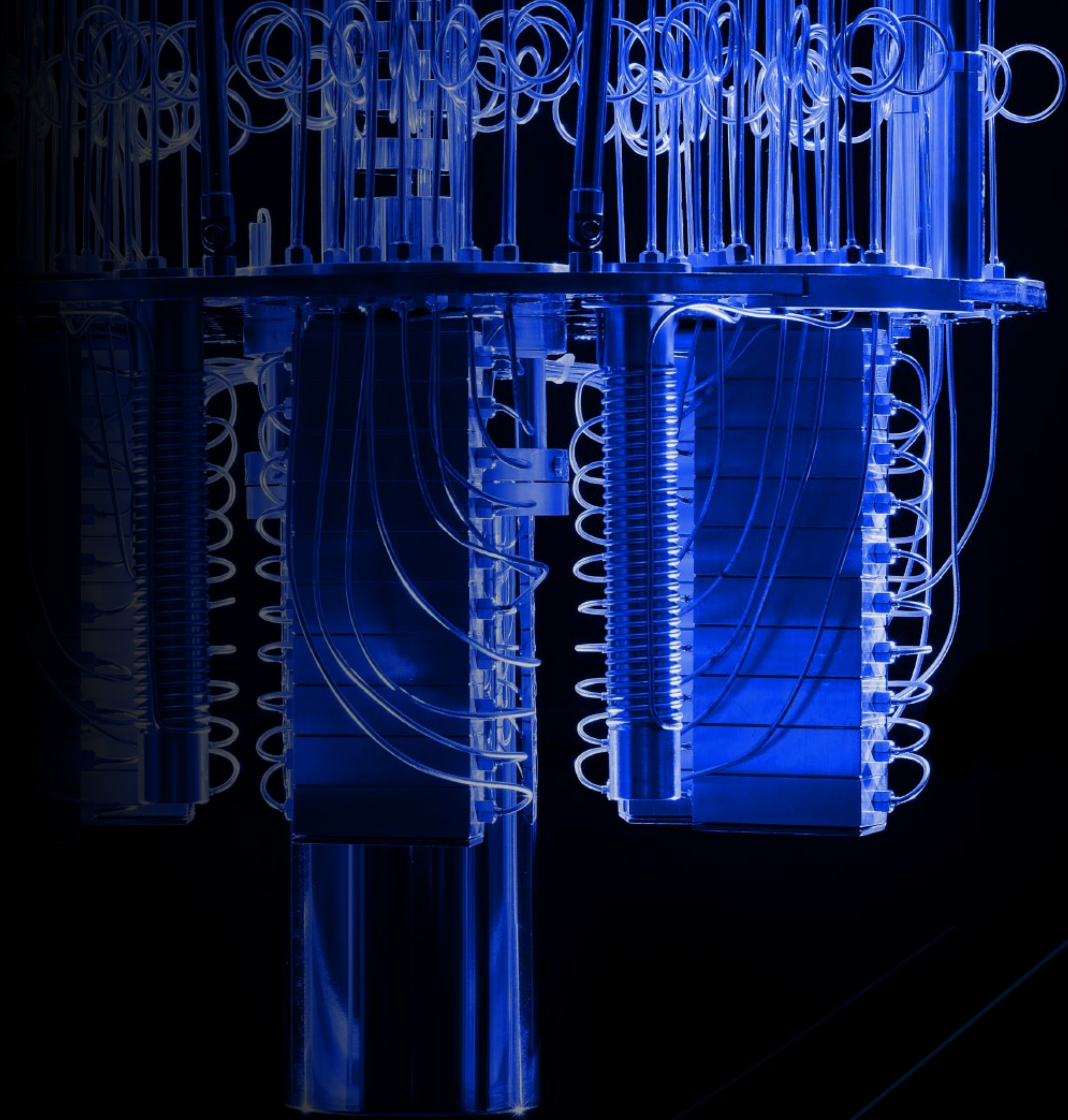


RAPORT QUANTUM
COMPUTING '22

POLAND
IBM Quantum Innovation Center

POLISH QUANTUM COMPUTING NODE

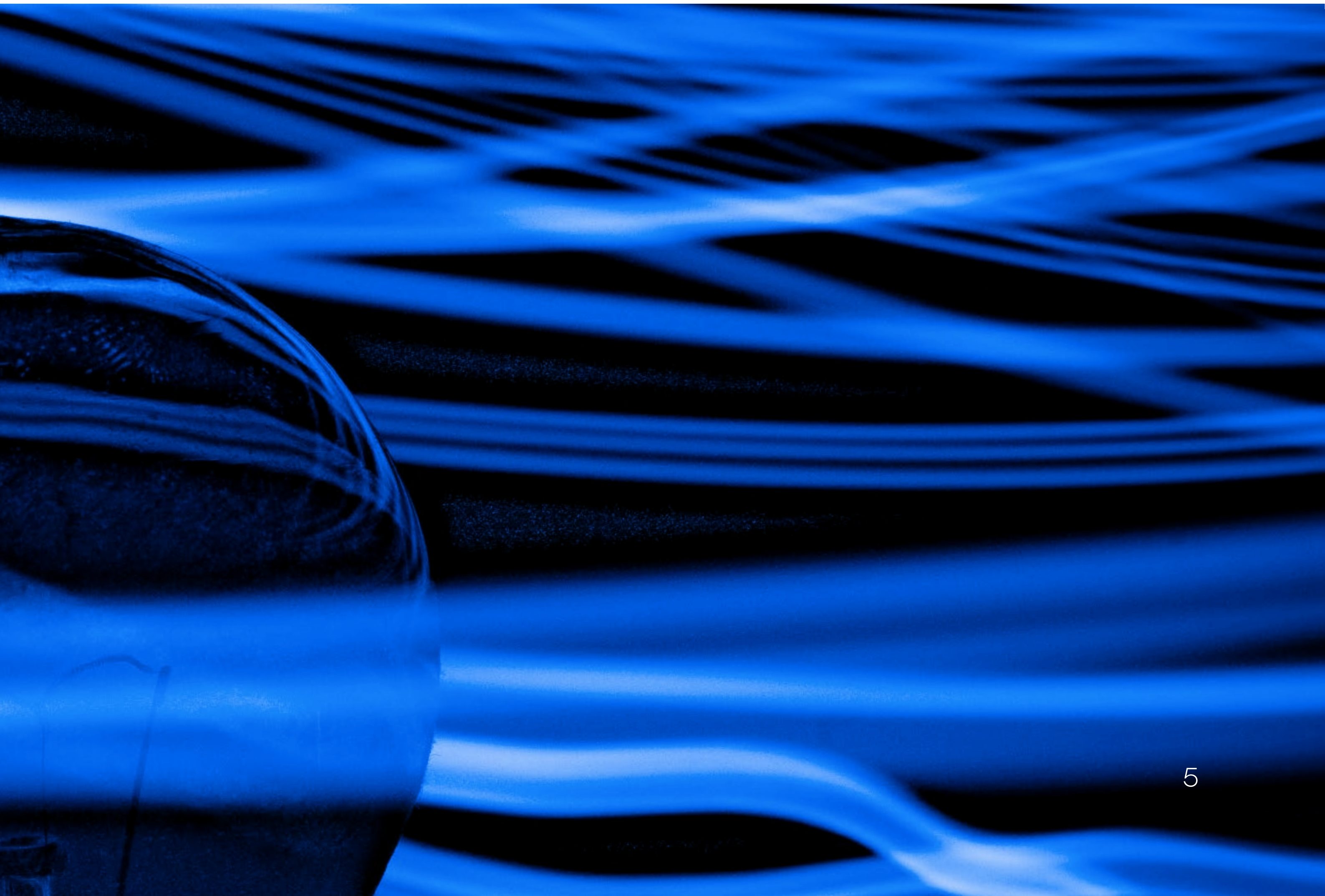
Table of Contents

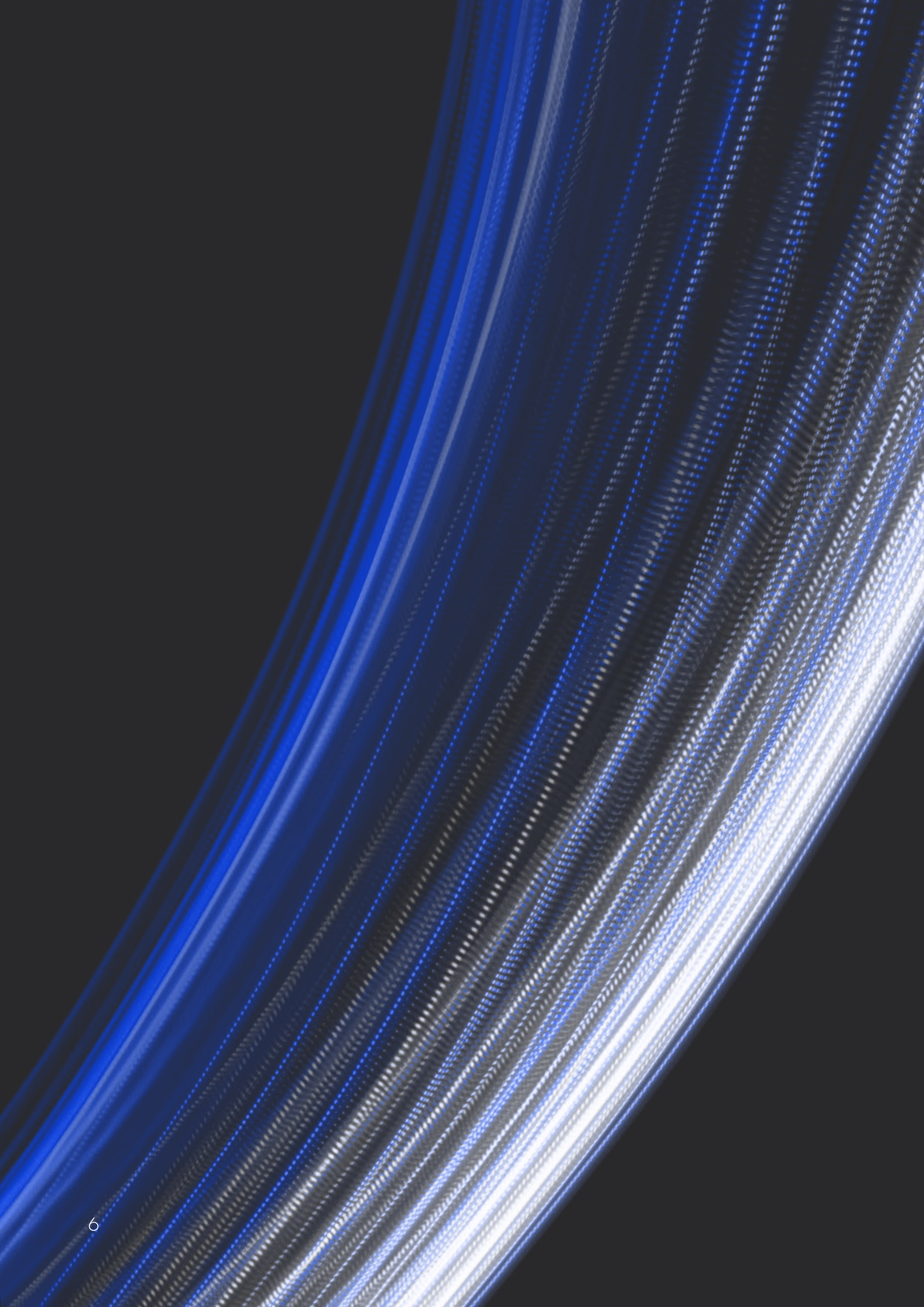
Preface

With this report, the reader is given the opportunity to familiarize themselves with the results of the activities of the Polish Node of Quantum Computing - IBM Quantum during the first stage of its operation in 2022. This document is the result of collaboration among many scientific and research teams in the country and is based on analytical, programming, and experimental tasks performed using access to the infrastructure of IBM Quantum quantum computers. Based on the gathered experiences, the report also provides insight into the current state of development of IBM Quantum's gate-model quantum computers in the context of various challenges and potential applications of quantum technology in simulations and computations. It should be noted that the report serves as a summary and does not exhaust the topics and issues addressed by

national research users. However, it aims to introduce the reader to the world of quantum technologies by explaining the physical foundations of how quantum computers operate. Efforts have been made to organize the report chronologically and thematically, focusing on the most important topics at the intersection of computer science and physics, with the aim of reaching a wider audience. As a result, the report has been divided into three complementary chapters.

The report dives into cutting-edge quantum tech, exploring its potential for simulations and computations. Plus, it highlights the wins of the Polish Quantum Computing Node's early days.





Chapter 01

Chapter 1 presents a series of fundamental topics along with examples and numerous illustrations to acquaint the reader with the principles that facilitate an understanding of the essence of how quantum computers function, their imperfections, challenges, and, at the same time, their enormous implementation potential. The introduction helps the reader comprehend the descriptions and numerous references presented in the subsequent chapters. This chapter also attempts to outline many limitations and challenges associated with classical approaches to high-powered computations.

Chapter 02

Chapter 2 summarizes the achievements of the main tasks within the Polish Quantum Computing Node and explains the technological aspects for more advanced readers interested in quantum computing and experimental access to the IBM Quantum computer infrastructure. This chapter also includes a review of technological solutions along with an assessment of the level of advancement and planned development of the provided IBM Quantum computers in the coming years.

Chapter 03

Chapter 3 provides a summary of the results gathered from experiments conducted by national scientific users who utilized the resources of IBM Quantum computers from February to November 2022 with the support of the Polish Quantum Computing Node. In this chapter, readers will also find identified potential areas of application for quantum computing and simulations based on the national scientific research potential and the possibilities of their utilization in science and the economy.

Introduction

Invention of the transistor - a key component on which all modern electronics is based.

The development of quantum technologies also includes the development of quantum computers.

Indeed, we have been witnessing an incredible race in the development of quantum technologies in recent years, driven by the world's strongest economies. Many leading technology companies involved in quantum computing development predict that the culmination of quantum technology development will occur by 2030. There is still some time to prepare for the upcoming **second quantum revolution.**

Currently, there are already many exemplary and practical solutions utilizing quantum technologies, but often these are not yet fully developed and widely available on the market. The situation with quantum devices (referred to as quantum computers later on) is similar, as their current state of advancement still requires significant effort in both hardware and software development. Until the first quantum computer emerges, with computational power significantly surpassing that of the most powerful supercomputers in solving complex problems, it is challenging to realistically assess the impact it will have on various sectors of the economy and society in the future. However, history teaches us that in the vast majority of cases, we underestimate the long-term potential of new, unexplored breakthrough technologies, and quantum technologies undoubtedly fall into this category. Quantum computers are not just faster computers or new generations of more efficient classical supercomputers. The fundamental principles underlying the construction of modern computing machines, from the smallest integrated circuits, microprocessors, to high-performance processors in personal computers or the most powerful supercomputers, significantly differ from how a quantum computer operates, where its operation is governed by quantum mechanics rather than classical computing principles.

In the report, we take a closer look at the current stage of development of quantum computers and how we can experimentally utilize them today. While engineers are working on improving successive generations of quantum computers, at the intersection of computer science, mathematics, physics, and many other scientific fields, new quantum methods and algorithms are being developed. It is through the collaboration of practitioners and theorists that the potential application area of quantum computing is expanding. At the same time, newer and more stringent requirements are being identified that new generations of quantum computers must meet to find practical applications.

Let's go back to the early 1980s when the development of classical computers was just gaining momentum. One of the key moments, as well as a strong impetus for theoretical work related to the applications of quantum computing, was the considerations by Richard Feynman. Using classical computers for modeling and simulating physical phenomena at the atomic and molecular levels, Feynman showed that the complexity of these problems is very high, and the time required for classical computations would have to be counted in billions of years, which is simply unacceptable. To tackle this challenging problem, Feynman proposed the idea of building a quantum simulator and utilizing its quantum nature for simulating quantum phenomena instead of classical calculations. This introduced new areas of application for quantum computers and breakthroughs that we can expect in materials engineering, biochemistry, nanotechnology, and more.

In light of this year's Nobel Prize in Physics, as mentioned earlier, to better understand the basic stages of quantum mechanics development, we need to go back to the 1960s and the famous Bell's theorem. John Bell addressed fundamental questions and scientific disputes that had been ongoing since the 1930s, with Albert Einstein at the forefront. Theoretical assumptions were experimentally confirmed, and this is already a small step towards the implementation stage.

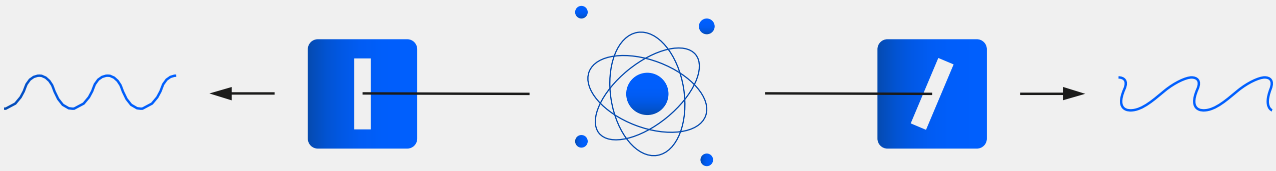
Quantum technologies encompass a wide range of potential applications that go far beyond quantum computing and calculations. This includes quantum communication and cryptography technologies, as well as new generations of sensors used in metrology and imaging techniques. Further technological advancements in each of these areas can bring about entirely new and difficult-to-predict consequences for society, science, and the economy in the coming years.

Quantum entanglement on the scale of a Nobel Prize

On October 4, 2022, the Royal Swedish Academy of Sciences announced the awarding of this year's Nobel Prize in Physics to three scientists - Alain Aspect, John F. Clauser, and Anton Zeilinger - **"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum computing."** Conducting these scientific researches was crucial in understanding the fundamentals of quantum mechanics as a fundamental science governing the laws of our world, and it paved the way for quantum technologies, including quantum computers.

This year's Nobel laureates can be considered as the fathers of the second quantum revolution, where entangled states and Bell inequalities play very important and widely utilized roles. Each of the Nobel laureates conducted groundbreaking experiments using entangled quantum states. The above-mentioned concepts are crucial not only for quantum computers and computations but also for quantum communication. In their experimental work using entangled photons, the laureates demonstrated that at the micro-world level, Bell's inequalities are not preserved. To understand the significance of this fact, let's consider **quantum entanglement** itself. First and foremost, it's essential to realize that the quantum world is not deterministic, and many "parallel" states can coexist with different probabilities, and it's only through measurement that one of them is actualized in a way.

Imagine that two photons are emitted in opposite directions, and measuring the state of one photon determines what we will observe when observing the second photon. We are then talking about the quantum entanglement of these photons. However, it's essential to remember that each of these photons is a **superposition** (an unobserved coexistence) of different states, and it's only through measurement that a specific value of the parameter being measured is manifested, simultaneously determining the measurement of this parameter in the other photon. It's shocking from our intuition's perspective because influencing the measurement of the second photon does not depend on how far apart it is. What happens in the context of one particle in an entangled pair automatically determines what will happen to the other particle, even if they are in distant locations (e.g., in opposite corners of a room or on the opposite edg-



es of a galaxy). At the same time, there has long been a discussion of whether this correlation in an entangled pair results from the particles having so-called hidden variables and instructions determining what the outcome of the experiment should be. This is where we need to turn to Bell's theorem and his inequalities. In a simplified way, the theorem states that if hidden variables exist, then the correlation between the results of a greater number of measurements will never exceed a certain threshold. At the same time, quantum mechanics predicts that a certain type of experiment violates Bell's inequality and, as a result, provides stronger correlation than is classically possible.

In 1964, John Stuart Bell described a theorem that pertains to quantum mechanics and demonstrates how it differs from classical mechanics. Bell's theorem, also known as **Bell's inequality**, was developed based on a fundamental assumption of quantum mechanics mentioned above: that the entangled state of two quantum particles (e.g., photons) cannot be reduced to a description of the states of its individual elements. A single particle in such an entangled pair does not possess a defined state. The theorem states that the correlations between measurement outcomes of properties of such particles can be stronger than if their states were defined. The main assumption of Bell's theorem, namely, "no local hidden variable theory can describe all phenomena of quantum mechanics," addresses the so-called **EPR paradox** [1]. The EPR paradox is an earlier result of Albert Einstein, Boris Podolsky, and Nathan Rosen's work, which is based on the assumptions that the parameters of quantum particles have values independent of the acts of observation, and physical interactions occur at a finite speed. In his work, Bell proved that the above theory of so-called local realism enforces statistical correlations of measurement outcomes that are not satisfied by quantum mechanics, thus showing that it is inconsistent with this assumption [2].

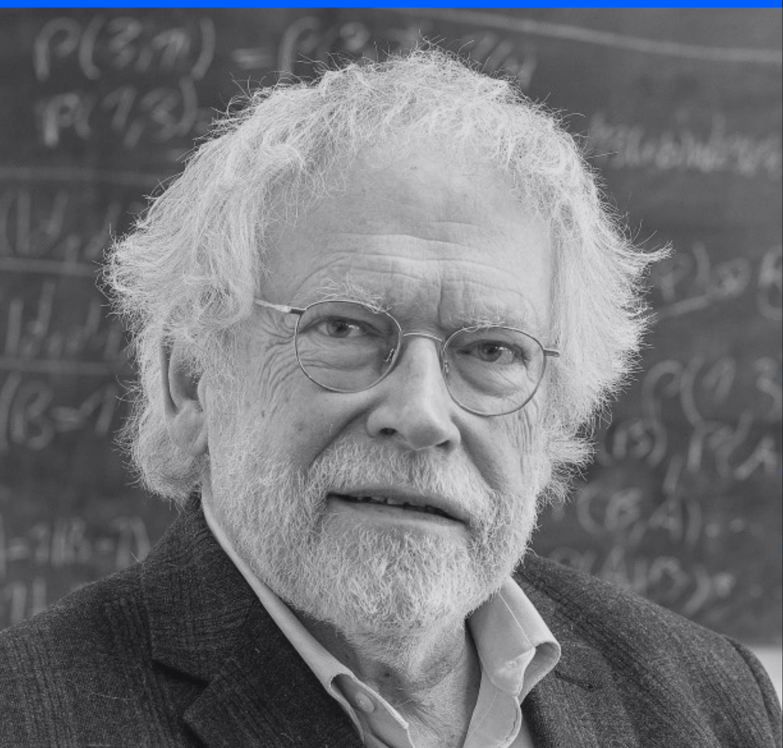
Bell's inequality can be illustrated quite simply: either reality does not adhere to the assumptions of local realism, or there is an error in quantum mechanics itself. Resolving this issue can only be achieved through experimentation, which is what this year's Nobel laureates worked on. Using a loose analogy, you could say it's a bit like observing pairs of twins running in opposite directions and noting different details about their appearance. In the world of large-scale physics, governed by Newtonian mechanics, all observed correlations would relate to objective, unambiguous, and inherent characteristics. If these pairs of twins were quantum, we would notice that looking at one of them determines what we see in the other. However, Bell's inequalities reassure us that these twins don't arrange in advance, at the moment they separate, how the details of their appearance will be, or how someone will eventually see them.

John F. Clauser

J.F. Clauser & Assoc., Walnut Creek, CA, USA

Alain Aspect

Université Paris-Saclay oraz École Polytechnique, Palaiseau, France



Anton Zeilinger

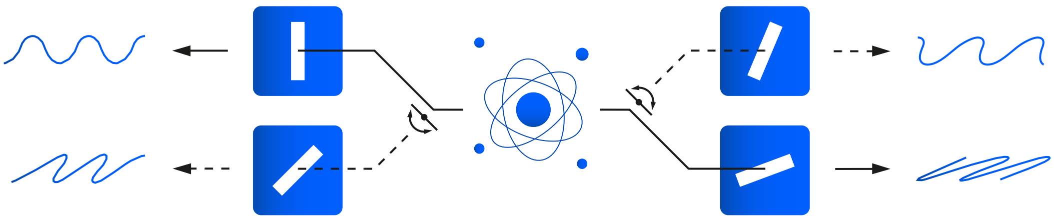
University of Vienna, Austria

John Clauser

John Clauser designed an experimental setup whose results disproved the so-called Bell inequalities, thus demonstrating that quantum mechanics rules out local realism. He used calcium atoms that, when exposed to special light, emitted entangled photons. He placed polarization filters on both sides of the atom for measuring particle polarization. A series of measurements ruled out the possibility of the existence of local hidden variables.

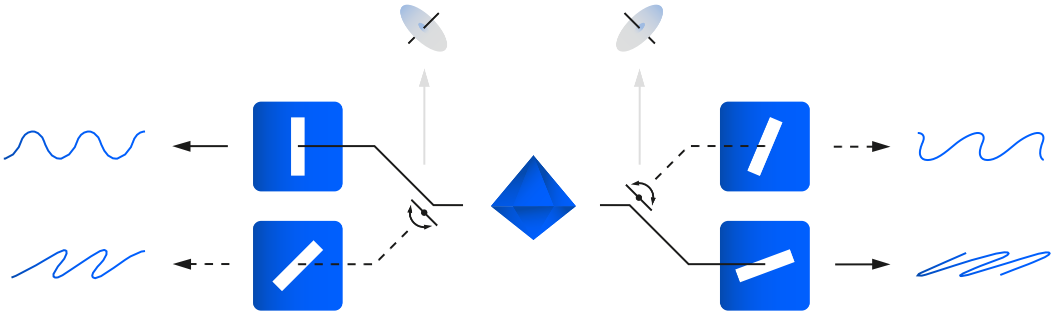
Alain Aspect

Alain Aspect repeated and improved Clauser's experiments and was the first to experimentally demonstrate the wave-particle duality of individual photons. He introduced a modification that allowed changing the filter settings after the photon was emitted from the atom. This confirmed that the initial setup of the research apparatus did not influence the results.



Anton Zeilinger

Anton Zeilinger conducted further tests of Bell's inequalities, this time using a special crystal as a source of photons and randomness to set the filter configurations. In one of the experiments, signals from distant galaxies were used to set up the apparatus, ruling out the possibility of their mutual interaction. Zeilinger also conducted research on quantum teleportation of particles and studied quantum entanglement of photons sent over long distances, allowing him to achieve a quantum communication channel of 144 km in length as early as 2004.



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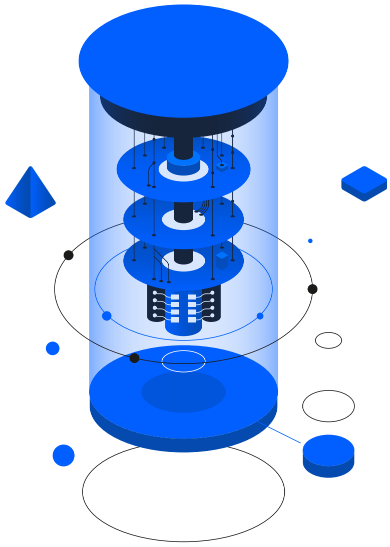
When classical computers **can't cope**



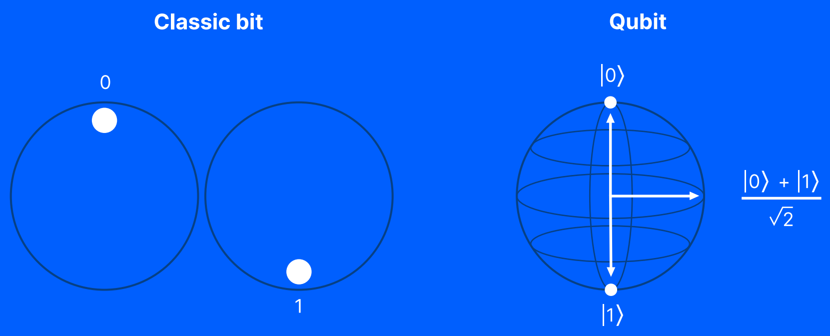
In today's world, it's hard to imagine a life without ubiquitous classical computers. They serve as the backbone for the functioning of institutions and businesses and have a wide range of everyday applications in many households. Starting from office work with documents, spreadsheets, and other advanced software, through the use of dedicated machines for work on industrial and production lines, to multimedia entertainment provided in the form of movies, music, games, or interactive simulations.

As we mentioned at the beginning, behind all the applications of classical computers are the laws of physics and electronics, and every operation on a classical computer is based on encoded and controlled flows of electrical energy encoded in binary sequences of zeros and ones. In essence, it is worth thinking of computer science as a computational science rooted in mathematics and physics, and therefore subject to its laws.

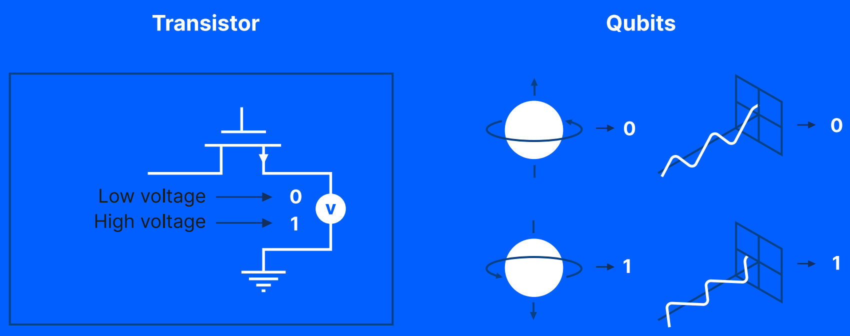
The basic unit used for processing information in classical computers is the **bit**. One bit is, in this case, the state of the aforementioned transistor acting as a simple switch. Broadly speaking, a logical "one" corresponds to a high voltage, and a logical "zero" corresponds to a low voltage. Although voltage can take any values within a certain range, only **two possible states** are distinguished for the purpose of encoding information. The equivalent of a classical bit as the basic unit of information in quantum computing is any two-state quantum system - a **qubit.**

A qubit, as a two-state quantum system and the fundamental quantum unit of information, can indeed be based on various quantum particles, such as:

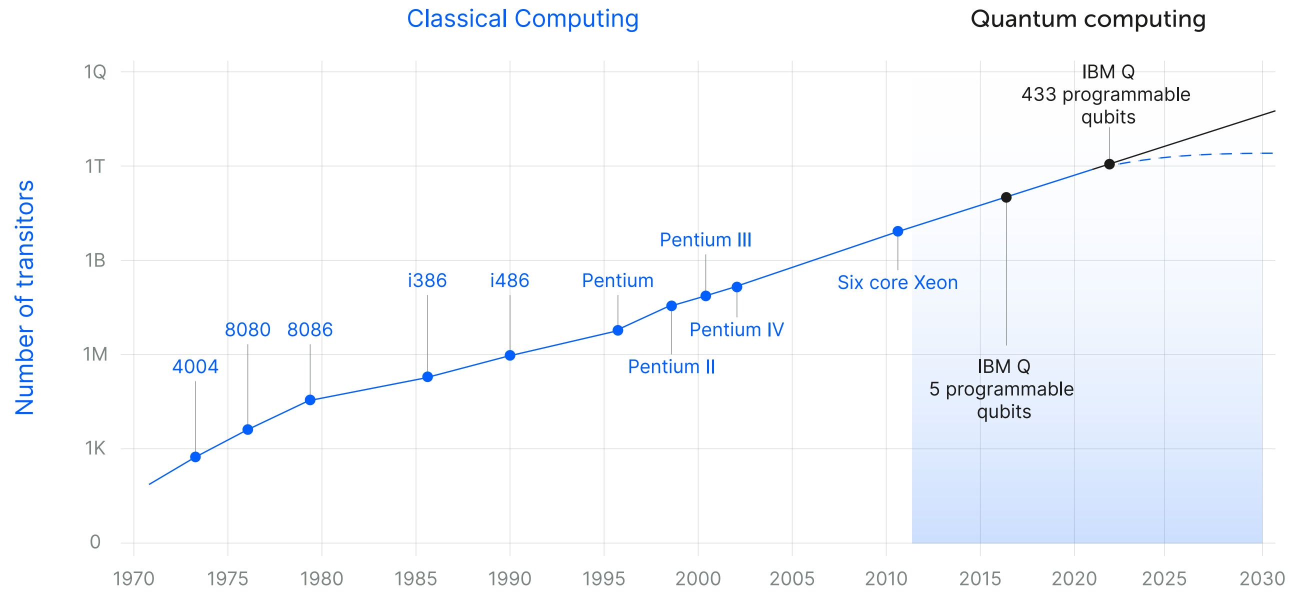
- Two electron spins.
- Two energy levels of an atom.
- A photon with two mutually orthogonal polarization states.



This is where we should look for an analogy between classical and quantum computers arising from the two-state nature of the fundamental unit of information. However, it does not change the fact that the way information is stored and processed in quantum computers is significantly different. It is also worth noting that the various quantum particles mentioned above are currently used as building blocks for experimental designs of different types of quantum computers. Unlike a bit, a qubit exhibits quantum nature because it can be in a superposition of two basic states. To put it figuratively, a qubit can exist in both states simultaneously, for example, be a bit more one and a bit less zero at the same time. In the case of a classical bit, this is, of course, impossible. Superposition is one of the fundamental properties of quantum objects used in quantum computers.



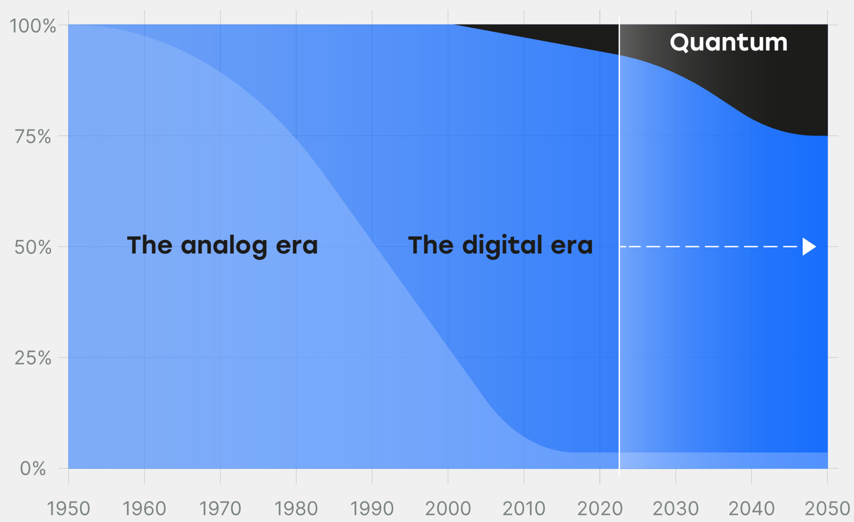
While at first glance, all operations performed in a classical computer appear to happen instantaneously, in reality, each of them takes a very short period of time. Although for today's digital machines, performing thousands or even millions of such operations is not a challenge, many tasks posed by both the modern economy and ordinary users are so complex that they still pose a challenge even for the most powerful supercomputers.



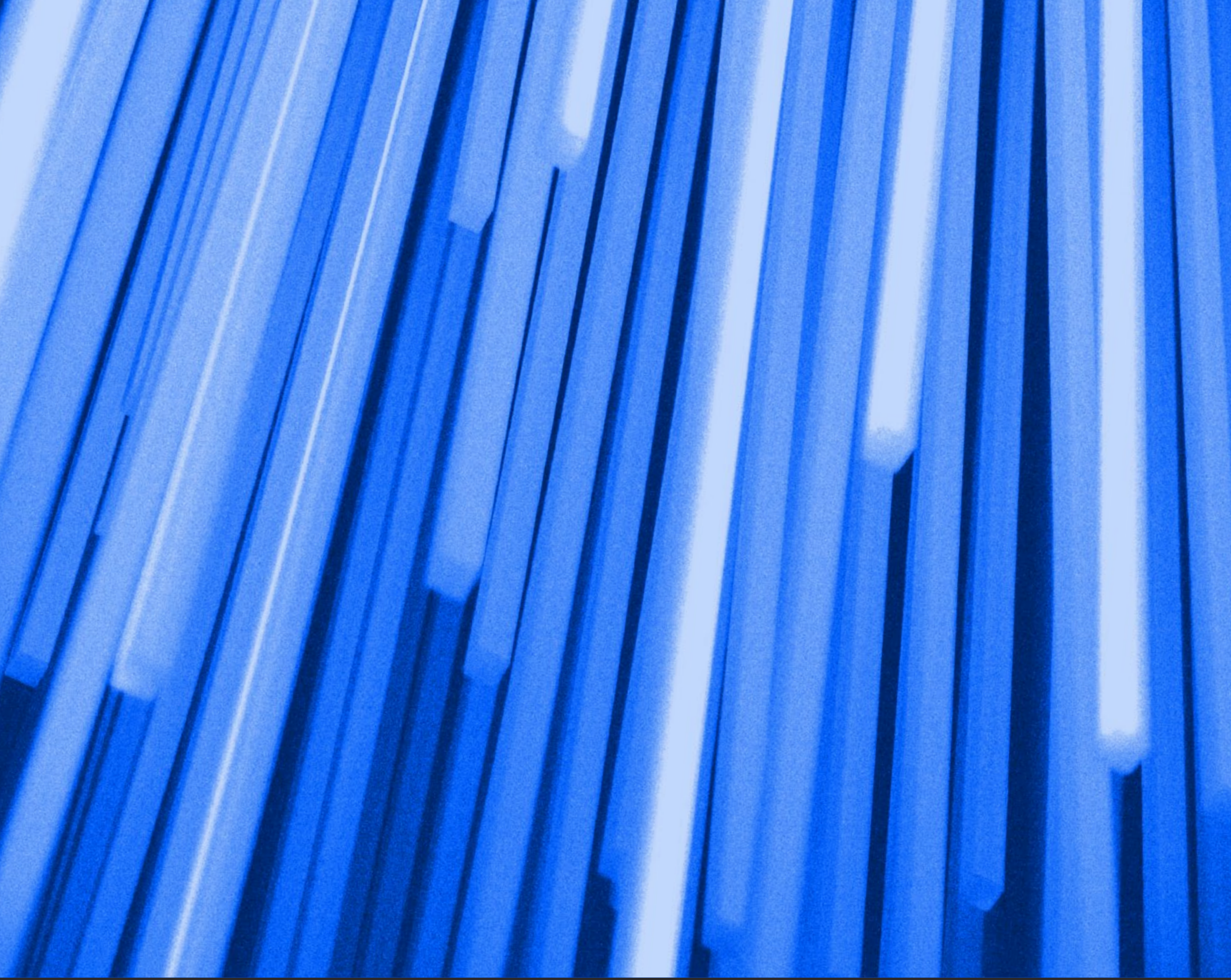
It turns out that classical computers, based on silicon transistor technology, have many limitations. While classical computers perform well for many tasks, such as displaying web pages or running utility programs for text, audio, or video editing, there are often challenges and problems in processing and analyzing larger amounts of data. An example of this is the production of electronic maps. Users usually have no problem displaying them, but creating them requires the use of the immense computing power of classical supercomputers. Editing one segment of a road's geometry often involves recalculating adjacent roads or checking the feasibility of the change itself. In general, such calculations are often approximated due to their computational complexity and can take seconds, minutes, hours, or even days, which is noticeable as a time overhead for end users.

In recent years, the development of classical computers has had a growth rate lower than what Moore's Law, mentioned at the beginning, suggests. Many point out that we are witnessing the end of the era defined by **Moore's Law**, which has characterized the dynamic progress of classical computers in recent decades. As explained at the beginning of the report, this is due to the physical size barrier of transistors, which are approaching the size of individual atoms. At such a small scale, quantum phenomena, which pose a significant obstacle to further miniaturization, play a crucial role in classical two-state systems. Therefore, increasing attention is being paid to new solutions that will allow us to maintain the pace of development and meet the growing demand for computational power in the modern world. One proposed solution to this problem is the use of quantum mechanical phenomena through a **programmable quantum computer**. The advances in quantum technology observed over the past decade or so suggest that the computational power of future generations of quantum processors will increase significantly.

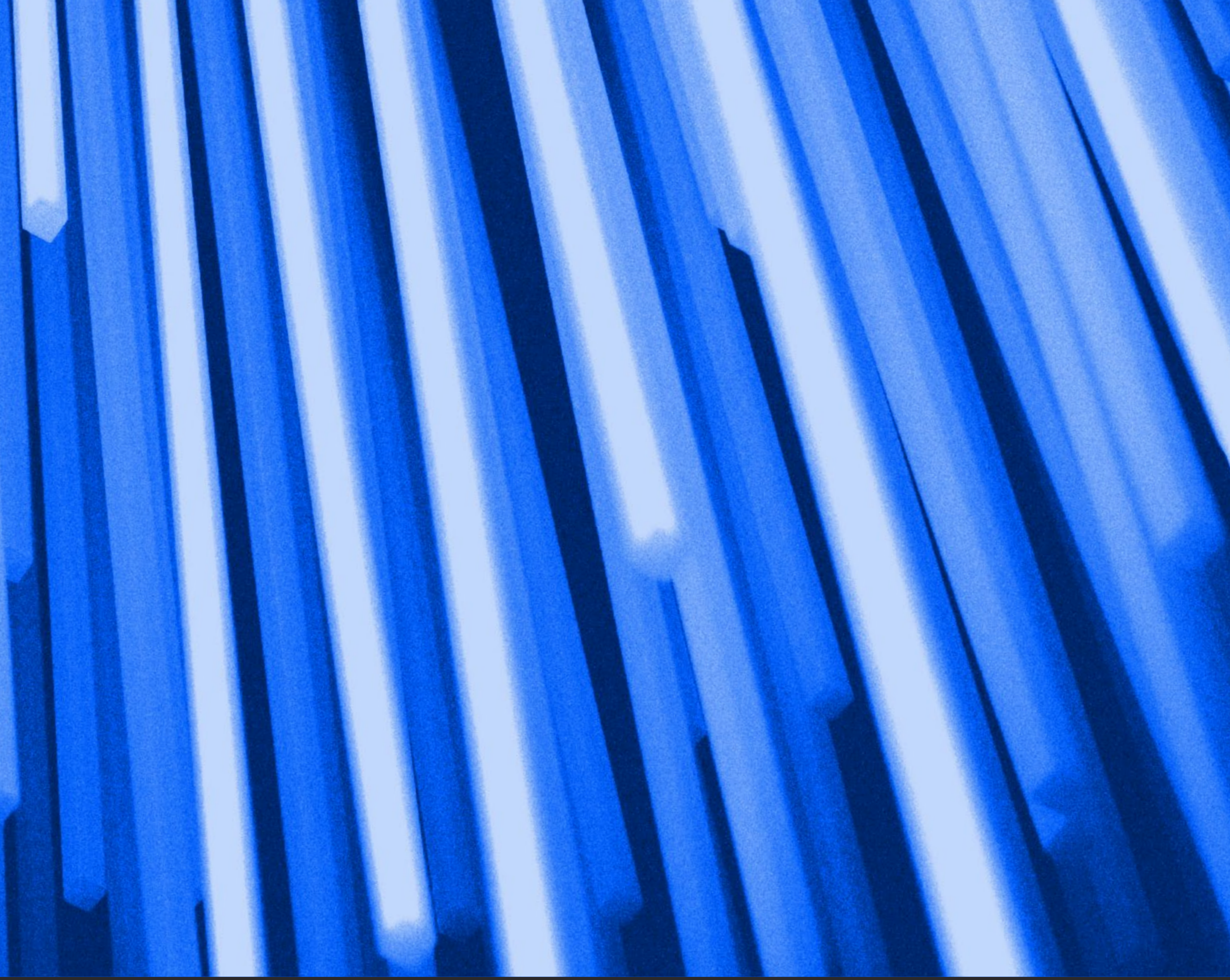
It is worth emphasizing that in the near future, quantum computers are not expected to completely replace classical computers. For the vast majority of everyday applications, classical digital devices are simply much better suited. Only for selected and demanding tasks does a quantum computer have a significant chance of gaining an advantage over its classical counterpart. Unfortunately, to date, **quantum supremacy has not been officially demonstrated in practice**. Intensive efforts are ongoing to achieve this next technological breakthrough. Nevertheless, in this report, we will attempt to highlight selected areas of tasks and issues important for industry, science, and society in Poland that may benefit from such quantum advantages in the first place.



The technological advancement in the capabilities of storing, transmitting, and processing information utilizes analog, digital, and quantum technologies.



World of quantum computers



CHAPTER

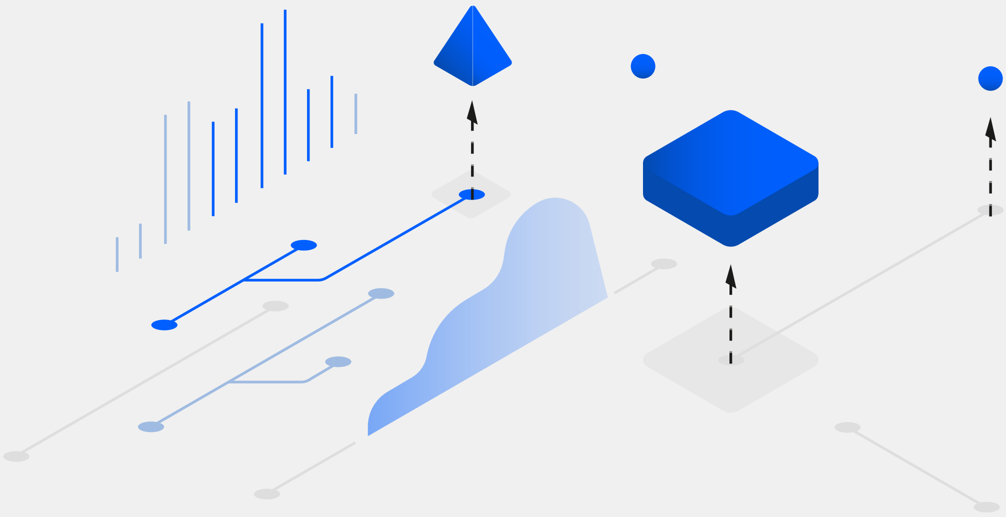
01

Introduction

The digital revolution, initiated in the mid-20th century and also referred to as the Third Industrial Revolution, brought forth tools and inventions that have permanently transformed the economy and industry, leading to the emergence of the so-called information society. Instead of labor and capital, data, information, and knowledge became strategic resources.

Before we delve into the basic principles of quantum computers, it's worth introducing the workings of classical computers. An event that significantly accelerated these changes was the invention of the transistor at the end of the 1940s – a key component on which classical computers rely. A transistor is a semiconductor device, which means it conducts current under certain conditions and doesn't under others. The operation of a transistor is based on controlling the flow of electric current using the physical properties of semiconductors. Transistors are the smallest components of a classical computer, which switch between two voltage states, i.e., binary states 0 and 1. Logic gates, built from transistors, perform basic logical functions of Boolean algebra, as well as various types of memory in classical computers. With the advancement of technology, the number of available transistors and the gates built from them increased at an incredible rate. Modern computers already use **millions of logic gates** to process information, i.e., data stored in binary form.

Logic gates represent a specific, albeit abstract, model that allows us to transition from a physical perspective on classical computers to a logical level. This is essential because this is where one can identify the subtle boundary between a purely physical and a mathematical understanding of how classical computers operate. Assuming a sufficient level of reliability in the operation of logic gates, from a certain point onwards, we didn't need to focus solely on technical aspects, the physical properties, or the control of electron flow in transistors.



As a result of technological progress, we naturally transitioned to a slightly higher, logical level and focused on the essence of how logic gates work, which involves operations on two binary states, 0 and 1. **The binary representation of information and its processing using multiple logic gates are the fundamental principles of operation for every classical computer.** Information processing in a computer occurs according to a finite and precisely defined sequence of instructions that implement a specific algorithm, enabling the execution of tasks and the solution of problems. One of the key properties of a classical computer is the ability to store and load a sequence of instructions in the form of computer programs written in various programming languages. As the number of available logic gates allowed for increasingly advanced data processing, the computational power of computers also increased. Simultaneously, high-level programming languages emerged, representing additional layers of abstraction that facilitated programming classical computers. Information technology deals with the processing of information, including the creation of computer programs, the description of algorithmic processes, problem-solving using computers, computations, and their complexity. In summary and simplification, when considering the operation of classical computers and illustrating the various layers of abstraction, we moved briefly from physics and mathematics to computer science.

Over the past few decades, we have become accustomed to storing and processing information based on binary data representation, logic gates, and integrated circuits, which are the main components of classical computer processors. Many of us view classical computers as personal and ubiquitous tools, often not contemplating their physical nature. Development has been ongoing, and everything indicates that classical computers will remain with us for a long time to come. However, not everyone realizes that, in a simplified sense, the number of transistors and logic gates comprising an integrated circuit has been steadily increasing at regular intervals since the 1950s. As a result, every two years, the computational power of classical computers doubled, following **Moore's Law.**

The problem is that for the past several years, engineers, scientists, and technicians have been struggling with further miniaturization of transistors, logic gates, and integrated circuits. New generations of processors are, of course, advertised as more powerful, but in general, they consist of an increasing number of cores. Unfortunately, these are not faster general-purpose processors produced using further miniaturization technology processes; instead, they are increasingly specialized integrated circuits and processors dedicated to specific functions. Their effective and concurrent use requires advanced programming skills and experience. In other words, it has become increasingly difficult from an application perspective to extract the potential computing power dormant in not hundreds, thousands, but hundreds of millions of processing units of the most powerful classical supercomputers in the world. Additionally, there are practical challenges and costs associated with the high energy consumption of supercomputers and the cooling required to maintain suitable working conditions for them. In short, further reducing the scale of integrated circuits introduces quantum effects that hinder or even prevent the production of faster classical processors. The scale of manufactured integrated circuits has currently reached sizes of just a few nanometers, which represents a kind of miniaturization **barrier between the well-known classical world and the as-yet undiscovered quantum world.** It is precisely the undesirable effects of quantum mechanics that stand as a barrier to the further development of classical computers. Thanks to tremendous efforts in science and technology, quantum effects that have hindered further transistor miniaturization in recent years are turning out to be a new and groundbreaking building block for quantum devices (referred to as quantum computers in this report). Thus, quantum computers can theoretically not only provide us with unimaginable computing power but potentially significantly improve the energy efficiency of information processing, leading to many new practical and breakthrough applications.

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Poland as the first quantum hub in Central and Eastern Europe

Janusz Cieszyński, Secretary of State, Government Plenipotentiary for Cybersecurity in the Chancellery of the Prime Minister, February 4, 2022.

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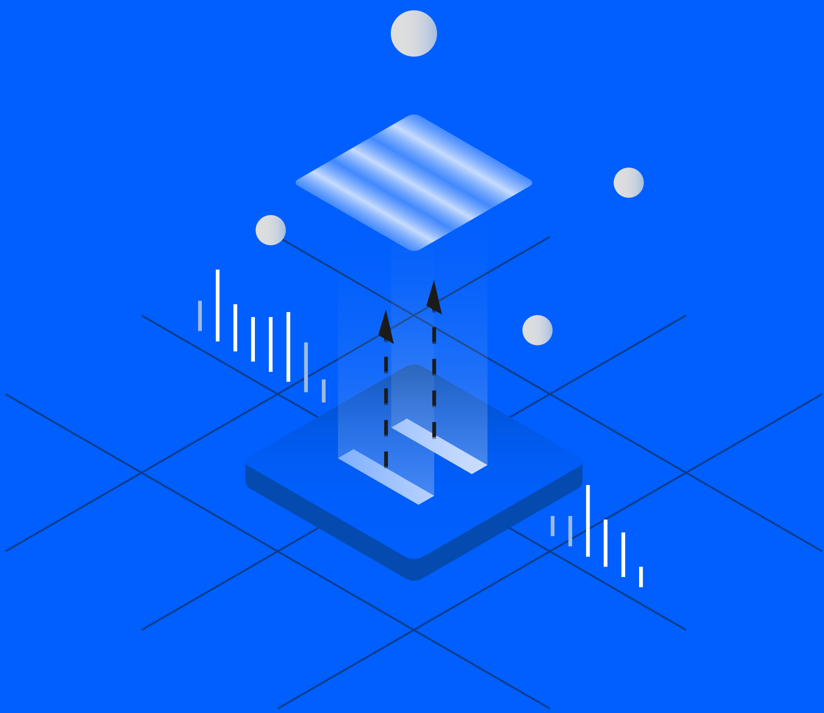


How does it actually work?

To illustrate how a quantum computer works, let's imagine searching for a specific manuscript that interests us. We've received information that the manuscript we're looking for is in an old library where, due to many years of neglect, the alphabetical arrangement of volumes has been disorganized. Trusting the information we received about the presence of the manuscript on the library shelves, we start our search. Beginning with the first bookshelf, we go through the volumes one by one, checking if any of them is the one we're looking for. However, we quickly realize that the search will take much more time than we initially thought. The library is vast, and the shelves on each of the dozens of bookshelves are overloaded with all sorts of books and writings, not to mention the crates left between the bookshelves.

We are unable to determine whether we will be lucky and find the book we're looking for right away after a few attempts, or if the worst-case scenario will play out, and we'll only discover it at the end of our search. If we were repeatedly searching through this library, statistically, we would find the sought-after book halfway through the maximum search time. However, common sense dictates that we plan for the time it would take to search the entire library.

Now, let's reconsider the same library but assume that both the library and the writings it contains have some specific, even astonishing properties. With precise knowledge of the specific item we are looking for, we can use this knowledge to gently shake the bookshelves in a way that causes the manuscript we're looking for to fall to the floor, **revealing itself**. Of course, shaking the shelf is much faster than examining all the books on it. Thanks to these remarkable properties, we have saved a lot of time. It's important to emphasize that we can do this **with any** book on the shelf, as long as we can definitively determine whether it's the book we're looking for or not.

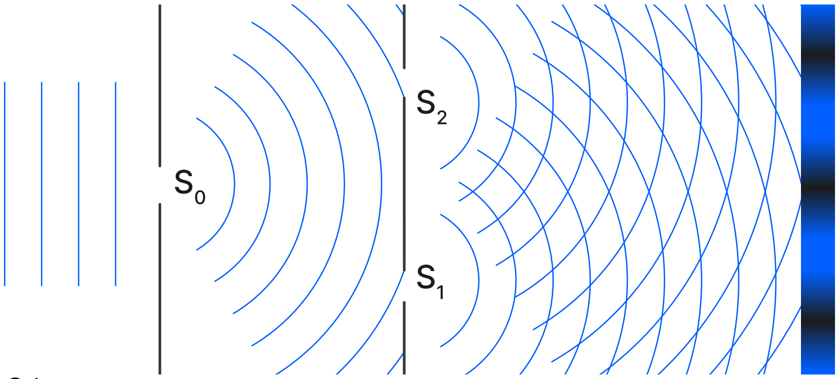
This scenario may seem unlikely in our macroscopic world, but it is a very good analogy for what we can actually observe at the quantum level.

The double-slit experiment

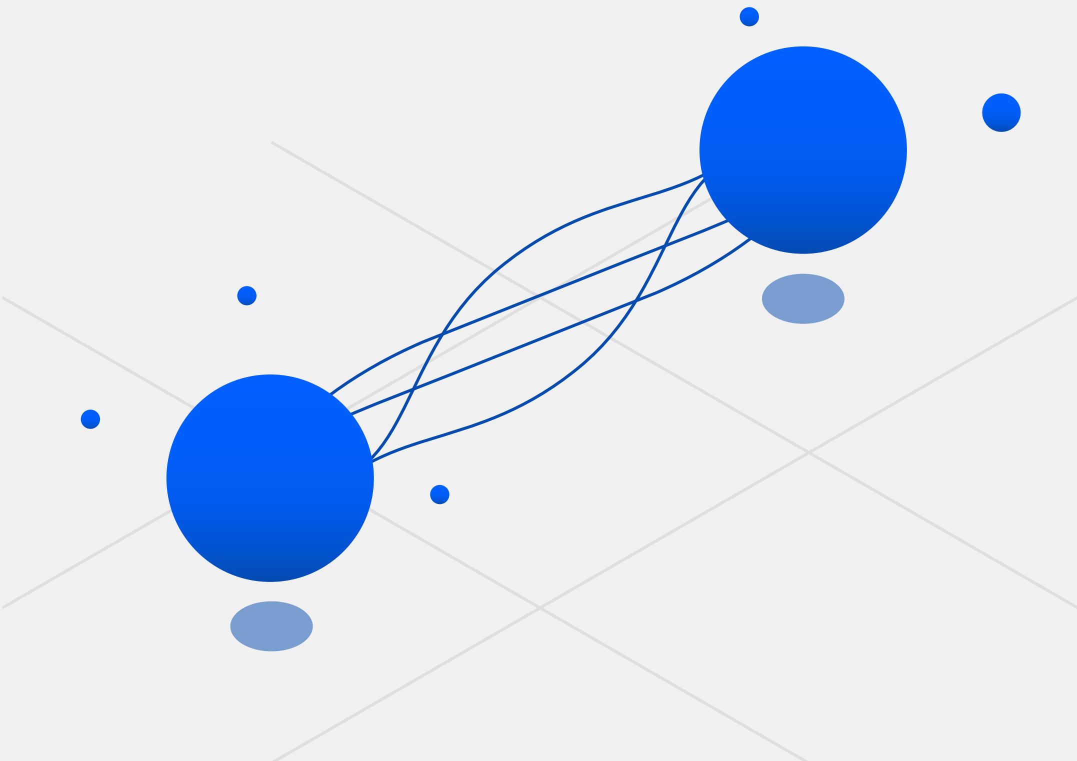
Quantum computers do not utilize classical physics but make use of effects known from quantum mechanics. One of the most well-known examples illustrating the remarkable quantum properties of particles is the famous double-slit experiment. The experiment was first designed and conducted by the English physicist Thomas Young in the early 19th century, which many of us may still remember from physics lessons.

In the experiment, candle flame light was used. Although it was not a perfect source of photons, it already allowed for the observation of an interference pattern on the screen, indicating the **wave nature of light**. However, it was not until about 100 years later that this experiment shook the scientific world when a coherent light source was obtained, enabling the generation of single photons. It turned out that a series of single photons passed through an identical slit setup also produced interference fringes on the screen. To create the interference pattern, the presence of a photon in both slits was required. Although this was difficult to accept and contradicted all previous intuitions about the laws of nature and classical physics, the only explanation had to be that the same single **photon existed in both slits simultaneously**! Today, after many years of experiments and theoretical considerations, including the involvement of this year's Nobel laureates in physics, we know that such a phenomenon indeed occurs, and it applies not only to photons but also to other elementary particles present in the micro-world. We call it superposition, and it manifests itself in the way that until a measurement is made, a particle behaves as if it were in every possible state simultaneously.

The surprising result of this experiment was the observation of the probabilistic nature of quantum mechanics. When a photon detector is placed at one of the slits, the interference pattern does not appear, and the detector detects the particle roughly in 50% of cases. Everything indicated that the act of measurement irreversibly affects the quantum state of the system. Furthermore, the act of measurement causes the quantum state to collapse with a certain probability. Such a state of affairs raises profound and fundamental questions about the laws governing nature.



Paradox **EPR**



Many prominent physicists, including Albert Einstein himself, disagreed with the interpretation of reality that quantum mechanics offered in the early 20th century. Einstein referred to entanglement as "spooky action at a distance." In 1935, along with Podolsky and Rosen, he proposed a thought experiment known as the EPR paradox [2].

Imagine an experiment in which two particles, such as photons, are prepared in a certain way and then separated by any arbitrary distance. If we influence the state of one of the particles in some way, it seems that the state of the entangled partner also changes instantaneously. This effect gives the impression that information about the change in the state has been transmitted at a speed greater than the speed of light, which blatantly contradicts the widely accepted **principle of locality**. In response to this paradox, according to the three scientists mentioned, there must exist hidden variables, potentially impossible to measure, that from the very beginning of the experiment contained information about how the entangled pair of particles would behave.

Bell's theorem

To illustrate Bell's theorem, let's use a simple analogy. Imagine a device with three buttons and a light bulb. Pressing one of the buttons causes the light bulb to illuminate in one of two colors. Another identical device is prepared in the same way and then separated from the first one in a manner that prevents any uncontrolled communication between them.

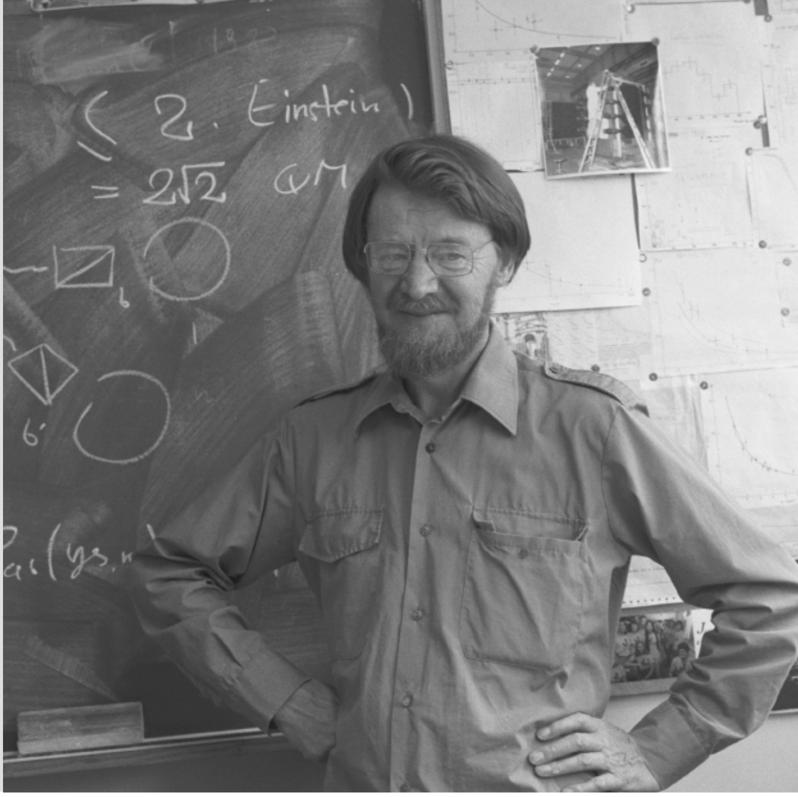
If you press the same button on both devices, both light bulbs always illuminate in the same color. Pressing the same button again makes the light bulb continue to shine in the same color. This situation is analogous to **two entangled particles.**

However, what happens if you press different buttons on both devices? In this case, there seems to be no apparent rule – sometimes the color of the light bulbs is the same, and other times it's different. There are two possible explanations for this behavior: either the result of pressing a specific button was pre-programmed in both devices, or it's entirely random, depending each time on the flip of a coin.

John Stewart Bell

The individual whose work brought humanity closer to understanding how the universe operates at the microscale is John Bell. In 1964, he mathematically demonstrated that the correlations in an entangled pair of particles cannot be explained by any local hidden variable theory.

Source: Photo by CERN PhotoLab



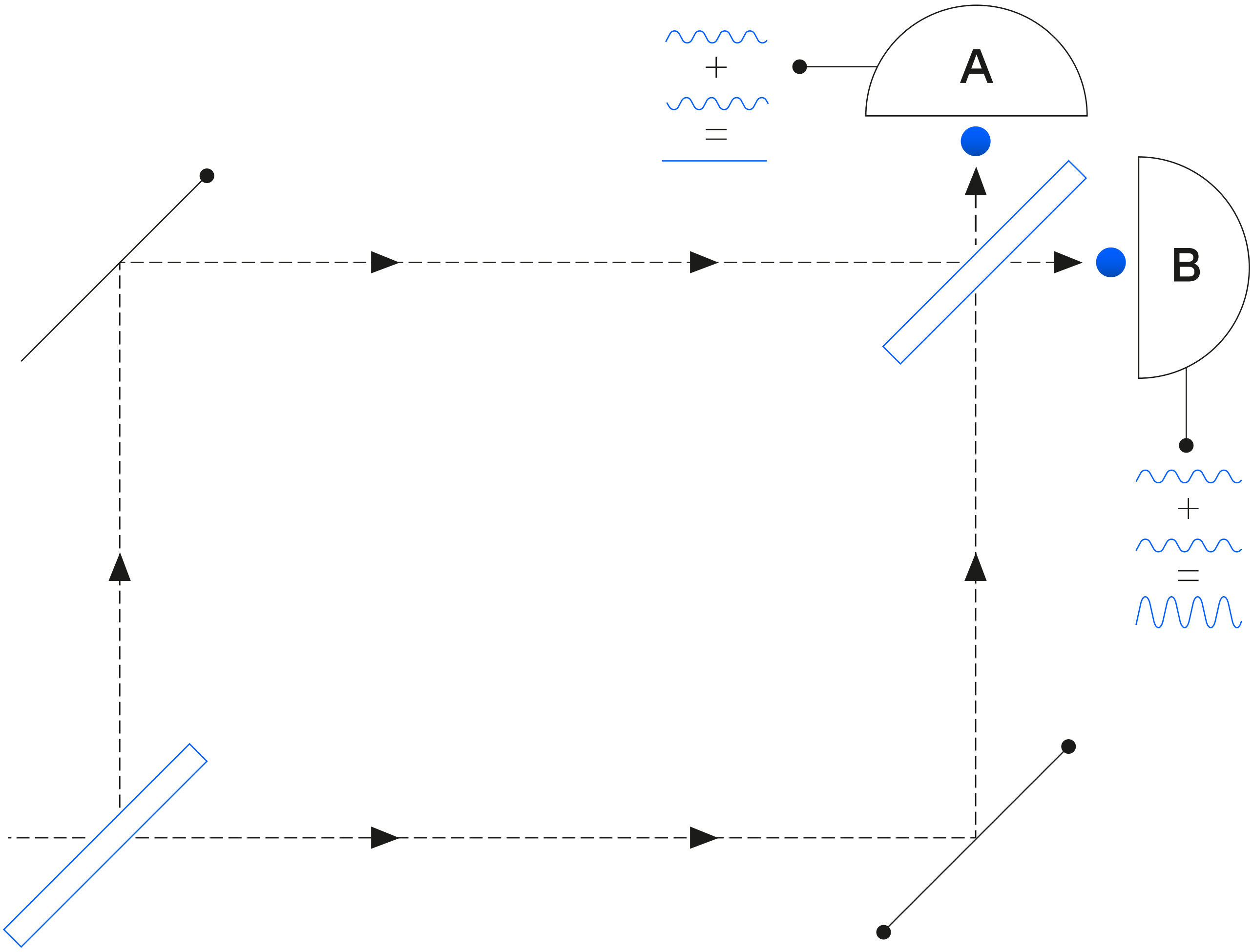
To determine which version is true, we conduct a simple test by pressing all possible button combinations on both devices one after the other. For example, let's assume that the hidden mechanism determining the behavior of both devices works as follows: button 1 lights up the bulb in gray, button 2 in blue, and button 3 in gray. We can present the results of the experiment in a table:

HIDDEN MECHANISM	BUTTONS							
1 2 3	1 - 1	1 - 2	1- 3	2 - 2	2 - 3	3 - 1	3 - 2	3 - 3
Same color?	Yes	No	Yes	No	Yes	No	Yes	No

As you can see, the bulb lit up in the same color in 5 out of 9 possible cases, which corresponds to a chance of approximately 55%. Because we assume the existence of a hidden mechanism, no matter how many times we repeat the experiment, we will always get the same results. Similar reasoning can be applied to any other combination of colors specified in this mechanism, and in each case, the result will be the same—consistency in 5 out of 9 cases. However, if the devices were operating randomly, in accordance with the principles of quantum mechanics, the chance that the colors would be the same would be exactly 50%.

According to Bell's theorem, in experiments with real quantum particles, we observe this second possibility, which means that there could be no hidden mechanism determining the outcome of a similar experiment in advance. The Nobel Prize in Physics for 2022 was awarded to three scientists who experimentally demonstrated the violation of Bell's inequalities.

Defusing the bomb



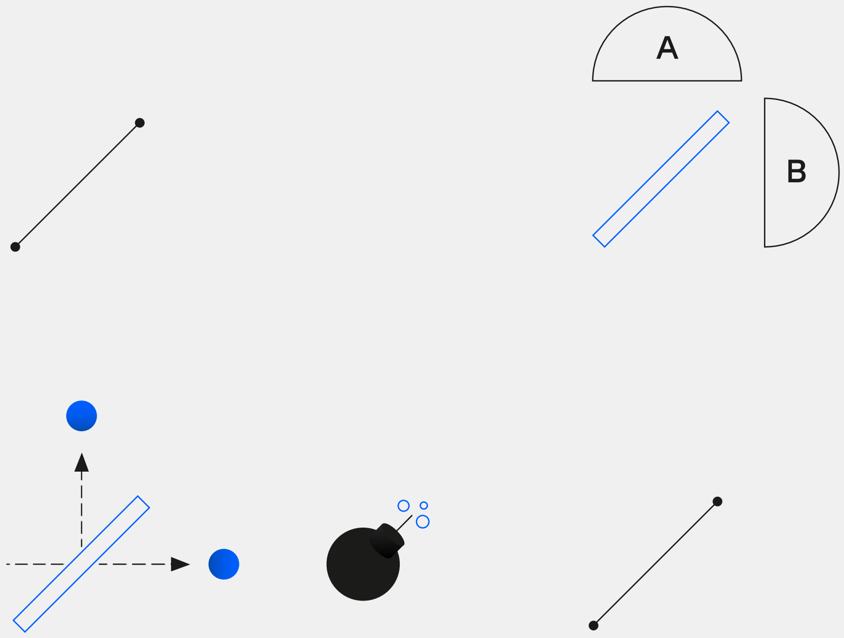
Using a simple example, we will show how **superposition and entanglement** can be used to create a bomb detector that is better than what is possible classically. To achieve this, we need to construct an optical circuit consisting of a photon source, two semi-transparent plates, two mirrors, and two detectors.

A single photon, after passing through the first semi--transparent plate, is in a superposition state, meaning it is simultaneously in the upper and lower paths. It then interferes with itself, causing extinguishing on the way to detector A and reinforcement on the way to detector B. Since there is destructive interference on the path to detector A, the probability of detecting the photon in detector B is 100%. This is a kind of transformation of the earlier two-slit experiment, in which a particle also interfered with itself, allowing the creation of an interference pattern on the screen.

Now, in one of the paths of the photon, we will add a bomb that explodes upon contact with the photon. Since the bomb's explosion constitutes a classical measurement, there is a 50% chance that the bomb will detonate. However, if the photon passed through the upper part of the circuit, it will again split into upper and lower beams with a 50% chance each, thus activating detectors A and B with equal probability.

The lack of interference is associated with the measurement performed by the bomb. From this point on, the photon is no longer in a superposition state but assumes a specific position in the system. In contrast to the previous case, we now have a chance to activate detector A. With a 25% probability, we can detect the bomb without the need for detonation.

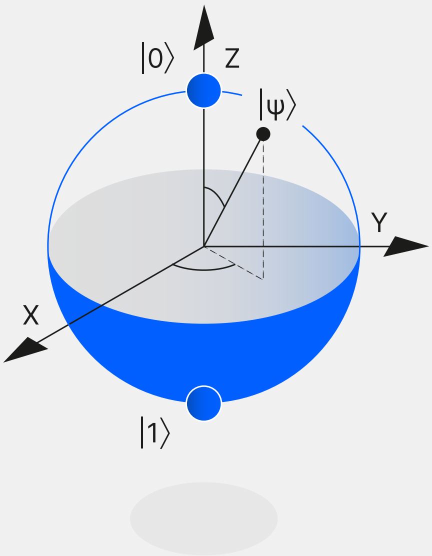
The probability of 25% may not seem high, especially when it involves the detonation of a bomb. However, it is still higher than what we could achieve using the principles of classical mechanics, where it would be impossible to detect the bomb without detonating it. Furthermore, by using different types of semi-transparent plates with transmission and reflection coefficients other than 50%, it is possible to approach a probability close to 100%.



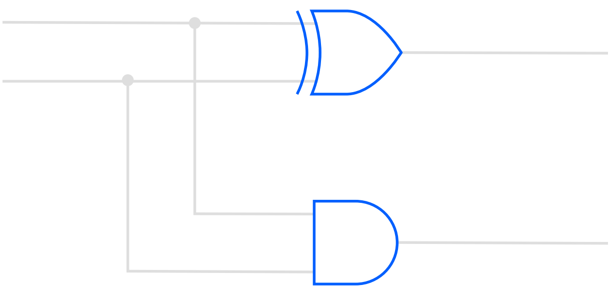
How to gain an advantage in computations?

In practice, many experiments can be designed to showcase intriguing quantum phenomena. An example of the application of such physical processes can be highly accurate quantum sensors. However, to perform quantum computations, we need to obtain variables that can be used in quantum algorithms. Therefore, similar to a classical bit—a variable that takes one of two binary values—0 or 1, we will now use our qubit—a quantum binary variable. When a qubit, introduced into a superposition state, exists in both states simultaneously, and only its measurement results in obtaining a specific value. We can utilize this property by performing multiple calculations in parallel using the same particle, and then quickly read the correct result. Achieving such acceleration would not be possible using a classical computer.

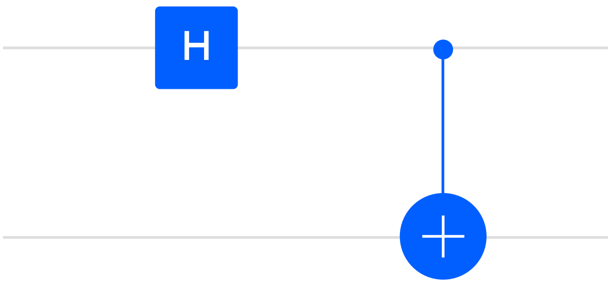
The graphical representation of a qubit is depicted using the **Bloch sphere**, which is a complex sphere with a radius of 1. Within this sphere, a qubit's point representation can be encoded using two angles. Operations on qubits can then be represented as rotations or transformations around the X, Y, and Z axes. Here, X and Z are the real axes associated with different qubit measurement bases, while the Y axis is related to the complex phase factor of the qubit. The probability of measuring a particular state depends on the vector's position relative to the poles of the sphere.



Digital circuit

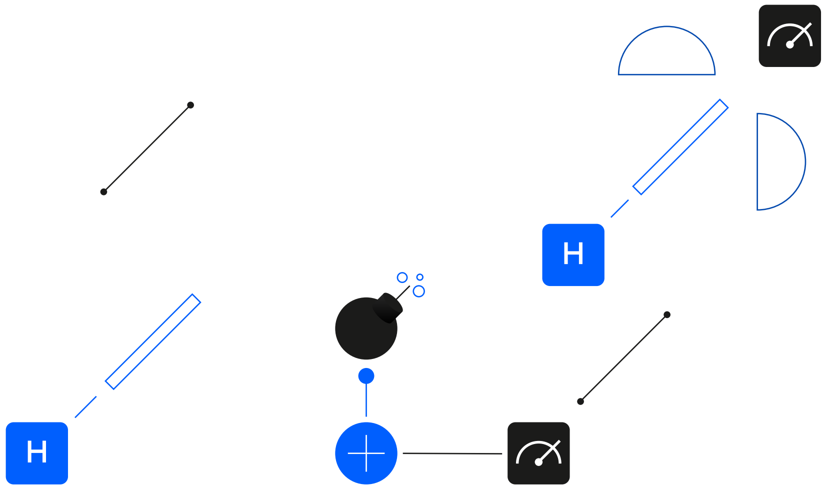


Quantum circuit

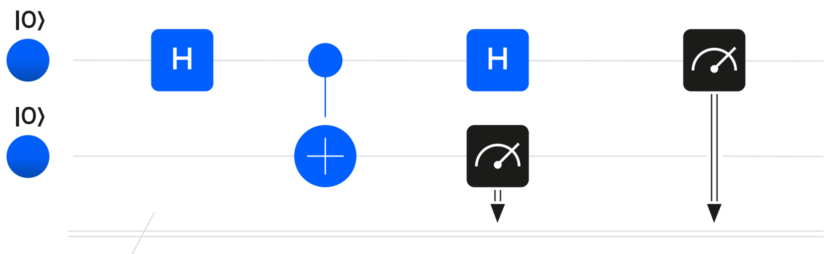


Each quantum algorithm can be expressed using qubit transformations. Analogous to digital logic circuits, quantum algorithms are represented using quantum circuits composed of gates. Some of the most popular gates include **X**, **Y**, and **Z** gates, which are used to rotate qubits around their respective axes on the Bloch sphere. Additionally, the **Hadamard gate (H gate) is used to create superposition**, and the two-qubit **CNOT gate generates entanglement between qubits**. The described setup with the bomb can be represented using such a quantum circuit, utilizing gates to create superposition and entanglement.

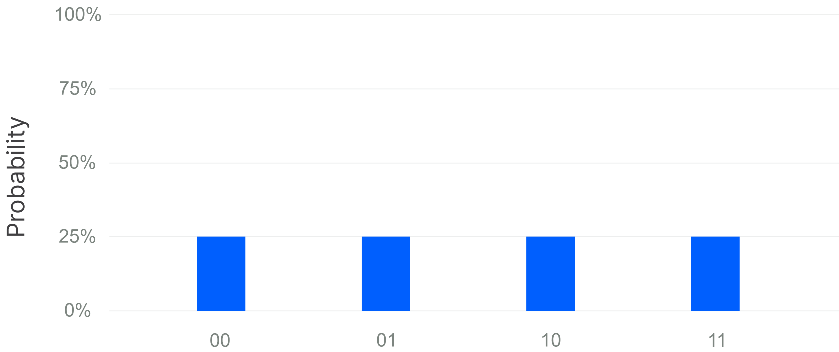
The results of running such a quantum circuit are probabilistic. However, by performing a certain number of trials, you can observe a distribution that closely matches the theoretical one. This is illustrated by a histogram with four possible outcomes. The value 1 of the first qubit represents the detonation of the bomb. If the bomb was not detonated, and the value of the first qubit is 0, there are two possibilities for the second qubit - 0 and 1. Their probabilities are equal and are 25% each.

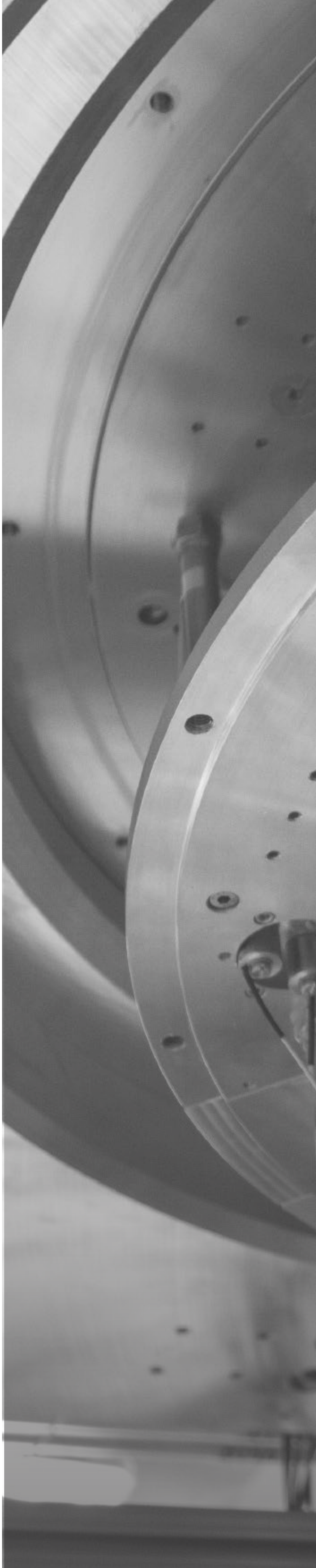


Programming quantum computers involves designing and building quantum circuits consisting of multiple quantum gates. Since measurement and obtaining results in a quantum computer are always associated with some probability, it is necessary to perform measurements multiple times to obtain meaningful outcomes.



One of the key tasks in programming a quantum computer is to create a quantum circuit in such a way that the **probability of obtaining the best result for the problem being solved is maximized.**





Source: IBM Quantum Computer Interior

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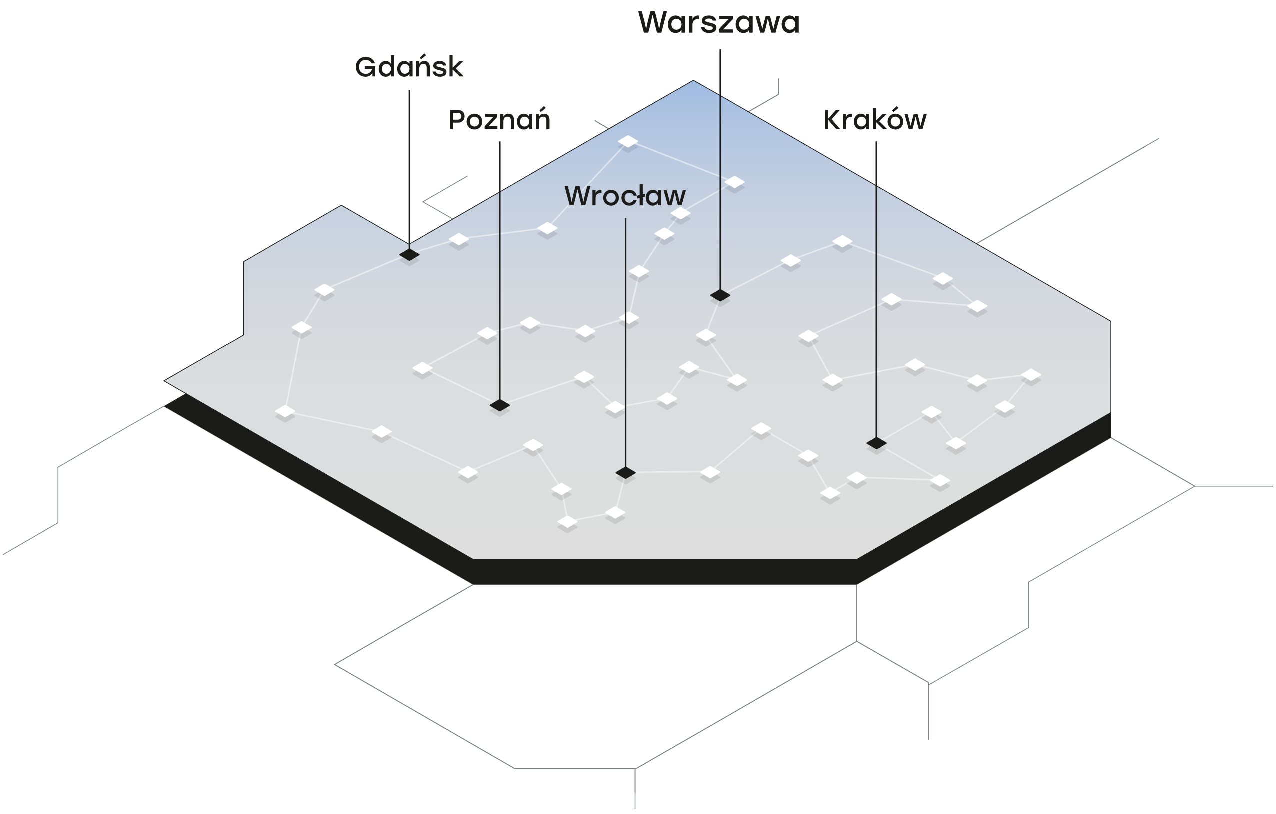
What can this be used for?



Let's take on the role of a salesperson

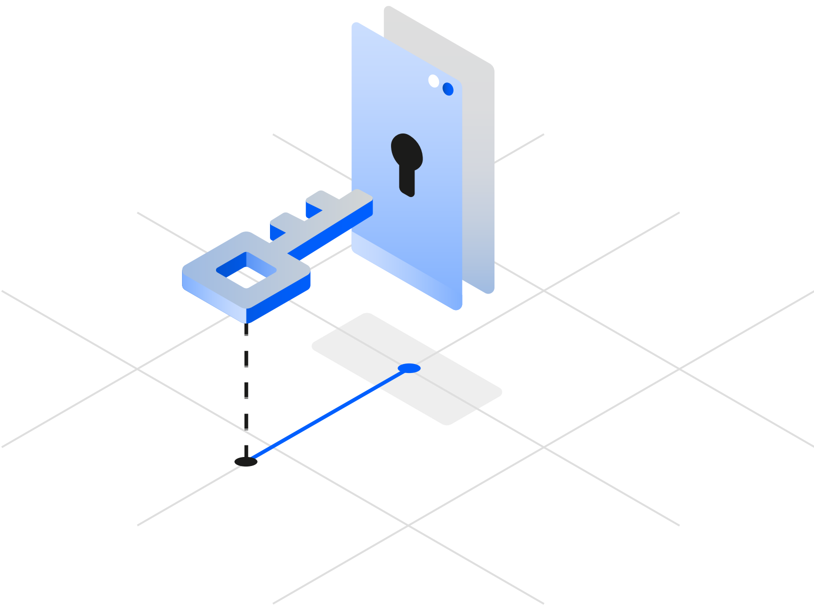
An example of a task that is too complex even for supercomputers but can be solved with the help of a quantum computer after suitable transformation is the optimal route planning for a salesperson to deliver packages to various locations in the shortest possible time. While a regular computer can calculate the optimal route quickly for a small number of points to visit, for a larger number of such locations (more than a dozen), the computational complexity grows to unimaginable proportions. This happens because the number of all possible routes, also known as permutations, increases very rapidly as the number of destination points increases. For example, if a driver wanted to find the fastest route between sixteen provincial capitals in Poland, the fastest supercomputer would solve this problem in one-hundredth of a second. This seems like a reasonable and acceptable time frame. However, what would happen if there was a need to

* Currently, the speed of the fastest supercomputers is at one exaFLOPS, or about 10^{18} floating point operations per second, which is about 10^{21} operations per hour, or about 10^{25} operations per year. All the routes a courier can visit cities are n!, so for 25 packages we have about 10^{25} possibilities. We assume for simplicity that one possible route only needs one operation, although in reality this number would be several times higher still.

visit nine more cities? It turns out that for 25 cities, calculating the shortest route using the world's fastest supercomputer would take an entire year! If we were to increase the number of cities further, it would become even more challenging. For a selected set of 37 cities in Poland with populations greater than 100 thousand, the computation time would be on the order of trillions of years (for comparison, the estimated age of the universe is 13 billion years), and for all county towns in Poland, such calculations would take 10^609 years. This period of computation time is so vast that it's challenging to even provide a reasonable and meaningful analogy.

Using quantum computers, we can "**parallelize**" computations. You can think of it as a situation where a quantum computer, leveraging the phenomenon of superposition and entanglement among multiple qubits, effectively checks all potential courier routes simultaneously and selects the best one.

Be aware of
Internet security



Shor's algorithm

One of the most popular applications for which quantum computers could be used is **quantum cryptography**. Currently, one of the most commonly used algorithms for encrypting passwords on websites or securing financial transactions is the RSA algorithm, based on a pair of asymmetric keys. Its popularity is due to the fact that, despite its simplicity, breaking the security, i.e., discovering the private key, is incredibly time-consuming for classical supercomputers. This is because of certain mathematical properties on which the RSA algorithm is based. One of the steps in generating a key pair (public - for encrypting messages, and private - for decrypting messages) is multiplying two very large prime numbers together.

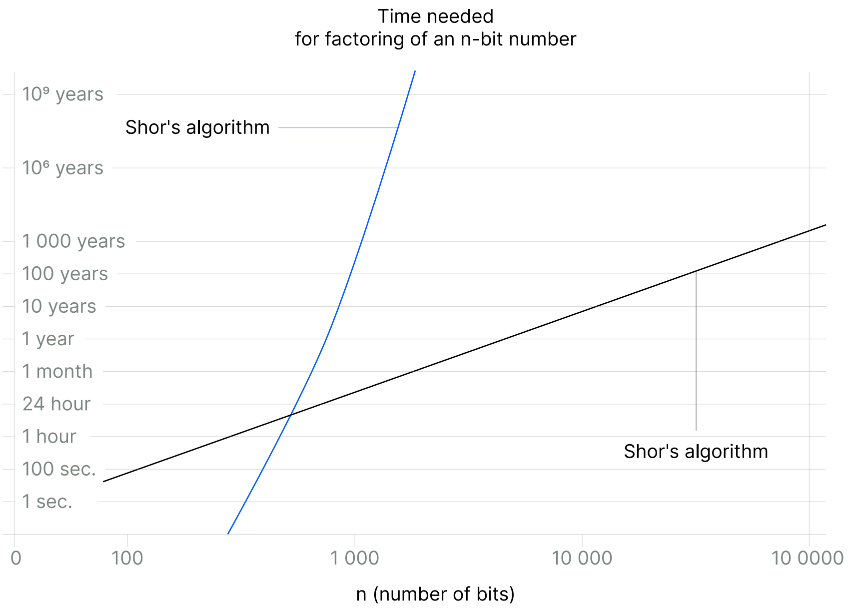
To decrypt the public key, it's necessary to reverse this process, which is called factorization, and for classical computers, it's an incredibly challenging task. For instance, to break a 2048-bit key, a regular classical computer would require trillions of years.

```python
from qiskit.algorithms import Shor
shor = Shor()
result = shor.factor(15)
```

However, it turns out that with the help of certain mathematical theorems related to factoring derived from number theory, we can modify the factoring problem in such a way as to introduce cyclicity into it. This was noticed by American scientist Peter Shor in 1994. Shor developed an algorithm using quantum Fourier transform and the negative interference of waves contained within it to find the frequency of this cyclic property, which ultimately leads to solving the problem. While this doesn't pose a threat to currently used security systems due to the limited power of available quantum computers, it's already necessary to take preparatory actions to ready the digital world for the moment when quantum computers will be advanced enough to break internet security measures.

POTENTIAL RISKS

- Identity theft
- Decryption of confidential data
- Retrieval of private keys
- Breaking RSA encryption



The critical use case remains the ability of quantum computers to break RSA encryption. On May 4, 2022, the Office of the President of the United States published National Security Memorandum 10 (NSM-10), requiring sensitive national systems to transition to quantum-resistant cryptography [17]. The United States is the first country to take systematic security measures against the potential threat associated with the unwanted use of quantum computers.

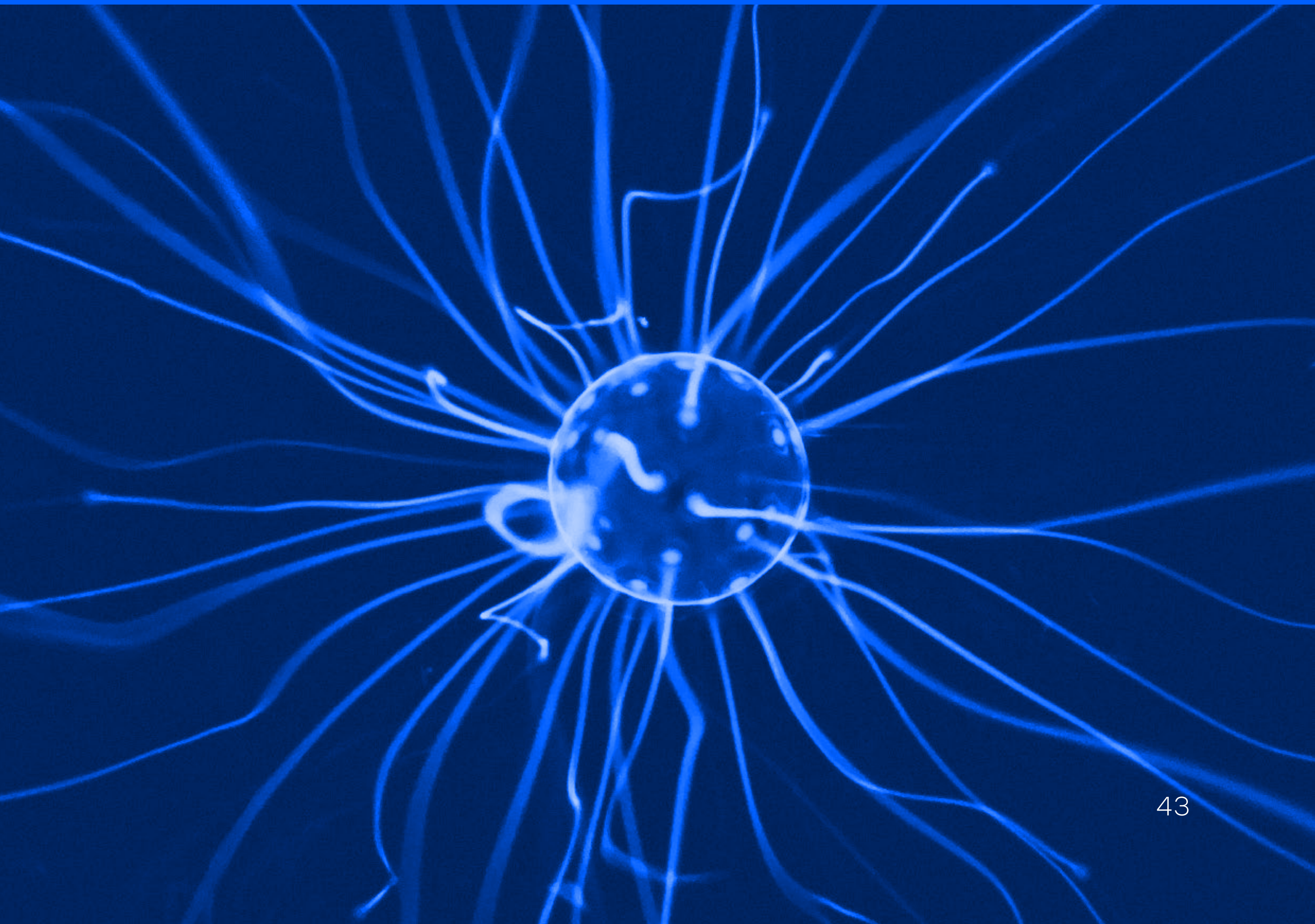
Quantum communication

One of the greatest threats to our digital world is the vulnerability of electronic communication to threats and security breaches. Hackers come up with ways to steal our identities, financial resources, and private data. **Cryptography** is the branch of knowledge dedicated to securing information from unauthorized access. It allows us to exchange information over long distances while remaining secret from unintended eavesdroppers. Most modern cryptographic methods are based on well-known mathematical problems such as **factorization**, which are difficult to solve by classical supercomputers. The possibility of future error-corrected and noise-resistant quantum computers requires us to reevaluate how we secure our computer systems.

Quantum Key Distribution (QKD) technology is used to secure information transmitted over computer network links over increasingly long distances. Within the PIONIER scientific network, it was possible to establish and secure a QKD connection spanning over 300 km between Poznań and Warsaw in May 2022.

In general, quantum communication involves encoding and transmitting messages using different configurations of subatomic particles and their physical parameters. In a full configuration of quantum communication, qubits are transmitted instead of classical bits. Currently, methods of this type of communication use the transmission of photons and their encoded quantum states. This approach and the concept of quantum communication itself enable an entirely new approach to the idea of communication and provide a way to transmit qubits between quantum computing infrastructure, allowing for the scalability of such computing infrastructure. The implementation of quantum communication requires the development of key methods for the efficient generation of entangled photon pairs and their distribution over longer distances, which requires the development of quantum regenerators. A key element of such a regenerator is a quantum memory. Quantum communication potentially offers many new applications, but one of the main and first proposed such applications is secure data transmission, where using the principles studied by quantum mechanics, we offer the integrity of the transmitted signal, data, and services. One of the proposed methods for this purpose is quantum key distribution.

Quantum Key Distribution (QKD) is a new form of cryptography based on the principles of quantum mechanics, and it keeps our information completely secure, even against attacks by quantum computers. The main goal of QKD is to create a shared secret key between two parties that is perfectly secure. In its simplest form, one party sends qubits in specific quantum states to the other party, which observes or measures them. An eavesdropper trying to listen in must also measure these qubits, which, as we know, leaves a detectable trace. This is due to the principles of quantum mechanics, which state that you cannot measure the quantum state without disturbing it. If the qubits have been disturbed, both parties know they should abandon the exchange and discard the key. Otherwise, the parties can use the key for secure communication. It's worth noting that there is ongoing development in the field of post-quantum cryptography, which focuses on cryptographic algorithms designed to be resistant to attacks by quantum computers. **Post-quantum cryptography** is a complementary approach to QKD and focuses on developing new classical cryptographic methods based on mathematical problems that are considered difficult to solve even for quantum computers. Fortunately, alongside the development of quantum computers, quantum ciphers (e.g., the Vernam cipher) and cryptographic protocols (e.g., BB-84) are emerging, whose resistance to various types of attacks is guaranteed by the quantum properties of particles.



Recipe for massive data volumes

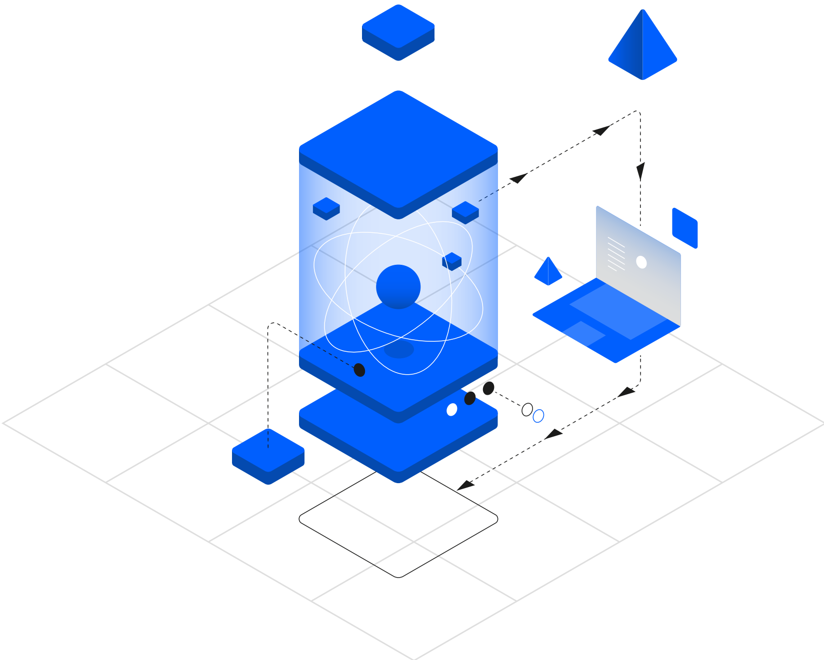
Grover’s algorithm

The analogy of searching through a library discussed at the beginning of the report is an example of the use of one of the most well-known quantum algorithms, namely Grover's algorithm, which was invented in 1996 by Lov Grover. Originally, Grover's algorithm was introduced as a quantum algorithm for finding a specific element in an unsorted database in quadratically faster time than other classical algorithms. The database can be any set of elements, such as the previously mentioned library, and its unsorted nature means that, for example, it is not sorted in any way, so we cannot use any strategy that would allow us to find the element faster. Finding a specific element means that we can recognize that element and - if we see it - unambiguously confirm that this is the element we are looking for. Quadratic acceleration here means that, for example, instead of waiting for 100 seconds for a solution, Grover's Algorithm will only take 10 seconds, but for larger data sets, for example, instead of 1,000,000 seconds, it will only take 1000 seconds, and so on.

Grover's algorithm is not only used for searching in an unsorted database but also in any other problem where we can determine, based on each element, whether it is the element we are looking for. Therefore, examples of using Grover's algorithm can also include finding the mean, median, or maximum value from a set of numbers. This algorithm can also be used to find solutions faster for many computationally difficult problems, such as finding a feasible solution for assigning individual train compositions to planned railway connections, for instance.

```
from qiskit.algorithms import Grover
grover = Grover()
result = grover.amplify(problem)
```

Quantum simulations



Modeling complex phenomena and processes known in chemistry, biology, pharmacy, or biomedicine, where at a certain spatiotemporal scale, the influence of quantum mechanics needs to be considered, poses a huge challenge for classical supercomputers. For many decades, various quantum phenomena have been attempted to be modeled using classical supercomputers and computationally expensive computer simulations. As mentioned earlier, Richard Feynman showed that in practice, classical calculations require a series of approximations, simplifications, and limitations, which, in turn, limit the accuracy of calculations in representing reality

The natural solution to this problem appears to be the utilization of a controlled quantum system that, after appropriate preparation, can reproduce all the phenomena occurring in the real studied system without the need for approximations. This idea has been the most promising area since the beginnings of quantum computing, where a new computing paradigm can gain an advantage over classical methods and make an invaluable contribution to science and industry. Results obtained in the laboratory can be verified and complemented using computer simulations, which, in turn, provide information leading to further discoveries.

The fundamental limitation of commonly used classical models is the need to apply certain approximations and simplifications to stay within the bounds of classical computational power of supercomputers. In the case of quantum computers, at least in theory, they are capable of modeling real quantum phenomena without the need for any approximations or simplifications.

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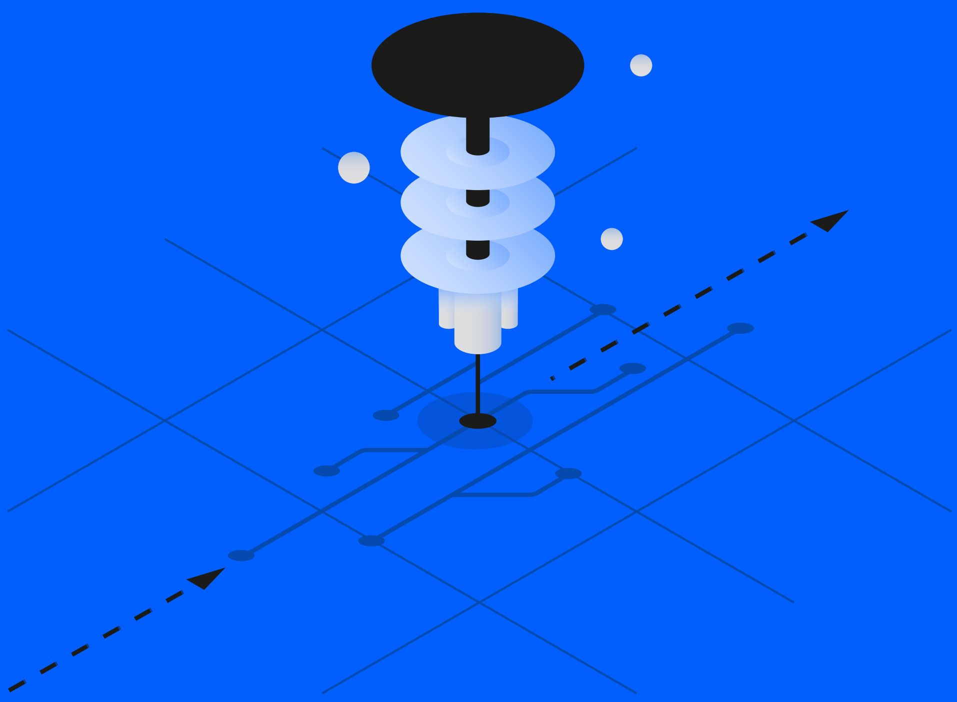
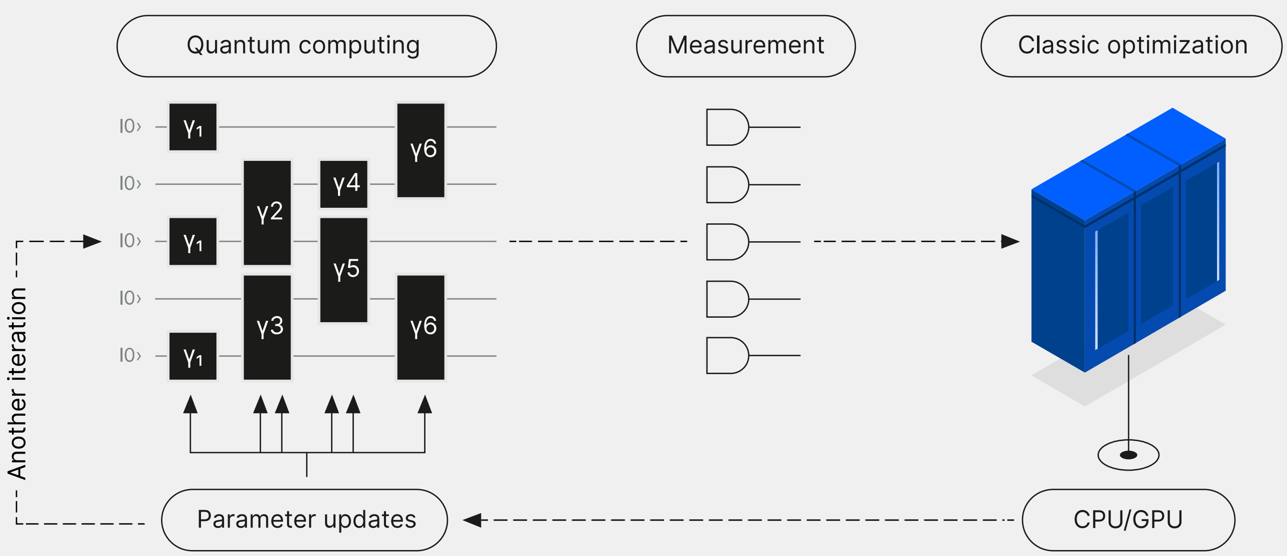


Is it real?

First quantum computers

We are at the beginning of the development of quantum computers and their applications. The first theoretical models of quantum computers began to emerge only in the 1980s.

Based on this work, well-known quantum algorithms, such as Shor's algorithm and Grover's algorithm, were developed, but they had to wait many years for their physical realization. It wasn't until 1998 that the first 2-qubit quantum computer was constructed, which could maintain its state for just a few nanoseconds. This computer was based on nuclear magnetic resonance technology, and its range of available operations was quite limited. A year later, the first designs for computers using quantum annealing were released. It wasn't until 2003 that the real operation of a CNOT gate, which is a crucial operation for entangling qubits, was demonstrated for the first time. In 2007, the world learned about the construction of a 28-qubit computer using quantum annealing architecture, and in 2009, scientists created the first universal 2-qubit quantum computer. Universality in a quantum computer means that, like a classical computer, it can perform any computation. Each operation on this computer had an average of a 10% chance of failure. In 2011, the company D-Wave was the first to provide commercial access to a quantum computer specialized in solving combinatorial problems, and in 2016, IBM provided remote access to a 5-qubit quantum machine.

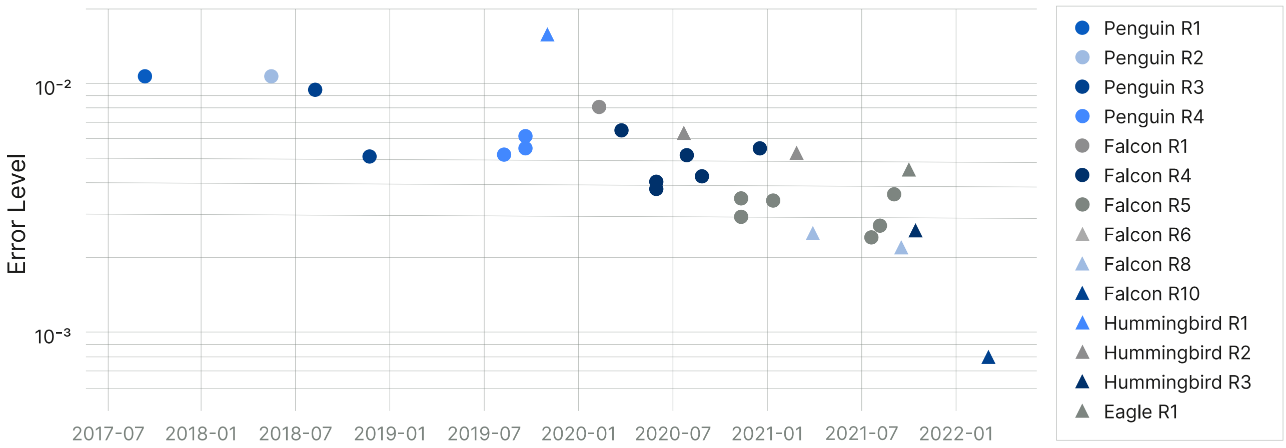


Currently, we are witnessing the era of **NISQ** (**Noisy Intermediate-Scale Quantum**) computers, which are quantum computers with a relatively small number of qubits. Due to their imperfections, they are not capable of processing complex circuits with high precision. These imperfections include various types of **errors and noise**, such as inaccuracies in qubit operations, measurement and readout inaccuracies, unintended interactions between qubits, and short coherence times of quantum states. Additionally, in practice, qubits are often sparsely connected to each other, making entanglement between distant qubits challenging. Complex qubit swapping operations are sometimes necessary to bring qubits closer together before they can be entangled and used for quantum computations.

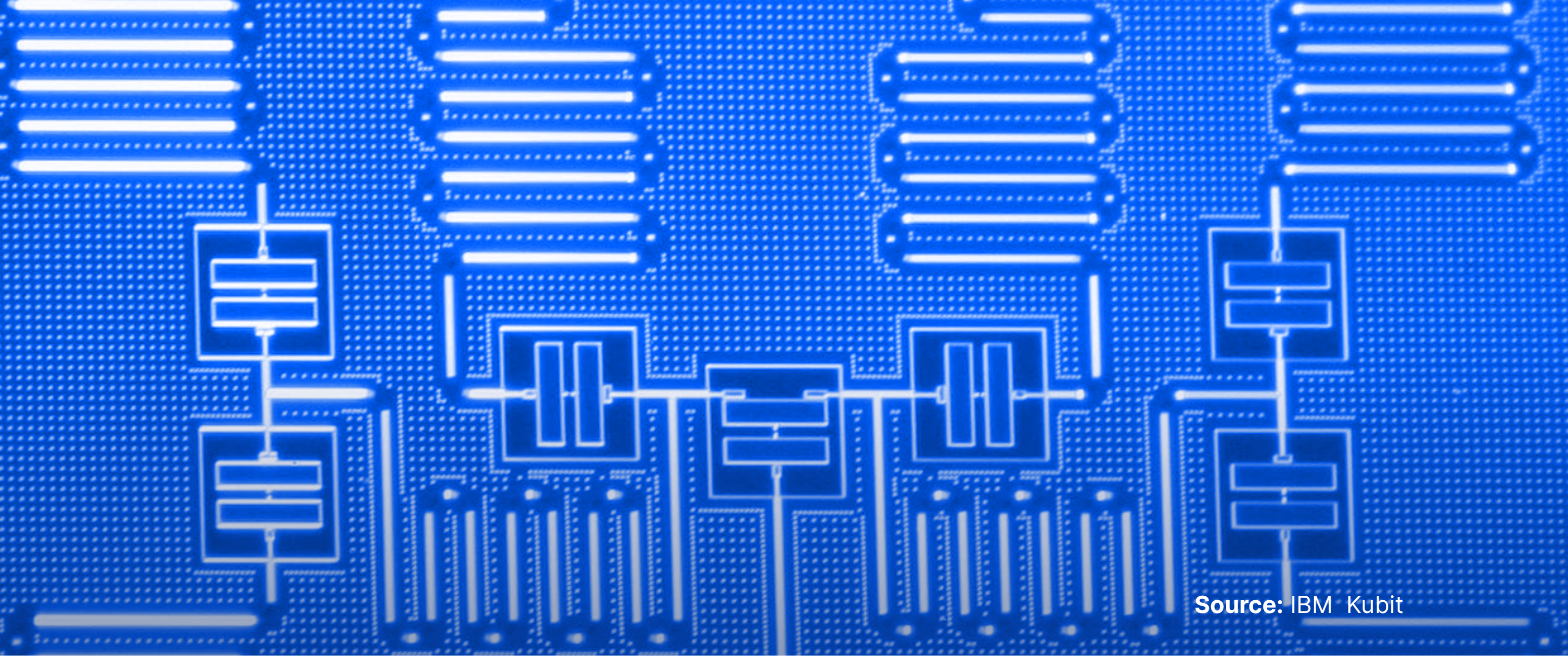
All of these factors necessitate the design and use of **hybrid algorithms**. In quantum algorithms, part of the computation is performed by the quantum computer, while the remaining computations are carried out by classical computers. Hybrid algorithms often involve feedback loops where the outcome of the quantum part depends on specific parameters adjusted and optimized by the classical computer. Optimizing these parameters can be a challenging task on its own, which is why supercomputers and High Performance Computing (HPC) technologies are preferred for this purpose.

The mentioned limitations associated with imperfections mean that the available quantum computers are not yet suitable for solving large-scale problems on a widespread basis. However, there is a strong practical need and a desire to experiment with the currently available quantum computers. When comparing the quality of quantum computers over the past 5 years, significant progress and development can be observed. For example, between 2017 and 2022, IBM was able to improve the quality of qubit entanglement by a factor of thirty. In 2017, one out of every 100 entanglement operations failed, and now it's only one out of every 3000.

The best quantum gate entanglement error rate in IBM Q



Source: https://quantum-enablement.org/hardware/historical.html



Source: IBM Kubit

Errors in quantum computations

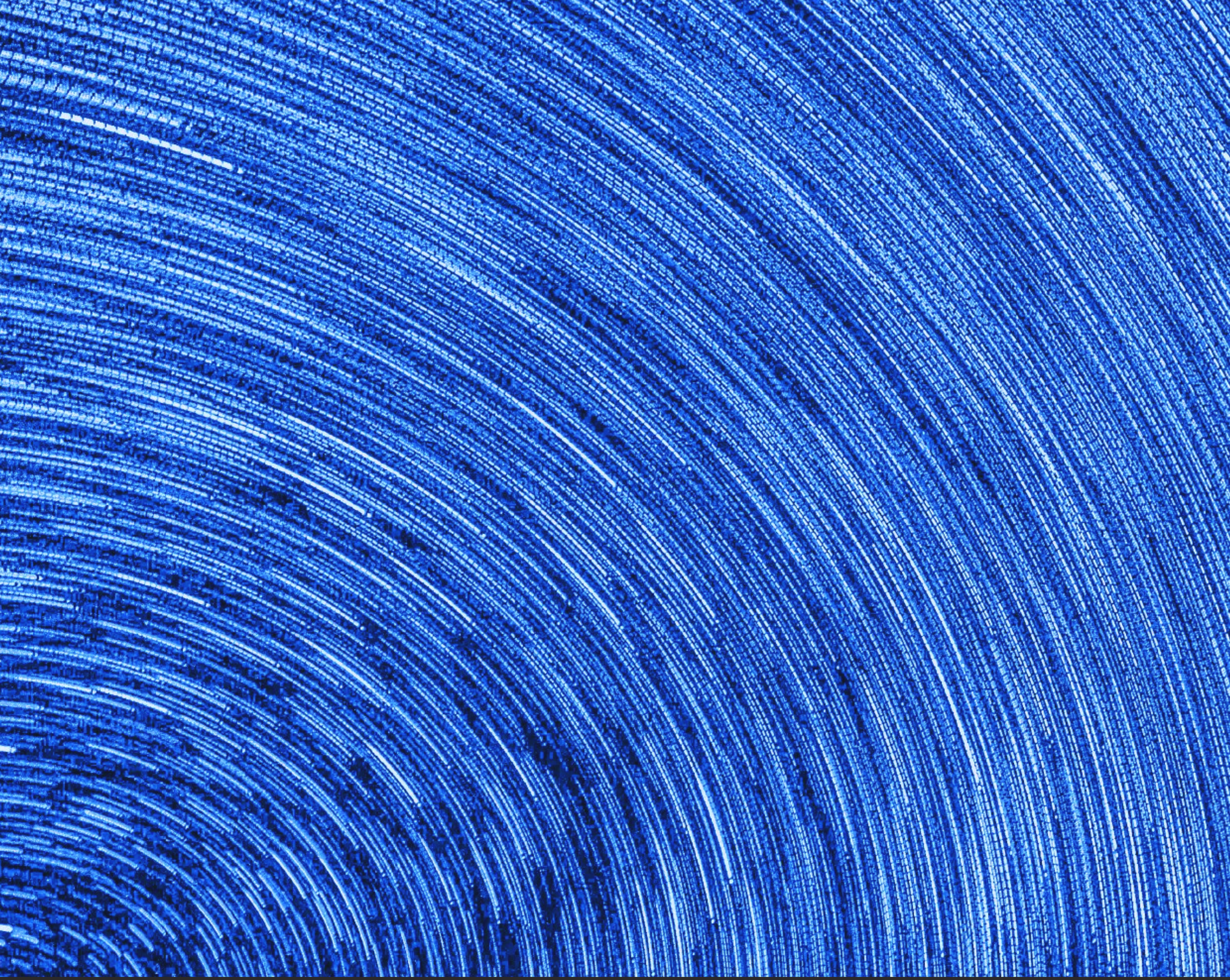
Due to the fact that qubits can take any value between 0 and 1, using them for computations resembles the idea of analog computers, which did not find wider use precisely because of their sensitivity to errors. However, it's essential to note a fundamental difference between these approaches. It has been proven that quantum computations can be made resilient to errors and inaccuracies if the error rate does not exceed a certain constant threshold. This means that, in theory, errors can be corrected faster than they appear. This idea is crucial from the perspective of the further long-term development of quantum computers.

In general, quantum error correction methods involve encoding the state of one logical qubit using an entangled state of multiple physical qubits. This ultimately allows for measurements to detect the type of error without affecting the state of the logical qubit. However, the best-known methods require a very large number of redundant qubits, making their practical use in currently available quantum computers with a relatively small number of qubits challenging. This doesn't mean that error rates cannot be significantly reduced in other ways. Increasing the accuracy of computations on quantum machines affected by various errors is a fascinating topic in **error mitigation**. Many research teams worldwide, including those in Poland, are developing new solutions that could have practical applications. Currently available error mitigation methods, combined with further advancements in the quality of quantum gates, may lead to gradual improvements in achievable results without the need for costly **error correction** implementations.

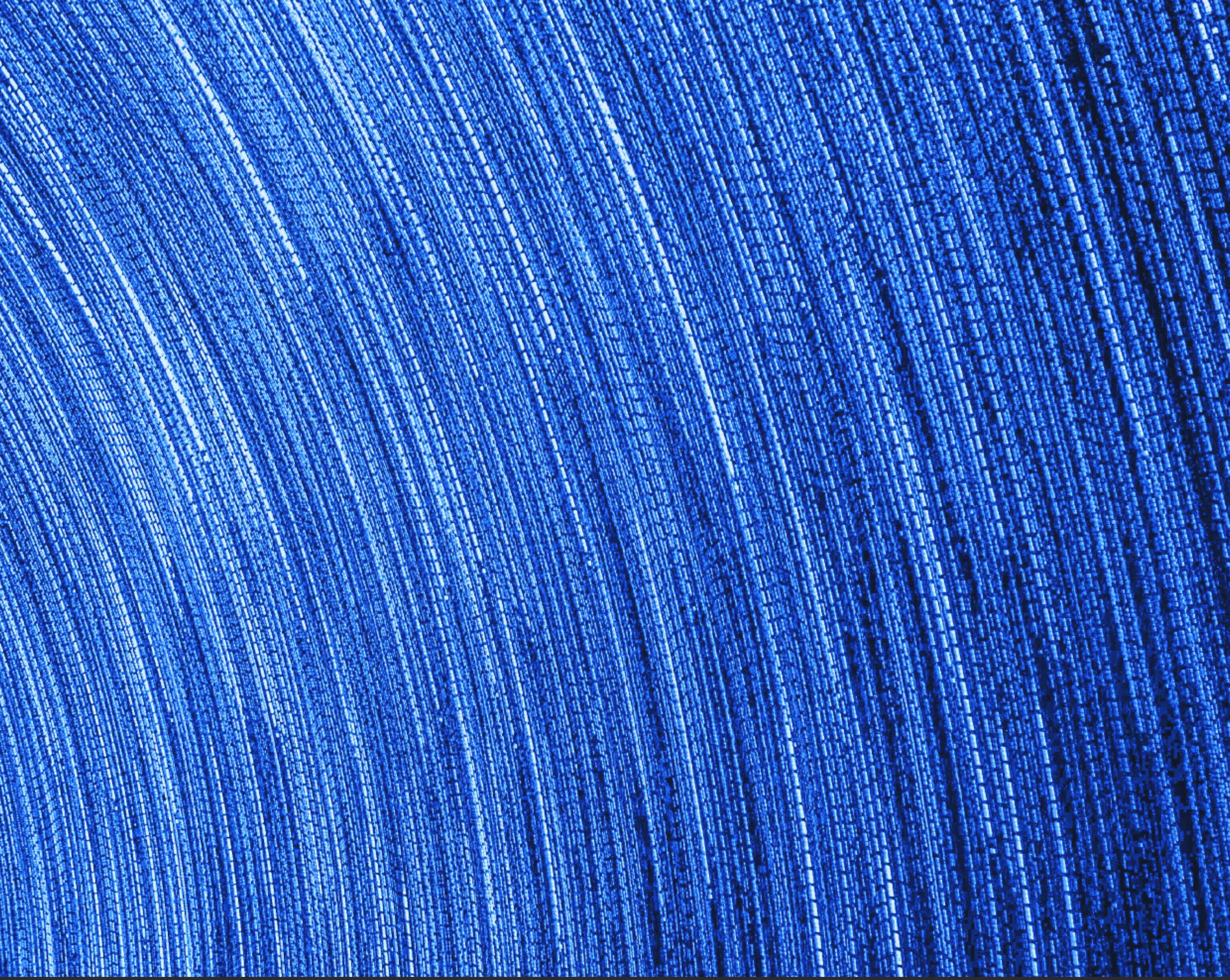
Current possibilities and architecture

TECHNOLOGY	PRODUCER	ADVANTAGES	DISADVANTAGES
SUPERCONDUCTING QUBITS	IBM, Rigetti, Google, IQM	**Universal computation model, high stability with more qubits, proven components**	Operation at extremely low temperatures, Limited connectivity options
ION TRAP QUBITS	Quantinuum, AQT, IonQ	**Universal computation model, operation at room temperature, potential for dense qubit connectivity**	Low stability with more qubits
NEUTRAL ATOMS	Pasqal, QuEra, Atom Computing, ColdQuanta	**Universal computation model, operation at room temperature**	Low stability with more qubits
QUANTUM ANNEALING	D-Wave, NEC	**Large number of qubits, possibility of dense qubit connections**	Operation at extremely low temperatures, Lack of universality
PHOTONIC QUBITS	Xanadu, Quandella, Quix, ORCA, Computing	**Operation at room temperature, ease of scaling architecture for a large number of modes**	Small number of qubits, Lack of universality

Tab. 1. Comparison of selected quantum computer architectures

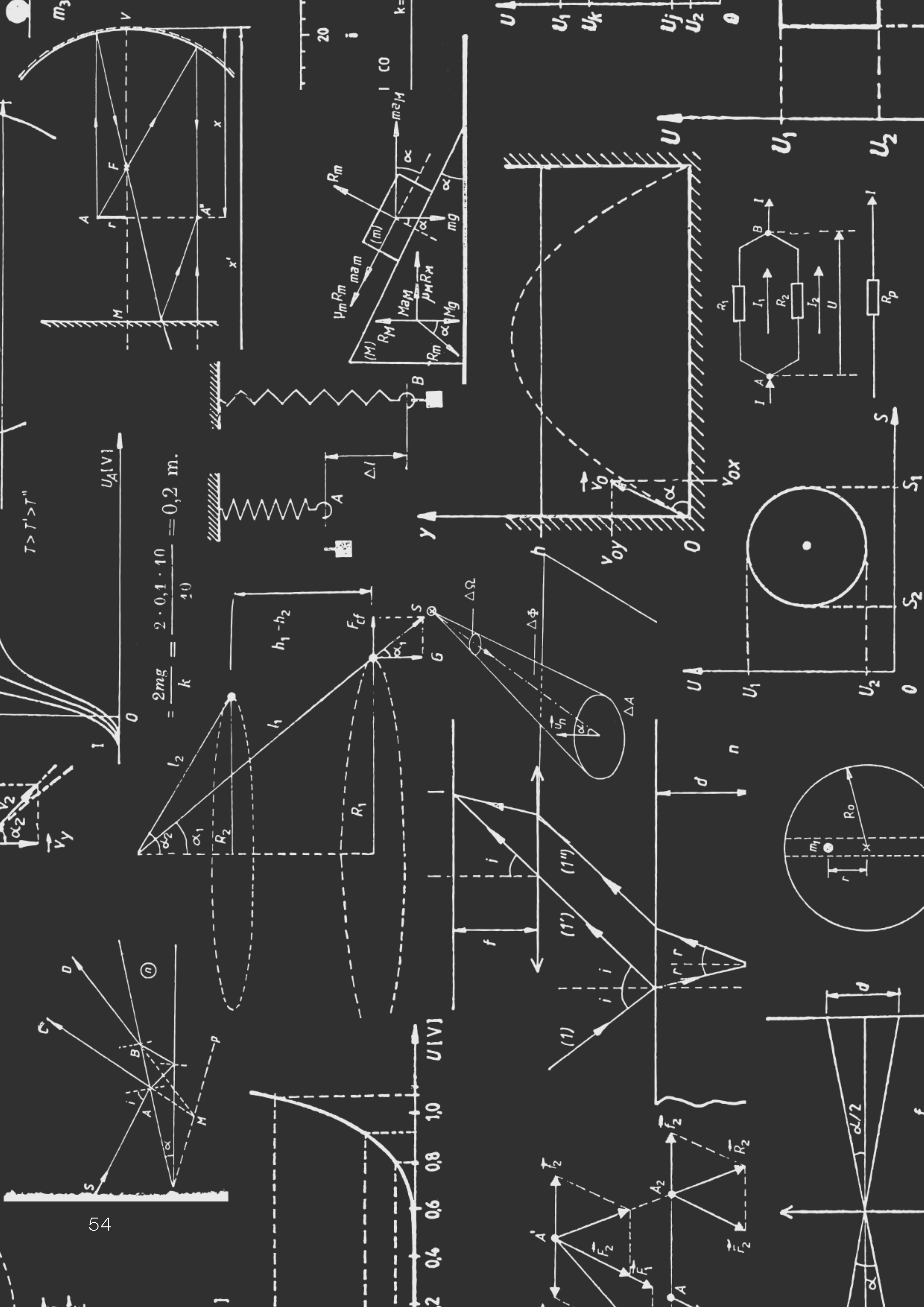


Polish quantum computing node



CHAPTER

02

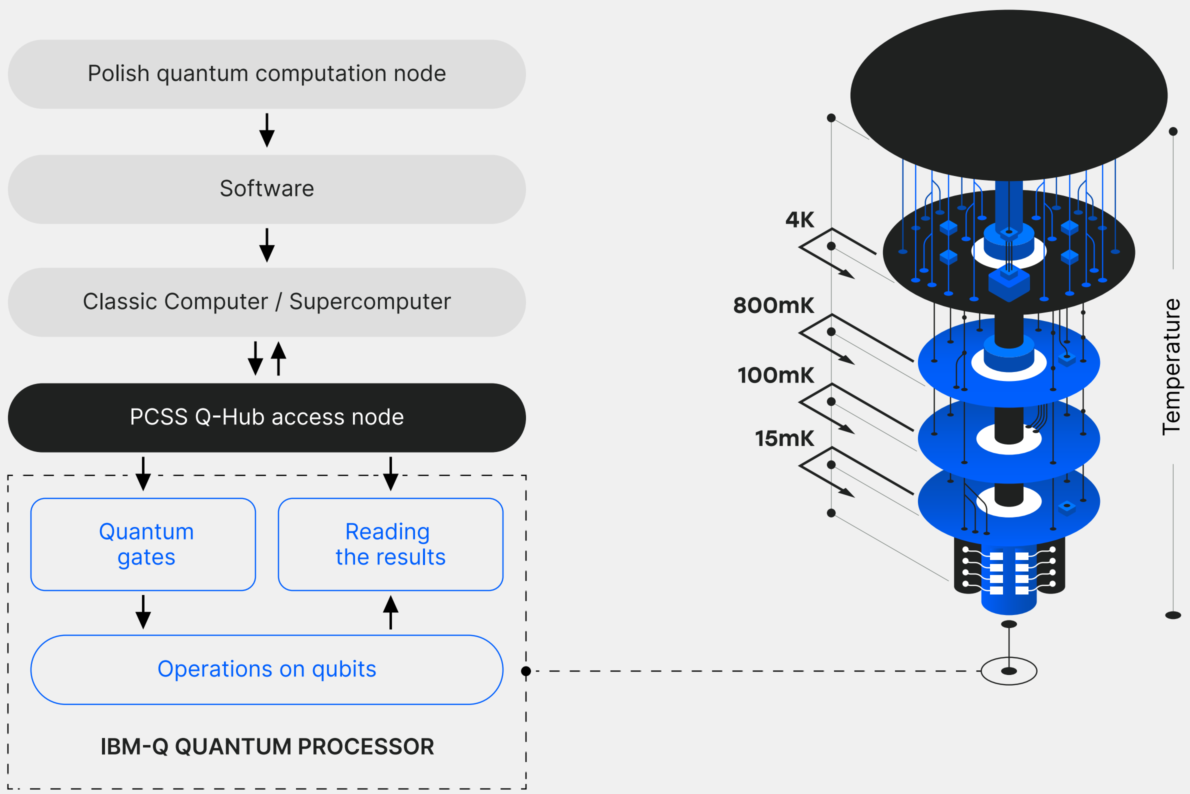


IBM Quantum Network

The IBM Quantum Network aims to optimally harness the potential of quantum computers and apply them to solve experimental problems. National institutions affiliated with this network have access to the most advanced and cutting-edge IBM Q quantum systems. This ecosystem has been systematically developed by IBM for many years. Users from Poland have access to the 127-qubit IBM Eagle quantum computer. In November 2022, IBM introduced the IBM Q quantum computer with an Osprey-class processor, offering 433 qubits. This is another step towards creating a programmable quantum computer with over 1000 qubits.

As part of the Polish quantum computing node initiative, access to the IBM Q Network of physical quantum computers has been launched.

https://quantum.psnc.pl



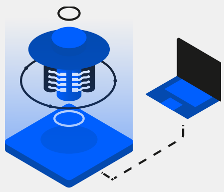
Milestones in 2022

2021.12.01

Commencement of preparatory work.

2022.02.04

Signing of the IBM Q System Hub Access and Software/ Technology License Agreement.



2022.02.28

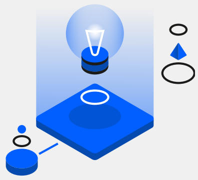
Quantum platform and quantum node (QuantumHub PL) with remote, shared access to IBM quantum computer resources.

2022.04.30

Results of initial user experiments.

2022.06.30

Expansion of programming libraries and digital tools for quantum computing.



2022.11.30

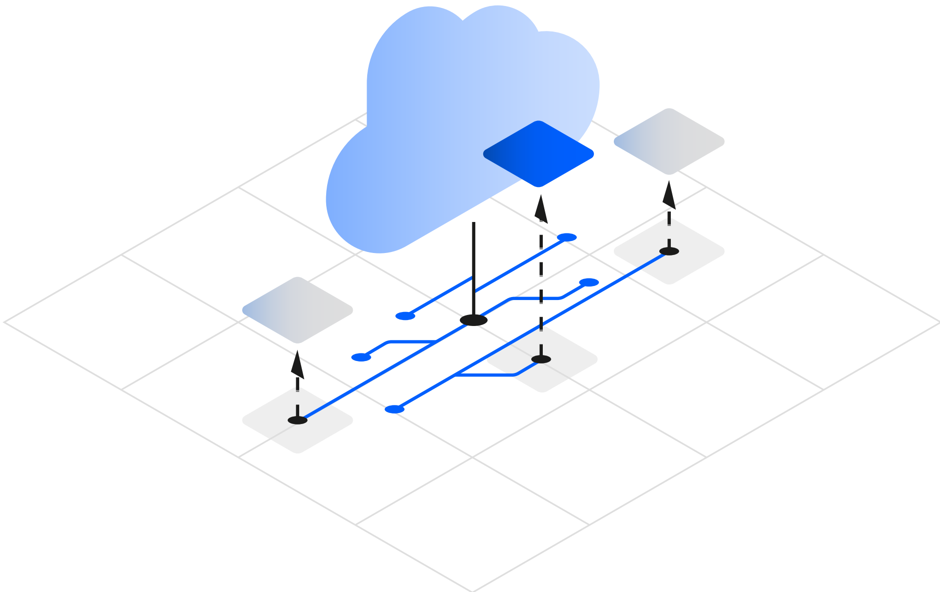
Annual report and summary of the first phase of activity for the Polish quantum computing node.

IBM Quantum Innovation Center in Poland

The Ministry of Digitalization, based on Decision No. DRI.ZPI.7220.10.2021 dated December 30, 2021, by the Prime Minister, entrusted the Poznań Supercomputing and Networking Center of the Polish Academy of Sciences with the implementation of the project "Support for entities implementing public tasks in the field of digital innovations for science and the information society, by providing access to e-infrastructure using quantum computing, including access to the IBM Q-HUB node." As a result of the project's implementation, the first Quantum Computing Node in Central Europe - the Polish Quantum Computing Node, was established at the Poznań Supercomputing and Networking Center as part of the global IBM Quantum Network.

Quantum Innovation Centers and Quantum Computing Nodes within the IBM Quantum Network worldwide form a high-class global community that brings together Fortune 500 companies, startups, academic institutions, and research laboratories working on the development of quantum computing and exploring practical areas of its applications. Members of the IBM Quantum Network, along with IBM Quantum teams, collaborate to research, test, and analyze how quantum computing can impact the development of the information society, science, and the economy.

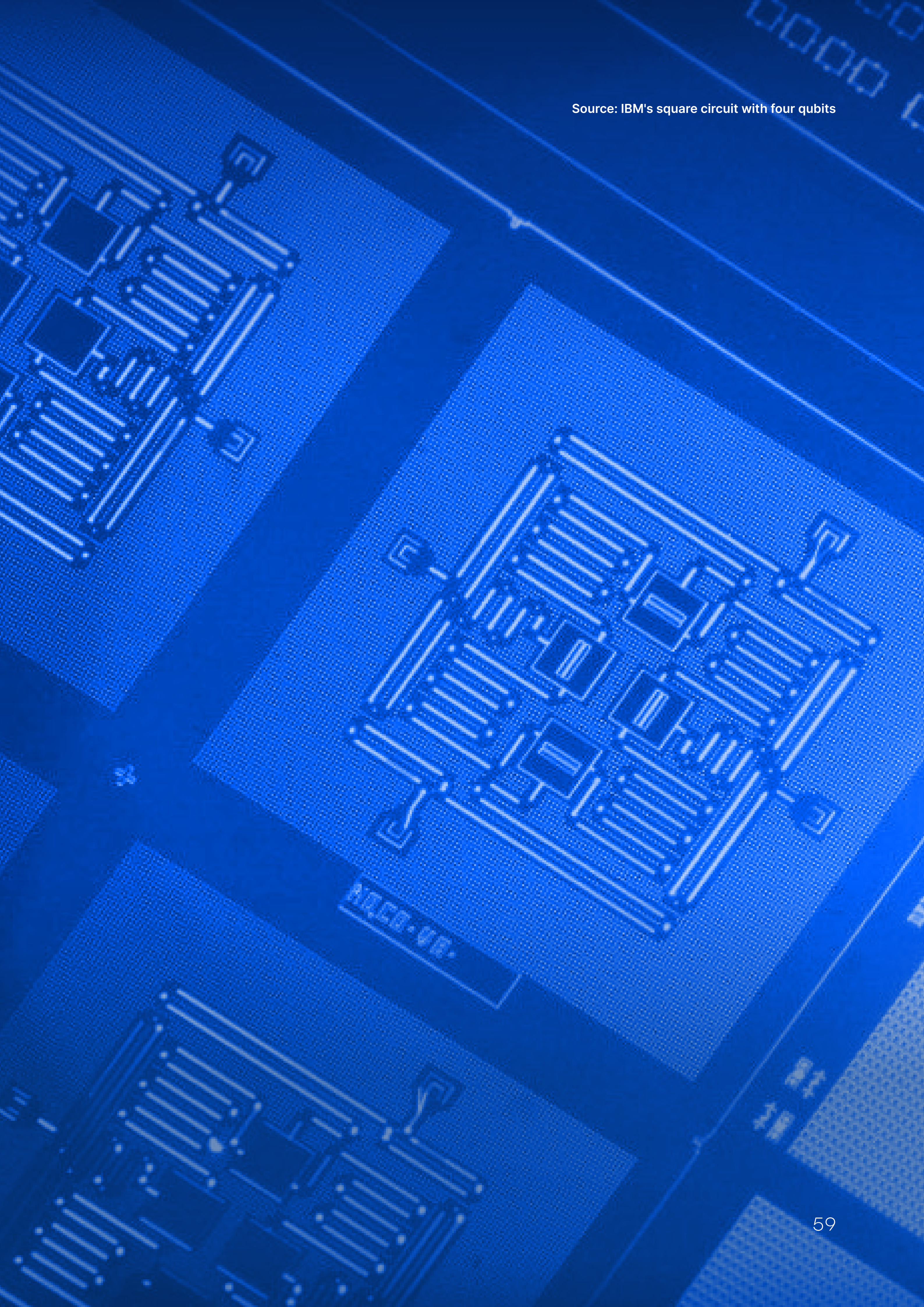
The Polish Quantum Computing Node provides support and remote access to various IBM Quantum computer architectures for national scientific users. The summary of experimental quantum computing by users is detailed in Chapter 3.



Thanks to extensive supercomputing resources, the center also provides classical supercomputing resources that allow users to run simulations of quantum computers but for a relatively small and limited number of qubits. The Coordinator of the Polish Quantum Computing Node, the Poznań Supercomputing and Networking Center of ICHB PAN, has a highly qualified team of experts with many years of experience in developing, building, and implementing infrastructural and service solutions for high-performance computing for science and the information society. With over two decades of experience in R&D projects in the field of information and communication technologies, including high-performance computational sciences (HPC technologies) using the potential of supercomputers, the center also has the necessary organizational and technical support for the development of the new generation of hybrid quantum algorithms that simultaneously leverage the computing power of classical and quantum computers.

Providing access and appropriate support to multiple expert teams and users in Poland through the Polish Quantum Computing Node at the current stage enables the initiation of the design and testing of various quantum algorithms. It also allows the commencement of software development that utilizes the new paradigm of quantum computing.

The mission of the Polish Quantum Computing Node is also to develop and disseminate knowledge about the current state of quantum computers among its partners, including research centers, universities, and, in the near future, companies interested in utilizing quantum technologies in various breakthrough applications. Enhancing the skills of users interested in quantum technologies, including conducting workshops, conferences, training sessions, and courses, is another important area of activity for the Polish Quantum Computing Node.


Source: IBM's square circuit with four qubits

Available gate-based quantum computers

As part of the Polish Quantum Computing Node, users have access to various programmable gate-based quantum computers from IBM. Since the initiative's launch, there are currently nine different quantum computers available within a few months, including a **127-qubit processor in the IBM Eagle** system in IBM Washington and 27-qubit systems in the Falcon architecture, including 3 systems with the highest Quantum Volume index of 128: IBM Kolkata, IBM Montreal, and IBM Mumbai. In the coming weeks, users of the Polish Quantum Computing Node are expected to have access to the largest **433-qubit processor, IBM Osprey**, whose hardware and software details were published in early November 2022 [5].

ibm_washington Exploratory
System status: Online
Processor type: Eagle r1
Qubits: 127 | QV: 64 | CLOPS: 850

ibmq_kolkata
System status: Online
Processor type: Falcon r5.11
Qubits: 27 | QV: 128 | CLOPS: 2K

ibmq_montreal
System status: Online
Processor type: Falcon r4
Qubits: 27 | QV: 128 | CLOPS: 2K

ibmq_mumbai
System status: Online
Processor type: Falcon r5.10
Qubits: 27 | QV: 128 | CLOPS: 1.8K

ibm_cairo
System status: Online
Processor type: Falcon r5.11
Qubits: 27 | QV: 64 | CLOPS: 2.4K

ibm_auckland Exploratory
System status: Online
Processor type: Falcon r5.11
Qubits: 27 | QV: 64 | CLOPS: 2.4K

ibm_hanoi
System status: Online - Queue paused maintenance
Processor type: Falcon r5.11
Qubits: 27 | QV: 64 | CLOPS: 2.3K

ibm_geneva Exploratory
System status: Online - Queue paused maintenance
Processor type: Falcon r8
Qubits: 27 | QV: 32 | CLOPS: 1.9K

ibmq_toronto
System status: Online
Processor type: Falcon r4
Qubits: 27 | QV: 32 | CLOPS: 1.8K

```
from qiskit import IBMQ

IBMQ.load_account()

provider = IBMQ.get_provider('ibm-q-psnc','internal','default')

backend = provider.get_backend('ibm_washington')
```

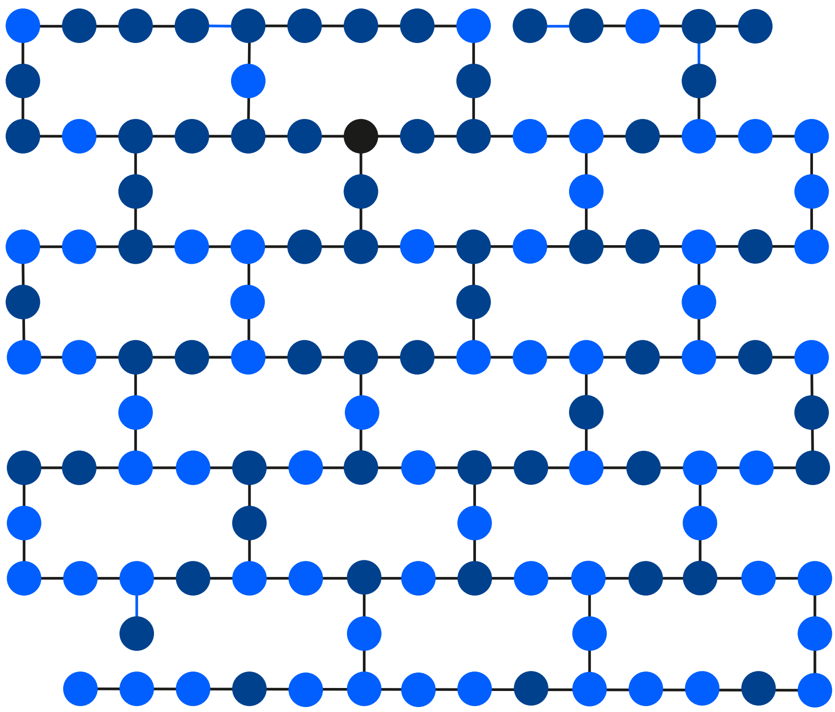


Figure 1. The connectivity topology between the qubits of the 127-qubit IBM Eagle processor in the IBM Q quantum computer.

The connectivity topology of qubits in the Eagle and Falcon processor architectures is based on a heavy-hexagonal structure, where not all qubits are directly connected to each other. This method of connections requires logical circuit transpilation but significantly reduces noise on quantum gates and allows for more accurate readings.

Full support for users.

Since the establishment of the Polish Quantum Computing Node, users have been provided with technical and substantive support for conducting experiments on the remote infrastructure of IBM Quantum computers. The national support team, along with IBM teams creating **open-source software tools** like **Qiskit**, can effectively assist users in designing, implementing, and test-running quantum algorithms. Full user support is also offered during computational experiments on various IBM Quantum computers, along with necessary assistance in result verification and analysis.

Within the Polish Quantum Computing Node, there are also various administrative tools available for monitoring the utilization of quantum computer resources by users. This includes monitoring the number of circuit executions on IBM Quantum computers, average wait times for computational tasks, and the utilization time of IBM Quantum computers.

Users within the Polish Quantum Computing Node also have the opportunity to reserve exclusive access to IBM Quantum computers such as IBM Kolkata and IBM Toronto. Such resource reservations allow users to conduct more advanced and resource-intensive quantum computing experiments without waiting in the queue for quantum computer tasks. Additionally, users have continuous access to quantum computer simulators running on classical supercomputer architecture, enabling them to verify their experiment results using both ideal and noisy quantum computation simulations.

In the first few months of the Polish Quantum Computing Node's operation, over 1.6 billion quantum circuits were executed on various IBM Quantum computers.

Sample statistics of IBM Quantum resource utilization by Polish users from February to November 2022

Name
ibm-q-psnc

Poznan Supercomputer and Networking Center

Total executions
2,149,386,591

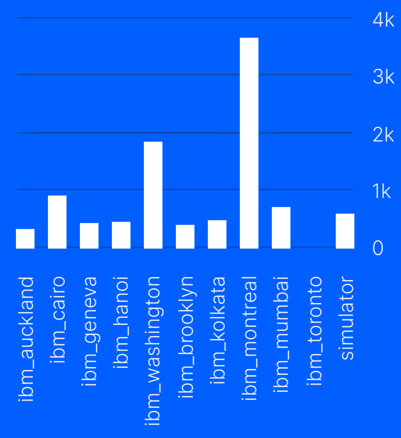
Total number of circuit executions on IBM Quantum computers by users

System time
8d 14h 24m 43.3s

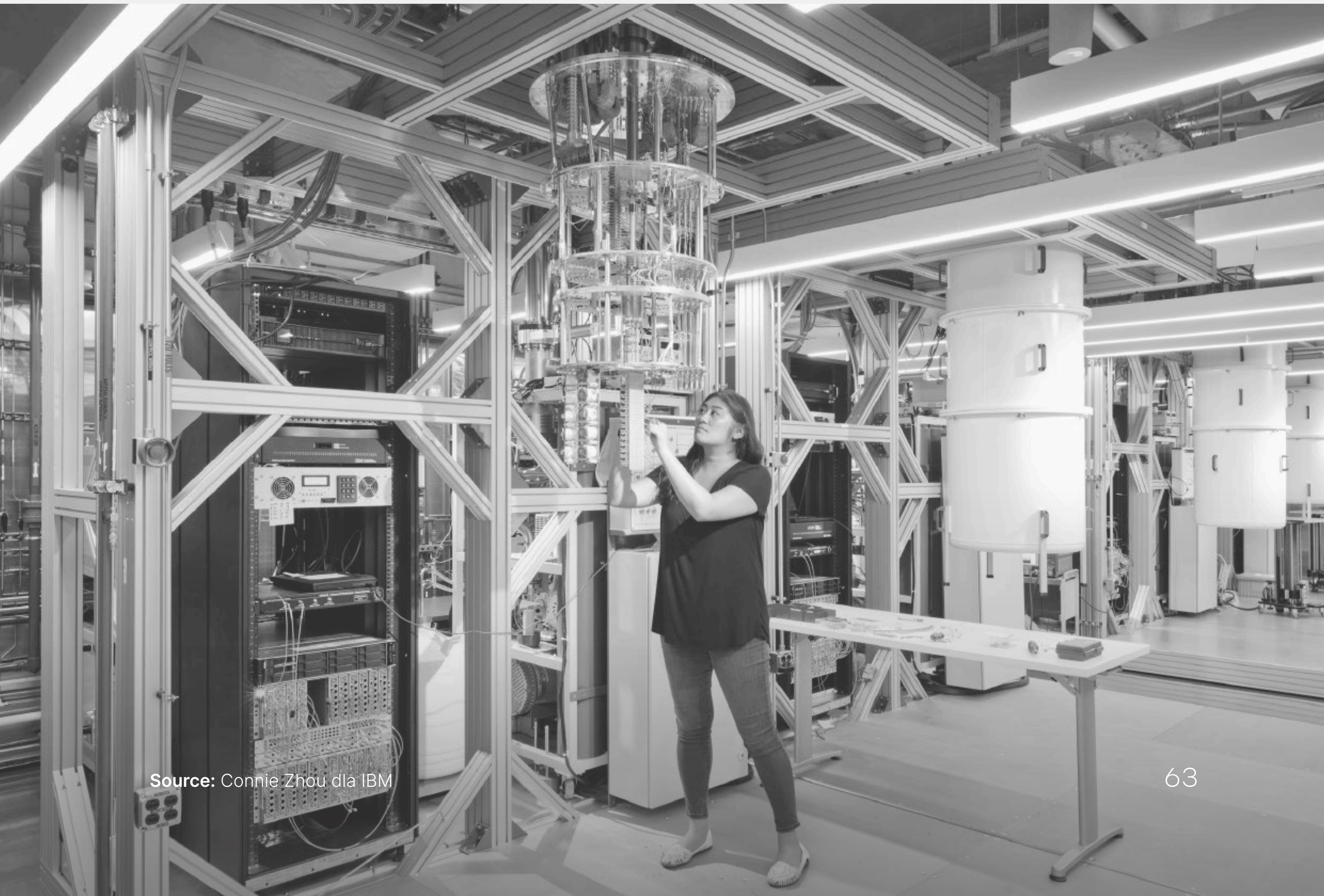
Total completed jobs
17,087

Average queue wait
4h 7m 54s

Total usage time of IBM Quantum computer resources, number of completed tasks, and average waiting time

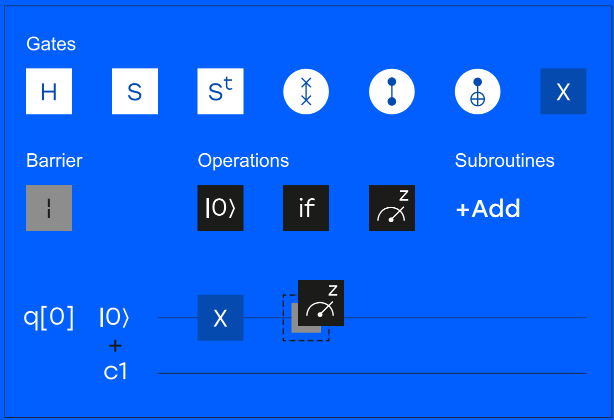


Distribution of usage across different generations of IBM Quantum computers



Source: Connie Zhou dla IBM

Drag-and-drop programming



High-level programming in Python and Jupyter Notebook

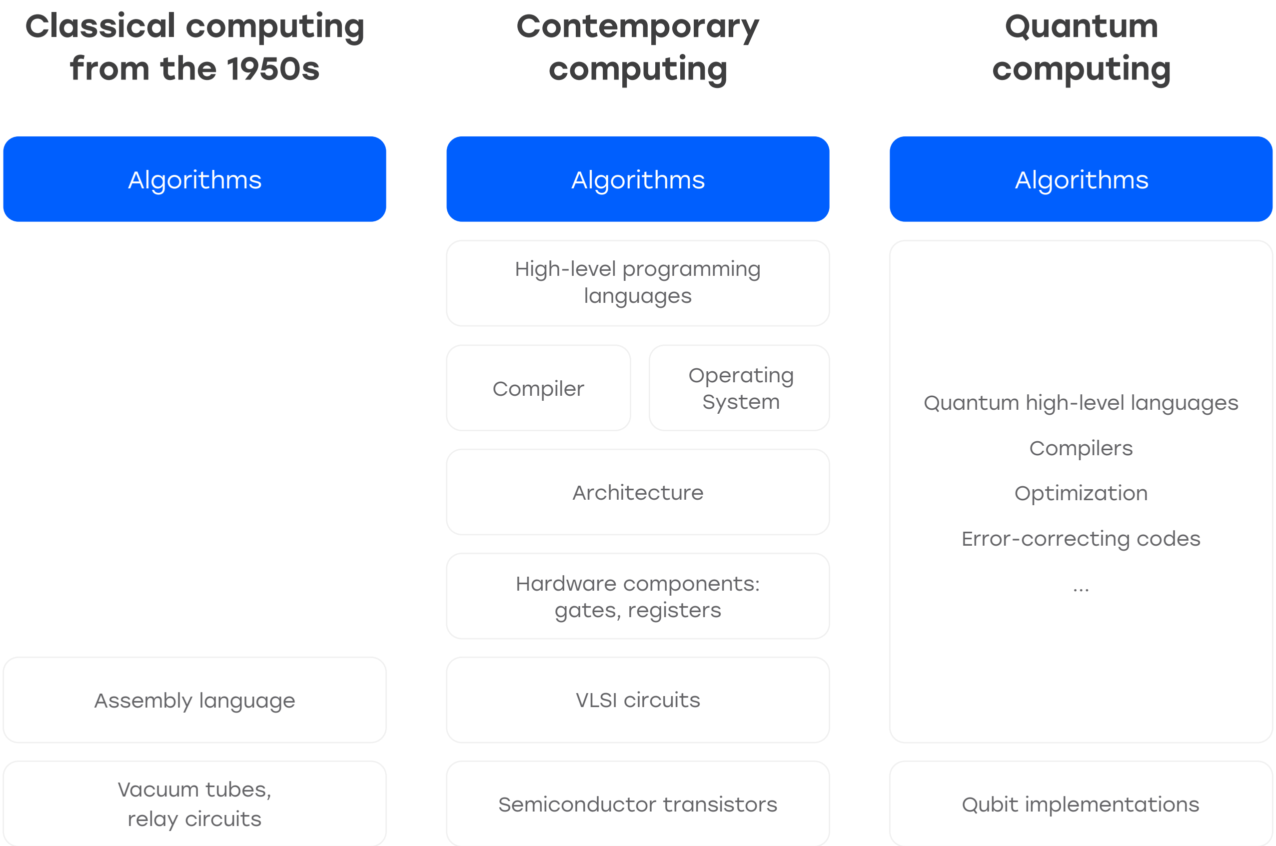
```
qc = QuantumCircuit( 2, 2)

gc.h(0)
qc.cx(0, 1)
qc.measure([0, 1], [0, 1])

backend = Aer.get_backend(’ qasm_simulator ’)
job_sim = execute(qc, backend)
sim_result = job_sim.result()

sim_result.get_counts(qc)
```

Quantum computing programming

From a technical and software development process perspective, a user interested in quantum computing must initially focus on designing circuits using basic quantum gates. This process resembles the well-known approach in electronics programming, where circuits are designed by connecting logic gates to create increasingly sophisticated digital systems. Currently, there are many different tools and programming libraries available to support the user in software development. The most advanced and, at the same time, very intuitive and user-friendly tool is the graphical user interface provided in conjunction with direct access to various IBM Quantum computer resources. The graphical user interface also supports a "drag-and-drop" mode, allowing even less experienced users to quickly construct any quantum circuit and see how individual quantum gates affect the entire process of changing qubit states during quantum computations.

In general, the code for a quantum algorithm can be written by the user in a high-level programming language like Python, which, in the form of a script or a popular interactive environment like Jupyter Notebook, can be run from the user's web browser.

Available tools allow for the use of a high-level programming language to program quantum computers, but strict control over the executed quantum circuits is still necessary. This is primarily due to the noise and errors that we encounter in the case of available quantum computers in the NISQ era. In order to achieve better quantum computation results, users should still check the detailed characteristics of the qubits available in a particular quantum computer before running each circuit. This should include considering the technical parameters of the qubits and the way they are interconnected. Currently, hardware and software solutions are being developed to make it easier for quantum computer users to select the appropriate quantum computer and map a given problem onto the quantum device's topology. This is an example of another programmable abstraction layer in the quantum computer software stack, which will allow users and programmers to focus on designing quantum algorithms and exploring their applications.



Perspectives within the quantum hub

01.

Increasing the efficiency of quantum computations and acquiring new users and institutions

02.

Practical support for competence development and education

03.

Computational experiments with complex quantum algorithms in various applications

The first year of operation of the Polish Quantum Computing Node was dedicated to developing test experiments and supporting the first users. For this purpose, a portal was launched, providing access to the quantum platform and quantum node with remote, shared access to various IBM Quantum computer resources, supporting the processes of designing, running, and monitoring quantum computations. Additionally, a virtual research-experimental and educational environment was developed and implemented for users interested in developing their skills in quantum technologies, using classical supercomputer resources to facilitate testing and the development of basic quantum algorithms. In collaboration with users, additional tools were also created for performing advanced quantum computations using QAOA [13] and VQE [16] methods, which are specialized algorithms for solving combinatorial problems and simulating physical systems.

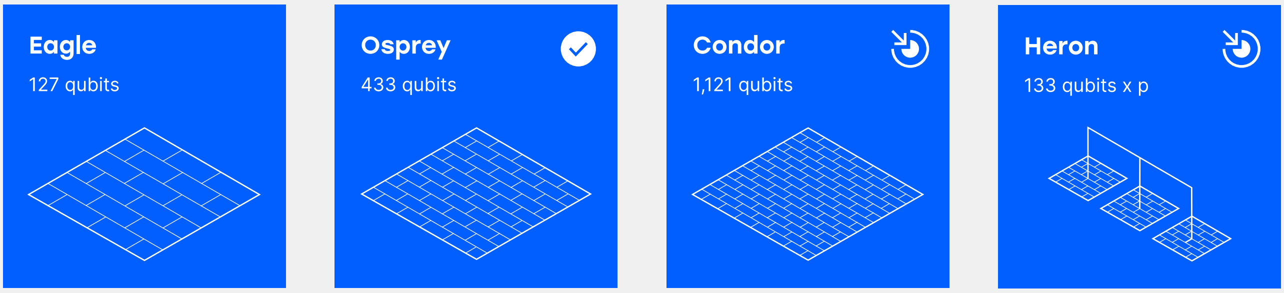
An important activity of the Polish Quantum Computing Node was the development of educational materials and training for researchers, students, and users of High-Performance Computing Centers. Support was provided during the international Workshop on Quantum Computing and Communication as part of the PPAM 2022 14th International Conference on Parallel Processing and Applied Mathematics. A series of seminars and meetings with users were also held, focusing on quantum computing topics and the limitations and possibilities of currently available quantum computers.

The path to quantum development

The stage we are currently in is just the beginning of quantum computing development. The dynamic pace of quantum computer development gives hope that their practical applications will be possible in the coming years. The development plan for quantum technology presented by IBM envisions a gradual increase in the quality and quantity of qubits produced in superconducting qubit technology, reaching several thousand by 2025. This is followed by providing quantum computers with lower levels of errors and noise, consisting of thousands, or even millions, of qubits. Development plans for quantum computers in the following years, based on other quantum technologies such as ion traps, photonic qubits, or neutral atoms, are also promising. IBM's defined metric for quantum computer performance - Quantum Volume, which takes into account the number of qubits in quantum processors as well as their quality and accuracy, allows for defining a new relationship for the growth of quantum computer capabilities over time [6]. It's worth noting that the performance of quantum

To further improve performance and maintain the pace of quantum computing scaling, it seems that in 2023, it will be necessary to connect quantum processors into larger processors using quantum communication links. This will enable the use of a significantly larger number of qubits but will require parallelization of quantum computations.

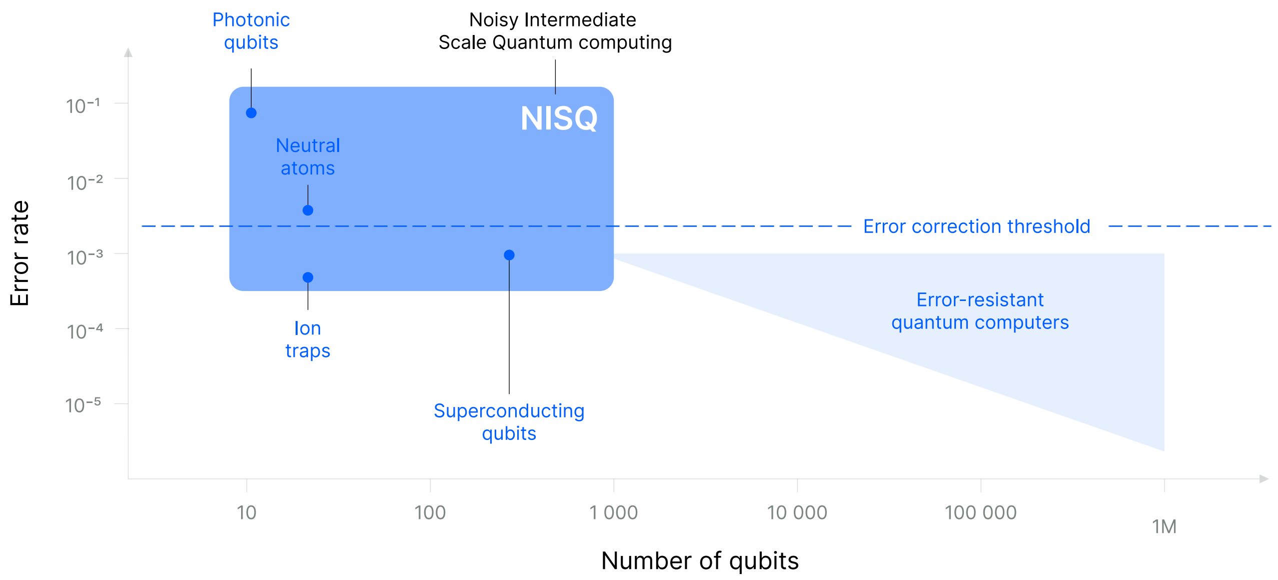
2021 | **2022** | **2023**



Eagle: Launch programs 100x faster with Qiskit Runtime

Osprey: Greater computational capabilities using dynamic quantum circuits

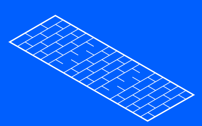
Condor: Expanding the application capabilities with flexible calculations and parallelization of the Qiskit Runtime service



computers, measured by the Quantum Volume parameter, doubles in less than a year. Thus, the end of the era dominated by Moore's Law marks the beginning of the NISQ era and the next stages of development of classical-quantum technologies used for computation and simulation. Over the course of a few months of operation of the Polish Quantum Computing Hub, significant improvements in quality and increased capabilities for serving more users have been achieved. The introduction of new abstract objects like Qiskit Primitives enables more efficient execution of quantum algorithms. In 2022, significant improvements in quality and increased capabilities for serving a larger number of national users were achieved.

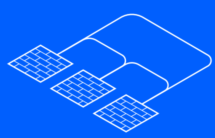
2024

Crossbill
408 qubits



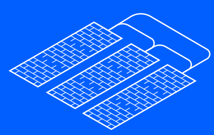
Improve Qiskit Runtime accuracy with scaled error mitigation

Flamingo
1,386+ qubits



2025

Kookaburra
4,158+ qubits



Scaling applications with quantum circuit interleaving

After 2026

Scaling within 10k-100k qubits using classical and quantum communication

Increasing the accuracy and speed of quantum calculations thanks to the implementation of error correction

Key competencies and topics

It is important to support the academic environment at various levels of education and research in science and the economy. To this end, additional support tools and educational content have been developed for domestic users in line with the framework for "Quantum Computer Programming" qualifications in the Integrated Qualifications System, covering topics such as:

- **LINEAR ALGEBRA BASICS**
  - Performs basic calculations on vectors and matrices
  - Performs calculations with complex numbers
  - Performs calculations using Dirac notation
- **BASIC THEORETICAL PRINCIPLES OF QUANTUM COMPUTING**
  - Applies basic knowledge of quantum mechanics
  - Discusses concepts in quantum computing
- **UTILIZATION OF REAL QUANTUM COMPUTERS AND SIMULATORS**
  - Utilizes a graphical interface for constructing quantum algorithms
  - Uses quantum computers with Qiskit software tools
  - Applies selected types of simulators
  - Discusses the parameters of quantum computers and minimizes the impact of errors on calculations
  - Optimizes quantum programs, taking into account the architecture of real quantum processors
- **UTILIZATION OF EXISTING ALGORITHMS WITH RESPECT TO THEIR COMPUTATIONAL COMPLEXITY**
  - Characterizes the elements of the theory of computational complexity
  - Uses quantum algorithms
  - Limitations and capabilities of QPU, noise, interference, errors and error correction Integration of hybrid supercomputing systems and quantum gas pedals kwantowych

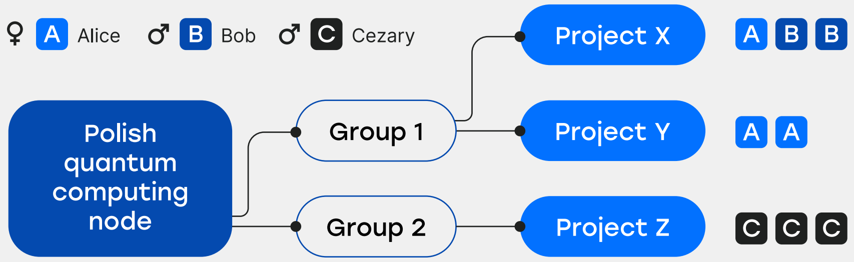
Source: Scientist Antonio Córcoles from IBM Quantum Compose

Administration and Quantum Computing Management

The core of the dynamic administration and management structure for quantum computing is the Poznań Supercomputing and Networking Center at ICHB PAN, which delegates the necessary permissions to Polish scientific institutions and their users for access to the quantum computer.

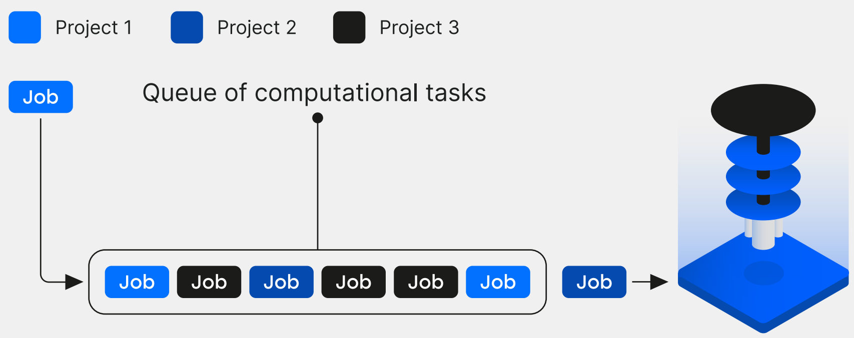
Quantum computing tasks

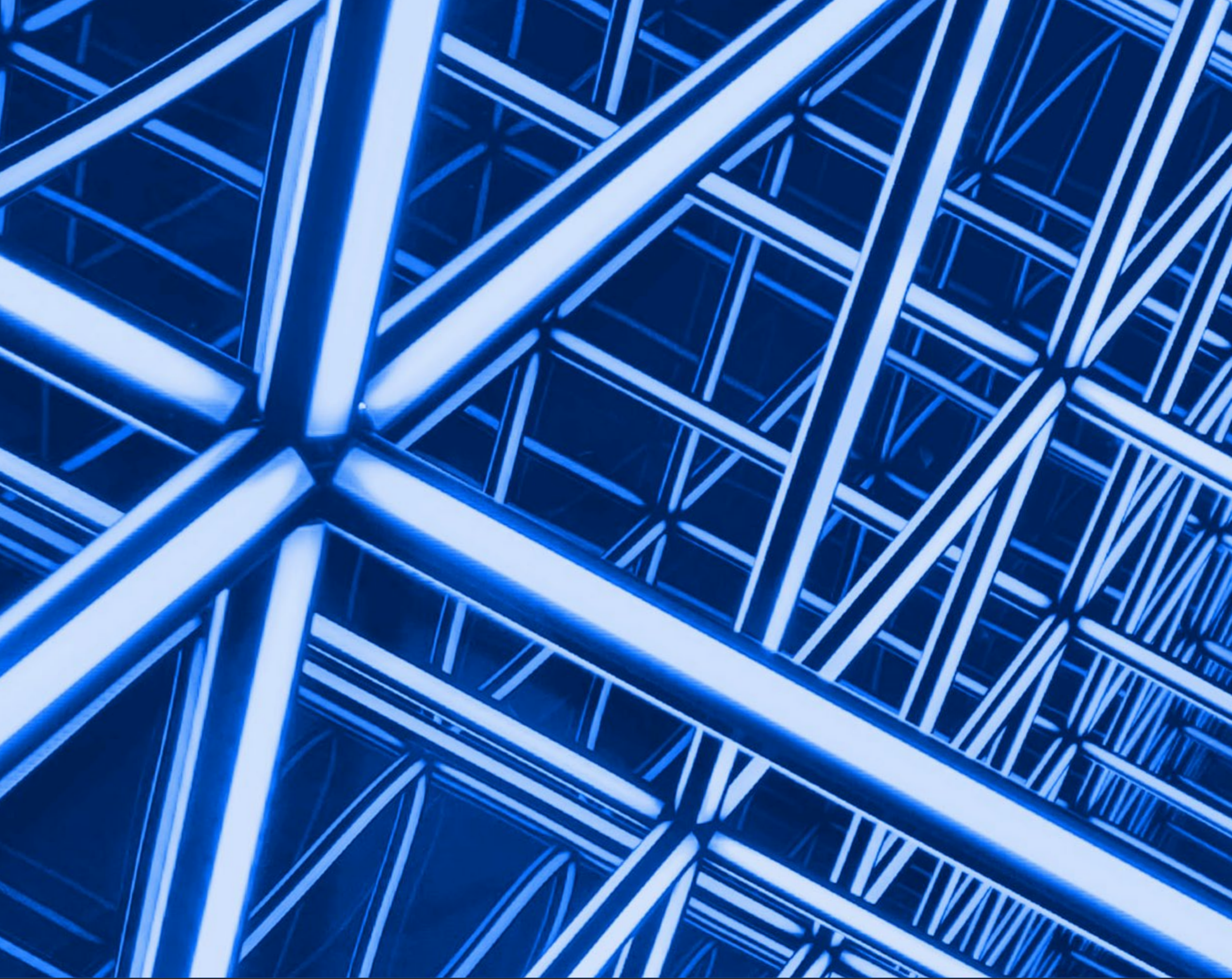
The Polish quantum computing node is associated with groups and projects. Users working within a project can submit computational tasks using the allocation assigned to a specific combination of group and project.



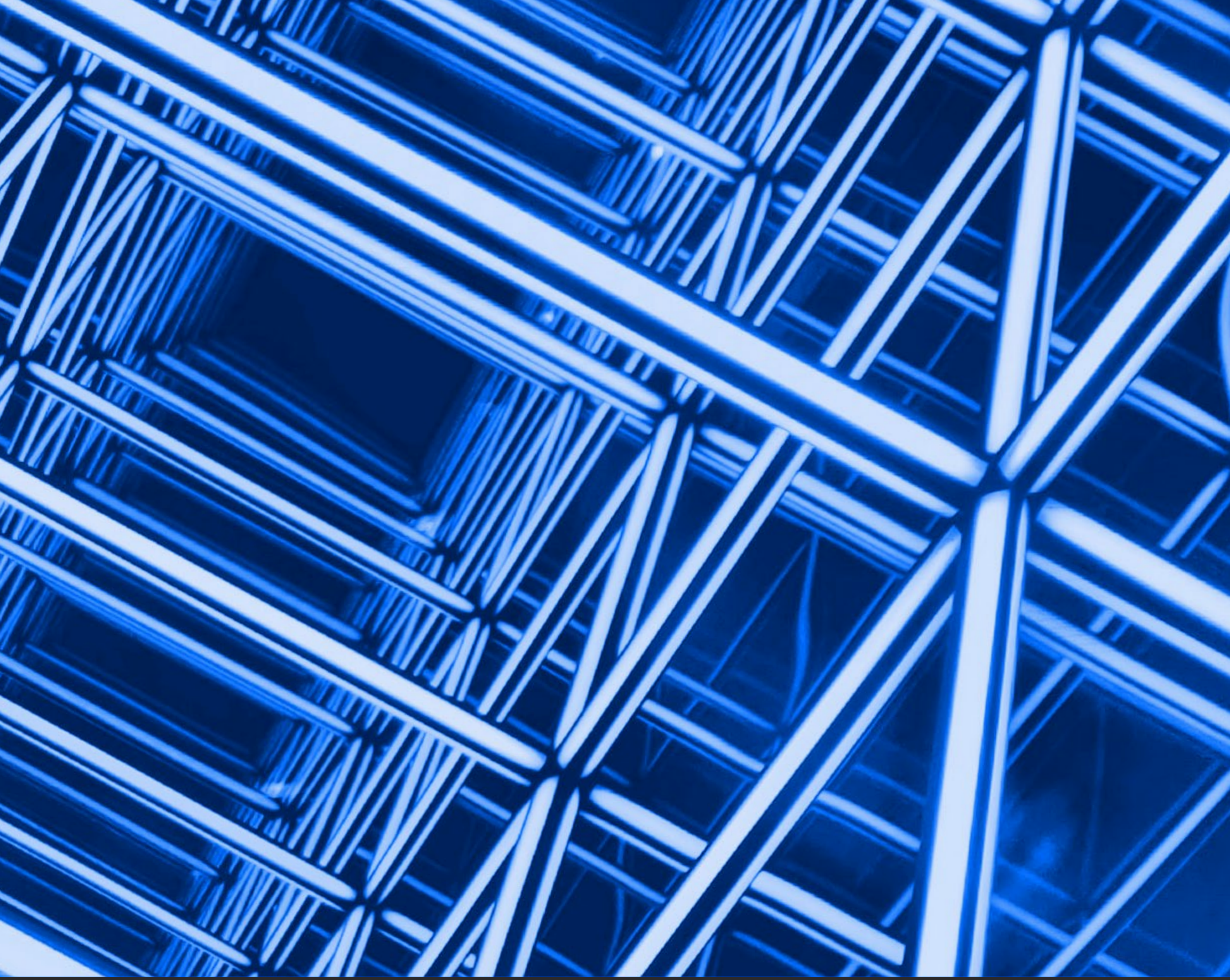
Queueing system

The handling and scheduling of tasks to be executed on the quantum computer are based on a dynamic queueing system that ensures a fair allocation of resources among different groups, projects, and their users.





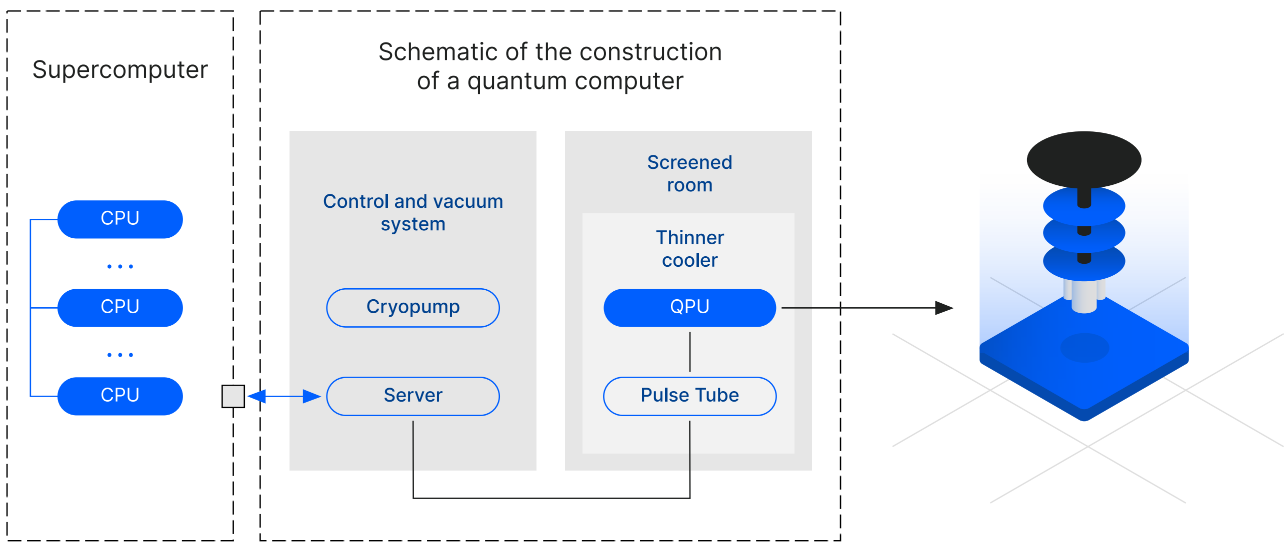
Applications



CHAPTER

03

Source: IBM Quantum Osprey Processor



The Polish Quantum Computing Node not only facilitates access to IBM Quantum computers but also actively collaborates with experts and scientists from various research centers and companies. Its main task is to support various activities related to the use of quantum computing to solve challenging problems in various fields of science and industry. Quantum computational methods are being studied both from a theoretical perspective and in the context of their practical implementation on available resources. A lot of attention is also given to methods aimed at solving the problems of quantum computers themselves, thereby bringing closer the moment when achieving quantum advantage becomes possible. In the following sections, areas of applications that were analyzed in the initial period of operation of the Polish Quantum Computing Node in collaboration with numerous partners and experimental users will be summarized.

Experimental quantum computations of national users

To prepare for the upcoming second quantum revolution and identify potential areas of quantum computer applications, a strategic vision for building a quantum ecosystem in Poland is needed. This vision should be based on close and cyclical interactions between four key components:

- Research and development in the field of quantum computing capabilities and limitations used to build quantum algorithms, applications, and services leveraging hybrid classical-quantum computational power.
- Qualification frameworks and key competencies in quantum technologies at the higher education, doctoral, and postgraduate levels.
- Active collaboration with representatives from various industries and economic sectors, including innovative Polish entities and startups.
- Ensuring infrastructure access to quantum computers and computing based on various quantum technologies.

Polish Quantum Computing Hub in 2022 undertook a series of actions in line with the strategic goals mentioned above. First and foremost, it secured and ensured users' access to quantum computers. Establishing closer and direct collaboration with users was also a crucial task. Exchange of experiences with numerous national research centers was key. Therefore, the initial efforts of many Polish expert teams in modeling, characterizing, and building quantum algorithms based on experiments using the most advanced IBM Q programmable quantum computers were supported.

Although the available quantum computers still lack the ability to solve many challenging and complex problems in practical applications, it's essential to emphasize that this is not a reason to refrain from supporting various activities that verify the efficiency and advancement of quantum algorithms, both from a theoretical [8] and an applied [9] perspective.

In the period from February to November 2022, as part of the Polish Quantum Computing Hub, efforts were made to identify Polish expert teams interested in accessing and supporting the development of quantum computing using real quantum computer infrastructure. Based on these activities, several areas were identified that, along with the development of quantum computers, could find practical applications in various fields of science and the economy, including:

Mitigation and error correction in quantum computers
Physics, Center for Theoretical Physics, PAN

Quantum algorithms in combinatorial optimization and their applications in scheduling problems
Computer Science, Poznań University of Technology

Quantum machine learning algorithms
Physics, Adam Mickiewicz University

Study of the chemical properties of hydrogen and helium
Quantum Chemistry, Adam Mickiewicz University

Methods for evaluating the performance of quantum computers
Computer Science, Institute of Theoretical and Applied Informatics, PAN

Quantum algorithms in positron emission tomography
Nuclear Physics, National Centre for Nuclear Research

Quantum algorithms in bioimage analysis
Bioinformatics and Medicine, Institute of Bioorganic Chemistry, PAN

Quantum algorithms in logistics and warehousing problems
Logistics, Łukasiewicz Research Network - PIT

Furthermore, scientific units functioning as High-Performance Computing Centers interested in joining and supporting users within the Polish Quantum Computing Hub were identified:

- **AKADEMIA GÓRNICZO-HUTNICZA**
  Cyfronet
- **POLITECHNIKA GDAŃSKA**
  CI TASK
- **POLITECHNIKA WROCŁAWSKA**
  WCSS
- **UNIWERSYTET WARSZAWSKI**
  ICM

As part of additional activities promoting quantum technologies, including the potential of quantum computing and computers, other scientific research units and companies interested in closer collaboration with the Polish Quantum Computing Hub in the following areas have also been identified:

AVIATION AND TRANSPORT:

Quantum algorithms for logistics, transportation, and airspace management problems

BANKING AND FINANCE:

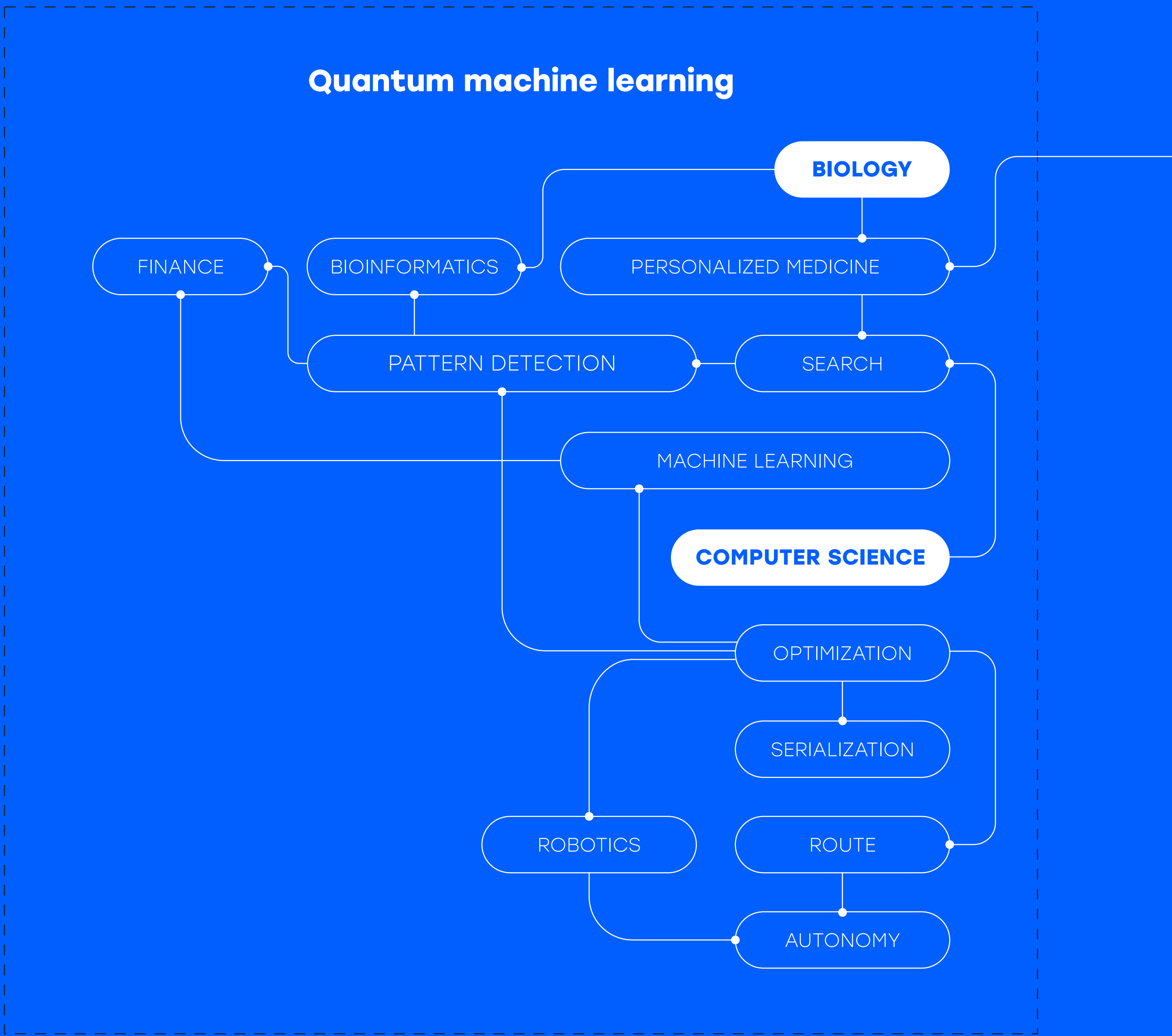
Quantum option pricing, enhancing financial models, and utilizing quantum financial mathematics

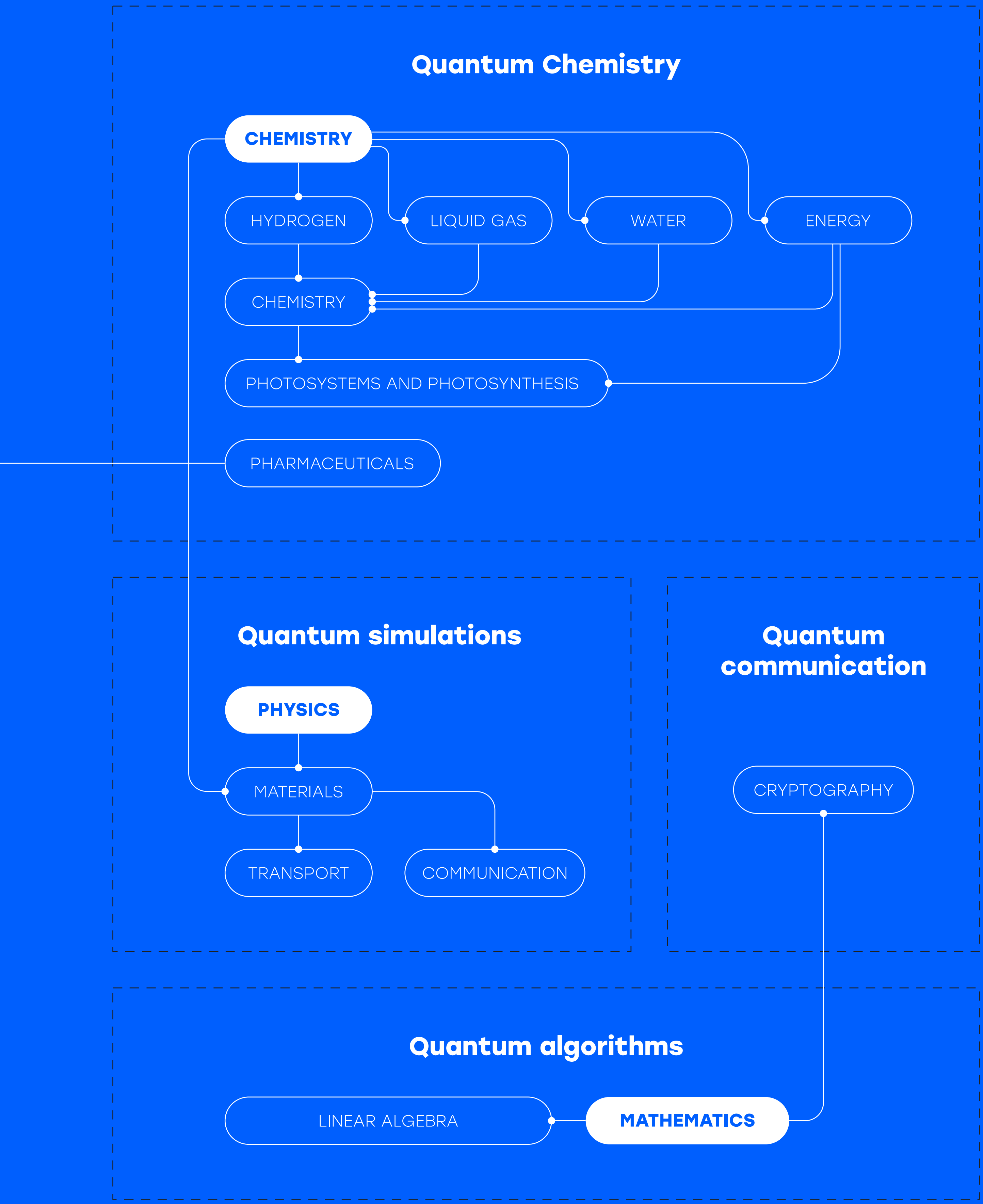
DEFENSE AND SPACE SECTOR:

Verification of the accuracy and quality of quantum algorithms

Source: IBM Quantum Lab

Applications of quantum computing



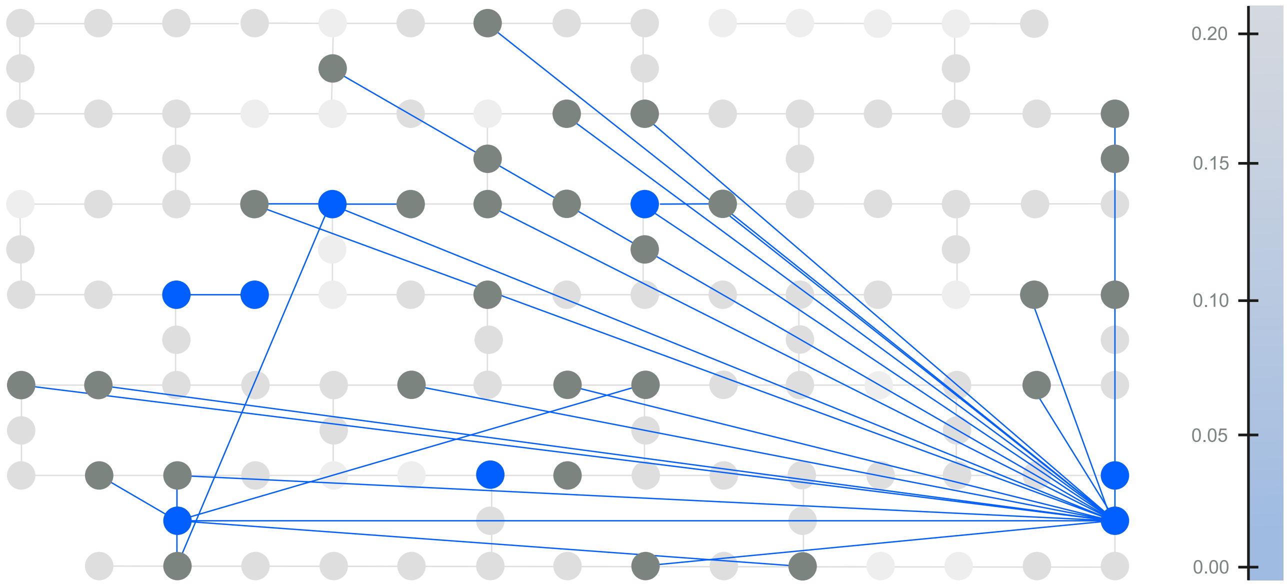

Quantum Chemistry
CHEMISTRY
HYDROGEN
LIQUID GAS
WATER
ENERGY
CHEMISTRY
PHOTOSYSTEMS AND PHOTOSYNTHESIS
PHARMACEUTICALS
Quantum simulations
PHYSICS
MATERIALS
TRANSPORT
COMMUNICATION
Quantum communication
CRYPTOGRAPHY
Quantum algorithms
LINEAR ALGEBRA
MATHEMATICS

Limiting and correcting errors in NISQ quantum computers

As we have already mentioned in previous parts of the report, calculations performed on currently available IBM Quantum computers in the ongoing NISQ era are susceptible to errors. This is because the current technology required for quantum error correction has not yet been developed. Errors in quantum computers come from several sources. Some are caused by imperfections in the implementation of quantum gates, which are the basic building blocks of quantum systems (similar to logic gates in classical digital circuits). Another source of errors is the measurement of the final quantum state of the device. Measurements are an integral part of quantum information processing, as every quantum algorithm ends with a measurement. Measurements are also an important intermediate step in quantum error correction procedures.

Preliminary research on some NISQ quantum computers has shown that the magnitude of errors in reading a single qubit is on the order of two qubit gates. This means that readout errors are quite significant and cannot be ignored. Furthermore, the characterization of measurement errors can be used in error mitigation methods to improve the quality of results.

So far, most analyses have not taken into account the possibility of correlated readout errors (sometimes referred to as cross-talk). Detecting and characterizing correlated measurement errors is a challenging task because the complexity of generic noise models describing correlations scales exponentially with the number of qubits. This means that characterizing correlated measurement errors in currently available devices, such as the 127-qubit IBM Washington computer available through the Polish Quantum Computing Node, cannot be accomplished using standard methods of quantum detector tomography.



The goal of the research conducted by the Center for Theoretical Physics of the Polish Academy of Sciences was to develop and test an efficient method for characterizing correlated readout errors. This method is an extension of standard quantum detector tomography, which allows for data acquisition in a parallel manner. Experimental results obtained by performing an appropriate set of quantum circuits enable the reconstruction of reduced (i.e., acting only on a subset of qubits) measurement operators that are executed on the quantum device. This allows for the verification of various aspects of measurement errors. Firstly, the structure of the reduced measurement operators allows for a quantitative characterization of the strength of correlations in measurement errors between qubits in the device. Interestingly, cross-talk has been found to occur even between qubits that are physically far apart on the device. Secondly, the developed techniques enabled the characterization of coherent errors. Preliminary results show that they occur in reduced measurement operators describing measurements on a sufficiently large number of qubits. Moreover, much of the current research is focused on stochastic models of measurement error noise, where the relationship between ideal measurement operators and operators implemented on the device is determined by a stochastic matrix. The method developed by the Center for Theoretical Physics of the Polish Academy of Sciences allows for the reconstruction of such a matrix for a class of local error models where correlations in measurement errors are limited to groups of qubits, known as clusters. Through experiments, it has been shown that error mitigation techniques using the characterization of measurement errors performed with the proposed method can significantly improve the estimation of the energy of many-body Hamiltonians. This is an important issue in quantum algorithms relevant for practical applications such as combinatorial optimization or quantum chemistry.

Combinatorial optimization

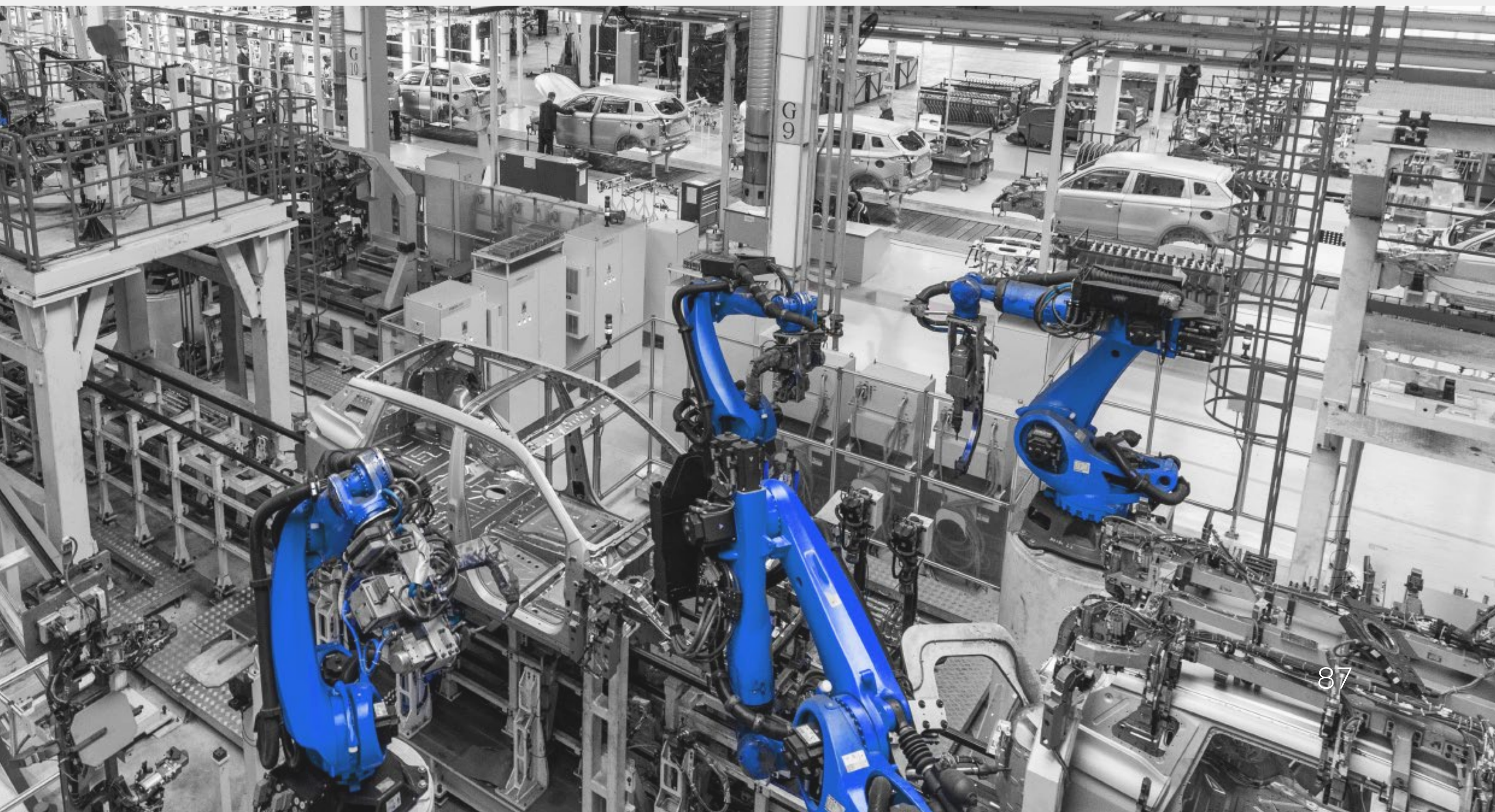
One of the main areas of quantum computing applications, as mentioned in the previous example, is computationally challenging combinatorial optimization problems. Combinatorial problems encompass many well-known problems in computer science, including the traveling salesman problem, the knapsack problem, the map coloring problem, various variants of task scheduling in production processes and computer systems, among others. Many of the classical algorithms developed to solve combinatorial problems have applications in solving appropriately modeled problems and processes in science and industry. Finding an optimal solution for these combinatorial problems is computationally difficult, to put it briefly, and for large instances of these problems, it is practically impossible to do so within a reasonable time frame using classical computers. In general, combinatorial problems can be divided into two classes: decision problems, where the solution involves finding a "yes" or "no" answer for a given instance of the problem, and search problems, where one seeks an optimal solution by evaluating it according to a defined objective function.

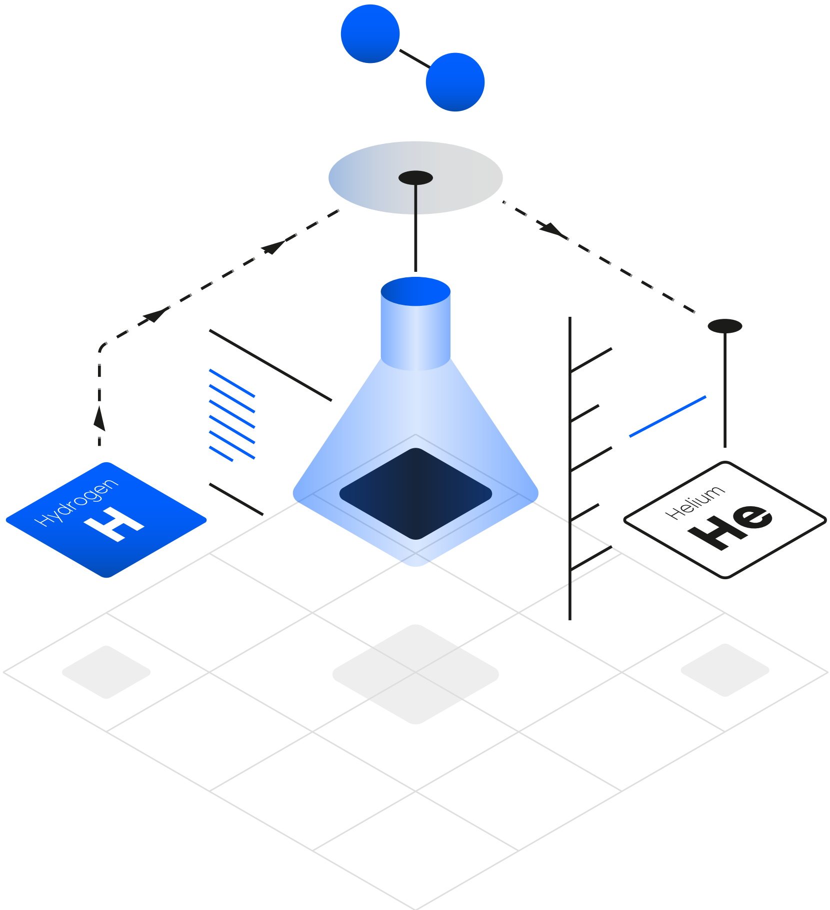
Practical problems that are of crucial importance to companies manufacturing complex products using both multifunctional and specialized machines and assembly lines are scheduling problems. Scheduling problems can be encountered in practically every production process consisting of at least several steps. Examples of applications include the production of precision electronics, manufacturing of parts and components, or material processing technological processes.

In practice, in many combinatorial optimization problems, the search is for solutions with the best value of the objective function among all feasible solutions. The number of feasible solutions depends strongly on the instance of the problem. Unfortunately, these are often problems where the scale of required classical computations grows much faster than the size of the problem instance. However, it turns out that classical combinatorial optimization problems can be transformed into forms in which the objective functions correspond to the energy levels of Hamiltonians, which are operators well-known to us from quantum mechanics.

Many of the mentioned combinatorial optimization problems can be naturally and classically modeled based on graph theory. Graph theory may seem to be a purely theoretical issue interesting only to mathematicians and theoretical computer scientists, but even here, we can find several potential applications of quantum computing. For example, the problem of finding the maximum clique in a graph, which is a subgraph where all vertices are mutually connected, often appears in economics, computer vision, chemistry, or biology. Both the maximum clique problem and the maximum cut problem (i.e., dividing the graph into two subgraphs so that the number of edges connecting different subgraphs is maximized) frequently occur during the design and production of integrated circuits. Solving such challenging problems can reduce production costs and improve their performance.

At the Poznań Supercomputing and Networking Center, ICHB PAN, performance experiments of IBM Q quantum computers have been conducted, including investigating the relationships between energy and the maximum execution time of all tasks in test instances of selected scheduling problems. Furthermore, in collaboration with the team from Poznań University of Technology, quantum algorithms for combinatorial optimization problems and classical scheduling problems have been developed and experimentally verified.





Quantum chemistry

Thanks to advanced computational methods implemented on supercomputers, it has become possible to study complex chemical systems outside the laboratory, usually in a cheaper and faster way. Achievements and progress in this field have enabled simulations that predict how real chemical molecules will behave under specific conditions. Computational chemistry is widely used in the process of designing new drugs and materials. Some of the properties that can be obtained from classical numerical modeling include molecular structure, intermolecular interaction energies, and the total energy of a molecule. Simulating molecules is based on the principles of quantum mechanics. However, precise results can only be obtained for the simplest systems, as modeling larger molecules would require computational power that is currently unattainable, as Richard Feynman mentioned almost four decades ago.

Therefore, it is inevitable to use various simplifications leading to classical calculations that are easier to perform but inevitably come with certain inaccuracies. In the case of highly complex systems, the level of these approximations makes it practically impossible to use the results obtained from classical simulations. The answer to the problem of simulating complex chemical molecules could be quantum computers. However, algorithms with the greatest potential, as in other fields, are currently beyond the reach of NISQ-era quantum computers. Therefore, it is essential to research and improve hybrid methods that combine the potential of classical and quantum computers. Such approaches can practically achieve quantum advantage before building a fault-tolerant, full-scale quantum computer. One of the leading representatives of this approach is the widely studied Variational Quantum Eigensolver (VQE) algorithm.

As part of collaboration with Adam Mickiewicz University, a series of experiments were conducted using IBM Q quantum computers to simulate the physical and chemical properties of molecules such as H2, LiH, and hydrogen and helium atoms. The calculations aimed to investigate the practical use of both the VQE algorithm and available IBM Q quantum computers. A lot of attention was paid to the critical difficulty associated with using VQE to calculate the properties of the studied system, known as the "measurement problem." This problem is related to the unfavorable scaling of the number of measurements required relative to the desired accuracy of the final result. The techniques used in the experiments allowed for a significant reduction in the impact of this problem and an improvement in the scaling of quantum calculations.

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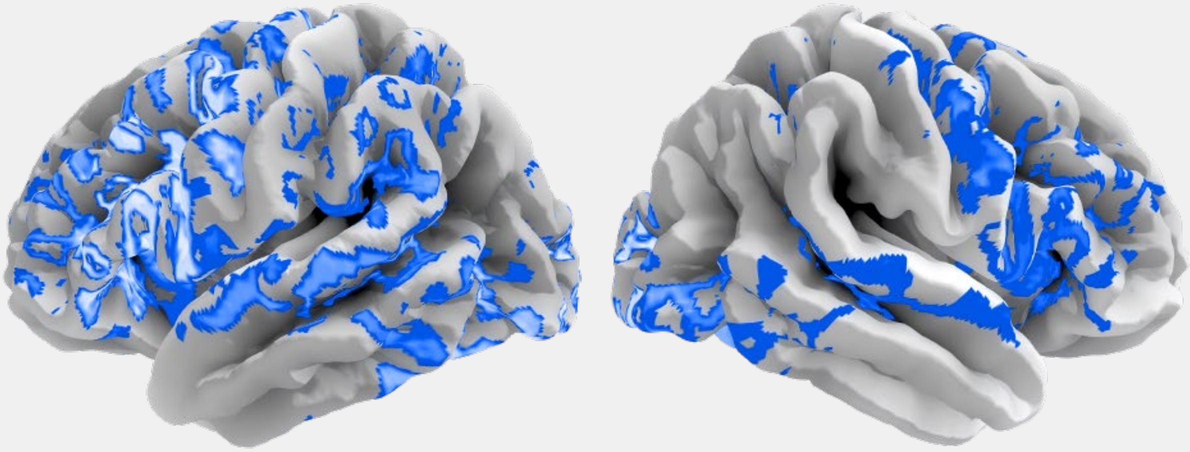
The ongoing research in quantum chemistry is focused on finding algorithms that can effectively harness the capabilities of quantum computers to reproduce results well-known from classical calculations. Observing the current trend in removing technical limitations in quantum computers, one can speculate that in the near future, computations performed using such computers will surpass classical computations in terms of efficiency. The current situation resembles that of the 1980s when the computational power of the computers available at that time significantly limited the predictive capabilities of quantum theory.

Artificial intelligence and machine learning

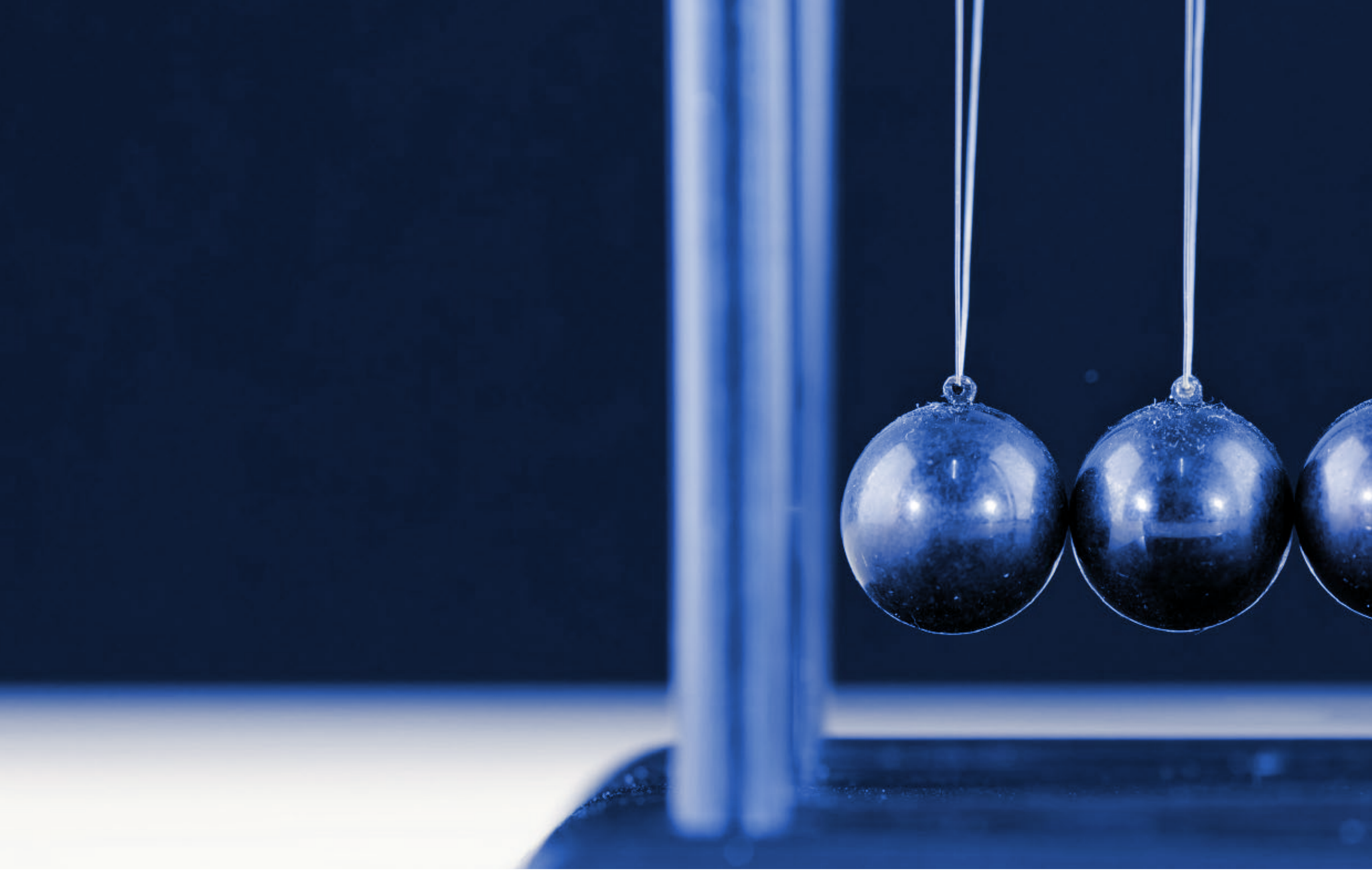
Machine learning is a branch of computer science and artificial intelligence that encompasses algorithms enabling machines to learn to perform various tasks based on data. Prominent examples of machine learning applications include autonomous vehicle control, autonomous robot programming, speech recognition, sound and image classification and generation. Many classical machine learning algorithms, such as deep neural networks, use various mathematical operations for computation. For simpler applications, the number of neurons in the model is not large, but as the complexity of the problem increases, the number of computational units grows enormously, and training them requires more and more time. The sizes of training datasets also quickly increase, which serve as input to the learning algorithm. Therefore, training large models becomes increasingly difficult, even when leveraging massively parallel classical computations on supercomputers and using advanced HPC (High-Performance Computing) technologies, including efficient graphics processing unit (GPU) accelerators.

Quantum computers address this problem by allowing the transformation of the problem into a multi-dimensional Hilbert space using quantum data representation. This saves computational resources and provides



greater capabilities for finding correlations in datasets, making learning faster and algorithm results more accurate. One of the primary experiments to test the potential of using programmable IBM Q quantum computers involved using and testing a quantum version of the Support Vector Machine algorithm called QSVM (Quantum-enhanced Support Vector Machine). The algorithm involves finding correlations between variables in the training set and finding transformations that enable correct classification. Thanks to the possibility of using a quantum solution space, which leverages entanglement between qubits, correlations were found in a multi-dimensional Hilbert space.

The first experiments on IBM Q quantum computers were conducted on the reference MNIST dataset, which consists of hand-written digit images with a size of 28x28 pixels. The QSVM algorithm learned to correctly detect specific digits based on the average brightness of pixels from square regions in the image.



Machine Learning

Another fundamental advantage of quantum machine learning algorithms is their ability to learn concepts of quantum nature, which is practically unattainable for classical machines. Using access to quantum computers, the team from the University of Adam Mickiewicz conducted experiments with Quantum Generative Adversarial Networks (QGAN) and the Quantum Counterpart of Generative Adversarial Network (QCGN).

Generative Adversarial Networks (GANs) have been one of the most exciting breakthroughs in machine learning and find applications in various demanding tasks such as image and video generation. Recently, the quantum version of such learning has been theoretically proposed, indicating its potential for exponential advantage over its classical counterpart. The research proposed a new approach to quantum adversarial learning, leveraging theoretical advancements in the distinguishability of quantum states.

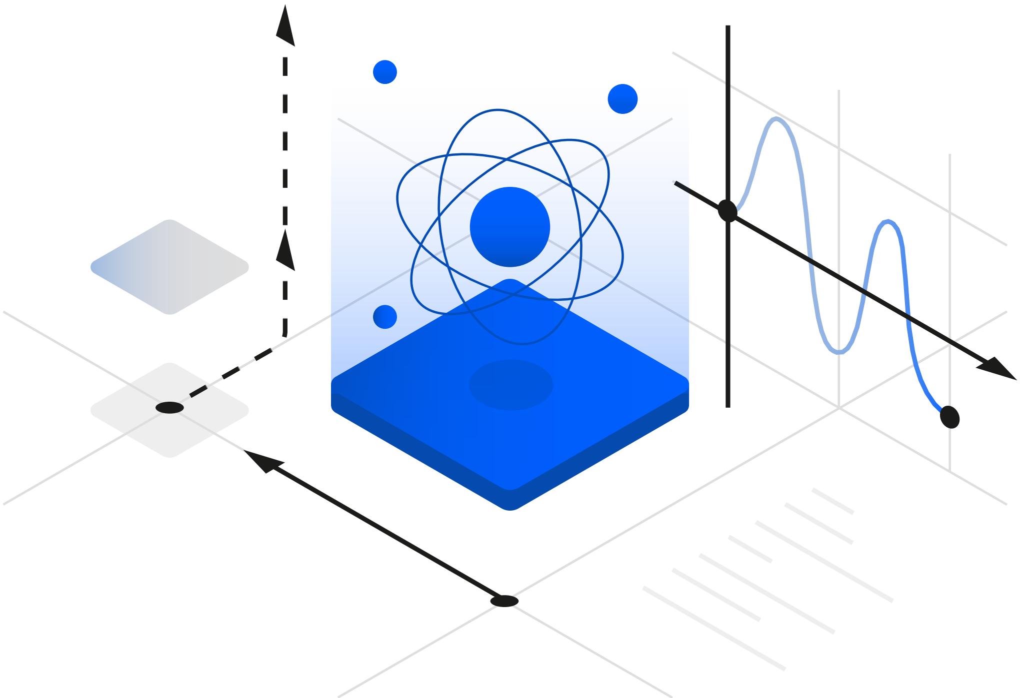
A series of experiments were conducted using real noisy IBM Q quantum processors, demonstrating the correctness of the new approach for a small number of qubits. However, practical implementation of such an approach requires further research work related to noise mitigation mechanisms.

Non-Hermitian quantum mechanics is a promising area of study within quantum mechanics that describes open systems, where noise appears. In the case of at-

tempting to compensate for losses in the system, there may be situations where initially different quantum energy levels become indistinguishable. These configurations are related to so-called exceptional points. It is assumed that studying such points will allow the development of quantum-enhanced methods for detecting physical processes and protecting against noise in quantum processes. This is of crucial importance for developing new quantum sensors and noise mitigation methods in quantum processors. In their research, the team from the University of Adam Mickiewicz developed a method for detecting exceptional points in the IBM Q quantum processor system.

The parameters for which the observation of exceptional points is possible have been identified. Developing a mechanism that utilizes exceptional points in practical applications requires further research work, including access to new generations of quantum computers.

High-energy physics and nuclear research



The expected increase in the number of cancer cases, coupled with the economic costs of cancer therapies, makes this problem one of the fundamental challenges that modern societies must confront. In this context, the continued development of new medical diagnostic techniques that allow for the early detection of diseases is of paramount importance, as it is one of the key factors in effective oncological therapy. Currently, non-invasive medical imaging techniques such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI), and Positron Emission Tomography (PET) are widely used in diagnostics. These techniques enable the creation of images of a patient's organs or the entire body. In recent years, with research into the new generation of PET scanners, especially those that encompass the entire patient's body (Total-body PET), there have been proposals to develop techniques that would provide additional information about pathological changes, expanding upon the classical information provided by patient imaging. The National Centre for Nuclear Research (NCBJ) conducted tests using simulators and real quantum computers as part of its research efforts.

For each of these, tests were conducted: an n-qubit random number generator (to check the deviation of the real machine from the theoretical model), the Deutsch-Jozsa algorithm, the Bernstein-Vazirani algorithm, the Simon's algorithm, quantum Fourier transformation, Shor's algorithm, Grover's algorithm, and quantum image processing. Tests were also performed on supercomputer cluster communication and simulations of quantum entanglement for a system of two photons from the parapositronium decay during Compton scattering, using Kraus operators available in the Qiskit toolkit library.

NCBJ plans further work on simulations and data analysis from the J-PET detector, which operates based on entangled quantum pairs and triplets of photons from electron-positron annihilation. This is a mature field pursued at NCBJ for a decade, with expected significant acceleration in image reconstruction using quantum algorithms. The second area is the predicted application of quantum algorithms in the reconstruction of electromagnetic cascade events in the electromagnetic calorimeter used to detect high-energy particles in the LHCb experiment at CERN. This is also an advanced area, closely tied to NCBJ's strong involvement in this specific experimental research. The third area involves structural research at the European XFEL (European X-Ray Free-Electron Laser), where NCBJ contributes significantly in the field of IT engineering and numerical methods. The reconstruction of particle images can be efficiently transferred to quantum resources, and the effective acceleration of their execution depends on the decomposability of the problem. The fourth area is computational fluid dynamics (CFD), with detailed applications in reactor simulations and environmental computations. A specialized department in the Department of Complex Systems Research at NCBJ deals with these issues.

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NCBJ envisions the development of several fields of quantum computing technology applications, ranging from experimental data analysis to advanced image reconstruction algorithms and computational tasks used in reactor and environmental calculations.

The financial sector

The financial sector is an important field of application for various types of optimization and large-scale computations. Portfolio optimization, with the aim of maximizing investment profits or minimizing risk, is a crucial part of operations for many institutions worldwide, especially financial institutions, banks, brokerage houses, and others. Traditionally, portfolio optimization involved complex criteria and input variables, making it a very challenging task for classical computers. As a result, heuristics or machine learning algorithms based on historical data were often used to solve this problem. Quantum computers offer the potential for finding optimal investment strategies and conducting efficient simulations of market behaviors across various asset classes by enabling parallel exploration of solution spaces. Multi-criteria optimization, considering both the quantity of decision variables and the diversity of objective functions, becomes feasible by aggregating all parameters into an energy function optimized by a quantum algorithm. A concrete example of quantum applications in this context is the quantum option pricing model, where the payout depends on the average price of an underlying asset over a certain time period, as opposed to standard options (American and European) where the payout depends on the asset price at a specific point in time (maturity) [15].

In cooperation with financial institutions, the possibility of performing experiments using reference and test financial data was explored. Preliminary tests of the possibility of using quantum computers, for the simple task of optimizing a financial portfolio, have been performed. The development of quantum infrastructure may soon provide the opportunity to extend these examples with additional input parameters and optimization criteria, taking into account new risks related to climate change of the evaluated investments, which will enable their use in new applications.

Other applications

Another important area of potential applications for IBM Q quantum computers, including the mentioned quantum machine learning algorithms, were experiments with medical data analysis conducted by the Poznań Supercomputing and Networking Center at ICHB PAN. The collected reference biomedical data is most often obtained using Magnetic Resonance Imaging (MRI) scanners while the subjects perform mental tasks related to language functions of the brain or motor skills. The aim of collecting such data is to gain a better understanding of the complex processes occurring in the cerebral cortex during seemingly easy, "automatic" everyday activities. An experiment analyzing Functional Magnetic Resonance Imaging (fMRI) results using a quantum computer may demonstrate that quantum models are a better representation of the complex brain processes than classical statistical models. This will have a direct impact on the accuracy of brain function models and may contribute to better diagnosis of central nervous system disorders such as aphasia and apraxia (speech and motor function disorders most commonly occurring after a stroke), as well as Alzheimer's disease, Parkinson's disease, depression, or schizophrenia.

Additionally, the Institute of Theoretical and Applied Informatics of the Polish Academy of Sciences has developed a tool called PyQBench for testing gate-based quantum computers, including the resources provided by IBM Q, based on their ability to distinguish between two von Neumann measurements in different bases. The developed tool allows for running benchmarks that utilize differentiation between computational basis measurement and measurement in a basis defined by a parameterized Fourier family. Users can choose whether the experiment will be conducted using post-selection or an alternative "simple sum" method, and control various aspects of the experiment, such as the number of samples used in sampling, qubit indices, angle ranges for the parameterized Fourier family. If a user wants to use a measurement in a different basis, they can use PyQBench as a programming library. This mode of use requires more effort but allows for extending the experiment's parameters. It's worth noting that in the case of quantum computer resources that provide information about qubit calibration, PyQBench supports error mitigation using the matrix-free measurement mitigation method. As part of the guaranteed access to IBM Q resources, a series of experiments were conducted based on the von Neumann measurement benchmark.

The experiment involving the analysis of Functional Magnetic Resonance Imaging (fMRI) results using a quantum computer may demonstrate that quantum models provide a better representation of complex brain processes compared to classical statistical models.

POTENTIAL AREAS OF APPLICATION	MATERIALS SCIENCE AND BIOLOGY	COMPLEX SYSTEMS AND CHALLENGES	EXISTING TECHNOLOGY AND RESEARCH
INDUSTRIES	Energy, food and agriculture, manufacturing, chemistry, medicine.	**Finance, transportation and logistics, industries with complex products (aviation, automotive, etc.).**	Industries with intensive use of AI, blockchain, and HPC technologies, energy and materials industry, communication.
EXAMPLES OF QUANTUM COMPUTING USE	Discovering and designing new molecules and materials, impacting various fields: advanced materials development, drug design, agriculture and fertilizers, green hydrogen catalysts, batteries, chemistry.	**Managing and optimizing complex systems with a large number of variables or unknowns, from highly complex scheduling problems, logistics, and supply chains to modeling financial portfolios and risk profiles.**	Managing and optimizing complex systems with a large number of variables or unknowns, from highly complex scheduling problems, logistics, and supply chains to modeling financial portfolios and risk profiles.
SOCIAL AND ENVIRONMENTAL IMPACTS	Reduced energy consumption, efficient materials and processes, more resilient and environmentally friendly plant species, accelerated reaction discovery, personalized medicine.	**Reduced energy consumption and emissions throughout the global network, circular business models.**	The potential to break current cryptography, the application of potentially stronger cryptography with higher levels of privacy and security. Accelerated exploration in fundamental scientific research.

POTENTIAL AREAS OF APPLICATION	MATERIALS SCIENCE AND BIOLOGY	COMPLEX SYSTEMS AND CHALLENGES	EXISTING TECH-NOLOGY AND RESEARCH
ILLUSTRATIVE EXAMPLES	Molecules with the right attributes for carbon sequestration. Naturally more resistant crops to improve food production while avoiding monocultures.	**Optimization of transportation and logistics for environmental and economic benefits. Real-time improvement of customer credit assessment.**	The potential to accelerate machine learning algorithm training processes. Breaking RSA and cryptocurrency encryption. Contributing to our fundamental understanding of quantum.
QUANTUM CORE CHALLENGES	Quantum simulation, combinatorial optimization, linear algebra, and prime number factorization.		

Tab. 2. Source: World Economic Forum, Global Future Council on Quantum Computing [7].

Summary and conclusions

All the topics discussed in the report and the example applications show that entering the era of quantum technologies is not only an interesting direction for scientific research but is indeed a necessary step to ensure cybersecurity and address the increasing challenges posed by larger volumes of data processed by classical computers. The report also attempts to answer many fundamental questions related to quantum technologies, computers, and computations that are often asked by users.

The report answers questions such as:

- Can we replace transistors and utilize quantum effects for computations and simulations?
- Is a quantum computer just a new, more efficient generation of supercomputers?
- Are there quantum computers available to domestic users, and if so, what types?
- What is the programming paradigm for quantum computers?
- What are the main technological barriers in existing and future quantum computers?
- What potential limitations could affect the practical applications of quantum computers?
- What types of problems can quantum computers be used to solve initially?
- What skills are required to start experiments with quantum computers?

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