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# Referee Report on the Ph.D. thesis by mgr. Paulina Lewandowska.

## Title: Methods of validation of modern quantum architectures (Metody walidacji współczesnych architektur kwantowych)

### Novelty of the subject and its relation to the development of the field (Czy tematyka rozprawy jest aktualna i jak jest zwiazana z rozwojem dyscypliny?)

Autor mgr. Paulina Lewandowska presented the thesis on methods of validation of modern quantum architectures. The subject is related to the field of quantum computing which is currently an intensely developed subject of interdisciplinary research. Apart from the purely scientific side related to the limits of knowledge that can be extracted from measurements of quantum objects this research consists of the engineering effort directed toward reaching limits of controllability of single quantum entities such as atoms, ions, quantum dots, quanta of superconductive flux, etc. in realistic conditions, which is: in the presence of different kinds of errors, noise, losses, finite efficiency measurement devices, and other imperfections the quantum systems are extremely sensitive to. Also, from the side of computer science the problem of quantum computing touches the limits of complexity of problems that can be still tractable by machines in reasonable time. This research is driven by predicted and expected industrial implementations and applications in potentially profitable markets. Therefore, it attracts the attention of both the government related funding agencies and private investors. Moreover, developing a vivid environment of researchers, engineers and industry with quantum technology capabilities is an element shaping not only the frontiers of the current global scientific landscape but also modern competitive economies.

Current quantum computing devices are developed on many platforms. Some offer advantages in areas in which others suffer from their weaknesses. At present, there is no single platform that is better than others in all relevant aspects. Moreover, the devices become more complicated and the calculations they provide sometimes reach areas in which their correctness cannot be efficiently checked or simulated by reliable devices like classical supercomputers. Also, the models and nature of errors are of principal importance for applications. Therefore, the problem of validation

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of current quantum devices which is studied in the thesis by mgr. Lewandowska is important for development of the field. Namely, it is important to have benchmarks of performance of quantum computing devices that have clear interpretations, are common for users and across platforms, and are easily controllable by the users. The research presented by mgr. Lewandowska is clearly situated in this area.

## Scientific problem and its formulation (Jaki jest problem naukowy podejmowany przez Autora i czy zostal on trafnie sformulowany?)

The general scientific problem posed by mgr. Lewandowska is related to different aspects of learning of quantum measurements in the most general framework, which is in the presence of quantum entanglement, and applying a multistep adaptive approach. The problem as posed in the thesis concerns several reasonable goals and has several practical consequences. One of the goals is to find a theoretical bound on the asymptotic number of steps in which von Neumann measurement can be learned. Another is a method that can be used in practice with a finite number of steps. Among consequences are using learning of specific measurements for validation of quantum devices and developing practical tools which can be easy to use and valuable for the community of users. The problems have been clearly stated, developed, and motivated based on relevant previous research.

## Proposed solution of the posed problem and methods applied. (Czy Autor rozwiazal postawiony problem i czy wykorzystal w tym celu wlasciwe metody?)

The problems posed by the Author are solved. Among the deliverables we find: proven mathematical theorems, especially Theorem 6 in Chapter 4 about the Fidelity of measurement learning with large number of steps; proposals of the so-called pretty good scheme of learning of measurement in finite number of steps which is presented in Section 4.3.1, where its performance has been clearly described; proposing and developing methods of discrimination and certification for measurements, Chapters 6 and 8, which are a basis of validation of quantum devices proposed and developed mainly in Chapters 7 and 8; finally an important deliverable is a user friendly software PyQBench that allow anyone to test quantum devices, the demonstration of which was also shown in this thesis in detail. All these deliverables are delivered satisfactorily using rigorous scientifical state-of-the-art methods including mathematical proofs, experiments on real quantum

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devices, simulations, data analysis, data interpretation, data presentation in forms of plots and tables, software development and its presentation.

Originality of the contribution. (Na czym polega oryginalny wklad Autora w dyscypline?)

This research is related to other research, for instance: learning quantum states, learning unitary transformations, or learning quantum channels. The presented research completes the previous explorations developing new results regarding learning of von Neumann measurements which are fundamental and widely used measurements in quantum physics. The results proven by the Author required advanced mathematical techniques, significantly different from the techniques used in the other related fields which I mentioned above. Also, the properties understood in learning and certifying measurements appear to be significantly different than those related to, for instance, unitary transformations. For example, the Author shows that for the former parallelism helps, while it was shown before that for the latter this aspect does not matter, see Remark 4 in Chapter 8. Moreover, the Author shows the connection between a mathematical tool from the operator theory, the so-called "numerical range", and the problem of measurement discrimination. Finally, the software for quantum device validation based on the results of this research is a high value and high-impact contribution of the research presented by mgr. Lewandowska.

The new contributions were also published in high class peer review scientific journals which further confirms novelty and originality of the presented research.

Scientific and practical impact of the contribution? (Jakie jest znaczenie poznawcze oraz znaczenie praktyczne wkladu Autora?)

The results delivered by mgr. Lewandowska have a significant meaning for both the theory and practice. She contributed to the fundamental research on limits of fidelity of learned measurements in quantum physics, Theorem 6. This problem was unsolved before and the solution shines new light on the role of quantum entanglement in the process of learning different operations. Without this result, that image was incomplete.

Moreover, the author proposed several implementable techniques and models of validation of quantum machines. Apart from the direct impact on validation of quantum computers, the research influences the development of quantum algorithms and tasks that can work with devices of given

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precision, especially in the regime of near-term intermediate scale noisy quantum devices. Development of the software contributes to working out practical benchmarks and standards for quantum technology.

## Technical science and detailed knowledge proficiency of the Author in the field of research? (Czy rozprawa swiadczy o dostatecznej wiedzy Autora w zakresie nauk technicznych i szczegolowej wiedzy odpowiadajacej zakresowi badan?)

In my opinion the thesis consists of high-quality research. It is written in a clear way. The problems are discussed and motivated providing relevant background, previous research, and breakthrough results. The way of writing and presenting the results show maturity in delivering high quality scientific research. The mathematical techniques applied are advanced and highly nontrivial yet presented in a clear and rigorous way which is easy to read and understand. Also, in several cases presented in the thesis the Author needed to modify and adapt models to the conditions in which the current machines work. For instance, replacing operations conditioned by measurements, which are currently not implemented in the devices which were used, by equivalent techniques with post-processing. These features of the thesis show that mgr. Lewandowska mastered a high level of proficiency in dealing with the problems related to validation of modern quantum devices. In my opinion the thesis shows that mgr. Lewandowska has enough theoretical and practical knowledge in the field and can further contribute with impactful and interesting research as an independent scientist with the Ph.D. title.

## Weaknesses of the thesis. (Jakie sa slabe strony rozprawy?)

Although I think that the thesis is rather complete in the sense of delivered results to the significant and well posed problems. More thorough discussions on related but slightly extended problems could be interesting for the readers. For example: potential generalization beyond the Fourier measurements on single qubits.

Reading the thesis I found a few typos, which are not essential for any part of the thesis and do not influence its evaluation. I can provide the list of them on request.

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## Summary

Summarizing this report. I highly positively evaluate the quality of the research and the thesis. I am convinced that the thesis satisfies all requirements expected by relevant Polish law as well as international scientific standards. I am strongly convinced that mgr. Paulina Lewandowska deserves the Ph.D. title. Moreover, as I think that the thesis satisfies all requirements with excess, I would like to propose to distinguish it.

Yokohama, July 14, 2023

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