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INAÊ SOARES DE FIGUEIREDO

Code Quality Metrics for Circuit Optimization in a Quantum Anomaly Detection Context

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Inaê Soares de Figueiredo

Code Quality Metrics for Circuit Optimization in a Quantum Anomaly Detection Context

Dissertação, apresentada à Universidade Estadual Paulista (UNESP), Faculdade de Ciências, Bauru, para obtenção do título de Mestraem Ciência da Computação.

Orientador: Profº Dr. Kelton Augusto Pontara da Costa
Coorientador: Profº Dr. Higor Amario de Souza

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Aos 05 de dezembro de 2025, às 10h, por meio de Videoconferência, realizou-se a defesa de DISSERTAÇÃO DE MESTRADO de INAÊ SOARES DE FIGUEIREDO, intitulada **Code Quality Metrics for Circuit Optimization in a Quantum Anomaly Detection Context**. A Comissão Examinadora foi constituída pelos seguintes membros: Professor Doutor KELTON AUGUSTO PONTARA DA COSTA (Orientador(a) - Participação Virtual) do(a) Departamento de Computação / UNESP / Câmpus de Bauru - FC, Prof. Dr. FELIPE FERNANDES FANCHINI (Participação Virtual) do(a) Departamento de Física e Meteorologia / UNESP / Câmpus de Bauru - FC, Professor Doutor RONALDO MARTINS DA COSTA (Participação Virtual) do(a) Instituto de Informática / UNIVERSIDADE FEDERAL DE GOIAS, Após a exposição pela mestranda e arguição pelos membros da Comissão Examinadora que participaram do ato, de forma presencial e/ou virtual, a discente recebeu o conceito final APROVADO. Nada mais havendo, foi lavrada a presente ata, que após lida e aprovada, foi assinada pelo(a) Presidente(a) da Comissão Examinadora.

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CODE QUALITY METRICS FOR CIRCUIT OPTIMIZATION IN A QUANTUM ANOMALY DETECTION CONTEXT

Dissertação apresentado(a) à Universidade Estadual Paulista (UNESP), Faculdade de Ciências, Bauru, para obtenção do título de Mestra em Ciência da Computação.

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RESUMO

A cibersegurança é uma preocupação crescente, sendo a privacidade e a proteção contra ataques pontos de discórdia importantes entre organizações e clientes. A aplicação de tecnologias modernas, como modelos de aprendizado de máquina para detecção de anomalias, pode ser eficaz para a privacidade e a segurança, e há uma urgência em compreender como a aplicação de tecnologias modernas, como computadores quânticos, pode trazer ainda mais avanços para essas aplicações. A computação quântica encontra-se atualmente em uma era de ruído, na qual os computadores quânticos existentes não conseguem executar tarefas sem gerar quantidades consideráveis de erros.

Este projeto de pesquisa visa analisar o desempenho de um modelo de Rede Neural Quântica quando aplicado a tarefas de detecção de anomalias usando os conjuntos de dados UNSW-NB15 e CSE-CIC-IDS2018. Além disso, avaliará como a remoção de "code smells" quânticos impacta as simulações e o desempenho do modelo. O modelo é reproduzido usando simulações com e sem ruído, e o impacto da otimização na redução de ruído também será avaliado.

Palavras-Chave: Computação Quântica, Detecção de anomalias, Aprendizado de máquina quântico, Engenharia de *software* quântica.

ABSTRACT

Cybersecurity is a growing concern, with privacy and protection against attacks being important contention points between organizations and customers. The application of modern technologies, such as machine learning models for anomaly detection, can be effective for privacy and security, and there is an urgency to understand how the application of modern technologies, like quantum computers, can bring even more advancements to these applications. Quantum computing is currently in a noisy era where the existing quantum computers cannot perform tasks without generating considerable amounts of error.

This research project aims to analyze the performance of a Quantum Neural Network model when applied to anomaly detection tasks using the UNSW-NB15 and CSE-CIC-IDS2018 datasets. Furthermore, it will evaluate how the removal of quantum code smells impacts the simulations and performance of the model. The model is reproduced using noisy and noiseless simulation, and the impact of the optimization on noise reduction will also be evaluated.

Keywords: Quantum computing, Anomaly detection, Quantum machine learning, Quantum software engineering.

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LIST OF ABBREVIATIONS AND ACRONYMS

AD	Anomaly Detection
ADS	Anomaly Detection System
alap	As late as possible
API	Application Programming Interface
asap	As soon as possible
CIC	Canadian Institute for Cybersecurity
CPU	Central Processing Unit
CSE	Communications Security Establishment
DDoS	Distributed Denial of Service
DoS	Denial of Service
DT	Decision Tree
FFT	Fast Fourier Transform
FM	Feature Map
FN	False Negative
FP	False Positive
FS	Feature Selection
GPU	Graphic Processing Unit
IDE	Integrated Development Environment
IDS	Intrusion Detection System
QaaS	Quantum as a Service
QADS	Quantum Anomaly Detection System
QC	Quantum computing
QDT	Quantum Decision Tree
QML	Quantum Machine Learning

QNN	Quantum Neural Network
QP	Quantum Program
QPU	Quantum Processing Unit
QSE	Quantum Software Engineering
QSVM	Quantum Support Vector Machine
ML	Machine Learning
NaN	Not a Number
NISQ	Noise Intermediate Scale Quantum
NN	Neural Network
NNC	Neural Network Classifier
OS	Operational Service
RAM	Random Access Memory
SDK	Software Development Kit
SVM	Support Vector Machine
TN	True Negative
TP	True Positive
UN	United Nations
VQA	Variational Quantum Algorithm

LIST OF SYMBOLS

$\|x\rangle$	Ket notation, represents a quantum state
$\langle x\|$	Bra notation, represents the transposed conjugate of a quantum state
$\|x\rangle \langle x\|$	KetBra notation, represents the external product, or vector product, of a quantum state
$\langle x\|x\rangle$	BraKet notation, represents the internal product of a quantum state
$\|\psi\rangle$	General state of a qubit
α	Alpha
β	Beta
γ	Gamma
ϵ	Epsilon
$\|\alpha\|^2$	Module of α squared
$\otimes$	Tensor product
$\mathbb{H}$	Hilbert Space
$\in$	Included in
$\mathbb{C}$	Complex numbers set
†	Dagger, represents the transposed conjugate of a vector or matrix
us	microsecond, 10^{-6}s
ns	nanosecond, 10^{-9}s

CONTENTS

A INTRODUCTION

Quantum computing, an area that has been studied for decades, finds itself in the middle of a boom of interest, investments, discoveries, and advancements. Part of the current excitement with the area comes from the fact that 2025 has been declared by the United Nations (UN) the International Year of Quantum Science and Technology (IYQ) (IWQ, 2025). Adding to the expectations that are being directed towards quantum technology developments, big companies that have spent years investing in quantum research have been announcing and making available more advanced resources.

IBM started their Quantum platform offering to the free plan users access to their 5 and 7 qubit quantum processing units (QPUs), but in less than 2 years made the 127 QPUs available. In the beginning of 2025, the company announced more changes to its platform, including making the Heron QPU (156 qubits) available in the free use plan (Roberts et al., 2025). By the end of 2024, Google unveiled its newest quantum chip, Willow, with the promise that it reduces error exponentially as more qubits are used (Neven, 2024). Microsoft recently presented the Majorana 1 topological chip, declaring that it paves the way for quantum chips with millions of qubits (Bolgar, 2025).

In the first months of 2025, Amazon Web Services scientist also announced a new quantum chip that has integrated error correction (Brandão; Painter, 2025). They propose that it makes the step of correction more efficient and less expensive in terms of energy and resources it requires to be implemented. Error reduction, or noise reduction, is another important research topic related to the necessity to minimize the amount of error that quantum computers generate to a point where it is no longer necessary to factor it in the evaluation of quantum programs.

Parallel to the advancements in quantum hardware development, research into other topics such as quantum networks, communication and data transference have gained traction, with promises that quantum computing could be the solution for safer network communications and better cryptography protocols (Hannover, 2025). In 2024, a group of scientist carried out the first demonstration of quantum teleportation using optical fibers carrying conventional telecommunications traffic (Thomas et al., 2024) and another group proposed a method for automatic polarization compensation, which is important to maintain the quantum information being transferred intact (Chapman et al., 2024). There is even research being conducted on the future of the Internet and the impacts of quantum computing on the safety and protection of data being shared over it, already considering the attacks that may be directed towards a quantum Internet and all the classical encrypted data that is shared today. To that extent, some researchers aim to find ways to transfer data that is more secure against interception (Kashi; Kues, 2025), and others focus on developing safer communication protocols (Hassani et al., 2025). The QIY institutions is also supporting events that promote discussions about cybersecurity in the quantum era, such as Quantum Safe: Quantum Communication for Data Security, a discussion panel set to happen later this year (QuIIN, 2025).

Another application for which quantum computers have been greatly applied is Quantum Machine Learning (QML). Many different models have been developed, considered equivalent to their classical counterparts, but most times they are unable to reach the same good results. Some of these models aim to implement Quantum Anomaly Detection ((Gouveia; Correia, 2020; Chen; Liu, 2022; Deng; Wan; Guo, 2022; Huang et al., 2017)), considering that the classical Anomaly Detection research would be greatly advanced by any application that could present high-quality real-time predictions and that could be possible with noise-free QC.

Quantum computing research has shown great improvement in recent years, with the development of machine learning algorithms with the potential to be advantageous compared to their classical counterparts (Li; Deng, 2022), the development of many different quantum machine learning models (Li; Deng, 2022; Larocca et al., 2023), and the researches into quantum communications. But the quality of these applications and future advancements depend greatly on finding the best solutions for the removal or correction of error in quantum codes. In 2023, a group of researchers (Chen et al., 2023) presented eight code smells that are prevalent in quantum code, proposing that the removal of them could be metrics to evaluate code quality in quantum environments. Other more recent researches on the Quantum Software Engineering (QSE) field agree with Chen et al. (2023) and propose a great variety of techniques and tools for identifying and removing problems from quantum code.

One thing that greatly impacts the error rate in quantum programs is the size of the circuit used, since every quantum gate and operation can introduce noise into the system, and the longer the execution time, the more vulnerable the system is to suffering physical interferences. Taking this into consideration, this research proposes to evaluate how well adhering to the above mentioned code quality metrics affects the results of quantum machine learning algorithms aimed at anomaly detection. This evaluation regards both the predictive capabilities of the models as well as the circuit generated after transpilation. The lack of work published on these themes is a strong motivator for this research, as the author believes that any advancement can be of great contribution to the whole quantum computing field. The recent publications also highlight the perceived importance of the topic.

A.1 OBJECTIVES

The quantum computing field has seen many changes and advancements in the last two years. Some of those affected directly this research project, causing it to suffer some changes and evolve into something more relevant to the current quantum computing challenges. The main focus of the research remained the same: to understand and explain the impacts of applying code quality metrics and removing code smells on the results obtained by machine learning models trained for anomaly detection on simulators and real quantum computers. But some of the steps to get to the final result were changed.

J.2 CONCLUSION

Developing research in areas that are still developing is rewarding because there is still a lot to discover. But it is also a challenge to have to work with constantly adjusting tools and limited resources. Nevertheless, it is a great learning opportunity to be dealing with new discoveries and updates in real time.

The main focus of this Masters research project was to evaluate possible code optimization techniques with the expectations that, when applied to a quantum development environment, they would result in better transpiled circuits that could yeld better results. In the end, it was verified that there are some steps that need to be taken when writing quantum circuits that will have this expected results, and these observations were validated by other researchers and by IBM Qiskit updates that reinforce the importance of well done pre-processing of the circuit before execution.

One innovative thing done in this project was testing different feature mapping techniques to find the one that generated the best data representation for the QAD problem at hand. It was observed that it varies depending on the dataset, as expected, and it does not generalize well from one to another in a noisy environment. The best results were obtained using the XY Pauli matrices.

The results from the various model configuration tests showed that each smell can affect the QNN's prediction capabilities in a higher or lower degree but they all change it in some way. Some effects were related more to longer training times than to actual metrics values, but that is also an important indicator to consider when choosing a learning model to train.

It is possible that the relatively small overall size of the circuit caused the interference of noise on results to be less pronounced, but it was still observable, indicating that having a code with too many smells is indeed detrimental to the development of good learning and classification models. Also, the chosen FM, the backend layout and the small number o qubits did not create the need for the inclusion of SWAP gates into the circuit, which is a gate that is known to add lots of noise to quantum circuits. The use of SWAP gates is a great exploration to be done in future work.

For cybersecurity applications a better QNN model would still need to be developed, or perhaps more qubits would need to be used. Either way, the metrics reached through the model trained for this research is far from the quality of state-of-the-art classical AD applications.

In relation to cybersecurity and the need for real time results, it needs to be considered that with the present model of quantum computing through online services this can not be achieved. Fo real-time applications, classical computation is still the only solution.

J.3 FUTURE WORK

The research conducted and presented in this document leaves many points to be explored with more time and resources. Some important topics for future work that the researcher would like to highlight are listed below:

- Execute and evaluate the developed and simulated codes on a real quantum computing backend;
- Test the effectiveness of the QNN Classifier on unbalanced datasets and other key cybersecurity datasets;
- Evaluate the effectiveness of other feature selection techniques;
- Implement different quantum circuit optimization methods proposed by authors in recent years;
- Compare other data encoding methods to the Feature Mapping technique evaluated in this research;
- Work with mode data features and consequently with circuits composed of more qubits;
- Personalize the QNN Classifier, changing optimizers, loss functions and other parameters that can be modified;
- Try multi-threading techniques to try and overcome the hardware limitations that were encountered.

BIBLIOGRAPHY

ABBAS, A. et al. The power of quantum neural networks. **Nat. Comput. Sci.**, Nature Publishing Group, v. 1, p. 403–409, jun. 2021. ISSN 2662-8457.

ACHARYA, N.; SARAVANAN, V.; SAEED, S. M. An attack on quantum circuits based on the error rates of nisq systems and a countermeasure. In: PARK, Y.; JADAV, D.; AUSTIN, T. (Ed.). **Silicon Valley Cybersecurity Conference**. [S.l.]: Springer International Publishing, 2021. p. 109–114. ISBN 978-3-030-72725-3.

AKPINAR, E.; ODUNCUOGLU, M. Hybrid classical and quantum computing for enhanced glioma tumor classification using TCGA data. **Sci. Rep.**, Nature Publishing Group, v. 15, n. 25935, p. 25935, jul. 2025. ISSN 2045-2322.

ALAWADI, S. et al. Fedcsd: A federated learning based approach for code-smell detection. **IEEE Access**, v. 12, p. 44888–44904, 2024.

ALTARES-LÓPEZ, S.; RIBEIRO, A.; GARCÍA-RIPOLL, J. J. Automatic design of quantum feature maps. **Quantum Sci. Technol.**, IOP Publishing, v. 6, n. 4, p. 045015, ago. 2021. ISSN 2058-9565.

ANDRILLI, S.; HECKER, D. Chapter 6 - Orthogonality. In: **Elementary Linear Algebra (Fifth Edition)**. Cambridge, MA, USA: Academic Press, 2016. p. 413–463. ISBN 978-0-12-800853-9.

BENNETT, C. et al. **Learn quantum computing: a field guide**. 2023. Disponível em: https://quantum-computing.ibm.com/composer/docs/iqx/guide. Acesso em: Online; accessed 29. Jul. 2023.

BIAMONTE, J. et al. Quantum machine learning. **Nature**, Nature Publishing Group, v. 549, p. 195–202, set. 2017. ISSN 1476-4687.

BISWAS, H. Data Encoding for VQC in Qiskit, A Comparison With Novel Hybrid Encoding. **arXiv**, mar. 2025.

BOLGAR, C. **Microsoft's Majorana 1 chip carves new path for quantum computing - Source**. 2025. [Online; accessed 3. Mar. 2025]. Disponível em: https://news.microsoft.com/source/features/ai/microsofts-majorana-1-chip-carves-new-path-for-quantum-computing.

BRANDÃO, F.; PAINTER, O. Amazon announces Ocelot quantum chip. **Amazon Science**, Amazon Science, fev. 2025. Disponível em: https://www.amazon.science/blog/amazon-announces-ocelot-quantum-chip.

BRONN, N. **Mitigating Noise in Quantum Hardware - Part 1 | Qiskit Seminar Series 2023**. 2023. Disponível em: https://youtu.be/Dv5cqB87nqk?si=UAcSADkiyzyJhsHA.

CHAPMAN, J. C. et al. Continuous automatic polarization channel stabilization from heterodyne detection of coexisting dim reference signals. **Opt. Express**, Optica Publishing Group, v. 32, n. 26, p. 47589–47619, dez. 2024. ISSN 1094-4087.

CHEN, Q. et al. The Smelly Eight: An Empirical Study on the Prevalence of Code Smells in Quantum Computing . In: **2023 IEEE/ACM 45th International Conference on Software Engineering (ICSE)**. Los Alamitos, CA, USA: IEEE Computer Society, 2023. p. 358–370. Disponível em: https://doi.ieeecomputersociety.org/10.1109/ICSE48619.2023.00041.

CHEN, S. et al. **The Complexity of NISQ**. 2022.

CHEN, Y.; LIU, F. Anomaly Detection of IoT Communication Equipment Based on Entropy Ideal Point Method: from the Perspective of Quantum Communication. In: **2022 3rd International Conference on Electronics and Sustainable Communication Systems (ICESC)**. [S.l.]: IEEE, 2022. p. 17–19.

CORPORATION, N. **Overview — NVIDIA cuQuantum**. 2025. [Online; accessed 14. Nov. 2025]. Disponível em: https://docs.nvidia.com/cuda/cuquantum/latest/overview.html.

CROSS, A. W. et al. Validating quantum computers using randomized model circuits. **Phys. Rev. A**, American Physical Society, v. 100, n. 3, p. 032328, set. 2019. ISSN 2469-9934.

DENG, L.; WAN, L.; GUO, J. Research on Security Anomaly Detection for Big Data Platforms Based on Quantum Optimization Clustering. **Math. Prob. Eng.**, Hindawi, v. 2022, ago. 2022. ISSN 1024-123X.

DICKSON, M. NON-RELATIVISTIC QUANTUM MECHANICS. In: **Philosophy of Physics**. [S.l.]: North-Holland, 2007. p. 275–415.

DONG, D. et al. Quantum reinforcement learning. **IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)**, Institute of Electrical and Electronics Engineers (IEEE), v. 38, n. 5, p. 1207–1220, oct 2008. Disponível em: https://doi.org/10.1109%2Ftsmcb.2008.925743.

DUAN, Y.; SONG, C. Relevant modes selection method based on Spearman correlation coefficient for laser signal denoising using empirical mode decomposition. **Opt. Rev.**, Springer Japan, v. 23, n. 6, p. 936–949, dez. 2016. ISSN 1349-9432.

FELEFLY, T. et al. An Explainable MRI-Radiomic Quantum Neural Network to Differentiate Between Large Brain Metastases and High-Grade Glioma Using Quantum Annealing for Feature Selection. **J. Digit. Imaging**, Springer International Publishing, v. 36, n. 6, p. 2335–2346, dez. 2023. ISSN 1618-727X.

GENTINETTA, G. et al. The complexity of quantum support vector machines. **arXiv**, fev. 2022.

GHOSH, S. et al. The journey of graph kernels through two decades. **Computer Science Review**, Elsevier, v. 27, p. 88–111, fev. 2018. ISSN 1574-0137.

GILES, M. Explainer: What is a quantum computer? **MIT Technology Review**, MIT Technology Review, ago. 2024. Disponível em: https://www.technologyreview.com/2019/01/29/66141/what-is-quantum-computing.

GOUVEIA, A.; CORREIA, M. Towards quantum-enhanced machine learning for network intrusion detection. In: **2020 IEEE 19th International Symposium on Network Computing and Applications (NCA)**. [S.l.: s.n.], 2020. p. 1–8.

GROSSI, M. et al. Mixed Quantum–Classical Method for Fraud Detection With Quantum Feature Selection. **IEEE Transactions on Quantum Engineering**, IEEE Computer Society, v. 3, n. 01, p. 1–12, jan. 2022. ISSN 2689-1808.

GUO, M. et al. Quantum algorithms for anomaly detection using amplitude estimation. **Physica A**, North-Holland, v. 604, p. 127936, out. 2022. ISSN 0378-4371.

GYONGYOSI, L.; IMRE, S. Circuit Depth Reduction for Gate-Model Quantum Computers. **Sci. Rep.**, Nature Publishing Group, v. 10, n. 11229, p. 1–17, jul. 2020. ISSN 2045-2322.

HANNOVER, L. U. Exploiting photon colors for a high-performance quantum internet. **Phys.org**, Phys.org, fev. 2025. Disponível em: https://phys.org/news/2025-02-exploiting-photon-high-quantum-internet.html.

HASSANI, M. et al. Privacy in Networks of Quantum Sensors. **Phys. Rev. Lett.**, American Physical Society, v. 134, n. 3, p. 030802, jan. 2025.

HAVLICEK, V. et al. Supervised learning with quantum enhanced feature spaces. **arXiv**, abr. 2018.

HELLSTERN, G.; DEHN, V.; ZAEFFERER, M. Quantum computer based feature selection in machine learning. **IET Quantum Commun.**, John Wiley & Sons, Ltd, v. 5, n. 3, p. 232–252, set. 2024. ISSN 2632-8925.

HERR, D.; OBERT, B.; ROSENKRANZ, M. Anomaly detection with variational quantum generative adversarial networks. **Quantum Science and Technology**, IOP Publishing, v. 6, n. 4, p. 045004, jul 2021. Disponível em: https://doi.org/10.1088%2F2058-9565%2Fac0d4d.

HOLMES, A. et al. Impact of qubit connectivity on quantum algorithm performance. **arXiv**, nov. 2018.

HONG, Y.-Y.; LOPEZ, D. J. D.; WANG, Y.-Y. Solar Irradiance Forecasting Using a Hybrid Quantum Neural Network: A Comparison on GPU-Based Workflow Development Platforms. **IEEE Access**, IEEE, v. 12, p. 145079–145094, out. 2024. ISSN 2169-3536.

HUANG, W. et al. An Anomaly Detection Method Based on Normalized Mutual Information Feature Selection and Quantum Wavelet Neural Network. **Wirel. Pers. Commun.**, Kluwer Academic Publishers, v. 96, n. 2, p. 2693–2713, set. 2017. ISSN 0929-6212.

I, V. et al. Ransomware detection using quantum neural networks. In: **2024 International Conference on System, Computation, Automation and Networking (ICSCAN)**. [S.l.: s.n.], 2024. p. 1–6.

IWQ. **IYQ 2025**. 2025. [Online; accessed 3. Mar. 2025]. Disponível em: https://quantum2025.org.

JOSHI, T.; GUHA, K. Quantum AI Algorithm Development for Enhanced Cybersecurity: A Hybrid Approach to Malware Detection. **arXiv**, set. 2025.

JURCEVIC, P. et al. Demonstration of quantum volume 64 on a superconducting quantum computing system. **Quantum Sci. Technol.**, IOP Publishing, v. 6, n. 2, p. 025020, mar. 2021. ISSN 2058-9565.

KAIST, K. A. I. o. S. . T. **Introduction to Quantum Information**. 2023. [Online; accessed 24. Jun. 2023]. Disponível em: https://www.coursera.org/learn/introduction-to-quantum-information.

KARAMCHAND, G. Quantum Machine Learning for Threat Detection in High-Security Networks. **1.**, v. 17, n. 02, p. 14–25, maio 2025. ISSN 2454-5767.

KASHI, A. K.; KUES, M. Frequency-bin-encoded entanglement-based quantum key distribution in a reconfigurable frequency-multiplexed network. **Light Sci. Appl.**, Nature Publishing Group, v. 14, n. 49, p. 1–16, jan. 2025. ISSN 2047-7538.

KASIRAJAN, V. **Fundamentals of Quantum Computing**. Cham, Switzerland: Springer International Publishing, 2021. ISBN 978-3-030-63689-0. Disponível em: https://link.springer.com/book/10.1007/978-3-030-63689-0.

KÜÇÜKKARA, M. Y.; ATBAN, F.; BAYLMŞ, C. Quantum-Neural Network Model for Platform Independent Ddos Attack Classification in Cyber Security. **Adv. Quantum Technol.**, John Wiley & Sons, Ltd, v. 7, n. 10, p. 2400084, ago. 2024. ISSN 2511-9044.

LAROCCA, M. et al. Theory of overparametrization in quantum neural networks. **Nat. Comput. Sci.**, Nature Publishing Group, v. 3, p. 542–551, jun. 2023. ISSN 2662-8457.

LI, A.; LIU, C.; STEIN, S. **Comparing Quantum Encoding Techniques**. 2024. [Online; accessed 4. Nov. 2025]. Disponível em: https://arxiv.org/html/2410.09121v1.

LI, T. et al. Quframe: A novel encoding ensemble framework for quantum neural networks. In: **2025 International Conference on Quantum Communications, Networking, and Computing (QCNC)**. [S.l.: s.n.], 2025. p. 583–590.

LI, W.; DENG, D.-L. Recent advances for quantum classifiers. **Sci. China Phys. Mech. Astron.**, Science China Press, v. 65, n. 2, p. 1–23, fev. 2022. ISSN 1869-1927.

LIANG, J.-M. et al. Quantum anomaly detection with density estimation and multivariate gaussian distribution. **Physical Review A**, American Physical Society (APS), v. 99, n. 5, may 2019. Disponível em: https://doi.org/10.1103%2Fphysreva.99.052310.

LIU, N.; REBENTROST, P. Quantum machine learning for quantum anomaly detection. **Phys. Rev. A**, American Physical Society, v. 97, n. 4, p. 042315, abr. 2018. ISSN 2469-9934.

LOSS, D. **Qubits – the building blocks of the quantum computer.** 2025. [Online; accessed 14. Nov. 2025]. Disponível em: https://www.unibas.ch/en/News-Events/Uni-Nova/Uni-Nova-130/Uni-Nova-130-Qubits-the-building-blocks-of-the-quantum-computer.html.

LU, S.; BRAUNSTEIN, S. L. Quantum decision tree classifier. **Quantum Inf. Process.**, Springer US, v. 13, n. 3, p. 757–770, mar. 2014. ISSN 1573-1332.

LUND, A.; LUND, M. **Spearman's Rank-Order Correlation - A guide to when to use it, what it does and what the assumptions are.** 2024. [Online; accessed 8. Nov. 2024]. Disponível em: https://statistics.laerd.com/statistical-guides/spearmans-rank-order-correlation-statistical-guide.php.

MALHOTRA, R.; JAIN, B.; KESSENTINI, M. QNet: exploring deep learning for quantum code smell detection. **Software Qual. J.**, Springer US, v. 33, n. 2, p. 25, jun. 2025. ISSN 1573-1367.

MANDAL, A. K. et al. Quantum software engineering and potential of quantum computing in software engineering research: a review. **Autom. Softw. Eng.**, Springer US, v. 32, n. 1, p. 27, maio 2025. ISSN 1573-7535.

MAO, X. et al. Towards defect prediction for quantum software*. In: **2025 IEEE/ACM International Workshop on Quantum Software Engineering (Q-SE)**. [S.l.: s.n.], 2025. p. 1–8.

MASHTURA, R. et al. A parallel quantum feature encoding scheme for effective classical data classification in quantum convolutional neural networks. In: **TENCON 2023 - 2023 IEEE Region 10 Conference (TENCON)**. [S.l.: s.n.], 2023. p. 1–5.

MAZOUZI, R.; HAREL, P. A Hybrid \. In: **ICSCA '20: Proceedings of the 2020 9th International Conference on Software and Computer Applications**. New York, NY, USA: Association for Computing Machinery, 2020. p. 67–73. ISBN 978-1-45037665-5.

MOUSTAFA, N.; SLAY, J. Unsw-nb15: a comprehensive data set for network intrusion detection systems (unsw-nb15 network data set). In: **2015 Military Communications and Information Systems Conference (MilCIS)**. [S.l.: s.n.], 2015. p. 1–6.

MÜCKE, S. et al. Feature selection on quantum computers. **Quantum Mach. Intell.**, Springer International Publishing, v. 5, n. 1, p. 1–16, jun. 2023. ISSN 2524-4914.

NEVEN, H. Meet Willow, our state-of-the-art quantum chip. **Google**, Google, dez. 2024. Disponível em: https://blog.google/technology/research/google-willow-quantum-chip.

PALTENGHI, M.; PRADEL, M. Analyzing Quantum Programs with LintQ: A Static Analysis Framework for Qiskit. **Proc. ACM Softw. Eng.**, Association for Computing Machinery, v. 1, n. FSE, p. 2144–2166, jul. 2024.

PENNYLANE. **Quantum embedding — PennyLane**. 2025. [Online; accessed 7. Mar. 2025]. Disponível em: https://pennylane.ai/qml/glossary/quantum_embedding.

PIATTINI, M. et al. Toward a Quantum Software Engineering. **IT Prof.**, IEEE, v. 23, n. 1, p. 62–66, jan. 2021. ISSN 1941-045X.

POWER, L.; GUHA, K. **Feature Importance and Explainability in Quantum Machine Learning**. 2024. [Online; accessed 4. Nov. 2025]. Disponível em: https://arxiv.org/html/2405.08917v1.

PRESSMAN, R. S.; MAXIM, B. R. **Engenharia de software - 9.ed.** Brazil: McGraw Hill Brasil, 2021. ISBN 978-65-5804011-8. Disponível em: https://books.google.com.br/books?id=FSE3EAAAQBAJ&printsec=frontcover&newbks=0&hl=pt-BR&redir_esc=y#v=onepage&q&f=false.

Qiskit Development Team. **textbook/notebooks/quantum-machine-learning/encoding.ipynb at main · Qiskit/textbook**. 2022. [Online; accessed 8. Mar. 2025]. Disponível em: https://github.com/Qiskit/textbook/blob/main/notebooks/quantum-machine-learning/encoding.ipynb.

Qiskit Development Team. **Qiskit**. 2023. [Online; accessed 25. Jun. 2023]. Disponível em: https://qiskit.org.

Qiskit Development Team. **Codificação de dados | IBM Quantum Learning**. 2025. [Online; accessed 4. Nov. 2025]. Disponível em: https://quantum.cloud.ibm.com/learning/pt/courses/quantum-machine-learning/data-encoding.

Qiskit Development Team. **EquivalenceLibrary (latest version) | IBM Quantum Documentation**. 2025. [Online; accessed 12. Nov. 2025]. Disponível em: https://quantum.cloud.ibm.com/docs/en/api/qiskit/qiskit.circuit.EquivalenceLibrary.

Qiskit Development Team. **Introduction to execution modes | IBM Quantum Documentation**. 2025. [Online; accessed 14. Nov. 2025]. Disponível em: https://quantum.cloud.ibm.com/docs/en/guides/execution-modes#job-mode.

Qiskit Development Team. **Introduction to primitives | IBM Quantum Documentation**. 2025. [Online; accessed 15. Nov. 2025]. Disponível em: https://quantum.cloud.ibm.com/docs/en/guides/primitives.

Qiskit Development Team. **Introduction to transpilation | IBM Quantum Documentation**. 2025. [Online; accessed 5. Mar. 2025]. Disponível em: https://docs.quantum.ibm.com/guides/transpile.

Qiskit Development Team. **Qiskit Aer 0.17.1**. 2025. [Online; accessed 15. Nov. 2025]. Disponível em: https://qiskit.github.io/qiskit-aer/index.html.

Qiskit Development Team. **Qiskit Machine Learning 0.8.4**. 2025. [Online; accessed 13. Nov. 2025]. Disponível em: https://qiskit-community.github.io/qiskit-machine-learning.

Qiskit Development Team. **qiskit_ibm_runtime (latest version) | IBM Quantum Documentation**. 2025. [Online; accessed 14. Nov. 2025]. Disponível em: https://quantum.cloud.ibm.com/docs/en/api/qiskit-ibm-runtime/runtime-service.

Qiskit Development Team. **Quantum Neural Networks - Qiskit Machine Learning 0.8.4**. 2025. [Online; accessed 12. Nov. 2025]. Disponível em: https://qiskit-community.github.io/qiskit-machine-learning/tutorials/01_neural_networks.html.

Qiskit Development Team. **Quantum neural networks (qiskit_machine_learning.neural_networks) - Qiskit Machine Learning 0.8.4**. 2025. [Online; accessed 15. Nov. 2025]. Disponível em: https://qiskit-community.github.io/qiskit-machine-learning/apidocs/qiskit_machine_learning.neural_networks.html.

Qiskit Development Team. **Transpile circuits remotely with the Qiskit Transpiler Service | IBM Quantum Documentation**. 2025. [Online; accessed 15. Nov. 2025]. Disponível em: https://quantum.cloud.ibm.com/docs/en/guides/qiskit-transpiler-service.

Qiskit Development Team. **Transpiler - IBM Quantum Documentation**. 2025. [Online; accessed 8. Mar. 2025]. Disponível em: https://docs.quantum.ibm.com/api/qiskit/transpiler.

Qiskit Development Team. **Transpiler stages | IBM Quantum Documentation**. 2025. [Online; accessed 12. Nov. 2025]. Disponível em: https://quantum.cloud.ibm.com/docs/en/guides/transpiler-stages.

Qiskit Development Team. **QPU information | IBM Quantum Documentation**. 2026. [Online; accessed 12. Feb. 2026]. Disponível em: https://quantum.cloud.ibm.com/docs/en/guides/qpu-information#median-t1-relaxation-time.

Quantum Mechanics Visualization Project. **Bloch sphere**. 2017. [Online; accessed 9. Mar. 2025]. Disponível em: https://www.st-andrews.ac.uk/physics/quvis/simulations_html5/sims/blochsphere/blochsphere.html.

QUERA, C. I. **What is Logical Qubit**. 2025. [Online; accessed 9. Mar. 2025]. Disponível em: https://www.quera.com/glossary/logical-qubit.

QUIIN, E. C. C. C. i. Q. T. **Quantum Safe: Quantum Communication for Data Security - IYQ 2025**. 2025. [Online; accessed 4. Mar. 2025]. Disponível em: https://quantum2025.org/iyq-event/quantum-safe-quantum-communication-for-data-security.

ROBERTS, J. et al. **The next evolution of IBM Quantum Platform | IBM Quantum Computing Blog**. 2025. [Online; accessed 3. Mar. 2025]. Disponível em: https://www.ibm.com/quantum/blog/iqp-upgrade?linkId=13158115.

ROSENHAHN, B.; OSBORNE, T. J.; HIRCHE, C. Optimization Driven Quantum Circuit Reduction. **arXiv**, fev. 2025.

ROSS, D. **I Don’t Understand Quantum Physics**. 2021. [Online; accessed 11. Nov. 2025]. Disponível em: https://www.southampton.ac.uk/~doug/quantum_physics/index.html.

SAKHNENKO, A. et al. Hybrid Classical-Quantum Autoencoder for Anomaly Detection. **arXiv**, dez. 2021.

SARMA, S. D.; DENG, D.-L.; DUAN, L.-M. Machine learning meets quantum physics. **Physics Today**, v. 72, n. 3, p. 48–54, 03 2019. ISSN 0031-9228. Disponível em: https://doi.org/10.1063/PT.3.4164.

SCHNEIDER, J.; SMALLEY, I. **Qubit**. 2025. [Online; accessed 14. Nov. 2025]. Disponível em: https://www.ibm.com/think/topics/qubit.

SCHULD, M.; PETRUCCIONE, F. **Supervised Learning with Quantum Computers**. 1. ed. [S.l.]: Springer, 2018.

SCHULD, M.; SWEKE, R.; MEYER, J. J. The effect of data encoding on the expressive power of variational quantum machine learning models. **arXiv**, ago. 2020.

SERRANO, M. A.; PéREZ-CASTILLO, R.; PIATTINI, M. (Ed.). **Quantum Software Engineering**. Cham, Switzerland: Springer International Publishing, 2022. ISBN 978-3-031-05324-5. Disponível em: https://link.springer.com/book/10.1007/978-3-031-05324-5.

SHARAFALDIN, I.; LASHKARI, A. H.; GHORBANI, A. A. Toward generating a new intrusion detection dataset and intrusion traffic characterization. In: **International Conference on Information Systems Security and Privacy**. [s.n.], 2018. Disponível em: https://api.semanticscholar.org/CorpusID:4707749.

SIAVASH, N.; MOIN, A. LLM-Powered Quantum Code Transpilation. **arXiv**, jul. 2025.

SINGH, D.; SINGH, B. Investigating the impact of data normalization on classification performance. **Applied Soft Computing**, v. 97, p. 105524, 2020. ISSN 1568-4946. Disponível em: https://www.sciencedirect.com/science/article/pii/S1568494619302947.

SOON, K. L.; SOON, L. T. A hybrid quantum neural network and classical gated recurrent unit for battery state of health forecasting incorporating SHAP analysis. **J. Energy Storage**, Elsevier, v. 136, p. 118596, nov. 2025. ISSN 2352-152X.

STEFANO, M. D. et al. An empirical study into the effects of transpilation on quantum circuit smells. **Empir. Software Eng.**, Springer US, v. 29, n. 3, p. 1–34, maio 2024. ISSN 1573-7616.

STEFFEN, M. **Differences in error suppression, mitigation, and correction | IBM Quantum Computing Blog**. 2022. [Online; accessed 9. Mar. 2025]. Disponível em: https://www.ibm.com/quantum/blog/quantum-error-suppression-mitigation-correction.

SZABO, F. E. **The Linear Algebra Survival Guide**. [S.l.]: Elsevier, Academic Press, 2015. ISBN 978-0-12-409520-5.

THOMAS, J. M. et al. Quantum teleportation coexisting with classical communications in optical fiber. **arXiv**, abr. 2024.

TREMBA, M.; HOVLAND, P.; LIU, J. **Is Circuit Depth Accurate for Comparing Quantum Circuit Runtimes?** 2025. [Online; accessed 12. Nov. 2025]. Disponível em: https://arxiv.org/html/2505.16908v1.

TURATI, G.; DACREMA, M. F.; CREMONESI, P. Feature selection for classification with qaoa. In: **2022 IEEE International Conference on Quantum Computing and Engineering (QCE)**. [S.l.: s.n.], 2022. p. 782–785.

USECHE, D. H. et al. **Computing expectation values of adaptive Fourier density matrices for quantum anomaly detection in NISQ devices**. 2022. [Online; accessed 22. Nov. 2023]. Disponível em: https://www.semanticscholar.org/paper/Computing-expectation-values-of-adaptive-Fourier-in-Useche-Bustos-Brinez/1853d08e1444713af408207173ba34df2c29b6dc.

WATROUS, J. **Basics of Quantum Information | IBM Quantum Learning**. 2024. [Online; accessed 11. Nov. 2024]. Disponível em: https://learning.quantum.ibm.com/course/basics-of-quantum-information.

WILSON, E.; SINGH, S.; MUELLER, F. Just-in-time quantum circuit transpilation reduces noise. In: **2020 IEEE International Conference on Quantum Computing and Engineering (QCE)**. [S.l.: s.n.], 2020. p. 345–355.

ZIMAN, M.; BUŽEK, V. All (qubit) decoherences: Complete characterization and physical implementation. **Phys. Rev. A**, American Physical Society, v. 72, n. 2, p. 022110, ago. 2005.

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PRODUÇÃO BIBLIOGRÁFICA	
FIGUEIREDO, I. S. de; FREDIANI, J. O. R. F.; ARAUJO, M. de T.; PRADO, S. das G. D.; COSTA, K. A. P., N. Modelo de Autoencoder Com Ensemble Learning e Clusterização para Detecção de Intrusão em Redes. Revista Contemporânea, [S. l.], v. 4, n. 6, p. e4910 , 2024.	
LUCAS, THIAGO JOSÉ ; DE FIGUEIREDO, INAÊ SOARES; TOJEIRO, CARLOS ALEXANDRE CARVALHO; DE ALMEIDA, ALEX MARINO G.; SCHERER, RAFA’; BREGA, JOSÉ REMO F.; PAPA, JOÃO PAULO; DA COSTA, KELTON AUGUSTO PONTARA. A Comprehensive Survey on Ensemble Learning-Based Intrusion Detection Approaches in Computer Networks. *In:* IEEE Access, 2023. V. 11, p. 122638-122676.	
FIGUEIREDO, I. S.; COSTA, KELTON A. P. Sobre Sistema de Detecção de intrusão: Estudo da aplicação de Boosting e do algoritmo MINAS na Melhoria de Desempenho. *In:* XXXIV Congresso de Iniciação Científica da Unesp: Reflexos da Pandemia no Letramento e na Cultura Científica, 2022, Atibaia. **Anais** do XXXIV Congresso de Iniciação Científica da Unesp: Reflexos da Pandemia no Letramento e na Cultura Científica. 2022.	
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