Quantum Computing—From NISQ to PISQ

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Given the impeding timeline of developing good quality quantum processing units, it is the moment to rethink the approach to advance quantum computing research. Rather than waiting for quantum hardware technologies to mature, we need to start assessing in tandem the impact of the occurrence of quantum computing in various scientific fields. However, to this purpose, we need to use a complementary but quite different approach than proposed by the NISQ vision, which is heavily focused on and burdened by the engineering challenges. That is why we propose and advocate the PISQ approach: Perfect Intermediate Scale Quantum computing based on the already known concept of perfect qubits. This will allow researchers to focus much more on the development of new applications by defining the algorithms in terms of perfect qubits and evaluate them on quantum computing simulators that are executed on supercomputers. It is not the long-term solution but will currently allow universities to research on quantum logic and algorithms and companies can already start developing their internal know-how on quantum solutions.

Quantum computing as a scientific field was launched shortly after a talk that Richard Feynman gave in 1986 to highlight the advantage of simulating quantum dynamics on controllable quantum systems, with respect to classical computers. This inspired the quantum physics community to look at these challenges and realistically start manufacturing these devices. The theoretical and applied benefits of quantum computing algorithms, discovered in the 1990s, established this field as a concrete research direction. Quantum computing received a huge boost from the slowdown of the Moore's law of transistor scaling, resulting in major industrial players investing in the development of scalable systems.[a] Before we briefly explain part of the full stack, we want to highlight the U.S.-consulting company Gartner's Hype cycle that shows the overinvestment in technology in the first cycle, then there is top of the cycle where the deliveries are not really realized and then underinvestment will appear. We see that quantum computing is in the first rise of the hype cycle. Universities and companies have to be careful about where to invest in what. This article will define what the common strategy for this technology in its current state could be.

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0272-1732 © 2021 IEEE
Digital Object Identifier 10.1109/MM.2021.3099195
Date of current version 14 September 2021.

[a]The main ideas of our quantum research came out of the collaboration between Intel and our research group in TU Delft, where we actively defined the full-stack quantum computing architecture. Many of the ideas formulated in this and other papers came out of that work. Concepts and tools developed as part of that collaboration is available in the public domain. In the context of this article, we are using a new version of the tools developed as part of QBeeX.

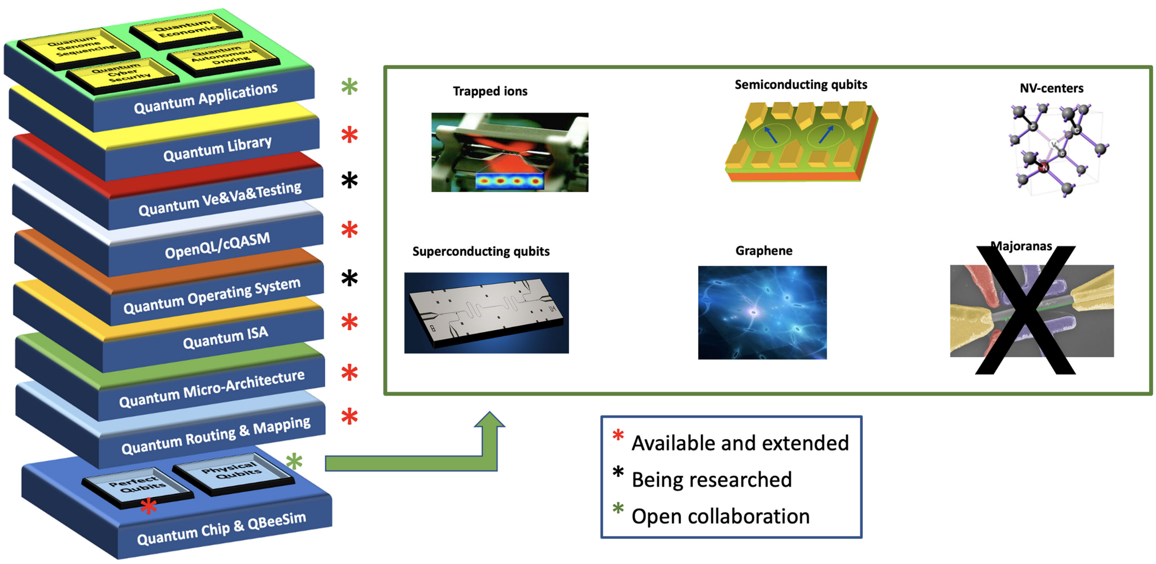

FIGURE 1. Full Stack and Qubit technologies.

where there are several of these technologies competing with each other to make a good quality qubit. The long-term goal is to fabricate a quantum chip with a high number of good quality logical qubits, which can be implemented using quantum error correction.

SOON MANY DIFFERENT APPROACHES WERE DISCOVERED TO MAKE QUANTUM BITS CALLED QUBITS. NOW WE ARE IN A PHASE WHERE THERE ARE SEVERAL OF THESE TECHNOLOGIES COMPETING WITH EACH OTHER TO MAKE A GOOD QUALITY QUBIT.

This is called fault-tolerant quantum computing (FTQC). The next step in quantum computing is noisy intermediate-scale quantum (NISQ) computing. The term "next" is actually not a next step but the physics people like Preskill understand that there is still a long way ahead during which a lot of challenges have to be solved and therefore it is actually going back to simpler qubits but trying to solve all the observed errors. In general, the word "noisy" refers to the gate errors and decoherence we observe in the physical qubits, the term "intermediate-scale" refers to the number of physical qubits, such that we cannot exhaustively simulate them on a classical computer. In this article, we introduce an alternate but closely related concept, called perfect intermediate scale quantum (PISQ) computing as will be explained later.

Figure 1 shows the full stack,[1,2] which can be briefly described by defining what the most important layers are that are already active. At the highest level, the application is formulated into a quantum algorithm, using the quantum logic primitives from the quantum library. The algorithms describe how many qubits need to be used and what operations need to be performed among them. The application is expressed in a programming language that many companies and universities have developed. We use the OpenQL language[3] and the compiler translates the OpenQL instructions to cQASM,[4] the common quantum assembly language. A microarchitecture receives the cQASM instructions and does an internal processing before sending it to the lowest level, which can be a physical quantum chip or a quantum simulator (or in the future to a quantum chip). The technologies which are still competing with each other are depicted in this figure as well. The high-performance quantum computing simulator[5] we use is developed by our team with a focus on scalability than any other simulator on the market. For every running QBeeSim simulator instance running on a single node, we can go up to 28 qubits in arbitrary superposition. Running multiple QBeeSim instances at the same time can substantially increase the number of qubits on which the algorithm is running, assuming the quantum logic is structured and application motivated, and not a deliberate worst case test to prove quantum supremacy. There are simulators around which can simulate up to 64 qubits on a multinode system.[6]

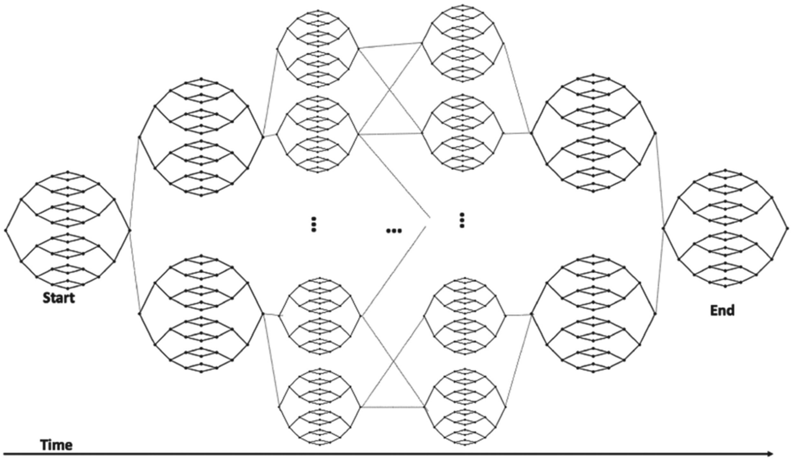

FIGURE 2. Number of Qubits grow and shrink during the execution of the quantum application.

It is important to understand that real quantum applications will consist of several parts, which are independent of each other. Only the result of the composing parts need to be transferred to the next step in the quantum applications, where multiple results from different preceding steps are combined. Figure 2 shows this evolution of number of qubits and one can imagine that the last, single node on the right goes in the execution of the next part of the quantum application. This is the main idea of combining in our case multiple instances of the QBeeSim simulator to achieve greater number of qubits used.

> *WE STAY VERY CONVINCED THAT QUANTUM COMPUTING WILL OFFER SUBSTANTIAL NEW ADVANCES IN ALL SCIENTIFIC FIELDS BUT WE STILL HAVE A LONG ROAD AHEAD.*

WORLDWIDE IMPLICATIONS

The quantum physics community is sufficiently aware that if certain quantum technologies do not produce any reasonable result after several years of effort, they should be gently removed from the list of quantum candidates. In the remainder of the article, we stay very convinced that quantum computing will offer substantial new advances in all scientific fields but we still have a long road ahead. Without going in too much detail, we mention universities and companies as the main drivers of education and research and economic applications. The first main observation to start from is that quantum computing will revolutionize the world as all concepts, theories, and applications will have to be redeveloped from scratch as the quantum concepts and corresponding ways to make computations will substantially change. Where in the classical hardware and software it was enough to recompile the same or changed algorithm to have the improved version running on the newest hardware, this is no longer true for the quantum technology. We have been working for the last three to four years on genomics and we have discovered that the algorithms are completely different than the classical genome sequencing algorithms. Functionally, they still do the same thing, for instance, reconstruct the genome based on experimental observations but the way the computations and logic are done has completely changed. We have started looking at financial and chemical applications and also there we see a radical change in the logic expressed in terms of qubits and quantum gates. The main implication of this observation is that anything in science for which we need a computer, needs to be redeveloped and looked at. It does not mean that we do not need classical computers anymore but the size of the problems we can look at will radically change and the kind of operations applied on the qubits will change as well. This observation has two main consequences. Every university will have to initiate quantum based research in every scientific field they are working on. This can never be done at a complete university level but every faculty should be invited to encourage young academic members to include quantum computing in their research. Every faculty will need to initiate that process and should hope that more and more faculty members will make the step to quantum research. It takes several years to arrive at a really good level of expertise and become a leader in the scientific field. The second consequence is for companies. Independent of the kind of activity a company is involved in, the influence of quantum computing will also be felt there. Whether the company is a car manufacturer, a bank or a chemistry-oriented company, the implications will be clearly felt. Similar to universities, it is not a challenge that needs to be resolved in three to four years time but companies should look at it now to start creating a small team of experts that show clear interest in quantum computing. A small team should ask for graduate students to base their thesis on the kinds of problems the company is looking at. Nothing groundbreaking should be expected, but cannot be excluded, but it takes time to have a group inside the organization capable of looking at the problems the company is looking at. Companies such as Airbus, BMW, and others are already looking at those kinds of directions and nobody should wait and see the competition has done it substantially and is bypassing the company.

Before describing in more detail the PISQ vision, we want to emphasize that the consequences for any scientific and economic field of ever building a quantum computer are simply enormous. When a new classical processor or computer came to the market, a mere recompilation of the existing or improved applications was enough to exploit the new hardware features. With a quantum accelerator, part of the research needs to lead to substantial changes to the proposed solutions. In the next pages, we will emphasize what the main physics-oriented challenges are in quantum computing and we will propose an alternative strategy and vision that keeps the research activities open for all kinds of scientific fields. We will describe the kind of research we are currently doing within a company we created but that we are also doing in collaboration with other universities.

QUANTUM PHYSICS CHALLENGES

There are several open issues in quantum computing. Here we review some of the more important ones. Our main starting point is a talk John Preskill gave in 2018 about the challenges in quantum computing. In two accompanying papers,[7,8] Preskill targets anybody actively involved in quantum computing as well as to a broader audience. We will just highlight the arguments that are relevant beyond the researchers involved in developing the physical chip layer. When we speak of qubits in this section, we only talk about physical qubits and their challenges:

- *Diversity in Quantum Technology:* As shown in Figure 1, there are still many technologies competing with each other to make the best qubit. It is uncertain what technology will win. For now, the Majorana approach seems to be falling off as the physics group behind it was not capable of repeating the experiments nor were they able to make a single physical Majorana qubit even after almost seven years. It is to be expected that many other qubit technologies will converge to a dominant approach in the coming years. We just need to remember that in transistor development, it took the entire world around 40 years to reach a VLSI level of transistor production, which is based on an idea formulated in 1936.
- *Number of Qubits:* Fifty physical qubits are what Preskill calls a significant milestone as it implies that the physical community is capable of going beyond the capacity of classical computers. The number 50 is motivated by the maximum number of qubits we can simulate and use in quantum circuits when we use modern computers. A quantum physical execution will never produce the amplitudes or the probabilities, but multiple runs of exactly the same quantum logic will produce a statistical estimate of the result. What remains to be seen is how good the solutions are that are classically simulated and how they compare to those from a physical quantum device. The main memory in supercomputers is used to store all the information of the full quantum circuit. This means that any qubit used in the solution is stored in the internal classical memory for which we need to store the amplitudes and ultimately the probabilities. In addition, and we will briefly discuss it in the following section, the full parallel execution path of the circuit needs to be defined.
- *Coherence of Qubits:* The coherence time is the time the information contained by the qubit is accessible and usable. This coherence time varies significantly depending on the quantum technology used. We have found numbers that go from a couple of seconds to multiple minutes, for instance, for ion trap qubits. What is important to realize is that the coherence time needs to be substantially longer than the time it takes to execute the full quantum circuit because otherwise all intermediate or final results will be lost.
- *Quality and Number of Quantum Gates:* The accuracy of the quantum gates is also a big problem as the error rates are way too high to implement any meaningful application that can be tested on its quantum formulation. Preskill suggests to limit it to 1,000 gates as the noise will be so high that it is difficult to assess the quantum results obtained. This is certainly meaningful for qubit development but we need to look at many other aspects too to have substantial improvements for any scientific,

technological, and in general society-relevant applications. Often quantum gates needs to be decomposed to a set of gates implementable on the hardware. Thus, a 1,000 gate substantially limits the complexity level of logical operations that can be implemented and tested.

- *Quantum Error Correction:* Given all the errors in the computations and the overall behavior of any qubit technology, there is a need to correct the quantum (intermediate) results such that the qubit states do not incorrectly accumulate all the errors of the preceding computations. These days, the error rates are $10^{-2/-3}$ and it is interesting to understand what the qubit engineering researchers want to achieve in, for instance, five years from now. In CMOS, we are used to having 10^{-15} and that is far too ambitious for the next ten years. But important to know is when can one expect to reach 10^{-6}, which most likely is still ten years or longer away. In that sense, we are supported by Preskill's latest paper in which he clearly states that it may even be much longer before there are really and sufficient amount of qubits.[8]
- *Logical Qubits:* An important attempt was to formulate logical qubits based on multiple physical qubits. The goal is to have an overall qubit behavior, which is more stable and scalable. An interesting approach was based on surface codes but for now we need around 49 physical qubits to have one logical qubit. So, also surface code and other logical-qubit approaches will have to be postponed or substantially reduced in size.
- *Scalable Fabrication of Qubits:* It is not yet conceivable to develop fabrication technologies as long as there is no understanding and agreement on what quantum technology can be used to produce good qubits. It is unlikely that all quantum technologies will survive and it will most likely be the role of a small number of big players that will outline what technology will reach the market. Some players focus on superconducting qubits while others are exploring semiconducting qubits. Photonics and ion-trap-based qubits are also very popular.
- *Quantum Oracles:* Most of the theoretical research on quantum algorithms proved speedups by looking at a specific part of the overall algorithm. While applying the algorithm in practice, it is needed to holistically consider the oracle as well, i.e., the part considered as a blackbox in the original formulations. The oracle is a way to verify what a particular function is computing, respecting the reversibility of quantum logic and without knowing what logic the oracle applies. Often explicitly specifying the oracle is hard and becomes intractable negating the quantum speedup achieved using the specific part.
- *Variational Heuristics:* More recently a lot of focus has been on variational heuristics where a parametric circuit is trained on a quantum computer using a classical optimizer. Algorithms like variational quantum eigensolver (VQE) and quantum approximate optimization algorithm (QAOA), while at one end promises quantum advantage in the NISQ, there are also many theoretical results that limit their universality. Thus, it is suggested to keep exploring a broader portfolio of quantum algorithms that might help for an application instead on going all in with variational approaches.

The NISQ approach is clearly a very promising direction in which quantum physics can continue researching the development of qubits. The list of challenges that we discussed in this section clearly focuses on a lot of engineering aspects that can be solved by researchers with a quantum physics background. What remains important is that enough resources keep on being available for the physics research. However, budgets for quantum physics research are certainly big enough and we are convinced that we will reach the goal of making good and scalable qubits but it most likely takes much longer than one expects. There is also no agreement on how we define the words *good* and *scalable* where scalability is needed to compensate for the errors we seen in qubit behavior as well as other factors, like dilution refrigerator and qubit connectivity. So, 50 really good qubits with error rates of 10^{-8} are very important for the world. However, as we are now only capable of making 50 qubits with error rates of 10^{-2}, it is very problematic for the world. That is why we propose an alternative approach where a wider interest community can start looking at the development of quantum solutions and algorithms.

PISQ—PERFECT INTERMEDIATE-SCALE QUANTUM COMPUTING

Given the full stack as shown in Figure 1, any scientific field should open up to other scientific areas, going beyond the physics dimensions. That is what Figure 2 represents. Similar to Preskill's message, we have to

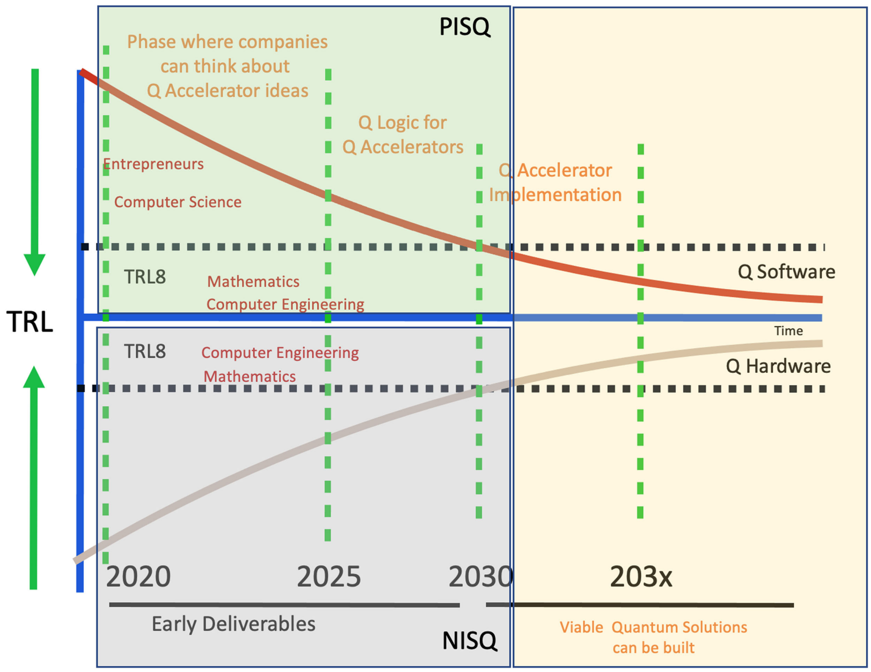

FIGURE 3. Complementary PISQ and NISQ quantum research activities.

start working substantially on a wide variety of application domains and expand the number of quantum gates and try to push the number of qubits on supercomputers higher than 50. Just to make the picture complete, we will also use the Tensor mathematics to formulate any quantum operation on any number of combined qubits.[9,10]

In that sense, we are advocating a scientific approach called *perfect intermediate-scale quantum* (PISQ) computing. The abbreviation is based on the NISQ vision, where **N** refers to noisy intermediate-scale challenges that we discussed in the previous section.

P refers to the use of *perfect qubits* that do not decohere and have perfect quantum gates. Our quantum compiler generates cQASM based on the OpenQL language. When we needed to test the superconducting or semiconducting qubits in the Intel context, we introduced a back-end compiler pass that translates the cQASM version to either the eQASM version for semiconducting or superconducting qubits. Our vision is that we can go to any qubit technology such as photonics or ion traps in the same way. However, for application and algorithm developers working on the highest layer of the full stack, it is clear that they only intend to express their concepts and ideas in terms of perfect qubits and verify the outcome of the computation. The *intermediate-scale* refers to the number of quantum gates in the circuits which for now goes to 20,000 or higher and the number of qubits is still restricted to 50. Important to highlight that most quantum computing companies (such as IBM, Rigetti, Google, Microsoft) supports quantum development platforms (such as Qiskit, Forest, CirQ, QDK) that includes compilers and simulators capable of generating and executing quantum logic in terms of perfect qubits.

Figure 3 divides the quantum research in three parts. We first have the green and gray periods that start now and run up to 2030. The gray part refers to the NISQ approach as formulated by Preskill and adopted by the quantum physics community. The green part then refers to the PISQ approach where it is assumed that the quantum applications are written in perfect qubits. The yellow part on the right of the figure represents the merging of quantum software and hardware in full accelerators and which have been substantially tested. We expect this to happen around ten years from now but it may be sooner or even beyond 20 years. We now present some of the challenges researchers need to look at when going for the PISQ approach:

› *Quantum Applications:* An important topic is the fact that quantum computer devices will change radically all scientific fields as the concepts and problems defined in terms of qubits and quantum gates will require a new generation of scientists to develop the tools and algorithms that will describe in a meaningful and consistent way how problems from chemistry, biology,

economics, etc., will look like and what kind of solutions they propose.
We just have to realize that the quantity of data available these days is orders of magnitude too big for the current computational power we have. We have already been looking at quantum genomics and we now start looking at quantum chemistry to understand what the impact will be of quantum accelerators on that particular science. This is therefore an open invitation to all university and research groups to start investigating the impact of quantum logic on their problems.

- *Parallelization:* There is one concern that cannot be overlooked by the researchers going in the PISQ direction and that deals with the parallelization of the quantum algorithm or circuit that will be executed on the classical supercomputer. In the NISQ approach, the parallelization is done in an implicit way by the qubits, which execute implicitly the possible solutions. When we want to execute a similar circuit on a supercomputer, we need to have an explicit parallel version of the circuit in order to have an equal amount of solutions that the quantum physics execution would generate.
- *Supercomputers:* Where Preskill talks about 50 qubits running on supercomputers as the upper limit, we will also be confronted with a similar limitation. But because the qubits are perfect, there is no uncertainty with respect to the generated results. Most quantum compilers have a compiler option to generate and simulate a circuit using perfect qubits. It remains to be seen how many more qubits can we superpose to go beyond 50 perfect qubits and execute it on a supercomputer.
- *Classical Memory Use:* Any quantum accelerator will have to represent the relevant qubit states after an intermediate step of the quantum application has been completed. This is needed as the quantum simulator such as QBeeSim needs to be reset and its memories need to be emptied. Intermediate solutions needed for the next step in the quantum application can be stored in the local memory of the quantum accelerator and be transferred to any simulator using it. Such local memory is classical and needs to represent the qubit basis as well as the amplitudes of each state.
- *Number of Qubits and Gates:* As discussed in the previous section, a second limitation that the NISQ researchers need to overcome is the size or length of the quantum circuits. From a physical qubit decoherence point of view, Preskill limited it to 1,000 gates but our PISQ-driven research can easily execute circuits with up to 10,000 gates and higher in reasonable runtime.

  We have noticed that the number of gates is not demanding additional memory use of the classical computer so we do not have to limit the size of the circuits to any particular number of gates. The main challenge stays the number of qubits that we can entangle or put in superposition. We are currently investigating how we can increase the number of qubits to get closer to 100 or 150 fully connected qubits using special kind of quantum simulators based on tensor networks and structure within the quantum circuit to be simulated.
- *Quantum Random Access Memory:* QRAM is a useful primitive to store the classical or quantum data of an algorithm in quantum memory so that it can be accessed on demand. While many quantum algorithms depend on the existence of an efficient QRAM, in practice QRAMs are difficult to build, and the assumption of these algorithms needs to be holistically reviewed and the focus on classical data load needs to be researched. At times, a much benign quantum read-only memory (QROM) suffices.
- *Specialized Quantum Gates:* Each qubit technology currently being investigated has their own native gate set that supports universal computing by translating other logic to a decomposition of the native gate set. These translations implies that some applications are much easier to translate for one qubit technology than other based on how easy it is to decompose the most used logic in that application algorithm for the qubit technology. In this view, it might be useful to develop quantum hardware that are specifically designed to support specific applications, e.g., specific controlled rotations for QFT.

In terms of applications, it is clear that the physics field is very inquisitive to explore complicated problems from their field. However, there is in principle no limitation to any topic for the quantum application layer. We personally work on quantum genomics[11] and quantum finance, but topics coming from chemistry, biology, and any other field are also fashionable. The

PISQ approach will allow universities to start developing research in any scientific field as the impact of QC on any scientific field will be incredible. It is advisable to start that new line of research perspective as soon as possible. It will take a new generation of scientists to study their core problems and find quantum algorithms that will solve that problem. It is evident that given the current state of supercomputers and qubits, the problems have to be reduced substantially that it can be executed by quantum simulators. This is the main reason to adopt the PISQ approach for young academic people as well as for dynamic entrepreneurs to start reasoning about their hard problems already now.

QUANTUM APPLICATIONS FORMULATED USING PERFECT QUBITS CAN BE EXECUTED AND TESTED ON CLASSICAL QC SIMULATORS. THIS WAY, WE CAN STUDY AND ANALYZE NEW QUANTUM ALGORITHMS FOR ANY KIND OF COMPLEX PROBLEMS, WHICH WE CANNOT ADDRESS EVEN WITH SUPERCOMPUTERS AND CLASSICAL PROGRAMMING.

CONCLUSION

In this article, we proposed a new name to refer to the PISQ-oriented research line such that many more people will step toward research for quantum computing from their domain. In our multiple years of past collaboration, we in the quantum computer architecture team focused on both semiconducting and superconducting qubits. We developed our OpenQL programming language[3] such that it could be translated to cQASM[4] and later to an eQASM[12] version, which could control either of the winning qubit technologies. The same approach is now continued much more explicitly using the already existing notion of perfect qubits. While most quantum computing framework also provide this as an alternative, the perfect simulator is typically not advocated in the final product development to encourage more widespread adoption of the NISQ era cloud-based platforms. In this article, we pointed out the pitfalls of using this for product development roadmaps, as well as the advantages and challenges of using an alternative approach.

Quantum applications formulated using perfect qubits can be executed and tested on classical QC simulators. This way, we can study and analyze new quantum algorithms for any kind of complex problems, which we cannot address even with supercomputers and classical programming. The constraint is that the number of qubits stay relatively low but one has a scalable formulation of the quantum solution, which can be immediately targeted to a quantum chip when they reach technological maturity.

To provide this important direction of research and development with an identifiable banner, we introduce the notion of PISQ computing. It is a complementary approach to NISQ, to work on quantum computing and it may have a substantial impact on all the scientific and even economic efforts world wide. The main advantage is that there is no direct dependence on the roadblocks and progress of the quantum physical chip development efforts, except for both NISQ and PISQ being eventually phased out in the long term by fault-tolerant quantum computing. That means that application developers do not have to worry about decoherence and quantum errors in the operations but rather focus on the quantum logic for important problems of their interest.

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