory (chasm theory for short thereafter) is focused on the behaviors of technology adopters.

As stated before, there are four main elements of innovation diffusion: (1) the innovation(s); (2) how innovations are communicated and perceived (communication channels); (3) how long it takes to spread the word (time); and (4) and the social systems that will support the innovation (the social system). A large part of an innovation's diffusion is the process of sharing information over time to reach a mutual understanding of the technology in a social system. Mass media and communications between individuals, especially influential decision-makers, are critical to the communication of technologies.

The adoption process follows stages that ultimately lead to the rate and success of adopting an innovation (Rogers, 2003). The stage in which the innovation is developed is called the innovation-development process. This stage starts with identifying a problem or a need and moves into the commercialization of research. The process leads to innovation adoption (or rejection) and the ultimate success of the technology (Beausoleil, 2018).

The adopters are the most important element of the social system for new technology diffusion. Rogers defines adopters into five categories that follow an S-Curve: (1) the innovators, the first to try something new; (2) early adopters, who are interested in the innovation and embrace change but may not want to be the first to use it; (3) early majority, the first set of followers, who need to understand that the innovation would work before they adopt it; (4) late majority, who are skeptical about changing but will try the innovation after others have successfully adopted it; and (5) laggards, who are most skeptical about changing and take the longest to get to adoption, if at all. The initial use and then continued use are the factors for acceptance of the innovation and its eventual diffusion (Rogers, 2003). Chasm theory takes this idea a step further. It looks at the behaviors and motivations of those in the first two categories, recognizing that those first two categories might learn at different rates. Behaviors and motivations tend to differ for the earliest adopters compared to the mainstream. For an innovation to diffuse, it might take a change of focus as adopters move through the S-Curve (Moore, 1991).

How adoption decisions are made and by whom in the social system are essential to determine whether an innovation will be accepted broadly. Specifically, in an organization, the stakeholders go through decision-making stages, starting with the initial knowledge of the innovation and then moving to the persuasion of stakeholders to experiment with the innovation. The decision to adopt is the third stage, eventually moving to the fourth stage, implementing the innovation. These stages are most important as many innovations fail at this point. Finally, there is confirmation that the decision to adopt was correct (or not). This is when most users follow the innovation, and others begin to adopt the innovation (Rogers, 2003). Chasm theory extends this by noting that some innovations are discontinuous, meaning people need to change their behavior to reach confirmation entirely.

3.0 Methods

This study applies DoI theory and its follow-on theory, chasm theory, to analyze how companies innovate with QC. Two methods were used: (1) a literature review to provide background on QC's history and inform the case studies; (2) case studies of QC through interviews and secondary data analysis.

3.1 Literature Review

We conducted a literature review of QC articles in both academic and practitioner outlets using Google Scholar as the primary point to collect research. We also used the search engine "CORE" to cross-reference papers found on Google Scholar. We were most focused on research papers that analyzed the history, uses, and business applications of QC. The main keywords in the search were "QC," "QC hardware," "QC innovations," and "QC software" to get a sense of the literature around QC, much of which was very technical in nature. To narrow down the literature related to this study, additional keywords used in the search were “applications,” “history,” “commercialization,” and “use cases of QC.” All searches on Google Scholar and CORE were done in “incognito” mode, not to be influenced by the user profile. Since QC's business and sociotechnical sides are emerging, no time limit was put on the research papers. However, the vast majority of papers were technical and were not considered for this study. As a result, 48 research papers were collected. Many were used for background information on QC and as secondary supporting analysis.

Regarding practitioners’ literature on QC, relevant publications were identified, including mentions of QC in mass media and press releases. This was done through searches on Google News and LinkedIn with the keywords of “end users,” “applications,” “commercialization,” and “industry involvement” concerning QC. Specific attention was given to articles detailing the use cases of QC and press releases from companies mentioning their work with QC. The time frame used was from January 1, 2017, to March 1, 2023. Again, articles that were technical in nature were not considered. As a result, 148 relevant articles and press releases were collected to represent practitioners’ literature on QC.

Next, through reading both the research papers and practitioners’ articles, we extracted company names, relationships, and use cases of QC within texts.

3.2 Case Studies

We identified several industries and companies from the literature review. Industries were ranked by the number of mentions, followed by the companies in those industries. The top four industries were pharmaceuticals, finance, automotive, and energy. Because these were mentioned the most in the literature, they were selected as the industries on which to do case studies. Then, companies in each industry were ranked by the most mentions. The interviewees were found through attribution in press releases or research papers related to a QC project. They either worked for a company working on QC projects or provided QC services (hardware or software) to the industry. Next, the paper's first author emailed those identified from each company, asking for an interview. Interviews were only done with those who accepted. In some cases, a highly-ranked company did not respond to the email and was not included in the case studies, so the next most mentioned company was selected. Table 1.1 illustrates the eight companies interviewed for the study. Names were omitted to protect the privacy of those interviewed.

Table 1.1 List of those interviewed for the study

Case Study Industry	**Company Name**	**Type of Company**
Pharmaceuticals	Biogen	Drug Developer
Pharmaceuticals	Accenture	Management Firm
Finance	Protiviti	Management Firm
Finance	Ally Financial	Financial Services Provider
Automotive	BMW	Auto Manufacturer
Automotive + Energy	Amazon Web Services (AWS)	Cloud Services Provider
Energy	Eni	Energy Provider
Energy	PASQAL	Full Stack Quantum Computer Developer

Interviews took place over Zoom with audio and, in some cases, video, all of which were recorded with permission. The interviews were approximately 45 minutes long. Conversations during the interview were semi-structured. All participants were asked the same ten preset questions created by the first author, with additional extemporaneous follow-up questions. The literature review findings informed the preset questions along with the DoI framework. This included how the company became involved in QC, a specific QC project the company was working on or had worked on, how they view QC spreading among organizations, and how they envision using QC in the future. The questions allowed participants to speak about whether QC benefited their company and how QC has spread through their industry. Last, interviews were transcribed by the first author. Coding strategies were used related to the diffusion of innovations theory to identify key points and then summarize to form the case studies. In addition, more secondary data from academic papers and articles (based on the interviews) were collected and analyzed to provide further contexts and interpretations for the case studies.

4.0 Findings from Case Studies

The use of early quantum computers for industry applications dates back to 2011 with the first sale of a quantum computing machine (Merali, 2011). That catalyst showed the potential of using QC technology for real-world applications while advancing technological development. As QC hardware and software have moved from research labs to commercialization in the "second quantum revolution," businesses have considered QC a new tool to work in parallel with HPC systems (Deutsch, 2021). Based on interviews and secondary information from the literature review, the following case studies show how corporations innovate with QC, and how QC is diffusing within four industries.

4.1 Pharmaceuticals

Molecular modeling for pharmaceutical development is an application of QC with the potential to outperform current HPC. The combination of early QC hardware and software has demonstrated faster computation of data sets for optimization (Zinner et al., 2022).

Optimizing molecular modeling using a quantum system was an early idea of the Canadian quantum software startup 1QBit. In 2016, the company published results for measuring similarities among graphs for molecular comparison using algorithms developed on quantum systems. The results created algorithms that restrict multiple variables from a molecule to propose only feasible solutions. This was the first time a quantum system, specifically an annealer, could solve a problem that way (Hernandez et al., 2016). The paper garnered the attention of the global professional services firm Accenture, whose research and development arm, "The Labs," is dedicated to conducting "business experiments" with emerging technologies.

Executives from Accenture referenced the creation of algorithms, like the one from 1QBit, and new approaches to optimization problems as a catalyst for Accenture's interest in QC. The Labs saw potential in these new approaches for determining molecular similarities for their client, drug manufacturer Biogen. 1QBit, Accenture, and Biogen conducted a business experiment using QC hardware and software, building upon 1QBit's algorithm run on D-Wave quantum annealing machines. The experiment aimed to accelerate drug development for neurological disorders by combining 2D and 3D graph models for improved outcomes in molecular development, which is difficult using computer design techniques (Accenture, 2017).

Biogen found advantages in the partnership and using quantum systems. Specifically, the advantages of using quantum systems were seen through increased computing speed and accuracy, and the results were of higher quality than traditional computer-aided design. However, Biogen found the experiment to provide few advantages over their HPC systems in 2017, as they focused on getting many models rather than quality. Biogen found the hardware “clunky,” though the algorithm worked well despite the limitations of the QC hardware. While the project did not continue, the team published a research paper (Hernandez et al., 2019). Accenture hopes to improve the algorithm to be “hybrid” (able to run on a specific quantum computer and an HPC). This will allow quantum benefits through simulation of modeling the quantum effects but on an HPC.

4.2 Finance

The financial services industry computes vast amounts of data daily for risk analysis and modeling, client portfolio management, and market predictions. A challenge facing the industry is that HPC cannot meet growing computing needs. The amount and complexity of data are outpacing advancements in computing and machine learning algorithms (Biondi et al., 2021). One of the industry's largest challenges is discerning the optimal solution for a problem, which takes a long time on a HPC and often has high error rates (Orús et al., 2019). These problems affect computing, for example, credit scores, foreign exchange arbitrage, and stock market portfolio optimization (Palmer et al., 2022). The industry has begun exploring whether QC can help complement current tools (Bova et al., 2021). For instance, since 2019, Ally Financial has used QC for indexing tracking of stock portfolios, which is essential to stock portfolio optimization and asset management strategies (Leffert, 2022).

One way of managing stock portfolio performances is through indexing, a statistical measure for tracking and evaluating data. Indexing can be challenging because it only replicates a limited subset of the assets in a portfolio, called cardinality constraint. Standard algorithms have difficulty deciding the best assets to evaluate (Jimbo et al., 2017). The industry has searched for a better way to replicate financial indexes and solve cardinality constraints. In early 2022, Ally Financial and the management consulting firm Protiviti identified this problem as one that QC could improve (Leffert, 2022). To develop a solution, Protiviti partnered with Multiverse Computing, which creates “quantum-based” software. The research team from Ally Financial, Protiviti, and Multiverse Computing created algorithms that ran on a “D-Wave Hybrid Solver Annealer,” a type of quantum computer. The algorithms developed were hybrid algorithms, meaning they could also run on HPC systems, replicating what is possible with a quantum computer. The quantum algorithm tracked companies' daily returns in the NASDAQ 100 and the S&P 500 over a year and optimized the stocks indexed, leading to a smaller set without reducing the indexing quality, increasing efficiency.

Protiviti and Multiverse Computing created a state-of-the-art QC product for Ally Financial in early 2022. The product included front-end and back-end development to run on a quantum computer in the cloud. The team published a research paper showcasing the results (Palmer et al., 2022). The next step is to advance the developments of QC even further. Recognizing that the innovation is dynamic, Ally Financial sees experimenting with quantum algorithms as part of being “quantum ready” for the future.

4.3 Automotive

Automotive development consists of complicated processes that must predict technology trends for yearly model development five years into the future. The process combines computations, manufacturing, and materials development. Many auto manufacturers and suppliers run massive HPC infrastructures to meet computing and machine learning demands. The industry's computing challenges include supply chain optimization, advanced molecular modeling, and machine-learning techniques (Open Data

Center Alliance, 2014). Automakers are competitive, and thus, they constantly search for new technologies. Some companies have turned to QC to boost capabilities and are developing early use cases for QC (Burkacky et al., 2020). Various automotive companies have taken on projects using quantum computers to optimize traffic routes and molecular development for more durable paints and materials (Bayerstadler et al., 2021).

BMW identified QC as a priority through its technology scouting efforts in 2017. The company cites the availability of D-Wave's quantum annealing machine as a turning point for their interest. Since 2021, BMW has funded a small internal QC team. Specifically, they explore hybrid algorithms (possible to run on quantum or classical computers) for problems with many possible solutions, such as robotic planning during the assembly process, all of which fit into their business value chain. BMW partners with cloud service providers, quantum algorithmic developers, management consulting firms, and QC hardware manufacturers to identify areas where QC can add value. Examples include using QC to solve differential equations, generating artificial situations, simulations of physical processes, and materials optimization and research. BMW has also used QC for generative modeling, such as the technology that goes into autonomous vehicles.

BMW partners with cloud service providers such as AWS's Braket and hardware developers to codesign quantum hardware and software. One such project is with Quantinuum, a QC company based on ion trap computing that uses charged ion particles as qubits in a shared trapped space to gather quantum information. Quantinuum and BMW are working on modeling the oxygen reduction reaction for a hydrogen fuel cell, using Quantinuum's InQuanto quantum software platform for modeling molecular systems on Braket. These models were beyond the simplistic molecule systems done on current computers, proving the advantages of QC for this use case.

4.4 Energy

As global energy demands grow, the industry uses HPC for geophysical and seismic information and sustainability modeling (Varadharajan et al., 2022). QC has attracted energy and utility companies, such as Eni, the multi-national energy company, which sees QC as a way to go beyond their current computing capabilities, even though they run one of the world's most powerful clusters of supercomputers for industrial applications.

Eni understands that the complexity of certain problems limits their best supercomputers. These “hard” problems increase exponentially as the data sets get larger, such as mapping catalytic processing and developing energy storage systems. The industry began looking into QC for these problems because research has shown that QC algorithms can scale better as information becomes more complex. These problems overlap with use cases for computational chemistry and materials development, which have already shown early successes for computational advancement using quantum computers and algorithms (Paudel et al., 2022).

Eni began exploring QC in 2018 to get ahead of technological advancements and keep up with trends in computing. Eni believes QC can help advance sustainability for the company’s operations and in oil and gas production and help them reach their net zero carbon state goal by 2050. The company has been experimenting with hybrid quantum algorithms for advanced molecular modeling to help optimize molecule development for cleaner gases. They also use QC tools to optimize their power consumption in their data centers. Eni recognizes the challenges in embarking on such a new technology and sees these efforts as research projects for the long term.

To improve their computing capabilities and advance QC research, Eni embarked on a project with PASQAL, a France-based QC startup company that is developing both hardware and software using arrays of single atoms manipulated by light beams to achieve readouts of quantum states (Henriet et al., 2020). The team started by trying to solve workflow and simulation problems of upstream and downstream drilling. The work includes the creation of bespoke algorithms that run on a PASQAL quantum computer. The project aims to accelerate the transition of energy production and enhance optimization and machine learning for drilling and workflows. PASQAL used what was learned through the partnership with Eni to guide the development of their next-generation full-stack quantum computer and future quantum simulation software.

5.0 Analysis and Discussion

Though QC is in its infancy, research, and commercialization have advanced to the point where major corporations are beginning to innovate to see if it can complement their current computing systems and provide business value (Seskir et al., 2022). The case studies demonstrate positive business value through the use of QC. The advantage has been sufficient that companies like BMW, Eni, and Ally Financial continue research projects with QC systems and are factoring the subsequent results into future products, showing that development and adoption go hand-in-hand for QC.

For this paper, the QC use cases were analyzed emphasizing the adopters under DoI theory and their behaviors through chasm theory. Various themes emerged. The first was using QC to complement HPC systems by creating bespoke hybrid algorithms. Each company found benefits with this approach, which is a testament to where quantum computing hardware is today. Additionally, the theme of partnerships to support projects was evident in all four cases. The companies studied needed the support of technology advisors and developers to advance their innovations with QC. As a result, all four companies found growth in partnership to advance QC research. Additionally, the case studies showed that the partnerships hardware providers have with the end users inform the future development of the hardware and software.

All of the companies studied expressed they would continue with QC projects somehow and saw the technology as useful in its current form, but not without challenges. They were proud to be among the first to use QC, exhibiting the characteristics of the earliest adopters laid out in chasm theory. However, all acknowledged that QC is in its infancy and expect the technology to advance, possibly replacing HPC systems. Differences in how the companies innovate with QC stemmed from how and why each company wanted to become involved with the technology. Biogen, for example, was influenced by Accenture to participate in a QC project. Further, BMW proved to be the most active through having a dedicated staff working solely on quantum technology projects.

While QC will likely never face consumers, DoI and chasm theories point out that organizations adopt innovations similarly to how they would be adopted by a group of individuals in a community. In an organization, innovation decision-making breaks down into two subprocesses: initiation and implementation. Initiation involves organizational exploration, which includes information gathering, conceptualizing, and making plans to adopt (Rogers, 2003). Other industries and organizations that have yet to undertake QC projects might be in the initiation phase and waiting for the technology to mature, where projects are not development projects. Implementation involves using the innovation such as the hydrogen fuel cell development with a quantum computer by BMW and the creation of financial modeling algorithms created by Ally Financial and Protiviti. These examples show development and application happening at the same time.

QC is going through the innovation-development process, with the innovation being dynamic and changing as QC progresses. This includes research, development, and commercialization by academics, large companies, and startups (Beausoleil, 2018). The case studies are examples of large companies participating in this process. The early uses of QC guide the design of future versions of quantum computers and software, proving that commercialization is happening simultaneously with the early uses, allowing companies to reap the benefits while technology advances. Understanding how businesses are innovating with QC and the motivations of organizations for taking on QC projects helps inform the advancement of the technology.

Rogers (2003, p. 268) states that, whether individuals or corporations, "innovativeness is the bottom-line behavior in the diffusion process." However, he also points out resistance by organizations to adopting new technologies (Rogers, 2003). Today, only a few companies are innovating with QC. Others are skeptical or waiting for the technology to mature, although there is the fear of missing out based on positive early results from a few companies, which is part of the challenge of QC. The companies using QC demonstrate the first category of adopters under DoI and chasm theory, the innovators. Companies such as BMW are willing to take the risk to invest in QC, a main characteristic of an innovator. Along with partners like AWS and Quantinuum, BMW, the innovator, is helping control the flow of new ideas into its industry.

The earliest uses of QC show the beginnings of adoption. The rest of this section analyzes how the four elements of innovation diffusion relate to QC, as detailed by the literature review and the case studies.

5.1 The Innovation

The first element of diffusion, the innovation, points to the “newness” of a technology. An innovation has to be perceived as new to those who might adopt it (Rogers, 2003). Even though the idea of using quantum effects for computing is nearly half a century old, the commercialization of QC has taken off only through advances of the second quantum revolution (Deutsch, 2021). The companies of this study see QC as a new and dynamic technology. For example, Eni chose to work with QC because the technology was novel and potentially better than existing computing, though not without challenges.

Most technologies have hardware and software components (Rogers, 2003). The case studies demonstrate that quantum computers can only work with specialized algorithms and access to quantum computers via the cloud or specialized partnerships. The algorithms help make QC novel now, whereas hardware development breakthroughs are what will keep the innovation novel into the future, especially for corporations looking to innovate with QC. QC is emerging as a package of innovations that involves partners developing the technology together. The early projects of QC show that cooperative partnerships can be successful, and what DoI theory calls “technology clusters” (hardware and software) of QC are pivotal for advancement.

5.2 Communication Channels

Communication channels help spread knowledge of innovation. When dealing with innovations that are not consumer-focused, DoI theory states that mass media is the most effective means of informing potential adopters about an innovation (Rogers, 2003). QC has been in the headlines of major publications, such as Forbes and Time magazine, touting significant advances and benefits of the technology. Keeping a positive message in the mainstream media is one way QC creates a "newness" impression needed to advance the perception by prospective adopters. All four companies in this paper communicated their results and will continue to. The communication of their successes legitimizes QC in the early days, which helps with adoption.

Communicating successes also spreads knowledge and informs competitors in an industry. The companies studied had scientific results, but it is hard to determine if the proper attention was garnered. In some cases, there were research papers detailing the results of early QC projects designed to spread information to those in the QC academic community. Under the DoI theory, communication spreads knowledge among peer groups, specifically those already using QC. However, this communication can also benefit those companies in the initiation phase of adopting QC.

Communication in the wrong form can also hurt the advancement of an innovation. The wrong communication, for instance, false promises or excessive hype, can lead to stakeholders not even considering an innovation. This was a fear of those working in QC in each of the industries identified. The downside is that the excitement of the potential of QC can come across as hype, especially for those uneducated in the field (Das Sarma, 2022).

5.3 Time

According to DoI theory, time involves three elements: the decision to adopt, who is adopting, and the adoption rate. The “innovation-decision process” is key to an organization’s decision to adopt and determines how quickly innovations can become successful. The process starts with initial knowledge and moves into the persuasion of key stakeholders (Rogers, 2003). For example, the initial knowledge and persuasion stages about QC at BMW and Accenture happened through technology scouting efforts. Next comes the decision to take on an innovation and implement it. After scouting for the technology, both companies embarked on a QC project, which also helped develop the quantum hardware and algorithms. Each project's success led to a formal implementation, during which both companies hired dedicated staff to advance their QC use cases and conduct future projects to innovate even further. While their implementation stage is still in the early stages, the success will dictate the final step in the process, confirmation.

Overall, QC will take longer to get to a confirmation phase, even with the companies in the innovator category, because the hardware needs to advance further. Applications will develop along with the technology, as seen through the case studies. Companies that are innovating with QC and getting positive results make confirmation within their organizations and industries. Those experimenting with QC are the innovators and represent the first and smallest group on the S-curve. They understand that QC is a “long game,” but as chasm theory points out, the behavior of adopters can change over time. The availability of multiple quantum systems on cloud platforms will continue to help the advancement of QC adoption as it increases accessibility. Further, adoption rates could accelerate if a QC platform reliably reaches an “advantage” over current HPC systems

(Terhal, 2018).

5.4 The Social System

The social system is a unit of people that share common goals and communication. The social system for QC can be as small as one organization or a government agency. It can also comprise of partnerships. For instance, when Ally Financial used QC for index tracking of stock portfolios, the social system comprised the company, their management firm Protiviti, the algorithmic developer Multiverse Computing, and the QC hardware company D-Wave. Alternatively, the social system can be large and comprise an entire industry, such as the automotive industry. It can also reflect an entire innovation ecosystem, such as HPC users that could overlap with QC. The social system for QC can also represent a large network of partners involved in using QC, such as an industry consortium. The field has seen a rise in these coalitions, such as the Quantum Economic Development Consortium in the United States (Bayerstadler et al., 2021).

In addition, the social system can change over time, as chasm theory points out. Each social system has external and internal factors that influence the adoption process. The growth of a social system and the ultimate adoption of an innovation is aided by opinion leaders and change agents. Change agents are influential people and organizations that spread innovation and get people to follow them. Management consulting companies such as Accenture and Protiviti seek to be the opinion leaders in the larger QC social system. Consequently, they publish reports touting the benefits of QC and research papers highlighting their results.

Behaviors of the social system are critical to accepting innovation (Rogers, 2003). If the social system has a history of embracing emerging technologies, such as the financial services industry, there is a greater chance that the social system will welcome other emerging innovations, such as QC. For instance, when Ally Financial used QC for index tracking of stock portfolios, the social system comprised the company, their management consulting firm Protiviti, the algorithmic developer Multiverse Computing, and the QC hardware company D-Wave.

6.0 Conclusion

Though today's quantum computers are in the "NISQ era," this paper demonstrates companies in four industries where QC is beginning to diffuse through the four elements of diffusion, despite the immaturity of the technology.

Table 1.2 Key examples of DoI elements from the case study findings

DoI Element	Example
The Innovation	QC hardware and software
Communication Channels	Media hype surrounding QC
Time	Evolution from technology scouting efforts in a company to QC projects conducted in that company
The Social System	The management firm, a client of the management firm, QC hardware company, cloud service provider all working on a QC project

While this paper has focused on the application and adoption of QC, not the development of the technology, these examples show how companies are innovating with QC and sometimes seeing an advantage over HPC systems. Specifically, QC shows promise over HPC for optimization problems, molecular modeling, and computation of large data sets with overlap across all of the industries studied. All companies in the study recognized the difficulties of mass adoption for QC and the long development timeline for technological advancement. They recognize that the innovation of QC is dynamic and must be developed further to advance the field.

The research leading to the "second quantum revolution" created QC and the momentum needed to get to this stage of its evolution, but much more still needs to be done before the technology can be used at scale. With research, commercialization, and private and government investment, QC has progressed significantly in the last decade (Bayerstadler et al., 2021). While QC is in the innovation-development phase, as defined by DoI theory, the study demonstrated that the partnerships among the adopters, cloud services providers, management consulting firms, and hardware and software developers are moving the technology from research projects to valuable tools for the future of computing within the four elements of diffusion. The companies in this study are looking to invest further in QC to give them a competitive advantage, especially in consumer-facing industries such as the automotive industry. Those working with QC today are among the few willing to take a risk by committing financial resources toward developing QC capabilities. Understanding how they innovate and fit within the four elements of diffusion shows the early stage of successful adoption. This knowledge informs developers and other adopters of what is working and how it is being perceived by those who will ultimately adopt the technology.

Under DoI and the chasm theory, the "innovators" have the foresight to match an emerging technology with an opportunity (Moore, 1991). Their behavior welcomes the "newness" of the technology. They communicate their positive results. Their excitement and success will help power the new field of QC forward. If these early successes were not shown, the decision of other organizations to adopt QC and the development of the social system as a whole would be different and even more difficult. Early technological innovations need success stories to help fuel what the DoI theory calls the decision-making process over time. However, diffusion is hard. While a few other companies and industries are exploring QC, moving to the next group of adopters, the “early adopters,” and even more so to the third group, the “early majority,” will be difficult, as their motivations and behaviors will differ. In the near term, QC will complement HPC, and the business value of QC will need to continue to be greater than current HPC to welcome more widespread adoption. This will include the development of hardware and software in order to move out of the NISQ era and refine quantum computers’ overall ease of use (Preskill, 2018). As QC technology advances, understanding how companies innovate with QC will inform the development of the next-generation technology and enrich the DoI theory with a realistic view of evolving innovations that diffuse within and across industries.

Essay 2: The Organizing Vision for Quantum Sensing: Case Studies in Neuroscience and Geophysical Surveying

Abstract

While quantum computing garners the most attention, quantum sensors are arguably the most advanced quantum hardware platform, with applications spanning medicine, aerospace, and environmental and energy monitoring, to name a few. These quantum sensors, such as scanning quantum interference devices (SQUIDs), atomic clocks, and optically pumped magnetometers, were commercialized in the latter part of the 20th century and are now used in specialized research and commercial settings. In the 21st century, through the advancement of the field of quantum information science, quantum sensors are driving the state of the art, with much hope and promise as to what they can do. This paper identifies examples of quantum sensor users and developers in two applications: medicine (specifically neuroscience) and geophysical surveying. Through primary data from interviews and secondary data from academic papers and practitioners' articles, I aimed to understand how users currently work with quantum sensors and how they envision using them. I applied the popular business theory of "organizing vision" to analyze how the users are advancing the innovation of quantum sensing.

1.0 Introduction

A sensor is “a device that produces an output signal to sense a physical phenomenon.” Conventional sensors typically rely on classic physics principles to measure output quantities of the phenomenon being sensed, such as heat, moisture, chemicals, or light (to name a few) (Sensors, 2024). Quantum sensors (used interchangeably between sensor/sensing in this paper as “QS”) rely on the principles of quantum mechanics for their outputs. More simplistically, QS produces its outputs from quantum effects, typically occurring at the atomic or molecular level. QS generally provides superior performance relative to conventional sensors in critical areas, such as sensitivity to physical phenomena (Kantsepolsky et al., 2023).

Conventional sensors of various kinds have been developed and used for centuries (Pirzada and Altintas, 2023). Beginning in the mid-twentieth century, the principles of quantum mechanics for sensing emerged from the advancement of the underlying physics, such as in magnetic resonance and atomic physics (Degen, et al. 2017). As researchers began to find real-world QS applications, commercialization of these sensors soon occurred. For example, QS was used for navigation positioning and detecting magnetic fields in the brain and heart beginning in the 1970s (Clarke et al., 2018; Körber et al., 2016). The twenty-first century has accelerated the development, engineering, and commercialization of QS technology even further, focusing on new materials used for sensing, the broadening fields of QS applications, and reduction of QS size, weight, power, and cost. The overall advancement of quantum technology has created excitement around QS applications and possibilities to push the state of the art for research and commercial use. Public and private research funding for quantum science and technology has helped fuel these advancements, most notably in quantum computing (QC), which has garnered significant attention and funding (Jurczak, 2023).

Quantum technologies, like QS and QC, face long roads to mass adoption. Making sense of the technologies is critical for good organizational decision making and the associated long-term diffusion of these technologies. In the field of information systems (IS), organizing visions (OV) are developed to facilitate such sense-making and diffusion of technologies, especially while it is in its infancy. An organizing vision is "a focal community idea for the application of information technology in organizations " (Swanson and Ramiller, 1997, p. 460). Each organizing vision is developed by and within an interorganizational community, with members contemplating the technology for their own situations while sharing a common mission of ultimate diffusion (Swanson and Ramiller, 1997). Every OV plays three key functions in adopting and diffusing the focal information technology: interpretation, legitimation, and mobilization (Swanson and Ramiller, 1997). For QS, an organizing vision is being developed by various stakeholders in their discourse about QS in and across different areas of applications.

To date, QS users include academics, industry researchers (with executives as decision makers), and government leaders. Often, these users collaborate with developers, component suppliers, and other parties interested in the technology and in creating a community and discourse to form an OV. This leads to the preeminent research question: *How are organizations using QS, and how do they envision using them in the future?* I answer this question through two case studies of QS applications in neuroscience (specifically magnetoencephalography) and geophysical surveying. The primary and secondary data (i.e., the respective interviews and QS articles) collected for the case studies are examples of the OV discourse around QS. QS technology will continue to be commercialized and funded. Understanding how users apply the technology, the discourse around it, and the diverse interorganizational community involved in OV development will help with the long-term adoption and diffusion of QS.

2.0 Background

Modern, conventional sensors, such as touch sensors in screen-based devices, motion sensors, safety sensors, and biosensors, have changed everyday life dramatically (Pirzada and Altintas, 2023). If QS lives up to its hype, it will provide similar, or perhaps greater, advances. QS hype is one of the key contributors to forming an OV community excited about its possibilities. To contextualize this symbiotic relationship, we need to understand QS's background and the associated OV theory. This section gives a short sociotechnical summary of QS and an overview of OV theory that was laid out in the 1997 paper *The Organizing Vision in Information Systems Innovation* by E. Burton Swanson and Neil Ramiller.

2.1 Quantum Sensing Background

As summarized above, QS has roots in the mid-twentieth century as quantum physics advanced. Physicists Jonathan Dowling and Gerard Milburn coined the term the “first quantum revolution” in their 2003 paper, *Quantum Technology: The Second Quantum Revolution*, to describe how scientific breakthroughs in understanding basic quantum effects underpinned many impactful technologies of the mid/late twentieth century. The beginnings of the modern information age stem from “the first quantum revolution” through the advancement of semiconductor physics and telecommunications (Dowling and Milburn, 2003). Additionally, what we know today as QS came from breakthroughs in atomic physics and magnetic resonance research during this time (Degen et al., 2017). Technological advances utilizing these breakthroughs include MRI machines, lasers, computer chips, and atomic clocks (Bobier et al., 2023).

Dowling and Milburn (2003) coined the phrase "second quantum revolution" to describe the emergence, in recent decades, of material states showcasing managed quantum attributes and the deliberate manipulation of optical, electronic, and other beneficial properties through these controlled quantum phenomena. These “quantum states” can provide extreme sensitivity to physical phenomena of interest, such as electromagnetic fields, temperature, and changes in gravity, leading to QS's utility in performing precision measurements (Humnabadkar, 2022). The advent of the "second quantum revolution" marked a transformative shift, transitioning quantum phenomena from mere theoretical understanding and application via aggregate quantum particle behavior (e.g., atoms, ions, photons) to technologies capable of manipulating individual quantum states and particle interactions, with wide-ranging applications of potentially great importance (Dowling and Milburn, 2003). This shift included extensive investigations into new materials and quantum systems that could be used as sensors, in quantum computers, or in networking devices via controlled quantum effects (Arndt et al., 2011). In particular, as the technology advanced, the commercialization of QS focused on exploiting a quantum system’s strong sensitivity to external phenomena of interest while decreasing the size, weight, power, and cost (Mohr et al., 2023).

Like any sensor, a quantum sensor (QS) provides an output based on measuring the physical phenomenon of interest. However, the term “quantum sensor” is not a catch-all term. Various types of architectures are based on the physical phenomenon a QS measures. The quantum modality employed in the QS has very different operating principles for each QS type (Aslam et al., 2023). This allows QS to have many applications but also gives rise to uncertainty as to which architecture best fits which application (Cohen, 2003). Depending on the application, a QS might measure gravity, electric fields, time, magnetic fields, or acceleration/rotation (Crawford, 2021), exploiting quantum mechanical effects to measure the quantity of interest (Degen et al., 2017). To make the measurement, a QS could use a variety of implementations, such as solid-state systems for measuring magnetic fields at the nanoscale, atoms for timing, or superconducting circuits for very weak magnetic fields at the macroscopic scale (Shepard, 2024). Table 2.1 summarizes common QS types, including those examined in this paper. To date, most commercial QS instruments have been expensive and bulky; in some cases, cryogenics or lasers are needed for operation, making adoption and scaling difficult (Bobier et al., 2023).

Table 2. 1 Example types of quantum sensors

Type of QS	**Modality**	**Applications**
Atomic clocks	Atoms or ions	Timing, positioning
Superconducting quantum interference device (SQUID) magnetic flux detectors	Superconducting circuits (e.g., Josephson junctions)	Medical, electronics characterization
Optically pumped magnetometers (OPMs)	Atoms	Medical, navigation
Quantum gravity gradiometers	Atoms	Ground surveying, navigation
Solid-state sensors of electromagnetic fields, temperature, pressure	Quantum defects in solids (e.g., NV-diamond)	Microscopy, medical, harsh environment sensing

2.2 Theoretical Framework: Organizing Vision

OV theory explains how communities adopt and implement information system (IS) technologies through common understandings and goals. An OV is developed and shared interorganizationally. Each diverse participant is part of the OV community and is interested in the focal technology, with similar or different reasons or motivations.

The community members are not just the developers or users of the technology. A range of supporters share the OV, including consultants, vendors, and even observers (Ramiller and Swanson, 2003). These members will have a cohesive discourse driven by shared “buzzwords” (i.e., terminology used in relation to the technology), which is often seen as hype. For positive diffusion, themes emerge, the technology is better understood, and the narrative grows richer. However, as new technologies emerge, it is often hard to differentiate hype from serious ideas that would lead to advancement.

According to Swanson and Ramiller, the OV serves three primary functions: “to provide a focus for interpretive efforts involved in creating the idea of the innovation, to legitimate that innovation, and to help mobilize and structure associated material and commercial processes” (Swanson and Ramiller, 1997, p. 461). The first function, interpretation, is how an OV community is created. Interpretation is crucial to explaining the relevancy of the innovation and its worthiness for consideration by adopters, specifically in the early stages. The second function, legitimation, occurs when the technology finds usefulness among the early users. Stories are communicated through an OV, linking it to business practices and a successful rationale for adoption by a broader set of stakeholders. Recognizing those who propagate the OV is essential, as members with “reputation” and “authority” have the most influence. The third function, mobilization, includes the “market forces” that lead to technology adoption. This comprises exposure beyond the initial community and begins to account for long-term adopters. With mobilization comes the change in discourse from buzzwords among a few members to attention from the mainstream media. The three functions work together to address some of the uncertainties of new innovations and help technologies assimilate over time. As technologies change in visibility and prominence, especially as they assimilate, the OV changes as well.

3.0 Methods

To understand how organizations use quantum sensors and envision their place in the future, case studies were conducted by collecting and analyzing primary and secondary data in two QS application areas.

To identify the application areas where QS is currently being used, I relied on both academic and practitioner literature. To collect academic literature, a search on Google Scholar using the terms “quantum sensing applications,” “commercialization of quantum sensing,” and “industries using quantum sensing” was conducted. Emphasis was put on articles and papers published in entities for the fields of physics and engineering, such as *Nature, Science*, The Institute of Electrical and Electronics Engineers (IEEE), and the American Physical Society (APS). No time limit was placed on the results; however, I prioritized the most recent articles to create a current snapshot of applications and users. The titles and abstracts of the initial results were read, and only papers of relevance to the study were kept. 62 articles were found.

For practitioners' literature on QS, I aimed to identify articles and press releases in mass media and quantum-related publications. Blogs (such as individual Substacks), secondary media outlets, or opinion pieces were not included to limit the findings to mainstream discourse on QS. I searched Google News and LinkedIn with the same search terms; however, I used the time frame of January 1, 2017, to February 1, 2024, as the most current users and applications was of interest. Articles that were deemed primarily technical in nature were disregarded. This resulted in finding 96 articles and press releases.

Using the results from academic and practitioner literature, application areas that were most frequently mentioned were identified. These were military/defense, navigation, semiconductor/electronics analysis, energy, geophysical (including surveying), medical/health/life sciences, and space.

With the QS application areas identified, I aimed to do case studies in two areas. The military/defense and the space applications needed to be eliminated, as much of the information needed to understand how organizations in that field use QS is classified and sensitive and thus restricted. The applications to study were chosen based on market size, resulting in two areas with the largest markets: medical and geophysical surveying applications. Since the medical application area is broad, I further defined this area to neuroscience, as this was the sub-application area most often mentioned in academic literature related to QS. The interviewees were found through attribution in the aforementioned literature. The participants either worked for an organization developing QS or were mentioned in the literature as users of QS at a company, research organization, or university.

I contacted potential participants via email if their email addresses could be obtained publicly; otherwise, I contacted them through direct message on LinkedIn. If someone did not respond to my emails, we moved on to another person in that organization. If no one from the organization responded, that organization was not included in the interviews, and I moved on to another organization mentioned in the findings. The positive response rate for an interview was 90% from those emailed.

Table 2.2 lists those interviewed for the study. Pseudonyms were used for each interviewee in order to protect their privacy.

Table 2. 2 Interviewees and their organizations in the case studies

Interviewee Names*	Interviewee's Role in Organization	Application Areas

CEResearcher	Civil engineering researcher at a UK University	Geophysical Surveying
Physicist1	Physicist in a UK University and Government Funding Agency	
Physicist2	Physicist at a UK University	
DirectorCSC	Director of Commercial Surveying Company	
CEOGravity	CEO of a Quantum Gravity Gradiometer Startup	
CEOOPM	CEO of an OPM Startup A	Neuroscience using MEG
CEOHelmetA	CEO of a MEG Helmet Startup A	
CEOHelmetB	CEO of a MEG Helmet Startup B	
NeuroscientistA	Neuroscientist in Research Hospital A	
NeuroscientistB	Neuroscientist in Research Hospital B	

* All names of interviewees and organizations in this table are pseudonyms

Interviews took place over Zoom with audio and video. All interviews were recorded with permission and then transcribed. On average, each interview lasted approximately one hour and was in a semi-structured format. Eleven preset questions were posed to users of QS, and eight preset questions were posed to developers. Additional semi-structured follow-on questions were presented as necessary. Findings from the literature search above and OV theory informed the pre-set questions. Questions included how the participant thought QS was relevant, how they viewed QS being used currently, and how they viewed QS being used in the future. The preset questions can be found in Appendix A.

Once the interviews were transcribed, coding strategies were used to look for an organizing vision, OV community development, current and future uses of quantum sensors, and common themes between the two application areas. To supplement the case studies, secondary data from academic papers and media articles were also collected and analyzed. This research provided further context and enriched the case studies. Specifically, relevant academic papers to the application areas (neuroscience and surveying) were found via Google Scholar, with emphasis placed on papers published by interviewees. Those papers were coded in the same way as the interviews and were used to supplement the case study. Press releases from the interviewees' organizations (e.g., the department at a university) and media articles mentioning the interviewees in relation to the application area were searched on LinkedIn, Google News, and Google Scholar. These articles were coded in the same way and considered as secondary data to supplement the interviews.

4.0 Findings from Case Studies

The case studies focused on two application areas of QS: medical (specifically neuroscience) and geophysical surveying. The goal of the case studies was to give examples of how organizations use QS and how they envision using them in the future. The following are the findings from the case studies, based on interviews and secondary data.

4.1 Neuroscience Using Magnetoencephalography (MEG) with Optically Pumped Magnetometers (OPMs)

MEG measures the magnetic field generated by the electrical activity of neurons in the brain (Singh, 2014). MEG, along with magnetocardiography (MCG), which measures electrical currents from the heart, make up the study of biomagnetism, "the study of magnetic fields of biological origin" (Körber et al., 2016). The "second quantum revolution" has broadened the applications of superconducting quantum interference devices (SQUIDs), which use quantum effects in wire loops to measure tiny changes in magnetic fields. Since SQUIDs have extreme sensitivity to magnetic fields, scientists in the mid-twentieth century began using the tool in medicine, including for MEG and MCG (Swithenby, 1987). Unlike the overall medical device market, the overall global market for MEG is not large because the tool is primarily used for research. In 2020, it was approximately $200M and is expected to reach $300M by 2028. The market for MEG is growing because of an aging population and a desire for noninvasive diagnostic testing for neurological disorders (Jousmäki, 2022).

In neuroscience, MEG using SQUIDs (MEG-SQUIDs) is used for cognitive research and has gained more traction as a diagnostic tool. MEG-SQUIDs have slowly progressed over decades, moving from laboratory tools to clinical research settings. Though used for the study of many neurological disorders, MEG-SQUIDs only have U.S. Food and Drug Administration approval for use with epilepsy patients (Jousmäki, 2022). MEG-SQUIDs have become an important tool for noninvasive brain imaging, and breakthroughs in research for neurological conditions have advanced due to these sensors (Brooks et al., 2022; Hari and Salmelin, 2012). However, because the sensors need to sit on a patient's scalp, MEG-SQUIDs have extreme limitations on the measurements they can make. The sensors are sensitive to the surrounding environment and need cold temperatures (cryogenics) to function (Aslam et al., 2023).

Further, MEG-SQUIDs are expensive, bulky, and typically “one size fits all,” which is challenging for children, patients with disabilities, or those with metal in their heads (such as from dental work). MEG-SQUIDs have yet to make the jump to be a preferred tool by hospitals for diagnostics because of their technical complexity and data analysis methods (Clarke et al., 2018; Wang, 2023). While some research organizations use SQUIDs and have greatly benefited from the technology, there has been a desire to overcome the limitations (Safar et al., 2024).

"The limitations of SQUIDs have left researchers to search for new solutions, including myself," said NeuroscientstA, who has used MEG-SQUIDs in their research for many years.

Like SQUIDs, optically pumped magnetometers (OPM) have roots in the mid-twentieth century, as sensing technologies grew out of advances in quantum physics. OPMs use a laser to prepare a gas of atoms in a quantum state to measure a magnetic field. The sensitivity, size, weight, and power of OPMs have dramatically progressed over the last decade; in fact, OPM performance is comparable to or superior to that of SQUIDs for a wide range of magnetometry applications, with additional OPM improvements expected with further development (Tierney et al., 2019). OPMs are also smaller and more functional than SQUIDs because cryogenics are not needed (Hill et al., 2024). "OPMs are having a breakthrough moment. The right technology, right fit, right place," said the CEOOPM in the interview. First, academic researchers and companies commercializing OPM technology have developed neuroscience as an application for OPMs to overcome the limitations of SQUIDs. "While SQUIDs can measure small magnetic currents from the brain, it is very much a struggle because you can not get very close to the scalp," said CEOHelmetA. "While still in a shielded room, an array of OPM sensors on a helmet-type device can go on just about anyone and be as close to the scalp as possible. You can even have people move around, something completely unheard of with SQUID devices. We think over time, once we get regulatory approval, our technology will replace SQUIDs," CEOHelmetA continued.

CEOOPM began commercializing and miniaturizing OPM sensors from academic research in 2012. While there are other uses and customers for the OPMs, the technology shows great promise for biomagnetism (Aslam et al., 2023). CEOOPM stated that one of the goals for OPMs is to change how QS is used for biomagnetism, specifically to improve beyond MEG-

SQUID. In 2018, OPM Startup A partnered with MEG Helmet Startup A, which spun out of a company that built and engineered shielded rooms. “We had the sensors, and they had the engineering capabilities to make a sensor array on a helmet work,” said CEOOPM. A second startup, MEG Helmet Startup B, is developing an OPM-MEG helmet and creating the whole product, from the sensors to the helmet engineering. While the companies are competitors, they take different approaches to how the helmets are built and how the sensors are arrayed.

To sell the first OPM-MEG helmet to neuroscience researchers, CEOHelmetA published results in academic papers and conference presentations about early results using OPMs for MEG. Several neuroscience research organizations purchased the helmets through grant funding. “We were very hopeful for something that could measure brain activity in children and were happy when we got better results than SQUID-MEG,” NeuroscientistB said. SQUID-MEG does not allow for any patient movement, in contrast to the OPM sensors. The helmet can also be adjusted to the size of a child’s head and is overall less complicated to use (Tierney et al., 2019). “Using the OPM-MEG helmet has opened up a whole new opportunity for Autism research on little children. We have seen some groundbreaking results and changes in Autism research thanks to the OPM-MEG helmet thus far,” said NeuroscientistA in the interview.

NeuroscientistA and NeuroscientistB have been using the OPM-MEG for about a year and have published papers benchmarking the OPM-MEG. “The cost of our system was over $1 million, and it took about three years for it to be delivered,” said NeuroscientistB. “It was worth it, and one sensor in the array can be replaced easily,” quoted NeuroscientistB. Though the OPM-MEG helmet is garnering breakthroughs for neuroscientists, the helmets are still in development. There is a partnership between MEG Helmet Startup A and NeuroscientistA, which requires a physicist from the company in the lab to operate the system and help iterate on future generations. There is hope that the OPM-MEG helmet will one day replace SQUIDs and serve as a diagnostic tool for brain disease. CEOHelmetB described the vision of using the OPM-MEG helmet as a diagnostic tool for neurological disease, similar to how PET scans are used in cancer diagnostics today. “The new tools will better diagnose neurological disorders in individual patients and provide more advanced and better data to inform big-data training sets,” said CEOHelmetB in the interview. Until the tool can be used in a hospital setting as a diagnostic tool, it will gain value as a research tool that is advancing neuroscience better than previous QS. The next phase in the development of the OPM-MEG helmet is the regulatory approval process, which is costly. However, if that happens, CEOHelmetA says, “The OPM-MEG helmet will become a clinical tool, and the sky’s the limit for quantum sensors.”

4.2 Geophysical Surveying Using Quantum Gravity Gradiometer

In most cases, infrastructure development and construction projects require geophysical and ground surveying before the project can begin. This is conducted to understand the earth's subsurface and to map where utility wires, pipes, or other hazards might be located (Wei, 2016). Surveying is also done for resource extraction projects. Since there is such a need for geophysical surveys, the global geophysical survey market will be $15.01B in 2024. This market is growing quickly due to aging infrastructure and a need for additional utilities (Seismic Survey, 2024).

Many tools are used by geophysical survey organizations, including sensors that can detect electromagnetic waves or changes in gravity in things underground (Stray et al., 2021). DirectorCSC described their suite of sensors as “tools in the toolbox,” but with each tool presenting its own challenges. Specifically, one of the preferred tool options for surveying is the gravity gradiometer, as described by DirectorCSC. “A gravity gradiometer directly measures the amount of mass at the subsurface. This is very good for looking for natural or man-made voids underground. However, the existing sensors need to correct for accuracy, giving a slower averaging time and lower spatial resolutions.", DirectorCSC stated. In addition, the measurements from current tools are often affected by their environment and are limited in penetration and depth (Boddice et al., 2017; Boddice et al., 2019).

As quantum research progressed in the early twenty-first century, physicists demonstrated very sensitive measurements of gravity using QS technology that was applicable to real-world settings, such as surveying. The quantum gravity gradiometer uses cold atoms held within a vacuum chamber and manipulated with lasers to detect changes in gravity in the local environment. A classical and quantum gravity gradiometer differs because the quantum version uses the "atoms themselves as test masses" (Yu et al., 2002). Using quantum effects, this QS can provide more reliable and consistent measurements than classical gravity sensors (Bongs et al., 2019).

Physicists at a UK University studying the physics behind the quantum gravity gradiometer technology began to see applications for commercial surveying. In 2010, Physicist1's lab began working with CEResearcher and the DirectorCSC to conduct lab experiments with the quantum gravity gradiometer funded by the UK Quantum Technology Hub. "Their input was essential to see if our technology would have legs," said Physicist1. CEResearcher described the outcome of their first project together "as a better way to discover objects buried in the earth's subsurface." CEResearcher also expressed their surprise at working in a cross-disciplinary manner with physicists and at the measurement quality improvements they achieved with the first experiments. Benchmarking results have been published, with additional follow-on studies.

As the quantum gravity gradiometer progressed as a lab tool for civil engineering, it began to get better results than the current state-of-the-art technology. To quote Physicist1, “Even the lab version of the QS had the ability to avoid ground noises, get within closer range of buried objects, and take measurements faster.” Results from papers written about the quantum gravity gradiometer found a significant improvement in the detection capabilities of the QS over traditional sensors in a simulation setting (Boddice et al., 2017). CEResearcher has incorporated the quantum gravity gradiometer into their research, and to date, they have had better overall results. “We have done simulations and taken the lab version of the sensor to the field and onto a ship. Each version has built upon the last, giving better preliminary results than current sensors. We understand this won’t solve all of our surveying problems, but this is a step in the right direction,” CEResearcher said.

Like other promising QS technologies, the quantum gravity gradiometer has sparked interest beyond the research lab (Choi, 2022). A startup company was created around the initial intellectual property from a UK university to commercialize the technology and build a commercial product. The Quantum Gravity Gradiometer Startup is working in conjunction with Physicist1, their academic collaborators, and CEResearcher to advance the technology from being used by research organizations to companies like the commercial surveying company. CEOGravity described the current state of the technology as “difficult but promising …Our goal is to create Google Maps for the underground.” While the startup secured some funding and has promising initial results, the key will be to create value for users such as the commercial surveying company. “When the sensor can be produced at scale, we plan to use it, provided it benefits our customers,” said DirectorCSC. He said that the quantum gravity gradiometer will likely need additional research, training, and support from the startup company before organizations adopt it. Still, they are optimistic about its success. DirectorCSC said, “This is a great tool for research organizations, but the key to long-term organization adoption will be if the QS can continue to collect data that is better than current gravity sensors and the cost to operate is reasonable compared to current sensors.”

5.0 Analysis and Discussion

From the interviews and secondary data, several conclusions can be drawn on how organizations use quantum sensors (QS) currently and how they envision using them in the future. In addition, as QS emerges, an organizing vision (OV) is formed to guide the adoption of the technology. The following is a comparison of the two case studies and a discussion of the OV for QS.

5.1 Case analysis- Common Themes

The OPM-MEG helmet for neuroimaging and the quantum gravity gradiometer for surveying are examples of QS used by organizations today. In both cases, the individual research groups in universities developing and adopting QS act as organizations, along with the startups commercializing the technologies and the companies that will use the technologies. While the medical and geophysical surveying fields differ, the actors making up the community are primarily researchers who are interested in advancing their field and using QS in their research. Those interviewed for the study emphasized the importance of presenting their research findings using QS as a way to show positive discourse around the use of QS.

The findings show that researchers in the neuroscience and surveying application areas have used sophisticated tools such as SQUIDs and gravity gradiometers for academic research and commercial purposes. These tools were limited in capabilities, and new QS tools show promise in overcoming some of those limitations. Through interdisciplinary experiments, new QS are pushing the state of the art in these two fields and have demonstrated that QS technology can gain important data that is either better or not even possible with current tools. This has led to the possibility of adoption by other organizations beyond universities and has added value to the future of QS. The quantum gravity gradiometer's importance to geophysical surveying comes from reducing noise and providing better images faster (Stray et al., 2021). Similarly, the OPM-MEG helmet's value comes from providing better data quality on a less complex imaging platform (Brooks et al., 2022). Already, both tools are gaining better results and providing ease of use over current sensors. At scale, these tools will not replace all sensors needed for geophysical surveying or brain imaging. In the short term, they will provide the next step in advancing research for their fields. In the long term, with more development, these tools will be able to be used commercially, such as in hospitals for diagnostics or within surveying companies.

To advance QS into commercial products, the two case studies found that organizations using new QS tools work hand in hand with developers to advance the technology. For example, NeuroscientistA hosts a physicist from an OPM-MEG helmet startup in their lab to note how patients respond to the tool. This collaboration makes on-site improvements to the hardware and software possible. Similarly, the commercial surveying company will contract with the quantum gravity gradiometer startup to work side by side with their engineers to teach them how to use the quantum gravity gradiometer. Both case studies noted that these relationships informed future generations of the device and showed that partnerships are still needed for long-term sustainability. This confirms what Boston Consulting Group (BCG) wrote in a 2023 report—-the second wave of QS is still early in its commercial life and very much in development (Bobier et al., 2023).

One of the main challenges discussed in the interviews and secondary data was how QS technology would be adopted for broader use beyond research organizations. This also was the biggest difference between the two case studies. The quantum gravity gradiometer already has one commercial surveying partner and likely has an easier path to adoption than the OPM-MEG helmet. The OMP-MEG helmet works well in clinical research settings, but there are lengthy regulatory hurdles to move the tool into a broader landscape. At this point, it is unknown if the OPM-MEG helmet could ever be a neurological diagnostics tool (Pedersen et al., 2022). The quantum gravity gradiometer has an easier path to adoption as it does not have to face regulatory approvals in the same way as the MEG-OPM helmet. Still, there is much promise for both devices. As the case studies found, startup companies are taking steps to build these research tools into commercial products. Even though all of the startup companies interviewed for the project are early in their development, they each have received funding (public, private, or both) to advance the next generation of QS.

In the future, more organizations will use QS if it can be a cost-effective tool and if it can offer better commercial solutions than current sensors (Islam et al., 2024). The findings from the case studies show that QS are still very expensive to develop and ultimately purchase. The OPM-MEG helmet and the quantum gravity gradiometer benefited from grants and government funding, which pushed their development forward and allowed for application work by researchers. For wider commercial use in the future, costs will have to make sense for businesses that do not rely upon government funding (Hoofnagle and Garfinkle, 2022). How organizations use QS in the future will depend on whether current limitations, such as cost, time to build, and size, can be overcome. While both case studies concluded that the QS were better than older tools, the long-term outlook for their usage is uncertain. However, if new QS can overcome the limitations and assimilate into application areas such as neuroscience and surveying, there is strong evidence for advancement.

5.2 The Organizing Vision for Quantum Sensing

"Organizing Vision (OV) exists because a collection of social actors agrees that it exists" (Swanson and Ramiller, 1997, p. 462). Under this framework, and with headlines such as "Quantum Sensors—Unlike Quantum Computers—Are Already Here," show that the social actors for QS agree that an OV exists (Hoofnagle and Garfinkle, 2022). With the primary function of the OV being for an IT to assimilate into society, the organizations involved with this study also demonstrated that ideas are coming together to form a collective vision for the overall field of QS. In this vision, new QS ideas are better than current tools for various applications. The following defines the diverse community of players and the functions of the OV in the two application areas.

5.2.1 Community of QS

A community emerges as various organizations try to make sense of an innovation. The community also designs and creates the innovation (Swanson and Ramiller, 1997). As an emerging technology with many applications and platforms, some organizations are trying to make sense of QS while others are simultaneously trying to create it. In the case study examples, the OV community for QS comprised those developing it and those adopting it. The actors of the OV for QS includes interdisciplinary players working across organizations, all of whom are interested in the long-term assimilation of QS for their applications and for the field of QS as a whole.

The OV framework can be applied to emerging IS technologies at the macro level (Parameswaran et al., 2023). At the macro level, the larger community comes together. OV community for QS is large and spans many applications where the community has to come together for long term advancement of QS technology. Swanson and Ramiller point out that even when "individual" organizations adopt an innovation, it is likely to engage others in the community, growing the community. The case studies demonstrated that engagement. The greater community is organically originated, with individual research groups acting as organizations. The macro QS community starts with the physics researchers in academia developing the basics of the technology before the companies commercializing the technology become part of the community. Finally, the community grows to include the organizations using the QS, such as the Neuroscientists interviewed for this study. From the physicists to the researchers, the greater community tries to make sense of QS by working together.

Table 2.3 provides examples of current members of the OV community for QS at the macro level. These additional players help shape the discourse about QS in a public forum. Swanson and Ramiller emphasize the importance of public forums, including conferences, exhibits, and news articles, in expanding the community and its discourse. The researchers using QS in this study have academic papers reporting their results and are attending conferences in their field and about quantum technologies in general. All of the actors of the QS community are creating a rich discourse that is shaping the vision for QS with future commercial applications in mind, forming the OV.

Swanson and Ramiller describe the community as consisting of many actors beyond developers and early users. For QS, this includes component suppliers, journalists, and management consultants. In the example case studies, these additional actors include QS component suppliers and management consulting firms, such as BCG and McKinsey, who report to a greater audience about QS. In the future, the community will grow to include additional organizations.

Table 2. 3 Examples of current members of the OV community for QS

Roles in Developing the OV for QS	**Examples of Individuals and Organizations**
QS academics	Researchers in quantum labs at universities
QS adopters and users	Research hospitals, ground surveying companies
QS developers	QS startups
Vendors	QS component suppliers
QS consultants	Management consulting firms
Other QS discourse providers	Conference organizers, journalists

5.2.2. Functions of OV for QS

The OV plays three key functions in adopting and diffusing technological innovations. The following outlines the three functions as they relate to QS.

Interpretation The first function of the OV is to explain the technology, why it exists, and why it is relevant, as “emerging IS technology is not necessarily grasped or understood” (Swanson and Ramiller, 1997, p. 460). With QS's many architectures and applications, much is left for interpretation (Harris, 2022). Through academic experiments and commercialization, what Swanson and Ramiller call the “pioneers” (academics) and entrepreneurs experiment with QS. These pioneers are similar to those interviewed for the case studies. Examples of the earliest interpretation of QS come from the papers in the 1970s reporting the use of SQUIDs for biomagnetism (Körber et al., 2016). At the time, quantum mechanics was only beginning to be understood in terms of what it could do for technology development. The interpretation was the start of how QS could become relevant to a medical application and the beginnings of an OV around the innovation. Much research has since followed suit, including that conducted by those interviewed for the case study on MEG.

Interpretation is also about developing a common story for the OV. While this type of discourse can happen on several levels, one of the main platforms for interpretation for QS has been in writing. First, academics write and publish articles and research papers that lay the groundwork for explaining the mechanics of QS, why QS exists, and why QS is relevant from an application and user standpoint. In the example case study of geophysical surveying, the initial results reported in a research paper showed that quantum technology could be useful to the civil engineering community (Boddice et al., 2017). Second, the media creates the "buzzwords" around QS and introduces the technology into the mainstream. This is where the OV expands into a wider community, as seen through headlines (especially positive ones), such as breakthroughs in autism research due to the OPM-MEG helmet (Delete and Sambi, 2021). The QS story is, at this point, still in its formation and discussion stage, giving academic papers and mainstream periodicals an essential role in interpretation.

Legitimation The main focus of the second function of the OV, legitimation, is to ask, "Why do it?" Swanson and Ramiller point out that the answer to the question is not because everyone else is doing it (Swanson and Ramiller, 1997, p. 461). For QS technology, the main answer to the "Why do it?" question has been about its benefits to disrupt current state-of-the-art sensors and discover unknown, superior functionality. Despite this purpose, it has been hard to convince governments and industry to adopt and fund QS (Bongs, 2023).The answer to the research question lies in the organizational use and ultimate commercialization of QS, now and in the future, would provide legitimacy to QS and would act as a function for the OV. Putting QS in the “real world” with users such as neuroscientists or geophysical surveyors validates the use of the technology in a wider setting, especially when the results in real-world scenarios have been positive. These results, as well as the initial testing and the continued use of QS for surveying, are further legitimation as part of the overall OV for QS.

Additionally, legitimation is promoted by “the reputation and authority of those who promulgate it” (Swanson and Ramiller, 1997, p. 461). BCG, McKinsey, and Citi are respected banking and management firms that analyze emerging technologies and an innovation's impact on global markets. These reports are read and considered by government officials, executives of prominent corporations, and public and private funders. Reports highlighting QS and its potential and applications have been created and widely distributed in the past few years: McKinsey in December 2021, BCG in July 2023, and Citi Global Insights in March 2024. Each of these reports explained the importance of future QS use, adding legitimation to the technology. The BCG report states, “Even if the use cases seem distant, the time to prepare is near,” implying that QS technology is legitimate (Bobier et al., 2023). Though all three reports mentioned that much more development is needed before QS can be adopted at scale, they stated the promise and positive effects that QS can have in the long term. These highly respected reports help answer “Why do it?” to less technical readers. These reports also add to the discourse and the community, building the OV and legitimating the technology.

Mobilization The function of the OV is to mobilize everyone into involvement with the innovation, from those already part of the OV community to future adopters and funders. The function of mobilization makes it critical to understand how organizations are using QS and how they will use it in the future because, as Swanson and Ramiller state, “Would-be adopters look to the market for needed resources, including hardware, software, and skills, following clues and guidelines embedded in the OV" (Swanson and Ramiller, 1997 p. 461). While QS is already a reality, there are barriers to vast mobilization due to usage challenges (i.e., SQUIDs for detection of biomagnetism), lack of expertise in QS, or the nascent nature of the technology. The case study of the OPM MEG helmet, however, is an example of the early mobilization of QS technology. While the technology started out in one research lab for the study of autism in children, it has now been used in several labs worldwide for research in various neurological disorders, from dementia to epilepsy (University of Nottingham, 2024; Pedersen et al., 2022). As discussed, with further mobilization, the OPM-MEG helmet could become a clinical tool used in diagnostics. Under OV theory, the OPM-MEG helmet is an example of "a creative force in activating and shaping the marketplace" (Swanson and Ramiller, 1997 p. 461).

Another part of the function of mobilization comes in the form of resources. Emerging technology needs funding to succeed. Venture capital has invested over $5.5B in the last three years into quantum technologies as a whole, with many governments creating public funding opportunities to advance quantum information science and commercialization. However, much of this funding has gone to QC (Jurczak, 2023). From an economic standpoint, the QS market is much smaller than the QC market. In fact, McKinsey estimates that the QS market is one-fifth the size of the QC market (Mohr et al., 2023). However, in 2023, venture capital funding to QS companies increased to over $80M invested (Islam et al., 2024). The increase in private funding demonstrates a mobilization of QS technology and private funder interest in being part of the interorganizational community.

5.3 Limitations and Future Research Opportunities

Criticism of QS comes from being seen as too varied in applications with small markers (Harris, 2022). While applications in industries might be varied, the initial search revealed nine industries working with QS. This study was limited to two promising application areas, medical (neuroscience) and geophysical surveying, to provide examples of how organizations currently work with QS and how they envision this work in the future. The study only examined two QS architectures, OPMs, and quantum gravity gradiometers. Various industries are experimenting with other QS platforms, including the two application areas in this study. For instance, solid-state defect QS are also used to explore biomagnetism in the heart and brain, but they are less advanced than OPMs and not currently in clinical settings (Aslam et al., 2023).

There can be follow-on work to this study with various other industries, applications, and sensing architectures. One suggested area to replicate this study is for military applications. Government and defense organizations use QS for enhanced measurement capabilities, specifically for GPS and timing (Krelina, 2021). The energy sector is another exciting application area of QS, and organizations in that field are using various QS platforms for research projects with the hopes of someday having sector-specific commercial products (Crawford, 2021).

This study was also limited in time. The initial literature review to identify application areas, interviews, and secondary data collection were done over a six-month period. QS is an emerging field, and as technology advances, a follow-on study looking more in-depth at QS development would add additional color to the study and allow for further evolution of organizations using QS. Lastly, this study focused on Western, English-speaking organizations, specifically in the United States, the United Kingdom, and Canada. QS technology development is not limited to the Western world. This technology is being developed worldwide, and many governments and private investors are interested in advancing it (Jurzack, 2023). Follow-on studies could enhance this research through additional comparisons to organizations using QS in different countries.

6.0 Conclusion

QS has emerged as an impactful pillar of quantum science with many benefits across economic sectors (Crawford, 2021). The “second quantum revolution” has allowed for technological advances in precision, quality, reliability, size, weight, and power of quantum technologies, which have historically and socially suited QS to form a community outside physicists' laboratories. With QS's highly diverse applications and potential for ease of scaling (especially compared to QC), the interorganizational community is developing and sharing an OV to advance their research and their field. The development of a vision for QS technology comes from knowing how organizations are using QS technology now and how they will use it in the future. Specifically, in the last decade, this discourse has evolved from promising science experiments into actual products, such as the OPM-MEG helmet and the quantum gravity gradiometer. With the rise of public and private funding for quantum technology, there is a drive to develop the technology into commercially available tools such as these for wider organizational use (Jurczak, 2023).

As the findings from the case studies showed, through interdisciplinary experiments, researchers are using QS to push the state of the art. This research has the potential for far-reaching implications beyond research organizations and will help dictate how QS is used in the future. The overall OV community for QS has become vast and broad, and the dialogue accompanying it has become richer. While this study only covered two application areas of QS, other applications are finding success through promising results and organizations using and adopting QS (Ali, 2023). However, significant development and mobilization are still needed for mass adoption by those interested in QS. It is quite possible that some QS architectures will take off and others will fail. The OV will continue to change over time to reflect this.

The evolution of QS does not have to be coherent under OV theory. The theory behind OV is that a vision forms with a community and through discourse. This is exactly what is happening, as seen through the case studies. Though the goals of an autism researcher and a civil engineering researcher are different, they are both part of the greater QS community and part of the interpreting, legitimation and mobilizing process for the adoption and diffusion of QS under OV theory. As QS progresses, the OV will guide the adoption and understanding of how organizations will use QS, both now and in the future. The key driver for long-term assimilation will be continued interpretation, legitimation, and mobilization in order to move from physicist's labs to commercial tools.

Appendix A: Preset Questions Asked to Interviewees

For Users of Quantum Sensor:

- Adoption: How are you currently using quantum sensors?
- Adoption: What is the driving factor for your company to take on quantum sensing projects? Were they internal or external factors (such as grants or customers)?
- Adoption: Were there/are there any expectations for quantum sensing projects?
- Adoption: How does the use of quantum sensors compare to other emerging technologies you have used?
- Adoption: How much are you relying upon partnerships with outside entities for quantum sensing development? If so, what type of companies are they (suppliers, startups, for example)?
- Benefits/Limitations: What, if any, benefit is you seeing with early quantum sensing technology, even if it is still in research?
- Benefits/Limitations: Do you believe your company has an advantage over others not working in quantum sensing in your field?
- Benefits/Limitations: What resources has your company dedicated to quantum sensing projects (e.g., staff, internal funds)?

- Benefits/Limitations: What are the most significant barriers to mass adoption of quantum sensors, both for your company and the field of quantum sensing as a whole?
- Future use: Do you see your company continuing to work on quantum sensing research/development of quantum sensors?
- Future use: What are you looking for in regard to future quantum sensors?

For Developers of Quantum Sensors:

- Describe the quantum sensing technology you are developing.
- What are the main use cases of the quantum sensors you are developing?
- How do sales happen?
- Are there any current users of your technology? If so, who?
- Describe the benefits and limitations of your technology.
- Who are some of your partners? How do you work with them?
- What is your long-term vision for your quantum sensors?
- What are the biggest barriers to quantum sensing technological advancement?

Essay 3: Understanding the Relationship Between Quantum Technologies and Artificial Intelligence

Abstract

Technologies harnessing the power of quantum mechanics hold great promise for the future. From quantum computers to quantum sensors to quantum cryptography, research organizations and large companies are beginning to investigate how quantum technologies (QT) can be integrated into business systems and processes. Similarly, artificial intelligence (AI) is starting to become incorporated into common systems and is advancing through research and commercialization. This Essay uses Grounded Theory techniques to examine the intersection of QT and AI through a literature review of academic and practitioner works. Findings from this review show that QT is advancing AI and machine learning (ML) through increased computational power and the creation of algorithms utilizing the effects of quantum mechanics. AI is advancing QT through better processing of quantum sensing data and playing a role in post-quantum security protocols. This essay also looks at current challenges in the relationship between QT and AI and makes recommendations for stakeholders involved with the technologies.

1.0 Introduction

"It's a partnership that could change the world" is a quote in *Forbes* online from November 2023 that describes the relationship between artificial intelligence (AI) and quantum computing (Reichental, 2023). The quote describes the transformational synergy between the two technologies. At scale, some believe quantum technology (QT) and AI have the potential to transform modern society (Najafi et al., 2022). Groundbreaking results from top academics fuel this sentiment and have brought about further technological exploration in recent years (Perez et al., 2023). Due to the aspirational nature of these technologies, both independently and together, combined with positive technological progress, QT and AI have received mainstream attention, which some leading academics have described as "hype" (Das Sarma, 2022). Much of the attention comes from business leaders and policymakers, who control public and private research dollars. For example, major corporations such as Microsoft, IBM, and Google have invested in research and business strategies to drive development and interest in the intersection of QT and AI and in the emerging subfield of quantum machine learning (QML), which combines the two technologies (Patel, 2024).

Though promising, the relationship between QT and AI is constantly evolving and the subsequent implications are unclear for both near-term technical progress and long-term application realization (Perez et al., 2023). There is much speculation and debate among relevant research communities about whether and how the relationship between QT and AI will advance existing capabilities and future applications (Herman, 2024). Therefore, it is important to understand the current capabilities and limitations of what the technologies can do together and to assess the dynamics of the QT/AI relationship, including how academic, government and commercial stakeholder communities can advance the technologies.

In their present form, the intersection of QT and AI needs much more research, development, and application maturation to establish necessary technical capabilities, provide commercial utility, and be accepted by the general population. Part of the necessary development for both technologies is their interplay, e.g., utilizing AI/ML for QT and vice versa, examining differences in relative technical maturity, and exploring tension in the near-term availability of investment. While AI/ML and QT researchers are beginning to find joint benefits and applications in certain areas, leaders of corporations, startups, universities, and governments are trying to understand the relationship between QT and AI and where and how they can exist and work together.

This dynamic situation leads to a critical research question: **What is the current relationship between quantum technology (QT) and artificial intelligence (AI)?** The answer will be explored through a descriptive literature review using Grounded Theory as a technique for analysis. Based on the analysis of these findings, this essay aims to provide recommendations to entrepreneurs, policymakers, and corporate and university leaders. In the short term, understanding the relationship in its current state can guide existing capabilities and future applications of QT and AI. It can also help discern between realistic progress and unfounded hype. In the long term, understanding this relationship is key to guiding the co-development of the two technologies and the future realization of their impactful applications.

2.0 Methods

This essay aims to provide an understanding of the relationship between QT and AI and make recommendations to organizational leaders. To do this, I conducted a literature review to analyze and examine a breadth of recent literature on the subject (Grant & Booth, 2009). This analysis combines academic and practitioner literature collected through various databases using key terms and then summarizes and synthesizes the literature on the relationship between QT and AI (Webster & Watson, 2002). The synthesis took on a "descriptive review format." The descriptive review format of "summarization of prior knowledge" reveals trends within a representative sample of published work (Paré et al., 2014).

While there are several theories to analyze the evolution and adoption of technologies (e.g., Diffusion of Innovations), this essay is focused on finding key concepts in academic and practitioner literature to make conclusions about the relationship between QT and AI. Therefore, the analysis of this literature review does not invoke any extant theories. However, under the descriptive review format, the prior knowledge still needs to be summarized and synthesized (Paré et al., 2014). To do this, the techniques of coding to reveal patterns and then generate theories found in Grounded Theory was used to provide the analysis for the literature review (Deering & Williams, 2020). Because the Grounded Theory approach is inductive in nature the technique identifies and analyzes trends, allowing for key concepts to emerge during the analytical process through coding making it ideal to form conclusions from the literature on the relationship between QT and AI (Wolfswinkel et al., 2013). While Grounded Theory is typically used as a method Wolfswinkel et al. states, "When use is made of Grounded Theory for literature review purposes, the data has the form of published papers rather than the documentary evidence coming from the customary open-ended interview; ethnographic observational notes or conversational analysis coded transcripts." The process of coding based on key concept words allowed for the development of a descriptive literature review of the current relationship between QT and AI; it also drew on patterns to make conclusions and recommendations. To give structure to this literature review, I followed the 5-stage method of Grounded Theory as a review technique outlined by Wolfswinkel et al. (2013): define, search, select, analyze, and present.

2.1 Define the Scope of the Literature Review

To start, it was necessary to understand the technical themes at the intersection of QT and AI to narrow the scope to relevant terms. To do this, terms referencing AI and ML were gathered from topics listed in the calls for papers, panel topics, or agendas from quantum conferences in 2024 based on a published list of quantum technology conferences (Quantum Technology Lab, 2024). First, I looked at conferences that had “machine learning (ML)” or “artificial intelligence (AI)” in the title. Second, I looked at conferences focused on applications of QT, business, or policy, such as the Quantum World Congress and the Q2B conference. Last, I looked for conferences hosted by large, well-known entities such as IEEE, Optica, and NVIDIA. In total, the research included visiting twelve conference websites. Nine of the twelve conferences mentioned AI/ML through panel sessions or a call for papers in 2024. The list of those conferences can be found in Appendix A.

For each conference selected in the previous step, terms referencing AI/ML were gathered from the topics listed in the calls for papers, panel topics, or agendas. Once duplicate terms were filtered out, I was left with twelve terms: (1) quantum neural networks; (2) quantum-enhanced machine learning/quantum machine learning (QML); (3) quantum simulations for ML; (4) quantum algorithms for machine learning tasks; (5) hybrid classical-quantum algorithms; (6) Noisy Intermediate-Scale Quantum (NISQ) era machine learning; (7) quantum reinforcement learning; (8) quantum driven deep learning; (9) quantum parallelism; (10) quantum enabled support vector machines; (11) generative AI models for quantum; and (12) ML decoding. These terms provided the technical themes at the intersection of QT and AI and were part of the scope for analysis of the relationship between QT and ML.

In addition to the technical terms I defined, more general search terms were created for academic and practitioner literature. The following search terms for academic and practitioner literature were used: (1) “quantum + artificial intelligence/AI”; (2) “quantum + machine learning/ML”; (3) “users of quantum + artificial intelligence/AI”; (4) “users of quantum + machine learning/ML”; (5) “applications of quantum + artificial intelligence/AI”; (6) “applications of quantum + machine learning/ML”; (7) “commercial applications of quantum technologies + artificial intelligence/AI”; (8) “commercial applications of quantum technologies + artificial intelligence/AI”; (9) “relationship between quantum technology/technologies and artificial intelligence/AI”; (10) “relationship between quantum technology/technologies and machine learning/ML”; and (11) “challenges of quantum technology/technologies and artificial intelligence/AI.”

Finally, since QT and AI are rapidly growing fields, I chose to narrow the scope of the literature to encompass only the last five years (2019 through the present day) to gain a current view of the relationship. Five years was determined to be an appropriate time to gain a current snapshot due to the ever-evolving natures of QT and AI.

2.2 Search the Literature

The academic literature search was done using Google Scholar, as it provided the most comprehensive database to gather academic literature. The search terms outlined in the scope of the review (listed in section 2.1) were used. In addition to academic literature, practitioners' literature on the relationship between QT and AI was investigated. To keep the search for practitioners’ literature consistent with the search for academic literature, the same search terms were used on LinkedIn, Google News, and NexisUni, which are trusted search engines for practitioner literature.

2.3 Select Articles

To narrow down the search results and select the articles to be read and considered for the review, the texts' titles and abstracts were first examined. Papers that were not focused on the relationship between QT and AI and their applications were eliminated. Papers with titles and abstracts emphasizing the relationship between QT and AI and their applications were selected, with attention paid to the terms gathered from the study of conferences. Additional papers were added to the sample by reviewing the reference lists of selected papers. In total, sixty-seven academic papers were collected.

The same elimination criteria used for the academic papers search was also used for the practitioner's literature search. The initial search results produced a high volume of articles, as practitioner's literature is typically written for broader audiences than academic literature. To eliminate articles that were not relevant, headlines were reviewed for relevance; if the source was still seemingly ambiguous, the full article was reviewed. Articles that were not application-focused or irrelevant to the relationship between the two technologies were eliminated. Only relevant articles and press releases came from reputable sources, such as *Forbes* and *VentureBeat,* as well as major newspapers, magazines, and international technical industry online media were selected, with emphasis on sources from Western countries. Reports originating from top management firms such as McKinsey & Company and Boston Consulting Group (BCG) that were relevant were also selected. Next, relevant articles from leading online technical and quantum media outlets, such as *The Quantum Insider,* were selected, along with articles published by reputable companies working at the intersection of QT and AI, such as Quera, IBM, and SandboxAQ. Finally, relevant LinkedIn articles from authors with a background in QT and/or AI were selected. In total, 129 practitioner’s articles were included.

2.4 Analyze the Selected Articles

In the Grounded Theory style, I started with open coding, and Figure 3.1 shows the coding scheme I used. First, as I read through all of the literature, I did open coding based on broad topics in the literature that would answer the research question. The broad topics that emerged were (1) the relationship between QT and AI; (2) applications of joint QT and AI; and (3) challenges of the relationship between QT and AI.

Next, I conducted four rounds of axial coding based on the broad topics of the open coding. First, I coded based on applications with repetitive mentions in the literature, such as energy, medical diagnostics, and financial services. Second, I coded for the type of quantum technology, including quantum sensors, quantum computers, quantum algorithms, and quantum cryptography. Third, I coded the literature using the twelve terms derived from searching QT conferences (listed in section 2.1). Finally, I coded the literature based on where I believed entrepreneurs, policymakers, and corporate and university leaders would find value in the information since this essay aims to make recommendations to these stakeholder groups. All the academic and practitioner literature selected fell into at least one category, and many encompassed multiple categories.

Last, I conducted selective coding, which is described as "the process of identifying and developing relations between the main categories" (Wolfswinkel et al., 2013, p. 51). In this step, I refined the coding framework to evaluate the main research question: what is the relationship between QT and AI? I looked for patterns in the literature and in the past coding rounds that denoted specifically how QT and AI were connected, along with the benefits and challenges of the technologies and their interactions. The main themes of the findings emerged: (1) QT is advancing AI; (2) AI is advancing QT; and (3) the challenges of the relationship. Figure 3.1

demonstrated the full coding structure. Memos were written to keep detailed notes of the findings. The memos provided a way to document insights needed for the literature review and recommendations.

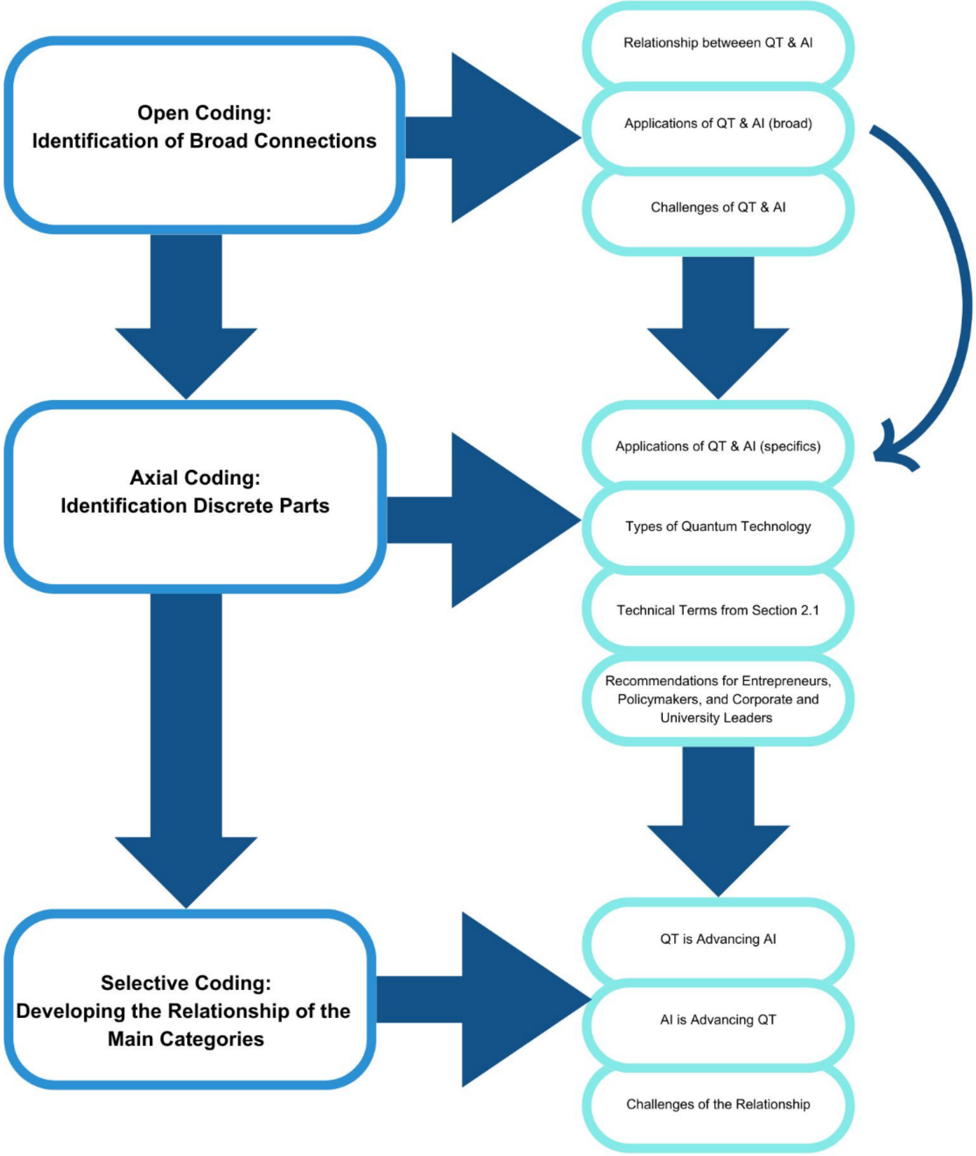


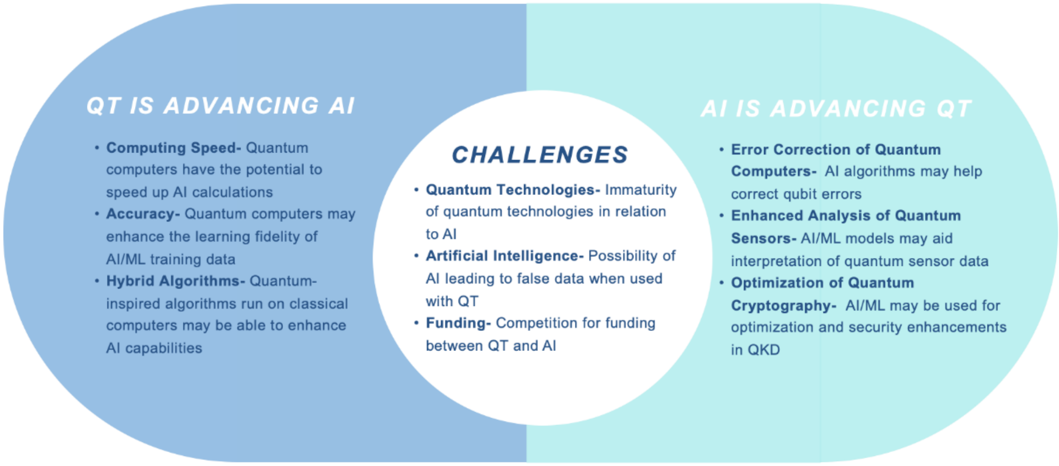
Figure 3. 1 Coding Structure

3.0 Findings

The rise in recent years of machine learning (ML) — a subset of AI in which a neural network is trained on, and thereby learns from, large data sets — has found great interest from researchers using ML in physics and combining it with quantum information science (Schuff et al., 2020). This effort is a natural progression, as ML computations involve linear algebra, which is also the core mathematical language of QT, specifically quantum computing (Arrazola, 2020). Therefore, one of the most exciting areas of growth in both QT and AI research has been quantum machine learning (QML), which marries the two fields (Peral-Garcia et al., 2024).

Since ML is made up of two components (the data and the learning), QML can consist of classical data run on a quantum machine or the process of data gathered from quantum experiments with classical machine learning methods (How & Cheah, 2024; Wei et al., 2023). Initially, only data generated by quantum computers could be analyzed on quantum computers. Due to research advancements over the last five years, classical and quantum data can be run on a quantum computer, leading to growth in the relationship between quantum computing and AI/ML (Zhang & Ni, 2024). Much of this growth comes from joint research and development projects where large companies are at the forefront of productizing the intersection of QT and AI, and academics working on QT are incorporating ML techniques into their research with positive results (Chauhan et al., 2022). The findings reveal that the relationship has grown to focus on two main points: QT is helping advance AI and AI is helping advance QT. Applications where the two technologies work together span industries from pharmaceuticals to finance. The literature around the relationship demonstrates an evolving and complicated partnership. Challenges surround technology maturity and the competition for limited funds. Ultimately, the relationship between QT and AI is symbiotic, with collaborative integration (Kim et al., 2021).

Figure 3.2 summarizes the findings of the literature review, with further detail in the subsequent sections.



QT IS ADVANCING AI

- **Computing Speed-** Quantum computers have the potential to speed up AI calculations
- **Accuracy-** Quantum computers may enhance the learning fidelity of AI/ML training data
- **Hybrid Algorithms-** Quantum-inspired algorithms run on classical computers may be able to enhance AI capabilities

CHALLENGES

- **Quantum Technologies-** Immaturity of quantum technologies in relation to AI
- **Artificial Intelligence-** Possibility of AI leading to false data when used with QT
- **Funding-** Competition for funding between QT and AI

AI IS ADVANCING QT

- **Error Correction of Quantum Computers-** AI algorithms may help correct qubit errors
- **Enhanced Analysis of Quantum Sensors-** AI/ML models may aid interpretation of quantum sensor data
- **Optimization of Quantum Cryptography-** AI/ML may be used for optimization and security enhancements in QKD

Figure 3. 2 Key Findings Summary

3.1 Quantum Technology Is Advancing Artificial Intelligence

QT, specifically quantum computers, have been a driver of the advancement of AI in recent times. Quantum computers use qubits, a linear combination of 1s and 0s simultaneously, made possible through quantum mechanics in a state known as superposition (Abdelgaber & Nikolopoulos, 2020). Superposition and the principle of entanglement (in which two particles are connected and affect one another even if far apart) make qubits unique and more powerful than classical bits. However, quantum computers are challenged by the level of sensitivity of the qubits to their surrounding environment. Even the slightest change in temperature or magnetic currents can disrupt the unique quantum benefits of the bits. Due to this, today's early quantum computers are noisy intermediate-scale quantum computers (NISQ) with limited capabilities (Gill et al., 2024). However, during this "NISQ era," quantum computers have progressed in recent years due to excitement about the possibilities, funding, and research (Preskill, 2018). The ability to error-correct qubits to make up for noise will advance AI and other uses of quantum computers, although much research and engineering is needed to get to that point (Bova et al., 2021). Similarly, AI is currently limited by the computing power from silicon-based hardware (classical computers) (Reichental, 2023). While much development is needed, there are core ways in which QT is advancing AI. The following sections provide current examples that will likely continue as further development happens.

3.1.1 Computing speed

Though quantum computing hardware platforms are still in early development, quantum computers, even in the NISQ era, are believed to have advanced computing power and calculation speed beyond the best supercomputers (Bova et al., 2021). This is because quantum computers can run computations in parallel, a process called quantum parallelism (Quera, 2023; Atadoga et al., 2024). The exponential speed-up of the power offered by quantum computers has become a driver for the advancement of AI. This is occurring because AI is a mathematically intensive form of calculating ML algorithms, often for many at once (Chauhan et al., 2022). For complex deep learning problems, such as some highly involved financial calculations, the process requires very powerful processors on special supercomputers housed at national labs and corporations to run these models. However, these computers are still inherently “classical,” meaning they run basic binary bits in 1s and 0s and will eventually reach their limits (How & Cheah, 2024). These computers are often slow and can lag even further as calculations get more complex (Rao, 2024).

Through experiments run on current quantum computers or through quantum simulations, researchers in companies and academia are seeing improvements in the speed, energy usage, precision, and accuracy of AI data (Pymnts, 2024). It is hypothesized that quantum computers are capable of solving problems up to 100 million times faster than traditional computers (Law, 2023). This translates to AI, through which the speed of calculations from QML has allowed for AI models for trading in the financial sector to make decisions faster (Atadoga et al., 2024). AI simulations of daily trading have also seen noticeable differences in speed when quantum is used over classical computing (Orus et al., 2019). As the relationship between quantum computing and AI develops, finance is just one example of a sector that will benefit from reducing computing time for AI calculations. Other sectors working at the intersection of QT and AI that would benefit from increased computing speed include the automotive and medical industries. Both fields process large amounts of data from images, which can be slowed due to complex algorithms computed on classical computers (QUTAC, 2021; Wei et al., 2023).

3.1.2 Accuracy of Machine Learning

In addition to increased speed, early research demonstrates that the relationship between quantum computers and AI has benefits for the accuracy of ML. Using the effects of quantum computers, such as superposition and entanglement, better data training may be possible when the learning models are deployed on a quantum computer (Abbas et al., 2021). Part AI's process is the identification of patterns, especially in large data models (Merritt, 2024). As the amount of data grows, neural networks can face significant computational challenges on classical computers and lose accuracy. These challenges often occur in image-heavy networks that require complex classifications, such as in medical imaging or media cataloging (Senokosov et al., 2024). With further development, machine learning done on a quantum computer could potentially recognize patterns that a classical computer might miss, especially in large networks (Castelvecchi, 2024). This potential application has implications for the medical diagnostics field, where AI has assisted highly trained medics in pattern recognition of medical images and comparison of medical data. With terabytes of information on just a single patient, the use of a quantum computer along with AI has the potential for greater accuracy in the prediction of a disease and its progression; this could be achieved through searching a larger space at one time and clustering results more effectively if done with a quantum computer (Ullah & Garcia-Zapirain, 2023).

3.1.3 Hybrid (Quantum-Classical) Algorithms

With quantum computing currently in the NISQ era, researchers have developed ways to take advantage of the benefits of quantum computing on current classical computers through hybrid quantum-classical algorithms. These specialized algorithms apply quantum software engineering and classical information processing to improve ML techniques and gain the increased speed and accuracy seen with early quantum computers (Chauhan, 2022). The creation of specialized hybrid algorithms has grown the relationship between QT and AI, because these algorithms can emulate quantum behavior on more easily accessible classical computers (Melnikov et al., 2023). Some of the earliest-use cases for new hybrid algorithms are the optimization and improvement of AI models and training (Pymnts, 2024; Cerezo, 2022). For instance, support vector machines (SVM) are a well-known ML method used for classifying data to gain optimization of the ML model. When run with quantum circuits, SVMs are able to take advantage of algorithms created for quantum machines, including faster training time (Kavitha & Kaulgud, 2024). The limitations of current quantum computers are consequently circumvented due to the use of classical machines (Karagiannis, 2023). Today, one of the fastest-growing areas of research between QT and AI comes in the form of hybrid algorithms because error correction of the qubits is not needed (Huynh et al., 2023). With the rise of data, for example, coming from connected devices, hybrid quantum algorithms are being investigated as solutions for the need to accelerate ML optimization tasks while still relying on classical computing (Peelam et al., 2023).

3.2 Artificial Intelligence Is Advancing Quantum Technology

Quantum technologies, whether hardware or software, have high barriers to entry and rely on component technologies for advancement (Kim et al., 2021). Examples of component technologies are the lasers needed for quantum computers or sensors and the cloud infrastructures allowing users to access quantum computers. Similar to those examples, AI is becoming a component technology that is advancing QT. While the relationship primarily has quantum computing advancing AI, AI has implications for various technologies using principles of quantum physics and their applications (Pinuaga et al., 2024). As experiments using QT gain sophistication and the technologies advance, new data sets will come from quantum experiments that AI and ML will be used to interpret or improve results (Abbasi, 2023). The following are examples of how AI is currently advancing QT and will likely affect it in the future.

3.2.1 Error Correction in Quantum Computing

One of the significant challenges in quantum computing is the future ability to scale quantum computers due to the qubit's susceptibility to noise. While quantum computing hardware companies have made progress in managing noise, it is a difficult process to error-correct the qubits (Gill et al., 2024). This lengthy process involves manipulating qubits into “logical qubits,” where multiple noisy qubits can accept quantum information, perform algorithmic operations with the qubits, and then detect and correct any errors (Zhao, 2023). Finding additional easier and faster ways to create and error-correct logical qubits could lead to increased usability of quantum computers. It is hypothesized that AI can play a crucial role in the error correction process by optimizing the quantum system (Abdelgaber & Nikolopoulos, 2020). Because AI techniques, such as reinforcement learning, are known to be good at decoding data, new research has shown that these techniques can create quantum error correction codes that detect and correct errors without direct access to the qubits in their delicate state (Papierz, 2023). Early research done on an IBM quantum machine has found that an ML-based decoder can process information obtained from qubit measurements and suggest corrections (Bravyi et al., 2024). As ML for quantum error correction advances, it can make quantum computing more reliable and efficient, leading to new applications for quantum computing (Papierz, 2023).

3.2.2 Enhanced Analysis of Quantum Sensors

The properties that make quantum computing qubits inherently fragile (for instance, superposition and entanglement) and extremely sensitive to the environment are the same factors that quantum sensors leverage to make high-precision measurements, such as those for gravity or magnetism (Pinuaga et al., 2024). However, quantum sensors can also be sensitive to unwanted aspects of their surroundings (e.g., variation in ambient temperature), and the resulting interference can affect the sensor's output and precision. Therefore, most types of current quantum sensors today require calibration, technical overhead to compensate for unwanted environmental effects, and regular characterization, which can be a complex process that increases instrument cost. In particular, the nature of reinforcement learning as part of ML algorithms can contribute to optimizing quantum sensors that require calibration, environmental compensation, or characterization, leading to increased efficiency in sensor performance (Cimini et al., 2019; SPIE, 2023). With ML techniques, higher-fidelity information can be extracted from the sensors by appropriately interpreting their output and controlling them via a network that has been trained with properly calibrated sensors under wide-ranging conditions. ML techniques will thus lead to more efficient system design and potentially better performance (Belliardo et al., 2024). In addition, as research and development of quantum sensors advance, new data will be coming from their increasingly diverse applications, snowballing into even better ML network training (Krelina, 2021). It is also possible that ML can play a role in the interpretation of complicated data by combining measurements of various quantum sensing experiments, such as those from particle accelerators (Castelvecchi, 2024). Furthermore, companies looking to monetize the data from quantum sensors are developing generative AI models to infer data for variables that cannot be measured directly (Kerstens, 2023). This could lead to more effective real-time monitoring of environmental conditions, space exploration, or biomedical imaging through the advancement of quantum sensors and ML (Jain, 2024).

3.2.3 Optimization of Quantum Cryptography

Classical cryptography uses algorithms based on mathematics (such as the factorization of prime numbers) to secure data. Quantum cryptography, and specifically quantum key distribution (QKD), does not use the same mathematical algorithms as traditional cryptography methods. Instead, quantum cryptography is rooted in the principles of quantum mechanics to secure transmitted data and detect eavesdropping (Chintakunta, 2023; Zhao et al., 2021). In classic cryptography, ML detects patterns and identifies abnormalities that could indicate cyber threats. From this point, the idea of using ML has expanded to quantum cryptography. Similar to classical cryptography, ML tools can help optimize quantum cryptography through the detection of patterns. This helps elevate security and effectiveness and makes quantum cryptographic security protocols more adaptable and efficient (Radanliev, 2024).

Further, QKD has been used to safeguard data in the early era of quantum computing to advance encryption methods to meet evolving technological challenges (Patel, 2024). Researchers have advanced QKD through ML to improve performance in such applications as predicted system-to-noise ratios (Zhao et al., 2021). Additional ML algorithms are being utilized to enhance the security of QKD systems by detecting potential attacks (Quantum News, 2024). These advancements have implications for future 6G networks, as the marriage of QKD and ML could foster technologies needed for the advancement of telecommunications (García et al., 2024). Additionally, post-quantum cryptography (PQC), the creation of security protocols and algorithms to secure digital communications from quantum computers, is emerging as a sub-field of quantum cryptography (Koon, 2023). These protocols use mathematical problems that are believed to be resistant to attacks by quantum computers. AI/ML adds value to the monitoring of PQC protocols and continues to be developed by cybersecurity companies and by the national security agencies of many countries (Pirone, 2023).

3.3 Challenges for the Relationship

The relationship between QT and AI has allowed both technologies to evolve together and create the new field of QML. However, as the relationship evolves, it also leads to challenges. Some of the biggest questions about the relationship surround the differences in the maturity of the technologies. QT are mostly still research projects, often with promising commercial applications, while AI is a rapidly changing technology in more frequent use (Coccia, 2024). The following are examples of the challenges of the relationship based on the immaturity of the technologies and their funding.

3.3.1 Challenges of Quantum Technology

Various types of QT are finding advantages in niche applications, but further research and development is needed for widespread commercialization (Bretzfield, 2023). Challenges in the QT and AI relationship have emerged because AI technology is developing faster than QT. With today’s AI/ML being more advanced than QT (specifically in computing), AI researchers are waiting for quantum computing to become further developed and more mainstream; this development will allow them to take advantage of the efficiencies quantum computing offers AI over classical computing (Galer, 2023). It is debatable whether these advantages can be replicated at scale or even better than current ML algorithms run on the best supercomputers (Castelvecchi, 2024). For example, when the benefits of using quantum computing for AI are seen, the error correction needed often diminishes any potential benefits, most glaringly in speed (Orus, 2019; Cerezo et al., 2022). In addition, in the near term, quantum computers do not have enough qubits, specifically logical qubits, to do large-scale ML tasks (Brandhofer et al., 2021). Because of this, classical computers are still the default for large ML data sets, and this will continue until quantum computing technology advances far enough to efficiently handle similarly sized sets. While hybrid quantum-classical algorithmic development is advancing the new field of QML, the long-term integration of classical data and quantum computers will be challenging (How & Cheah, 2024). This immaturity, combined with the availability of quantum computers, leads to questions about the future integration and scalability of QT and AI (Pal, 2023).

3.3.2 Challenges of Artificial Intelligence Technology

Similar to QT, AI applications are still being explored and understood as the development of AI algorithms and ML networks can be a complex undertaking (Swayne, 2023). Part of the complexity between QT and AI is that there is no standard architecture for quantum computing. Therefore, some AI algorithms can not be standardized, making it harder to further develop them for quantum computing (Wadhwa & Kop, 2022). Additional challenges of the relationship include the need for data to be encoded into a quantum state for QML to be effective. This process is complicated, time-consuming, and difficult, posing challenges in research and future applications (Houssein et al., 2022). While much of the workaround has been contained in the development of hybrid algorithms or through the conduction of quantum simulations, the development of ML models to take advantage of quantum properties is still very complex in relation to the current state of AI. These models will need to become more efficient, especially as quantum systems develop further (Krenn et al., 2023). Even when quantum neural networks can be created, their ability for training is immature and difficult to replicate at scale (Abbas et al., 2021). This has implications for the advancement of ML analysis of quantum data, such as that obtained from quantum sensors. AI training on quantum computers will have to get better as both technologies advance so that the relationship will be symbiotic in the long term.

3.3.3 Funding Challenges

“Deep tech” technologies requiring large amounts of research and development before realizing a viable commercial product are cash and time intensive. QT falls into this category, as does AI; however, AI can also be applied commercially in non–deep tech areas, giving AI a current advantage over other emerging technologies (Metinko, 2024). While AI and QT are symbiotic technologies, they are also competitors in the deep tech landscape, specifically in the race for private funding. The comparison leads to challenges in the relationship's growth, as AI has been accelerating and QT still has a long road to widespread use. In recent years, AI has risen in popularity and gained attention due to GenerativeAI, such as ChatGPT, which has attracted capital from parties interested in near-term returns. Overall, the current widespread perception is that AI technologies can make a societal and economic impact sooner than QT (Gold, 2024).

In contrast, the consensus view of QT is that it is costly to build and maintain, leaving businesses skeptical about investing (Pal, 2023). Additionally, AI and QT (specifically quantum computing) are often lumped together in the press and for funding considerations. Therefore, QT companies have had to compete for resources with AI companies, specifically for private, venture-backed dollars (Swayne, 2024). This competition is one reason private funding for quantum computing has dropped in recent years, in contrast to the rise in funding for AI (Gold, 2024; Robinson, 2024). A 2024 report by QT startup IQM Quantum Computers and venture capital firms OpenOcean and Lakestar, in partnership with the media firm The Quantum Insider, cited an over 50 percent drop in venture capital investment to QT companies in 2023. The report also cites that the hype around AI could potentially cannibalize the attention around QT (IQM, 2024). To deal with these challenges, several QT startups have been created or have recently pivoted to develop AI products and services to meet the interest of the mainstream investor community and satisfy the need for funding (Dargan, 2024). For example, SandboxAQ spun out of Google in 2022 to address the intersection of QT and AI through products using both QT and AI in simulations, sensing, and cryptography (Pinuaga et al., 2024). Funding challenges often follow deep tech, but the relationship between QT and AI adds complexity due to the competitive funding landscape.

4.0 Recommendations

With QT and AI considered rapidly emerging technologies, many are trying to understand how the technologies work together and how they can benefit various stakeholder groups. These groups are investigating how the technologies, both together and separately, can integrate into current ecosystems (How & Cheah, 2024). The following outlines recommendations based on the findings from the literature for four different stakeholder groups that will interact with QT and AI in the near term and how to prepare for the long term.

4.1 Entrepreneurs

As AI/ML technology has advanced, QT startups are building AI/ML offerings into their products and services and trying to differentiate themselves through this process. In addition to companies created at the intersection of QT and AI, like Sandbox AQ, existing QT companies can build the relationship between QT and AI. Examples of this are Multiverse Computing, which has created products that can run large ML models using “quantum-inspired” techniques, and quantum computing hardware company Pasqal, which has begun emphasizing AI as an application of their quantum computers (Gallardo, 2024; Sharma, 2024). In addition to current QT startups integrating AI technology into products, as the relationship between QT and AI strengthens, there will be opportunities for new startups to emerge. Entrepreneurs could create new ways of analyzing quantum data (such as that coming from quantum sensors) or develop new ML algorithms focused on applications to be run on future quantum computers (Dargan, 2024). With less private funding going into QT in favor of AI technologies, QT entrepreneurs can take advantage of additional funding opportunities by working on AI while advancing the AI/ML relationship and technology ecosystem.

4.2 Governments and Policymakers

Policymakers must understand the role they play in the acceleration of technological innovations through increasing funding to areas that foster the development of new scientific knowledge (Coccia, 2024). In recent times, many governments have made QT and AI technological priorities and begun realizing the potential impact (Taylor, 2020). This includes the $40 billion committed by 30 countries, which will be deployed over the next decade for QT (IQM, 2024). QT and AI academic researchers, corporate and government labs, and startup companies have benefited from these government programs. The European Union and other

European countries have led the way in the creation of these programs (European Commission, 2024).

Additional funding for programs to promote the convergence of QT and AI, as well as roadmaps for technological development and usage, must be created to enhance those already in place. It is in a government's best interest to do this thoughtfully yet quickly in order to gain an international advantage in technology development (Taylor, 2020). Governments can also foster the convergence of QT and AI technology by being procurers, developers, and researchers of new technologies and products that encompass both sides of this relationship. For instance, NASA has created the Quantum Artificial Intelligence Laboratory using a quantum computer purchased from the startup company D-Wave (Taylor, 2020). This lab works collaboratively across NASA, companies, and universities to conduct research on quantum computing and AI (NASA, 2024). Additional programs like this should become a priority to advance both QT and AI using their relationship. Other government programs at the convergence of QT and AI could include those that advance the AI algorithms for quantum cryptography, which has implications for national security, as well as programs designed to use AI to study the data coming from quantum sensors in various fields.

4.3 Academic Leadership

The fields of QT and AI encompass physics, engineering, computer science, and material science. When application research using both QT and AI comes into play, many more academic disciplines can become involved, and active academic research can occur. This is the case in the life sciences where QT-enabled bioimaging analyzed with AI/ML methods or QML-enhanced clinical diagnostics have been taken on as research projects (Wei et al., 2023). Universities have the unique opportunity to encourage faculty to embark on cross-disciplinary work at the intersection of QT and AI, which could potentially be foundational for applications and advancement in the field. This could be done through university-sponsored seed projects or through funding from philanthropic donors or foundations.

Additionally, as the two fields grow, there will be an increased demand in the workforce for employees trained in both QT and AI (not just one or the other). Currently, there are not enough experts or trainees in the pipeline at the intersection of QT and AI, which poses future problems for organizations looking to hire such rare talent (How & Cheah, 2024). According to a 2022 McKinsey & Company report, the lack of technical talent experienced in both AI and QT threatens to stall progress. The report cites the growing creation of AI graduate programs as a potential pipeline of talent to address this shortcoming. However, since quantum physics can be considered more difficult for students, quantum engineering and technology graduate programs have received less attention to date, and specific training programs for both AI and QT are essentially nonexistent. The lack of students trained in both AI and QT poses difficulties in addressing research challenges at the QT/AI interface (Mohr et al., 2022).

Still, there is an opportunity for colleges and universities to create programs at this disciplinary intersection to educate students and professionals on essential critical skills. To keep up with the pace of demand for the future QT and AI workforce, universities should prioritize the development of "quantum talent" and "AI talent," emphasizing the creation of programs that marry the two disciplines. This includes putting additional funding into STEM educational programs (even as early as high school) that focus on training to promote and enables application areas for QT and AI, both individually and together. As this multidisciplinary activity matures, it will ideally grow into its own discipline (Taylor, 2020).

4.4 Corporate Leaders

Technology development is often driven by competition among companies. In the NISQ era of quantum computing and with other QT applications in their infancy, competition in the quantum field is constrained by the high hardware development costs, extensive necessary capital investment, and lack of talent. Companies interested in the future of QT and AI need to invest in programs to advance the technology. This can include partnering with startups, academia, or other corporations developing QT or AI applications. Entities that have the "killer app" will be at an advantage as the field grows (Taylor, 2020). Companies that hold foundational intellectual property (IP) in QT will also be at an advantage, as the earliest patents can be the most valuable. AI is a more mature technology, and thus has lower barriers to entry and faster time scales (Wadhwa & Kop, 2022). The relationship between QT and AI allows innovative companies to take advantage of joint applications (Patel, 2024). That includes corporations and startups that are competing to develop products and solutions at the intersection of quantum and AI (Dargan, 2024). The companies that will hold an advantage in the future are those currently developing application solutions with QT and AL, including what could be a "killer app" and foundational IP. For instance, Hyundai has partnered with quantum computing company IonQ to help advance ML for mobility in future autonomous vehicles (Smith-Goodson, 2022).

5.0 Conclusion

This descriptive literature review, which uses Grounded Theory techniques to review academic and practitioner literature, summarizes the current relationship between quantum technology (QT) and artificial intelligence (AI). By identifying 196 sources of literature, it was concluded that the relationship between QT and AI is symbiotic, with both technologies advancing through interaction with each other. QT, specifically quantum computing, is advancing AI through research and development; this may lead to increased computing speed and accuracy of trained AI approaches, known as machine learning (ML). Additionally, hybrid algorithms are advancing the new field of quantum machine learning (QML) in the short term by creating ML algorithms to be run on a classical system but gaining some of the benefits of a quantum system (Pulicharla, 2023). Similarly, the essay provides examples of how AI is advancing QT. This includes aiding quantum computing error correction, quantum sensing data analysis, and quantum cryptography development.

The literature points to many positive and collaborative aspects of the QT and AI relationship but also to the challenges that face new deep technologies, especially ones that are developing in parallel. The challenges of the relationship stem from the need for both technologies to develop at scale for various diverse applications, ranging from health care to defense and aerospace (Patel, 2024). In particular, the immaturity of quantum computing is one of the hindrances to the growth of the QT and AI relationship. Examples of this are the limited number of qubits in current quantum computers and the encoding methods needed to convert classical data to quantum (Houssein et al., 2022). Additional funding and workforce development is needed to advance the convergence of the technologies and explore potential applications. However, within the last year, QT (specifically quantum computing) and AI have added complexity to the relationship as the technologies increasingly compete for private funding. Future studies can build from this literature review, providing greater depth and detail on funding opportunities for QT and AI and the advantages QT and AI stand to gain from each other. Additional studies can examine the historical relationship, as this literature review is limited to a five-year period.

Until recently, the QT and AI relationship has been more fortuitous than collaborative. Moving into the future, a collaborative relationship would include solutions involving both ML computer scientists and quantum physicists (Martín-Guerrero & Lamata, 2022). Startups, governments, academia, and corporate entities have the unique opportunity to advance the long-term relationship of QT and AI by being innovative in advancing the technology, creative in funding opportunities, and active in identifying ways for applications of QML to be tested in the real world. The relationship between QT and AI will continue to grow due to their likely achievable and shared long-term goals (Swayne, 2023).

Appendix B- Quantum Conferences

The following are the websites of the eight quantum technology conferences we visited that had calls for papers or programming on Al and/or ML:

- Quantum Machine Learning Conference 2024
- Joint ICTP-WE Heraeus School and Conference on Frontiers at the Intersection of Quantum Simulation and Machine Learning
- Quantum Techniques in Machine Learning
- Quantum World Congress
- NVIDIA: Quantum Computing Conference Sessions
- IEEE Quantum Week 2024
- Quantum Computing In Finance Conference
- Q2B: The Roadmap to Quantum Value
- Workshop on Quantum Machine Learning for Condensed Matter Physics

Conclusion

2025 has been declared the "International Year of Quantum Science and Technology" by the United Nations. This upcoming yearlong celebration will highlight the historical contributions of quantum globally (Banks, 2024). It will also emphasize the importance of quantum science and technology now and in the future. The unifying theme of the celebration is the potential of quantum technology (QT) to bring about change and solve unanswered problems of great importance in health, national security, sustainability, and elsewhere. There is broad consensus that as quantum information science moves from ideas to deployable products at scale, QT will significantly impact the global economy. The World Economic Forum calls this "The Quantum Economy," in which QT will impact many critical industries and drive new business models (World Economic Forum, 2024). Governments have supported the idea of a "Quantum Economy" by pledging more than $40 billion to the future of quantum science over the next decade through academic grant programs, as well as support for QT businesses (IQM, 2024).

The magnitude and range of these developments — as shown by the recognition from the United Nations, investments into QT and quantum science, and the emergence of the "Quantum Economy" — strengthens the view that QT has important implications and a future beyond academic labs (Roberson, 2021). From this consensus, efforts to advance, validate, and grow the emerging QT market worldwide have gained momentum. However, QT is not without uncertainties, ranging from technical to economic to geopolitical issues (MacQuarrie, 2022). Thus, there is a solid scholarly basis and motivation for studying the current and envisioned applications of different QTs, including how the technologies are developing and the symbiotic relationships that advance the field overall. In particular, scholarly assessments may provide key perspectives to help mitigate the uncertainties in QT's development and validate likely commercial benefits across diverse sectors. Such research may also advance the understanding of how users are currently deploying QTs and how these technologies could be used in the future.

Through three Essays, this dissertation has analyzed use cases of quantum computing and quantum sensing and has examined the relationship between QT and AI. While each Essay addresses its own research question, the overall dissertation's theme surrounding the applications of QT will contribute to the scholarly community through analysis of specific early-use cases of QT, i.e., areas where QT is likely to provide near-term impact. From the use cases studied for the dissertation, several key conclusions bring all three Es together. First, users of early QT often conduct research with the technologies, whether in the private sector (large or startup companies) or academia. The partnerships between those developing QT and end users (often researchers themselves) are key for the growth of the field of QT. Early and promising results from researchers in academia and corporations subsequently fuel further development of QT. Therefore, a unifying implication of this dissertation's three Essays is highlighting promising QT areas that merit further research, development, and investment.

Second, QT have use cases in the short term and great potential for long-term impact with further development. Essay 1 demonstrates aspects of this conclusion through the unique perspectives of end users in the pharmaceutical, finance, automotive, and energy industries innovating with quantum computing. Tying this idea to the *Diffusion of Innovation* (DoI) theory adds to the scholarly work of that theory and identifies the "innovators" (the earliest users on an S-curve of an innovation's adoption) of quantum computing. Similarly, Essay 2 reinforces QT's short-term uses and impact through two case studies of organizations that use quantum sensors for neuroscience research and geophysical surveying. This study supports the key takeaways of the dissertation by identifying an emerging organizing vision around quantum sensing; this vision will help guide the long-term decision-making of organizations and their ultimate adoption of quantum sensing, typically as a key component integrated with traditional (and other emerging) technologies, including quantum computing studied in Essay 1. Essay 3 focuses on the impact QT can have in relation to artificial intelligence (AI) and synthesizes and assesses the current literature on this topic. The conclusions regarding how QT and AI are synergistically advancing each other — and the associated challenges in such co-development — will add to the scholarly discussion on how these two technologies can work together to have a significant long-term impact, coupled with further development and use case exploration. The collaborative relationship between QT and AI also showcases an early success, which can help drive long-term impact, partnerships, and eventual additional funding.

Third, QT are not without their challenges. There are long roads ahead for all quantum-related technologies to reach adoption. For instance, Essay 1 demonstrates that moving from the "innovators" on the adoption S-curve to "early adopters" (part of the DoI theory) will take time. Similarly, the findings for Essay 2 show that though quantum sensors have early promise, scaling the technology long term will be a challenge. With that, all three Essays show that one of the greatest challenges is funding the development of QT. Without adequate funding, these technologies cannot advance. In their current state, it is better for developers of QT to under-promise and then over-deliver versus promising to over-deliver. The combined Essays conclude that communication is critical to the advancement of QT, and while hype can be a negative factor, keeping a positive discourse can help as the field grows.

As the field of QT grows, associated disciplines will grow as well. Due to ongoing breakthroughs in quantum science and the commercialization of various QTs in recent years, quantum engineering has grown into a discipline of its own to build, apply, and service quantum products, such as the hardware and operational software of quantum computers and sensors (Ackerman, 2020). Similarly, as QTs establish their importance and value within society, additional scholarly work will be needed to analyze the interactions between the various elements of these technologies, as well as the cultural implications, practices, and relationships between QT and society. While small now, the associated socio-technical disciplines of QT scholarly study, including in business and policy, can be expected to grow over time.

The research of this dissertation can provide a basis for such future socio-technical work on QT. For instance, just as Essay 1 uses the lenses of the *Diffusion of Innovations* theory (Rogers, 2023) and the follow-on insights by Geoffrey Moore (Moore, 1991) to analyze how quantum computing is spreading within society, other social science theories with ties to business or policy studies could be used to further analyze applications and adoption of QT. One such theory is the disruptive innovation theory, first introduced by Clayton Christensen (Christensen, 2016). The theory describes how smaller companies, often startups, can challenge larger, more established organizations through easier accessibility to innovations and the pursuit of niche markets. Follow-on work to this dissertation could include identifying the niche markets in which QT startups can have a greater impact than larger companies in the short term and investigating sectors where QT may disrupt current technologies (e.g., classical high-performance computers or state-of-the-art sensors) in the long term through the lens of the disruptive innovation theory. Additionally, both Essays 1 and 2 provide background assessments of specific QT (computing and sensing, respectively). Future work building on this dissertation could provide additional detail about the historical development of specific QTs and trace their social and economic impact over time.

The culmination of the three Essays concludes that QTs, while in their infancy, are on a path to develop further technologically and economically, with greater societal adoption over time. Often, technological development is in tandem with application development, leading to the early successes of QT. This, combined with supporting efforts from governments and elsewhere, is highlighted with monikers such as the “International Year of Quantum Science and Technology” and the “Quantum Economy,” define that quantum technologies hold great promise. There are also many challenges to long-term adoption, starting with the current immaturity of the technology and the necessity of sustained, significant funding for sustainable commercial success. However, beginning to study how quantum technology is evolving and being adopted gives insights into early success and future development and evolution. This dissertation is the start of such a field of study.

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