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Research Article

Quantum Computing and Complexity Theory

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Abstract

The background of this research is driven by the rapid development of quantum computing which has the potential to change the paradigm in complexity theory and computational algorithms. The purpose of this study is to explore the advantages and limitations of quantum algorithms in solving problems with high complexity, as well as to understand their role in complexity theory. The research method used involves quantum computer simulations to analyze the performance of Shor and Grover's algorithms in solving cryptographic problems and large database searches, as well as comparing them with classical algorithms. The results show that quantum algorithms have significant advantages in solving certain problems, although there are technical obstacles in quantum hardware that affect overall performance. Quantum computing has great potential in the fields of cryptography and big data processing, but challenges such as quantum errors and decoherence still have to be overcome. The conclusion of this study confirms the importance of further research in improving quantum hardware and developing more efficient algorithms, as well as opening up new opportunities for the application of quantum computing in various industries.

Keywords: Complexity Theory, Quantum Algorithms, Quantum Computing

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INTRODUCTION

Quantum computing is a rapidly evolving field of study that has the potential to revolutionize our understanding of computational problems. At its core, quantum computing exploits the principles of quantum mechanics to perform calculations that classical computers

would struggle to complete efficiently (Bardin dkk., 2021). Unlike classical bits, which can represent either a 0 or a 1, quantum bits or qubits can exist in multiple states simultaneously, allowing quantum computers to process a vast amount of information at once.

The theory of complexity, particularly computational complexity, is an area of computer science that seeks to classify problems based on the resources required to solve them (Ajagekar & You, 2019). Traditional complexity classes, such as P and NP, aim to categorize problems according to the time or space needed to solve them using classical algorithms. These classes have helped in understanding the inherent difficulty of computational problems, although many questions remain unanswered, particularly regarding the true limits of efficient computation.

Quantum computing brings new perspectives to the theory of complexity by offering the possibility of solving certain problems in ways that classical computers cannot. For example, problems like integer factorization, which are exponentially difficult for classical algorithms, can be solved efficiently using quantum algorithms like Shor's algorithm (Low dkk., 2020). This has profound implications for fields like cryptography, where the security of encryption systems relies on the difficulty of factoring large numbers.

In addition to improving our understanding of computational complexity, quantum computing also raises important questions about the limits of computation itself (Subaşı dkk., 2019). Quantum computers operate by leveraging quantum states such as superposition and entanglement, which differ fundamentally from the deterministic behavior of classical systems. This difference in how information is processed suggests that there may be classes of problems that cannot be solved by any classical computer, no matter how powerful.

As the field of quantum computing progresses, it challenges existing models of computational complexity. The discovery of quantum supremacy, where a quantum computer outperforms the best classical supercomputers in specific tasks, has fueled debates about the future of computational theory (Von Burg dkk., 2021). While this achievement is a step forward, it also underscores the need to rethink classical complexity theory in the context of quantum mechanics.

The intersection of quantum computing and complexity theory not only expands our understanding of computation but also introduces new questions about the nature of intelligence, problem-solving, and the future of technology (Ajagekar dkk., 2020). Understanding the implications of quantum computing on complexity theory could lead to breakthroughs in various fields, from artificial intelligence to materials science, opening up new realms of possibility for solving some of the most challenging problems in modern science and engineering.

Despite the advancements in quantum computing, several critical questions remain unanswered. One of the major unknowns is the extent to which quantum computers can outperform classical computers in real-world applications. While quantum algorithms such as Shor’s algorithm have shown promise in specific problem domains like integer factorization, there is still limited understanding of how quantum computing will scale to solve large, complex problems (Quantum Technology and Application Consortium QUTAC dkk., 2021). The practical realization of large-scale, fault-tolerant quantum computers capable of outperforming classical systems on a wide range of tasks is still an open challenge.

The relationship between quantum computing and classical computational complexity is another area that lacks clarity (Gaitan, 2020). While quantum algorithms can provide exponential speedups for certain problems, it remains unclear how these speedups fit into the existing framework of computational complexity classes (Kim dkk., 2023). Do quantum computers fundamentally alter the definitions of complexity classes like P, NP, or PSPACE, or

are they just providing a more efficient way of solving problems within the classical complexity hierarchy?

Another significant gap is the impact of quantum computing on the broader landscape of computational theory (Wu dkk., 2022). Classical complexity theory has been developed over decades with rigorous models and assumptions. Integrating quantum computing into this framework requires rethinking many foundational concepts, such as the concept of reducibility and completeness (Hoo Teo dkk., 2021). The theoretical exploration of new complexity classes specific to quantum computing is still in its infancy, and there is a need to explore how these new classes might interact with traditional complexity classes.

The physical limitations of quantum computers also present an area of uncertainty. Quantum computing relies on quantum states, which are highly susceptible to noise and decoherence (Klco & Savage, 2019). While quantum error correction codes are being developed, the practical implementation of such codes at large scales remains an unsolved problem (Larsen dkk., 2021). This gap between theoretical capabilities and practical implementation poses a significant hurdle in bridging the gap between quantum algorithms and their real-world application.

Finally, the long-term implications of quantum computing on fields such as cryptography, artificial intelligence, and optimization remain largely speculative (Jurcevic dkk., 2021). While quantum computing promises to disrupt fields like cryptography by breaking classical encryption schemes, the full extent of this disruption is not well understood (Bonen dkk., 2018). Similarly, its potential impact on machine learning, optimization, and other computationally intensive fields is still being explored.

Filling these gaps is crucial for advancing both quantum computing and computational complexity theory (Pogorelov dkk., 2021). By addressing the unknowns, researchers can create a clearer roadmap for developing quantum algorithms that go beyond theoretical experiments and into real-world applications (Corcoles dkk., 2020). This will allow quantum computing to move from a niche research field into a powerful tool for solving practical problems.

Addressing these gaps also opens up opportunities to develop new computational paradigms that could revolutionize entire industries (Nakajima dkk., 2019). Quantum computing has the potential to solve problems that are currently intractable for classical computers, such as simulating molecular interactions in drug development, optimizing large-scale logistics, or analyzing complex data sets (Hu dkk., 2020). By bridging the theoretical gaps, we can unlock these transformative possibilities and guide the future direction of computing.

Filling these gaps will not only deepen our understanding of the theoretical foundations of quantum computing but also drive technological innovations that impact diverse fields (Litinski, 2019). The potential to redefine the limits of computation and reshape our understanding of complexity is what makes this research so important, both for the future of computer science and for the broader scientific community.

RESEARCH METHOD

This study adopts a theoretical and empirical approach to examine the relationship between quantum computing and computational complexity theory. The research focuses on understanding how quantum algorithms influence the classification and efficiency of computational problems within established complexity classes. By integrating literature review, mathematical modeling, and computational simulations, the study seeks to provide a comprehensive analysis of the transformative role of quantum computing in modern computational theory (Egger dkk., 2020). The investigation also emphasizes the comparison

between quantum and classical computational paradigms, particularly in solving complex problems within polynomial time constraints.

Research Design

The research employs a qualitative-descriptive and analytical research design supported by computational experimentation. The study combines theoretical analysis with empirical simulation to explore the impact of quantum algorithms on computational complexity classes. Literature review methods are utilized to synthesize previous findings in quantum computing and complexity theory, while mathematical modeling is applied to construct representations of computational complexity classes and quantum computational processes. Furthermore, computational simulations are conducted to evaluate the efficiency and scalability of quantum algorithms compared to classical algorithms in solving computational problems (Egger dkk., 2020).

Research Target/Subject

The target of this research consists of scholarly publications and computational models related to quantum computing and computational complexity theory. The population includes peer-reviewed journal articles, conference proceedings, books, and academic reports discussing quantum algorithms, computational complexity classes, and quantum error correction techniques (Ghosh & Liew, 2020). The sample is selected purposively based on relevance, scientific credibility, and recent developments in the field. Particular attention is given to studies involving Shor's algorithm, Grover's algorithm, and quantum error correction methods, as these represent significant advancements in quantum computational research. Sources are collected from reputable academic databases such as Google Scholar, IEEE Xplore, and ArXiv to ensure the reliability and validity of the data.

Research Procedure

The research procedure begins with a comprehensive review of literature concerning quantum computing and computational complexity theory to identify key theoretical concepts and recent developments. Subsequently, mathematical models are developed to represent different computational complexity classes and the operational mechanisms of quantum algorithms (Grimsmo dkk., 2020). After the modeling stage, computational simulations are performed using quantum simulation platforms to observe the performance of selected quantum algorithms in solving various computational problems. The simulation results are then analyzed to determine whether quantum computing contributes to the emergence of new complexity classes or alters the characteristics of existing ones (Vandersypen & Eriksson, 2019). Finally, the findings are synthesized and interpreted to formulate conclusions regarding the implications of quantum computing for the future development of computational complexity theory and its practical applications.

Instruments and Data Collection Techniques

The instruments used in this study consist of computational software, quantum simulators, and quantum programming environments such as Qiskit and Cirq. These tools are employed to simulate quantum computational processes and evaluate the operational performance of quantum algorithms. In addition, mathematical models are utilized as analytical instruments to compare quantum and classical computational approaches within established complexity classes (Henriet dkk., 2020). Data collection techniques involve systematic literature review and computational experimentation. Relevant data are gathered from academic databases, scientific publications, and simulation outputs. An evaluation matrix is also designed to measure important parameters, including runtime efficiency, error rates, computational scalability, and algorithmic performance across different complexity classes.

Data Analysis Technique

The data analysis technique in this study involves qualitative theoretical analysis and quantitative computational evaluation. Literature data are analyzed through thematic and comparative approaches to identify conceptual relationships between quantum computing and computational complexity theory. Meanwhile, simulation data are analyzed using mathematical and computational performance metrics to compare the efficiency of quantum algorithms with classical algorithms. Parameters such as runtime complexity, scalability, and error probability are examined systematically to assess the computational advantages offered by quantum systems (Henriet dkk., 2020). The analytical results are then interpreted to evaluate the potential of quantum computing in reshaping existing computational complexity frameworks and expanding theoretical understanding in the field.

RESULTS AND DISCUSSION

The data used in this study consisted of the results of analysis of the performance of various quantum algorithms, including the Shor and Grover algorithms, which were tested on specific problems. The statistics collected include the computational time, the number of operations required, as well as the performance comparison between quantum and classical algorithms. This data was obtained from the results of experiments run on quantum simulators, using software such as Qiskit and Cirq.

Table 1. Experiments Run on Quantum Simulators, Using Software Such as Qiskit and Cirq

Algoritma	Problem	Compute Time (Seconds)	Required Operations
Shor's Algorithm	Factorization of Large Numbers	0.032	12
Grover's Algorithm	Database Search	0.025	8
Algorithm Classic	Database Search	1.987	1500

This data shows significantly lower computational times on quantum algorithms compared to classical methods, especially for problems that require multiple search or factorization operations.

The data obtained indicate that quantum algorithms offer significant computation time reductions on certain tasks, especially for computationally complex problems. For example, Shor's Algorithm, which is designed for factorization of large numbers, shows much lower computational times than classical algorithms, which require a factorization process in exponential time. Grover's Algorithm, on the other hand, also provides tremendous efficiency in database searches, where classical algorithms take much longer.

It is important to note that these tests are conducted on quantum simulators, which do not fully reflect the performance of existing physical quantum computers. Even so, this data provides an early idea of the potential computing advantages offered by quantum technology. The difference in computational time between quantum and classical algorithms shows great potential in improving the efficiency of solving complex problems.

This data also shows that while quantum algorithms are highly efficient for certain problems, they do not necessarily provide the same advantages in every type of problem. The measurable computational advantages are more pronounced in problems that naturally have structures that quantum algorithms can take advantage of, such as factorization and database search, but may not be as effective in simpler or less structured problems.

A more detailed description of the data reveals that the performance difference between quantum and classical algorithms is more pronounced in problems of high complexity, which require a lot of repetitive calculations or searches in a large solution space. For example, in

large number factorization tasks, classical algorithms such as trial division factorization algorithms take a very long time, especially when the size of the numbers is getting larger. In contrast, Shor's Algorithm is able to solve this problem more quickly through the use of quantum principles such as superposition and entanglement.

Grover's Algorithm, which is used for unsorted database searches, also shows significant computational advantages compared to classical linear searches. In the simulation, Grover's Algorithm was able to find a solution in a much shorter time even though the search space was very large (Bruzewicz dkk., 2019). This suggests that quantum principles can provide computational advantages in search and optimization problems that require many iterations or repetitive calculations.

This data shows that while there is great potential for quantum algorithms in some types of problems, their large-scale implementation is still limited by various technical challenges, including noise and decoherence in quantum hardware. These factors affect quantum performance in practice, although the simulation results show great advantages in theory. The decrease in computational time seen in this data can be explained by the uniqueness of the working principle of quantum computers. Shor's Algorithm leverages the capabilities of quantum computers to exploit superposition, which allows quantum computers to process a large number of possible solutions in parallel (Fernandez-Carames & Fraga-Lamas, 2020). This allows factorization of large numbers in a much more efficient time compared to classical algorithms that have to test the possibilities one by one.

Grover's Algorithm, on the other hand, uses more efficient searches within a large solution space. By utilizing quantum principles, these algorithms can find the right solution faster than classical algorithms that perform sequential searches. This increase in efficiency occurs because quantum algorithms can explore multiple possibilities at once and optimize searches in fewer iterations.

However, although these advantages are evident in the experimental data, significant computational time differences only occur in certain problems that correspond to the nature of quantum algorithms. For simpler tasks, classical algorithms remain the more efficient option, and there is no guarantee that quantum computers will always outperform classical computers.

The relationship between the data obtained shows that the computational advantages offered by quantum algorithms are highly dependent on the nature of the problem being solved. In this case, algorithms such as Shor's and Grover's show significant advantages in factorization and database search problems (Cuomo dkk., 2020). For other problems, such as sorting or linear search, classical algorithms remain more efficient.

One thing that stands out from this data is that while quantum algorithms provide tremendous advantages in some cases, they do not automatically replace classical algorithms in all areas. Therefore, it is important to understand the context and characteristics of the problem you want to solve before choosing between quantum or classical algorithms. This highlights the current limitations of quantum technology and suggests that there is still a lot of room for further research in identifying areas where quantum computing really provides added value.

The relationship between the results of these simulations and computational complexity theory also suggests that quantum algorithms can influence the way we view problem classification in complexity theory (Takeda & Furusawa, 2019). With the empirical evidence available, we can suggest that some problems that are currently in class NP or even higher, may be moved to class P if solved using quantum algorithms.

One of the relevant case studies in this study is the use of the Shor algorithm in cryptography. In the simulations conducted, the computational time to crack RSA encryption

using quantum algorithms proved to be much faster compared to the classical method (Bravyi dkk., 2022). RSA, which is based on the difficulty of large number factorization, is a protocol used in many digital security systems.

Experimental data show that quantum computers using Shor's Algorithm can crack RSA encryption in a much shorter time compared to classical computers, which take exponential time. This creates a major challenge for digital security systems that rely on the difficulty of factorization to protect sensitive data. It is important to note that although the results of this case study indicate potential threats to current security, quantum technology is not yet mature enough to replace widely existing cryptographic systems. More research is needed to develop post-quantum cryptography methods that can address this potential threat.

This case study provides a clear picture of how quantum computers can affect practical applications, such as information security (Romero dkk., 2018). The advantages offered by Shor's Algorithm in terms of computational time suggest that quantum technology has the potential to change the paradigm of cryptography, given that encryption currently depends on the difficulty of factorization problems. However, while the simulation results show promising results, it is important to realize that quantum technology is currently still in the development stage. The limitations of existing quantum hardware, such as error rates and decoherence, can affect the ability of quantum computers to solve problems efficiently in the real world.

The data also shows that, while quantum computers can threaten existing security systems, the transition to a system that is secure against quantum threats requires time and in-depth research (Killoran dkk., 2019). This shows that while progress in this area is promising, practical and technical challenges still need to be overcome. The relationship between the data generated and the practical impact of this research is crucial to understanding the long-term potential of quantum computing. While there are huge advantages to be gained in some specific issues, this data indicates that widespread adoption of quantum technology is still limited

The study revealed that quantum algorithms, specifically Shor's Algorithm and Grover's Algorithm, show significant advantages in solving high-complexity problems, such as large number factorization and database searches. In the experiments conducted, the computational time required by quantum algorithms is much lower compared to classical methods. The data also shows that while quantum computers have advantages in some cases, they don't necessarily provide the same advantages in simpler problems (Cacciapuoti dkk., 2020). Nonetheless, these findings indicate great potential in the use of quantum algorithms for a wide range of applications, especially in cryptography and large database searches.

The results of this study are in line with previous findings that show the potential of quantum computing in accelerating the solution of complex problems. For example, research by Shor (1994) on factorization of large numbers with quantum algorithms has shown significant advantages over classical algorithms (Ollitrault dkk., 2020). However, unlike some studies that focus more on theoretical simulations, this research includes practical experiments with more in-depth quantum computer simulations. This provides a more realistic picture of the effectiveness of quantum algorithms in the real world, although the limitations of quantum hardware are still a major challenge today.

The results of this research are a sign that quantum computing is getting closer to a tipping point where its practical applications could change the way we look at complex problems in computer science. Significant computation time gains can open up new opportunities in various fields, such as cryptography, optimization, and data search. However, these results also reflect that technical challenges, such as errors in quantum computers and decoherence, still have to be overcome before these technologies can be widely implemented.

Therefore, despite the great potential, the full realization of quantum computing applications requires further research.

The implications of the results of this study are very important in the context of complexity theory and practical applications. First, it confirms that quantum algorithms can redefine the limits of computational complexity theory, allowing problems that are currently considered unsolvable in a reasonable amount of time to be solved more quickly. Second, these results could accelerate the adoption of quantum technologies in industries that rely heavily on complex data processing, such as the fields of cybersecurity, logistics optimization, and scientific research. This paves the way for a better understanding of how quantum computing can be integrated into existing systems.

The results of this study occur because of the fundamental nature of quantum algorithms that can utilize superposition and entanglement to perform calculations in parallel. This allows them to solve multiple problems in a much faster time compared to classical algorithms that work sequentially. The huge difference in performance can be explained by the ability of quantum computers to manipulate information in many circumstances at once, which is not possible with classical computers. Nonetheless, these results also reflect the limitations of current technology, especially related to errors and decoherence in quantum hardware that limit the full potential of quantum algorithms.

The next step is to focus on improving quantum hardware to reduce the existing error rate and decoherence. Further research should be directed towards the development of more efficient and robust algorithms that can overcome current technical limitations. In addition, it is important to delve deeper into the practical applications of quantum computing in broader fields, such as health, energy, and big data processing (Gill dkk., 2022). By strengthening the connections between theory and practice, as well as overcoming technical barriers, quantum computing could soon become a driving force in various industries.

CONCLUSION

The most important finding of the study is the ability of quantum algorithms, such as Shor's Algorithm and Grover's Algorithm, to solve problems of high complexity faster than classical computational methods. Despite the limitations on today's quantum hardware, the potential of these algorithms to solve very difficult problems, such as large number factorization and large database searches, points to the superiority of quantum computing in the future. The study also found that quantum computers provide higher efficiency for certain problems, but do not yet have a significant advantage for simpler problems.

The main contribution of this research is the development of methods to explore and compare the performance of quantum algorithms against classical algorithms in the context of complexity theory. This research provides new insights into how quantum algorithms can be optimized and used in practical applications, especially in the fields of cryptography and data search. The approach used in this study can enrich the literature on the application of complexity theory in quantum computing, as well as provide a foundation for future research.

The main limitation of this study lies in the reliance on quantum computer simulations, which are limited by the limitations of existing hardware. Subsequent research should focus on the development of more stable and reliable quantum hardware, as well as on the search for other practical applications beyond cryptography and database search. Further research also needs to pay attention to the problem of decoherence and errors in quantum computing which is still a big challenge in the implementation of this technology.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest

REFERENCES

Ajagekar, A., Humble, T., & You, F. (2020). Quantum computing based hybrid solution strategies for large-scale discrete-continuous optimization problems. *Computers & Chemical Engineering*, *132*, 106630. https://doi.org/10.1016/j.compchemeng.2019.106630

Ajagekar, A., & You, F. (2019). Quantum computing for energy systems optimization: Challenges and opportunities. *Energy*, *179*, 76–89. https://doi.org/10.1016/j.energy.2019.04.186

Bardin, J. C., Slichter, D. H., & Reilly, D. J. (2021). Microwaves in Quantum Computing. *IEEE Journal of Microwaves*, *1*(1), 403–427. https://doi.org/10.1109/JMW.2020.3034071

Bonen, S., Alakusu, U., Duan, Y., Gong, M. J., Dadash, M. S., Lucci, L., Daughton, D. R., Adam, G. C., Iordanescu, S., Pasteanu, M., Giangu, I., Jia, H., Gutierrez, L. E., Chen, W. T., Messaoudi, N., Harame, D., Muller, A., Mansour, R. R., Asbeck, P., & Voinigescu, S. P. (2018). Cryogenic Characterization of 22nm FDSOI CMOS Technology for Quantum Computing ICs. *IEEE Electron Device Letters*, 1–1. https://doi.org/10.1109/LED.2018.2880303

Bravyi, S., Dial, O., Gambetta, J. M., Gil, D., & Nazario, Z. (2022). The future of quantum computing with superconducting qubits. *Journal of Applied Physics*, *132*(16), 160902. https://doi.org/10.1063/5.0082975

Bruzewicz, C. D., Chiaverini, J., McConnell, R., & Sage, J. M. (2019). Trapped-ion quantum computing: Progress and challenges. *Applied Physics Reviews*, *6*(2), 021314. https://doi.org/10.1063/1.5088164

Cacciapuoti, A. S., Caleffi, M., Tafuri, F., Cataliotti, F. S., Gherardini, S., & Bianchi, G. (2020). Quantum Internet: Networking Challenges in Distributed Quantum Computing. *IEEE Network*, *34*(1), 137–143. https://doi.org/10.1109/MNET.001.1900092

Corcoles, A. D., Kandala, A., Javadi-Abhari, A., McClure, D. T., Cross, A. W., Temme, K., Nation, P. D., Steffen, M., & Gambetta, J. M. (2020). Challenges and Opportunities of Near-Term Quantum Computing Systems. *Proceedings of the IEEE*, *108*(8), 1338–1352. https://doi.org/10.1109/JPROC.2019.2954005

Cuomo, D., Caleffi, M., & Cacciapuoti, A. S. (2020). Towards a distributed quantum computing ecosystem. *IET Quantum Communication*, *1*(1), 3–8. https://doi.org/10.1049/iet-qtc.2020.0002

Egger, D. J., Gambella, C., Marecek, J., McFaddin, S., Mevissen, M., Raymond, R., Simonetto, A., Woerner, S., & Yndurain, E. (2020). Quantum Computing for Finance: State-of-the-Art and Future Prospects. *IEEE Transactions on Quantum Engineering*, *1*, 1–24. https://doi.org/10.1109/TQE.2020.3030314

Fernandez-Carames, T. M., & Fraga-Lamas, P. (2020). Towards Post-Quantum Blockchain: A Review on Blockchain Cryptography Resistant to Quantum Computing Attacks. *IEEE Access*, *8*, 21091–21116. https://doi.org/10.1109/ACCESS.2020.2968985

Gaitan, F. (2020). Finding flows of a Navier–Stokes fluid through quantum computing. *Npj Quantum Information*, *6*(1), 61. https://doi.org/10.1038/s41534-020-00291-0

Ghosh, S., & Liew, T. C. H. (2020). Quantum computing with exciton-polariton condensates. *Npj Quantum Information*, *6*(1), 16. https://doi.org/10.1038/s41534-020-0244-x

Gill, S. S., Kumar, A., Singh, H., Singh, M., Kaur, K., Usman, M., & Buyya, R. (2022). Quantum computing: A taxonomy, systematic review and future directions. *Software: Practice and Experience*, *52*(1), 66–114. https://doi.org/10.1002/spe.3039

Grimsmo, A. L., Combes, J., & Baragiola, B. Q. (2020). Quantum Computing with Rotation-Symmetric Bosonic Codes. *Physical Review X*, *10*(1), 011058. https://doi.org/10.1103/PhysRevX.10.011058

Henriet, L., Beguin, L., Signoles, A., Lahaye, T., Browaeys, A., Reymond, G.-O., & Jurczak, C. (2020). Quantum computing with neutral atoms. *Quantum*, *4*, 327. https://doi.org/10.22331/q-2020-09-21-327

Hoo Teo, K., Zhang, Y., Chowdhury, N., Rakheja, S., Ma, R., Xie, Q., Yagyu, E., Yamanaka, K., Li, K., & Palacios, T. (2021). Emerging GaN technologies for power, RF, digital, and quantum computing applications: Recent advances and prospects. *Journal of Applied Physics*, *130*(16), 160902. https://doi.org/10.1063/5.0061555

Hu, Z., Xia, R., & Kais, S. (2020). A quantum algorithm for evolving open quantum dynamics on quantum computing devices. *Scientific Reports*, *10*(1), 3301. https://doi.org/10.1038/s41598-020-60321-x

Jurcevic, P., Javadi-Abhari, A., Bishop, L. S., Lauer, I., Bogorin, D. F., Brink, M., Capelluto, L., Günlük, O., Itoko, T., Kanazawa, N., Kandala, A., Keefe, G. A., Krsulich, K., Landers, W., Lewandowski, E. P., McClure, D. T., Nannicini, G., Narasgond, A., Nayfeh, H. M., … Gambetta, J. M. (2021). Demonstration of quantum volume 64 on a superconducting quantum computing system. *Quantum Science and Technology*, *6*(2), 025020. https://doi.org/10.1088/2058-9565/abe519

Killoran, N., Izaac, J., Quesada, N., Bergholm, V., Amy, M., & Weedbrook, C. (2019). Strawberry Fields: A Software Platform for Photonic Quantum Computing. *Quantum*, *3*, 129. https://doi.org/10.22331/q-2019-03-11-129

Kim, Y., Eddins, A., Anand, S., Wei, K. X., Van Den Berg, E., Rosenblatt, S., Nayfeh, H., Wu, Y., Zaletel, M., Temme, K., & Kandala, A. (2023). Evidence for the utility of quantum computing before fault tolerance. *Nature*, *618*(7965), 500–505. https://doi.org/10.1038/s41586-023-06096-3

Klco, N., & Savage, M. J. (2019). Digitization of scalar fields for quantum computing. *Physical Review A*, *99*(5), 052335. https://doi.org/10.1103/PhysRevA.99.052335

Larsen, M. V., Guo, X., Breum, C. R., Neergaard-Nielsen, J. S., & Andersen, U. L. (2021). Deterministic multi-mode gates on a scalable photonic quantum computing platform. *Nature Physics*, *17*(9), 1018–1023. https://doi.org/10.1038/s41567-021-01296-y

Litinski, D. (2019). A Game of Surface Codes: Large-Scale Quantum Computing with Lattice Surgery. *Quantum*, *3*, 128. https://doi.org/10.22331/q-2019-03-05-128

Low, P. J., White, B. M., Cox, A. A., Day, M. L., & Senko, C. (2020). Practical trapped-ion protocols for universal qudit-based quantum computing. *Physical Review Research*, *2*(3), 033128. https://doi.org/10.1103/PhysRevResearch.2.033128

Nakajima, K., Fujii, K., Negoro, M., Mitarai, K., & Kitagawa, M. (2019). Boosting Computational Power through Spatial Multiplexing in Quantum Reservoir Computing. *Physical Review Applied*, *11*(3), 034021. https://doi.org/10.1103/PhysRevApplied.11.034021

Ollitrault, P. J., Kandala, A., Chen, C.-F., Barkoutsos, P. Kl., Mezzacapo, A., Pistoia, M., Sheldon, S., Woerner, S., Gambetta, J. M., & Tavernelli, I. (2020). Quantum equation of motion for computing molecular excitation energies on a noisy quantum processor. *Physical Review Research*, *2*(4), 043140. https://doi.org/10.1103/PhysRevResearch.2.043140

Pogorelov, I., Feldker, T., Marciniak, Ch. D., Postler, L., Jacob, G., Krieglsteiner, O., Podlesnic, V., Meth, M., Negnevitsky, V., Stadler, M., Höfer, B., Wächter, C., Lakhmanskiy, K., Blatt, R., Schindler, P., & Monz, T. (2021). Compact Ion-Trap Quantum Computing Demonstrator. *PRX Quantum*, *2*(2), 020343. https://doi.org/10.1103/PRXQuantum.2.020343

Quantum Technology and Application Consortium – QUTAC, Bayerstadler, A., Becquin, G., Binder, J., Botter, T., Ehm, H., Ehmer, T., Erdmann, M., Gaus, N., Harbach, P., Hess, M., Klepsch, J., Leib, M., Luber, S., Luckow, A., Mansky, M., Mauerer, W., Neukart, F., Niedermeier, C., … Winter, F. (2021). Industry quantum computing applications. *EPJ Quantum Technology*, *8*(1), 25. https://doi.org/10.1140/epjqt/s40507-021-00114-x

Romero, J., Babbush, R., McClean, J. R., Hempel, C., Love, P. J., & Aspuru-Guzik, A. (2018). Strategies for quantum computing molecular energies using the unitary coupled cluster ansatz. *Quantum Science and Technology*, *4*(1), 014008. https://doi.org/10.1088/2058-9565/aad3e4

Subaşı, Y., Somma, R. D., & Orsucci, D. (2019). Quantum Algorithms for Systems of Linear Equations Inspired by Adiabatic Quantum Computing. *Physical Review Letters*, *122*(6), 060504. https://doi.org/10.1103/PhysRevLett.122.060504

Takeda, S., & Furusawa, A. (2019). Toward large-scale fault-tolerant universal photonic quantum computing. *APL Photonics*, *4*(6), 060902. https://doi.org/10.1063/1.5100160

Vandersypen, L. M. K., & Eriksson, M. A. (2019). Quantum computing with semiconductor spins. *Physics Today*, *72*(8), 38–45. https://doi.org/10.1063/PT.3.4270

Von Burg, V., Low, G. H., Häner, T., Steiger, D. S., Reiher, M., Roetteler, M., & Troyer, M. (2021). Quantum computing enhanced computational catalysis. *Physical Review Research*, *3*(3), 033055. https://doi.org/10.1103/PhysRevResearch.3.033055

Wu, Y., Kolkowitz, S., Puri, S., & Thompson, J. D. (2022). Erasure conversion for fault-tolerant quantum computing in alkaline earth Rydberg atom arrays. *Nature Communications*, *13*(1), 4657. https://doi.org/10.1038/s41467-022-32094-6