

# Educational Issues Raised by the Availability of the Quantum Computer

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**Abstract.** The development of quantum computers is bringing major changes to the IT sector. These computers, based on completely new principles, can provide effective solutions to previously unsolvable problems. Regulations have already been introduced in the European Union and Hungarian law to confirm that we are getting closer to the era of quantum computers. Therefore, we believe that education and teachers should follow the development of these machines so that future students in the field of information technology, whether they are IT teachers, physicists, or programmers, are not caught unawares. In this article, we present some examples from abroad where quantum computing topics are already included at certain levels of education.

**Keywords:** quantum computing, quantum physics, primary school, secondary school, higher education, specialization, STEM, education

## 1. Introduction

News about quantum computing research has become part of our daily lives, with quantum informatics news, speculation, and reports on developments by big companies [11] in the science sections of the online and print press. Legislation and regulations have also been published among countries in the European Union and in Hungary on post-quantum encryption and to support the development of quantum computers [22, 23, 24, 41, 52, 63].

The emergence of these clearly raises interest, speculation along with data security and password protection issues related to quantum computers. There is an increasing need for people to obtain information from credible sources on the operation of quantum computers, their physical basis, their applications, current developments and the expected social and economic impact.

A number of questions have become important: What exactly is a quantum computer? What are the concepts associated with it? What is the basic unit of storage and transmission of quantum data? How is it defined? How is it stored? How do quantum computers work in general? What are the physical principles that underlie the construction of these machines? Are quantum computers likely to replace the computers we have today, and where can we see, try out and buy a machine that works according to this new paradigm?

## 2. Historical overview

The roots of quantum mechanics in the classical sense can be traced back to empirical physicochemical research in the early 19th century. When investigating the relationship between temperature radiation and spectral analysis, black lines were found in the spectra [7, 8, 54, 55]. This anomaly raised many new questions for researchers, which by the early 1900s were being answered by questions from the field of quantum mechanics, which was becoming a science in its own right.

By the early 1900s, research that correctly described the spectra but used classical theoretical approaches had failed time and again. Planck chose a new way of interpreting the physical properties of atomic oscillators, starting from entropy instead of phenomenological thermodynamics [49, 50]. The relationship between entropy function and thermodynamic probability was already known, as well as the fact that an isolated system takes its maximum value in equilibrium. His assumption was that the number of microstates associated with each thermodynamic probability can be counted, and this is only possible if the energy is divided into

parts (finite energy units). In other words, the energy of thermal radiation (mechanical oscillator) is not continuous but quantized.

He reported his quantum hypothesis at a scientific meeting of the Royal Prussian Academy in Berlin on 14 December 1900 in a lecture entitled "Ueber das Gesetz der Energieverteilung im Normalspectrum", which is considered the birthday of quantum physics.

It was a true paradigm shift, which was received with reservations by the leading community of physicists who set the scientific trend and only ratified it years later. However, the initial uncertainty did not prevent the new direction from unfolding, as the first three decades of the 1900s saw a succession of old and new results being overturned year after year. By the end of the first decade, a new discipline had emerged alongside quantum physics: the theory of relativity.

### **3. The limits of traditional computers**

There is a huge demand for quantum computers as a new technology because the Neumann computers currently in use will soon reach - and at some points have already reached - the limits of their technological development, as the trends shown in the following three graphs clearly illustrate.

Moore's Law illustrates the rapid technological development of classical computers. It is not in fact a law, but an empirical observation that the number of transistors in integrated circuits doubles every 1.5 years. The observation is attributed to Gordon E. Moore, one of the founders of Intel, who first wrote about the trend he observed in an article published in *Electronics Magazine* in 1965 [27]. Although Moore's original formulation was not the same as it was widely reported, it had a major impact on the pace of development by processor manufacturers. According to the original formulation, the complexity of the lowest-cost component is roughly doubling every year, and this rate of development is unlikely to change significantly in the future. For chip designers, this observation became a target to be met and a self-fulfilling prediction for the future, i.e. a complete forecast of the production cycle for many years to come.

So much so that the age of transistors was replaced by the age of integrated circuits, and the classic operating principle was retained, but the desired rate of progress was achieved by means of different technological elements.

The graph below [56] clearly shows the increase in the complexity of integrated circuits, which at first glance appears to be a linear increase, but if we look closely, the vertical axis is logarithmic in scale, so we can see that it is an exponential increase. The horizontal axis shows the year of release of each processor and the vertical axis shows the number of transistors in each chip. This means that smaller and smaller transistors are being built into computer chips, with the most modern processors today fitting a transistor into an area of 20 x 20 silicon atoms. It is clear that this development is unsustainable since sooner or later miniaturisation will reach the atomic scale and then limit the development of the classical type of Neumann computers.

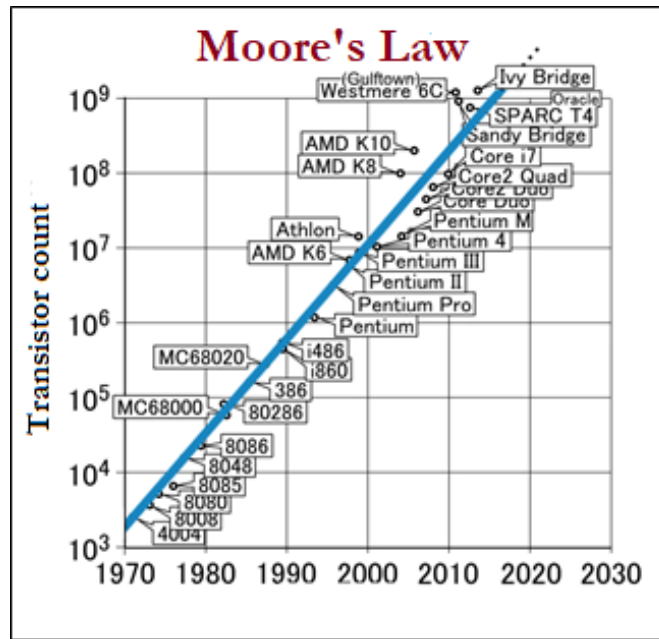


Figure 1: Trend of Moore's law. Edited by Csilla Prantner based on [56].

The extrapolation graph below shows the characteristics of microprocessors as a function of time: number of transistors, single-thread performance, CPU frequency, power consumption, and number of cores [36]. The signal in 2004 indicates the breakdown of the Dennard scaling rule.

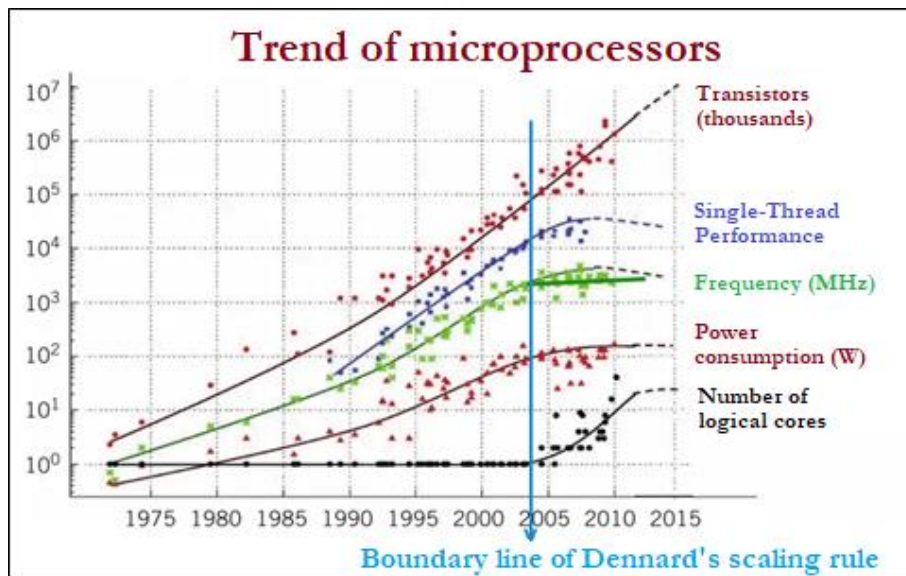


Figure 2: Dennard scaling rule. Edited by Csilla Prantner based on [36].

The rule is also known as Dennard's scaling law, which states that as the size of the transistors is reduced, the power density remains constant, i.e. no matter how small the transistors become, they will still be able to deliver the same power. This discovery foresaw and ensured the development of high-throughput processors for many years to come. The law was originally formulated for MOSFETs based on a 1974 article by Robert H. Dennard. [17].

Looking at the middle of the factors on the right side of the graph, where the rate of change of clock speed is located, since 2004 we see a linear function, i.e. since 2004 processors have been clocked at 3-4 Hz. In the last few years, it has not been possible to increase the clock speed, and

since computers perform tasks at the same rate as the clock, the speed at which they are performed cannot be increased. This also shows the limits of the current development of traditional computers.

The third diagram illustrates Amdahl's law, which relates to parallel programming. In principle, parallel programming allows us to speed up the execution of algorithms since several processors can work on the same problem at the same time.

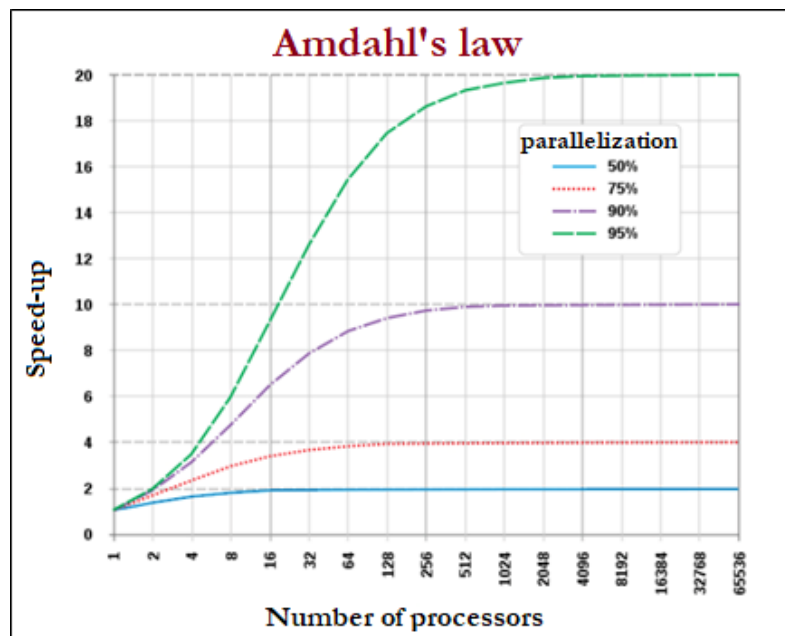


Figure 3: Amdahl's law. Edited by Csilla Prantner based on [66].

Gene Amdahl, who also worked for IBM, spoke at the AFIPS conference in 1967 about how the relatively few instructions to execute in a parallel processing program is a limiting factor on the speed of the program, so adding more processors does not necessarily make the program run much faster. A precise formula for this observation has been formulated by the expert [1]. The basic problem is that there are few tasks that are truly able to be parallelized, i.e., that the individual program threads are so separable that they do not rely on each other's computations or partial results, i.e., the execution of one part of the program does not depend on or influence another. A good example of a problem which can be parallelized is map analysis, where, for example, a large area is divided into smaller areas of the same size and these are analysed in parallel, e.g. which parts contain water or forested areas, etc. In this case, too, the results from each analysed area must be combined to produce a summary. So the point is that there are a few problems that can be well parallelized. Figure 3 illustrates the impact of increasing the number of processor cores on program execution speed for algorithms that can be parallelized in a certain percentage [66].

If we assume that we are solving a problem that is 95% able to be parallelized (green dashed line, only in very special cases), even a number of processors higher than 2048 does not bring any improvement. If we can parallelize 50% of the problems (blue solid line, which is rare), then even more than 16 cores will not bring faster performance. So above this, increasing the number of processor cores is more of a publicity stunt than a real opportunity to be exploited, since the fundamental limit is good parallelization of programs at the logical level.

The diagrams presented all show that we have reached the limits of Neumann computers and that we should be thinking about a completely different technology; quantum computers, based on different physical solutions, represent a paradigm shift.

## **4. Development of Quantum Computers, Their Applications**

### **4.1. Fields of Application**

The last decade has witnessed a breakthrough, with news of the development of quantum computing, the impact of which will be felt in various fields. In addition to the leading powers, countries such as Australia and Switzerland are investing huge sums of money in their development. The aim of these developments can be divided into four main areas.

The first, and most widely known, is to multiply today's computing power, on the basis of which today's supercomputers could in the future be replaced by quantum machines. The computing power that can be achieved could be applied to a wide range of fields, from improving the efficiency of weather forecasting to scientific research [59].

Another popular application area is materials and drug discovery, in general, any research area where high computational power could be used to replace or reduce the practical execution and testing process [59].

The quantum internet could represent a leap forward in today's networking technologies, based on the possibility of communication-based on the interconnection of entangled quantum bits. This, in addition to the realisation of a super-fast Internet connection, makes it clear that the confidentiality of the transmitted data is not compromised.

The fourth direction of development is to improve the quantum computer itself, the construction of which still poses a number of problems today.

### **4.2. Physical Solutions**

Without a basic understanding of quantum physics, a precise understanding of the physics of a quantum computer is quite difficult, and sometimes even its programmers do not have a full understanding of it. Such a machine can be built based on a number of different physical phenomena, ranging from the polarisation of light [31, 46], and the spin of an atomic nucleus [6, 37] to the position of electrons.

Since most machines can be maintained at temperatures around absolute zero for a few seconds at most, there is still a lot of research going on to find a better physical base with more favourable properties.

### **4.3. Basic Concepts**

Quantum is a Latin word meaning quantity, the plural of which is quanta. The word was introduced into physics directly from Latin by Max Planck, in 1900, with the concept of the "minimum quantity of an existing quantity"; Einstein confirmed it in 1905. Quantum theory dates from 1912 and quantum mechanics from 1922. It is the smallest possible unit in physics by which the value of a measurable unit can be increased [62]. It is usually applied to the properties of atomic or subatomic particles such as electrons, neutrinos or photons [44].

The machine works on the basis of the so-called qubit, which is the elementary unit of the machine and is most similar to, but significantly different from, the bit of a conventional computer. While a bit can have only two values (zero or one), a qubit can have these and any value in between, even simultaneously, in the so-called superposition. In superposition, the quantum particles are in a combination of all possible states at the same moment in time, but with different probabilities, which allows a quantum machine to compute many values at once. Thus, some sources say that a 30 qubit machine would have the performance of today's fastest supercomputers. The difference between a binary position and a superposition can be illustrated with a coin, for example. Binary states (heads or tails) are easy to understand. A superposition, on the other hand, is similar to flipping a coin and having it spin continuously. In this case, any value can be the result, at each instant of time it takes a certain percentage (amplitude) of the possible values, so a certain percentage for heads and a certain percentage for tails. To use another example, if we are looking for the result of a calculation with, say, integers 0-9, each value can be the solution with a certain percentage certainty at any one time. The outcome will be the one that yields the highest probability on a sustained basis, thus the percentage will peak there.

The difficulty in quantum informatics is that quantum particles are constantly changing, and fluctuating until they are measured. So qubits are extremely sensitive, and one of the most disadvantageous consequences of this is that their state can only be read out once, after which the value stored in them is lost. In addition to superposition, quantum particles have another very interesting property: entanglement. When qubits are entangled, they form a single system and interact with each other. Measurements from one qubit can be used to draw conclusions about the other and vice versa. When you add more qubits to a system by entanglement, the computer can compute infinitely more information and solve more complex multi-variable problems. For this reason, this technology is good for calculations where many factors, effects or components need to be considered simultaneously and their interactions are taken into account. Entanglement can be used to correlate the measurement results of individual quantum particles and this property can be exploited to excellent advantage in quantum informatics.

Quantum interference is the behaviour of a qubit, due to its superposition property, which can be used to influence the probability of coincidence with one or another value. One of the major challenges in creating quantum computing machines is to reduce interference as much as possible for more accurate results [43].

Several technologies are used to achieve this goal, all of them aiming at stabilising the quantum particles by manipulating their structure, for example by cooling or by surrounding them with chemical compounds that protect them from external interference.

Quantum computers exploit special forms of quantum physics behaviour in computing, such as superposition, entanglement and quantum interference. All these bring new ideas compared to traditional algorithms and programming methods.

## 5. Quantum Algorithms

Theoretical research on quantum machines has already made significant progress in the 1980s. David Deutsch devised versions of logic gates adapted to quantum machines [18], and in 1994 Peter Shor published one of the most famous algorithms [60], which can fundamentally challenge the data security of systems in use today.

### 5.1. The most important quantum algorithms

The Deutsch-Jozsa algorithm [16] was the first quantum algorithm that, in addition to revealing the potential of quantum algorithms, was able to determine a bit-parity function faster than classical algorithms. The unknown logic function expects a single bit as input and returns a single bit such that either all input bits are even or all input bits are odd. The algorithm can be used to determine the nature of the unknown function in a single quantum measurement.

The Bernstein-Vazirani algorithm [21] allows the analysis of more complex problems and functions than the previous one (Deutsch-Jozsa algorithm). The function  $f$  is given by  $f(x) = a_1x_1 + a_2x_2 + \dots + a_nx_n + b$ , where  $x$  is the  $n$ -bit long input,  $a_i$  is the weight on  $x_i$ , and  $b$  is a constant. The algorithm can be used to determine the values of  $a_i$  and  $b$  in a single quantum measurement.

The Grover algorithm [30] is an optimized search algorithm for unordered sequences that is  $2^{(n/2)}$  times faster than classical search methods.

Shor algorithm [60] is actually an optimal algorithm for factorization.

Simon algorithm [15] is a bit-parity algorithm that can solve the problem with much lower energy consumption and in less time than classical algorithms.

The Harrow-Hassidim-Lloyd (HHL) algorithm [32] is an algorithm for solving systems of linear equations that requires less memory and is much faster than classical algorithms for similar tasks.

The VQE algorithm [14] is a hybrid algorithm based on quantum mechanics that can be used to determine optimal balance states.

### 5.2. Encryption algorithms

Currently, widely used encryption algorithms are based in large part on the mathematical problem of prime factor resolution<sup>1</sup>. The protection is provided by the multiplication of the huge prime numbers generated by the process, which makes it virtually impossible to compute the prime numbers in a conventional computing environment.

Algorithm	Typical usage	Sustainability
AES	Encryption	safe with a longer key
SHA-2, SHA-3	Hash creation	Longer output is needed
RSA	Digital signature, key matching	Insecure
ECDSA, ECDH	Digital signature, key exchange	Insecure
DSA	Digital signature, key exchange	Insecure

Table 1: Usability of encryption algorithms in the post-quantum world.

Edited by Ferenc Koczka.

<sup>1</sup> a mathematical.

Shor's quantum algorithm solves this problem: it performs a prime factor resolution of a number at extremely high speeds, making some IT systems protected by algorithms based on prime factor resolution insecure<sup>2</sup>. Although in some cases the algorithm itself remains usable by modifying the operational parameters, e.g. key sizes, in practice these modifications can often only be made by the developers of the individual systems. The protection capabilities of today's most common crypto algorithms in the post-quantum<sup>3</sup> world are described in the table above.

Shor's algorithm is just one example of the paradigm-shifting impact of the quantum machine, and algorithms that can withstand the massive computing power of the quantum machine need to be found and incorporated into current systems. In the third phase of research conducted by the US National Institute of Standards and Technology (NIST) Computer Security Centre, several quantum-safe algorithms have been published that provide solutions for everything from hash fingerprinting to electronic signatures. Hungarian legislation has also started to address the problem, and as a result, the requirement for state and local government bodies to prepare for the use of post-quantum algorithms was included in the 2013 Act L. Although many organisations, such as businesses and educational institutions, are not covered by the law, owners and operators will have to take into account the potential exposure of their systems in the future.

Despite current developments, it is unlikely that quantum computers could replace the computers in use today. In addition to the technical difficulties, their scope is extremely limited and they cannot run regular or business-related software. However, the accelerated pace of development makes the emergence of this technology in the training of programmers, physicists and in general education, obvious.

## 6. Education

Not only is it important for people watching the news to be aware of these new computers, but it is also worth thinking about how the subject could be integrated into education.

to prepare society for the emergence of quantum computers and the changes they generate. Many specialists will be needed to operate quantum computers. Without them, it will not be possible to prevent and manage the potential damage they can cause, to maintain data security and to carry out the research and development that quantum computers can support. For example, training in physics, data protection, research and development in the field of quantum computing, and programming are all strongly linked to the construction of quantum computers.

Similarly, the preparation of specialist training is important, so some concepts may be worth introducing in the upper grades of secondary education. It is important that young learners should not be left to their own devices with questions, but should be able to find out about the substance of the subject and its context from a credible source, filtered, organised and processed by teachers.

### 6.1. Are We Late?

Regardless of how advanced quantum computing is at the moment, the question must be asked: are we too late in teaching it? The statement encoded in the question could be too strong, but it is actually true if the trend of progress in this field over the last 15 years continues at the same

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<sup>2</sup> Shor's algorithm can be run on a six-qubit quantum machine, which has been available for years.

<sup>3</sup> The post-quantum refers to the era of computing in which quantum computers are expected to be used.



intensity. It is well known that quantum computing has a history of almost 70 years, but in the mid-2000s some significant progress was made. Exactly what that was is neither our purpose nor our responsibility. Let us say that it was a series of events that led to the fact that today there is so much competition between the various technological giants [11] in this field that articles and news about new developments and achievements appear almost every week or month. Let's look at the reasons why we are afraid we have missed something!

One reason is that we have witnessed an exponential explosion in the development of this new area of IT over the last 15 years. In classical education systems, it takes at least a decade for age-appropriate and target-group-specific subjects - from primary school to higher education - to appear and be integrated into curricula, from exposure to the subject in lower grades to the foundation of the curriculum. What makes integration into the curriculum even more difficult is that, in addition to IT skills, this area requires a high level of knowledge of chemistry, quantum physics and mathematics, and, unlike in the past, a much more complex problem-solving ability [3]. The problem is that recent graduates in higher education have not been prepared to take on this new field and pass it on to future generations.

Where is quantum computing now? Today, a large number of quantum computers [34, 67] and simulators [13] are available to try out and write quantum programs [35]. There are many online courses [12, 20, 65], tutorials [42, 51, 67] and animations available to demonstrate quantum computers working on different principles.

### 6.3. Primary School

With the recent digital transformation, information technology permeates almost every aspect of life, and children are increasingly exposed to concepts such as embedded systems, Big data, IoT, artificial intelligence and quantum computing. We would like to ask some thought-provoking questions for this age group:

- Should quantum computing be taught in primary school?
- Is it viable to talk about this field in primary school?
- What does quantum computing mean for this age group?

Quantum information science is already mentioned in the media on a daily basis with some kind of preconception. Unfortunately, it is quite often presented in a negative light, as a life-changing and life-affecting technology that cybercriminals can use to hack into computer systems, even those that protect bank accounts. This type of negative news can create inner tension and questions in children, to which they expect reassuring and exhaustive answers. We believe it is important to prepare IT teachers for these kinds of questions, to be informed and to be able to give professional answers. They should not only answer questions with negative emotions but also be able to explain that quantum computing offers new ways of secure data transmission, opening up new avenues for simulations, revolutionising pharmaceutical research, developing new materials, making meteorological forecasts more accurate and valid over time, etc. Quantum technology is therefore both an opportunity and a risk for society [10, 58].

The primary aim of IT education is to provide the right basis for navigating the digital world. There is a consensus in research on IT education that, rather than focusing on short-term technologies, more emphasis should be placed on teaching basic concepts, algorithms and principles. [2, 48, 64].

We believe that today's computer science teachers need to be familiar with the basics of quantum computing in order to be able to inform children in public education about the developments in

this field; it is, therefore, inevitable that it should be part of the university education of computer science teachers.

We also believe that it is inevitable that, in time, quantum informatics will be mentioned in primary school curriculum for upper secondary school students. This age group is already confronted with the term "quantum" in the media on a daily basis, not only with the quantum computer but also with the quantum mobile phone, for example. We should explain to them what the word quantum actually means, and what physical phenomena quantum computers are based on, help them to imagine how they work, understand their purpose, understand the concept of quantum bits, and make them understand the scale and potential of quantum computing, even if it is not necessarily easy for an adult teacher of the subject to understand.

Still, we feel it is important that they are introduced to the concepts and know what the word quantum refers to. Moreover, it would also be a goal to be able to recognise and filter the content of advertisements, to see that the products advertised often do not contain real quantum computers, but merely devices with a kind of "quantum" characteristic. Just like a vacuum cleaner that has no artificial intelligence, which does not undergo a learning process, but can only stop a few centimetres in front of an obstacle using an infrared sensor. One important goal of education is to learn to think correctly about a problem.

#### 6.4. High School

While the 10-14 age group can only be introduced to basic concepts, the secondary school age group can be provided with a deeper theoretical background. An adequate background in mathematics and quantum physics is a prerequisite for the transfer of theoretical knowledge. A number of studies confirm that the introduction of quantum computing into primary and secondary school curriculum is not only possible but necessary [3, 25, 33, 45, 47, 57, 58, 67].

Stadermann and colleagues [61] analysed quantum physics curricula and syllabuses in 15 countries from different perspectives. Quantum physics subjects at the secondary school level have only recently appeared in national curricula and their integration has been far from seamless [3]. The main content elements are designed to give students an insight into modern physics and its applications and to enable them to discuss the nature and aspects of the discipline. Common elements in the curricula of the countries surveyed include discrete atomic energy levels, interactions between light and matter, wave-particle duality, but also Broglie theory, Planck wavelength, engineering applications, Heisenberg's uncertainty principle, and the nature of quantum physics [40]. Challenging aspects such as interpretations and epistemological aspects of quantum physics are taught in only a few countries. It is a common experience that the curricula produced are still in their infancy and are therefore not necessarily the best curricula. Most of the current ones correspond to the elements of a simplified undergraduate quantum mechanics course. Curricular innovations are time-consuming, and the development and modification of national rules is a complex and complicated process [25]. Elements [5, 44, 38, 70] that would facilitate understanding, such as philosophical aspects of quantum physics, quantum entanglement and its applications, are only included in the Norwegian and German curricula.

Anastasia Perry and her colleagues [47] created a ten-chapter curriculum for high school students aged 15-18, which was presented to them in a five-day course. The aim of the course was to create a link between secondary school and university. The curriculum was organised around the key concepts of quantum information science, namely superposition, quantum measurement and entanglement. The curriculum moves from basic concepts through quantum gates and quantum

algorithms to quantum teleportation. It is important to note that a high level of knowledge of electricity and magnetism is not assumed, nor is computer programming experience required. Both before and after completing the course, participating students were asked to list as many concepts in quantum mechanics and quantum computing that come to mind. It was found that, in addition to a significant improvement over the survey written at the beginning of the course, students were motivated by the feedback to pursue physics and computer science [33].

Pashaei et al have created an online accessible courseware that can be used to effectively introduce the basic concepts of quantum computing at the elementary and secondary school level. In addition to creating a usable online curriculum, they have also sounded the alarm bell in Canada. The concepts of quantum mechanics are not part of everyday life, even though learning about them can have a positive motivational impact on students. They point out that introducing quantum physics and quantum computing at an early stage of education can contribute to the development of a society that understands the importance of science, thus bringing it to the forefront [45].

The field of quantum computing is mature and accessible to students. Angara and colleagues have reported on the results of workshops in quantum computing. They held short workshops primarily for students who had no prior knowledge or experience with quantum informatics. They took a programming-based approach, introducing students to the IBM Q Experience through Qiskit [51]. Based on their experience, they found that quantum computing concepts can be understood and processed by high school students. They also point out that their experience shows that early exposure to quantum computing develops students' problem-solving skills and expands and contributes to the competencies they need to acquire before applying to university [3].

## 7. Conclusion

In summary, the fundamental question is: should this area be addressed outside higher education? Can we claim that it could soon be part of education, as a mere mention in primary school, and as an introduction to concepts and the use of simulation quantum machines in secondary education, since we already see a number of examples of this abroad?

As far as we know at present, quantum computers are not expected to replace traditional Neumann computers, but the results of the last decade and a half [4, 9, 63], the plans of the tech giants [11] and national governments [26, 29] suggest that they will almost certainly become a visible segment of computing in the next ten years.

It is clear that, like all trends, it has its followers and researchers who have considerable reservations about the results and whose vision for the future is far from optimistic. In their view, it is impossible to build a general-purpose quantum computer with even the qubit needed to achieve the current computing capacity and operate within an acceptable margin of error [39].

In light of all this, we can say that both experimentation and uncertainty are outlined in the field of education. But we see that even if quantum computers remain stuck at the current level, i.e. only capable of generating well-specified subproblems and non-pseudo random numbers, they can be used to improve problem-solving ability, broaden horizons, deepen the understanding of time complexity, popularise physics or promote understanding of quantum physics [19].

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