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► **To cite this version:**

Michel Dyakonov. When will we have a quantum computer?. Solid-State Electronics, 2019, 155, pp.4-6. 10.1016/j.sse.2019.03.004 . hal-02302517

**HAL Id: hal-02302517**

**<https://hal.science/hal-02302517>**

Submitted on 22 Oct 2021

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## When will we have a quantum computer?

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**Introduction, historical background.** The idea of quantum computing was first put forward in a rather vague form by the Russian mathematician Yuri Manin in 1980. In 1981, it was independently proposed by Richard Feynman. Realizing that (because of the exponential increase of the number of quantum states) computer simulations of quantum systems become impossible when the system is large enough, he advanced the idea that to make them efficient the computer itself should operate in the quantum mode: "Nature isn't classical and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy". In 1985, David Deutsch formally described the universal quantum computer, as a quantum analogue of the universal Turing machine.

The subject did not attract much attention until Peter Shor in 1994 proposed an algorithm that could factor very large numbers on an *ideal* quantum computer much faster compared to the conventional (classical) computer. This outstanding theoretical result has triggered an explosion of general interest in quantum computing and many thousands of research papers, mostly theoretical, have been and still continue to be published at an increasing rate.

During the last 20 years one can hardly find an issue of any science digest magazine, or even of a serious physical journal, that does *not* address quantum computing. Quantum Information Centers are opening all over the globe, funds are generously distributed, and breathtaking perspectives are presented to the layman by enthusiastic scientists and journalists. Many researchers feel obliged to justify whatever research they are doing by claiming that it has some relevance to quantum computing. Computer scientists are proving and publishing new theorems related to quantum computers at a rate of *one article per day*. A huge number of proposals have been published for various physical objects that could serve as quantum bits, or *qubits*. As of September 25, 2018, Google gives 71,400,000 results for "quantum computing", 1,280,000 results for "quantum computer", and 331,000 results for "quantum computing with", and these numbers increase every day. The impression has been created that quantum computing is going to be the next technological revolution of the 21st century.

When will we have useful quantum computers? The most optimistic experts say: "in 10 years"; others predict 20 to 30 years (note that those expectations have remained unchanged during the last 20 years), and the most cautious ones say: "not in my lifetime". The present author belongs to the meager minority that has been answering "not in any foreseeable future" [1], and this point of view is explained below.

**The idea of quantum computing** is to store and process information in a way that is very different from that used in conventional computers, which basically operate with an assembly of on/off switches, physically realized as tiny transistors.

At a given moment the state of the *classical* computer is described by a sequence ( $\uparrow\downarrow\uparrow\uparrow\downarrow\downarrow\downarrow\dots$ ), where  $\uparrow$  and  $\downarrow$  represent *bits* of information – realized as the *on* and *off* states of individual transistors. With  $N$  transistors, there are  $2^N$  different possible states of the computer. The computation process consists in a sequence of switching some transistors between their  $\uparrow$  and  $\downarrow$  states according to a prescribed program.

In *quantum* computing one replaces the classical two-state element by a quantum element with two *basic states*, known as the quantum bit, or *qubit*. The simplest object of this kind is the electron internal angular momentum, *spin*, with the peculiar quantum property of having only *two* possible projections on *any* axis:  $+1/2$  or  $-1/2$  (in units of the Planck constant  $\hbar$ ). For some chosen axis, we can again denote the two basic quantum states of the spin as  $\uparrow$  and  $\downarrow$ .

However, an *arbitrary* spin state is described by the *wave function*  $\Psi = a\uparrow + b\downarrow$ , where  $a$  and  $b$  are complex numbers, satisfying the condition  $|a|^2 + |b|^2 = 1$ , so that  $|a|^2$  and  $|b|^2$  are the *probabilities* for the spin to be in the basic states  $\uparrow$  and  $\downarrow$  respectively.

In contrast to the classical *bit* that can be only in *one of the two* states,  $\uparrow$  or  $\downarrow$ , the *qubit* can be in a *continuum* of states defined by the quantum amplitudes  $a$  and  $b$ . This property is often described by the rather mystical and frightening statement that the qubit can exist *simultaneously* in *both* of its  $\uparrow$  and  $\downarrow$  states. (This is like saying that a vector in the  $x$ - $y$  plane directed at  $45^\circ$  to the  $x$ -axis *simultaneously* points *both* in the  $x$ - and  $y$ -directions – a statement that is true in some sense, but does not have much useful content.)

Note that since  $a$  and  $b$  are complex numbers satisfying the normalization condition, and since the overall phase of the wave function is irrelevant, there remain two free parameters defining the state of a single qubit (exactly like a classical vector whose orientation in space is defined by two polar angles). This analogy does not apply any longer when the number of qubits is 2 or more.

With two qubits, there are  $2^2 = 4$  basic states:  $(\uparrow\uparrow)$ ,  $(\uparrow\downarrow)$ ,  $(\downarrow\uparrow)$ , and  $(\downarrow\downarrow)$ . Accordingly, they are described by the *wave function*  $\Psi = a(\uparrow\uparrow) + b(\uparrow\downarrow) + c(\downarrow\uparrow) + d(\downarrow\downarrow)$  with 4 complex amplitudes  $a$ ,  $b$ ,  $c$ , and  $d$ . In the general case of  $N$  qubits, the state of the system is described by  $2^N$  complex amplitudes restricted by the normalization condition only.

While the state of the classical computer with  $N$  bits at any given moment coincides with *one* of its  $2^N$  possible discrete states, the state of a quantum computer with  $N$  qubits is described by the *values of  $2^N$  continuous variables*, the quantum amplitudes.

This is the origin of the supposed power of the quantum computer, but it is also the reason for its great fragility and vulnerability.

The information processing is supposed to be done by applying unitary transformations (*quantum gates*), that change these amplitudes  $a, b, c...$  in a precise and controlled manner.

The number of qubits needed to have a useful machine (*i.e.* one that can compete with your laptop in solving certain problems, such as factoring very large numbers by Shor's algorithm) is estimated to be  $10^3$ – $10^5$ . As a result, the number of continuous variables describing the state of such a quantum computer at any given moment is at least  $2^{1000}$  ( $\sim 10^{300}$ ) which is much, much greater than the number of particles in the whole Universe (only  $\sim 10^{80}$ )!

At this point a normal engineer, or an experimenter, loses interest. Indeed, possible errors in a classical computer consist in the fact that one or more transistors are switched off instead of being switched on, or *vice versa*. This certainly is an unwanted occurrence, but can be dealt with by relatively simple methods employing *redundance*.

In contrast, accomplishing the Sisyphean task of keeping under control  $10^{300}$  *continuous variables* is absolutely unimaginable. However, the QC theorists have succeeded in transmitting to the media and to the general public the belief that the feasibility of large-scale quantum computing has been *proven* via the famous *threshold theorem*: once the error per qubit per gate is below a certain value, indefinitely long quantum computation becomes feasible, at a cost of substantially increasing the number of qubits needed (the *logical* qubit is encoded by several *physical* qubits). Very luckily, the number of qubits increases only *polynomially* with the size of computation, so that the total number of qubits needed must increase from  $N = 10^3$  to  $N = 10^6$ – $10^9$  only (with a corresponding increase of the *atrocious* number of  $2^N$  continuous parameters defining the state of the whole machine!) [2].

In this context, Leonid Levin, professor of mathematics at Boston University, has made the following pertinent remark: *What thought experiments can probe the QC to be in the state described with the accuracy needed? I would allow to use the resources of the entire Universe, but not more!*

**ARDA Experts Panel roadmap.** Sixteen years ago, in 2002, at the request of the Advanced Research and Development Activity (ARDA) agency of the United States government, a team of distinguished experts in quantum information established a roadmap for quantum computing, with the following five- and ten-year goals:

"by the year 2007, to

- encode a single qubit into the state of a logical qubit formed from several physical qubits;
- perform repetitive error correction of the logical qubit; and

- transfer the state of the logical qubit into the state of another set of physical qubits with high fidelity;
- and by the year 2012, to
- transfer implement a concatenated\* quantum error-correcting code."

The 2007 goal requires "something on the order of ten physical qubits and multiple logic operations between them", while the 2012 goal "requires on the order of 50 physical qubits, exercises multiple logical qubits through the full range of operations required for fault-tolerant QC in order to perform a simple instance of a relevant quantum algorithm".

While a benevolent jury could consider the first two of the 2007 goals to be partly achieved by now, the expectations for the third 2007 goal, and especially for the 2012 goal, are *wildly off the mark*. So are some other predictions of the ARDA panel: "As larger-scale quantum computers are developed *over the next five and ten years*, quantum simulation is likely to continue to be the application for which quantum computers can give substantial improvements over classical computation".

Very recently, in late 2018, another expert panel assembled by the U.S. National Academies of Science, Engineering and Medicine issued a detailed 205-page report discussing some of the challenges facing QC as a technology of practical value [3]. The authors of the report admit that no quantum computer will be capable of breaking cryptographic codes based prime number factoring within the next decade, although QC research is lauded as contributing to our fundamental understanding of complex quantum systems.

**Experimental studies** related to the idea of quantum computing make only a small part of the huge QC literature. They represent the *nec plus ultra* of the modern experimental technique, they are extremely difficult and inspire respect and admiration. The goal of such proof-of-principle experiments is to show the possibility to realize the basic quantum operations, as well as to demonstrate some elements of quantum algorithms. The number of qubits used is below 10, usually *from 3 to 5*.

Apparently, going from 5 qubits to 50 (the goal set by the ARDA Experts Panel roadmap for the year 2012!) presents hardly surmountable experimental difficulties and the reasons for this should be understood. Most probably, they are related to the simple fact that  $2^5 = 32$ , while  $2^{50} = 1,125,899,906,842,624$ .

By contrast, the **theory of quantum computing**, which largely dominates the literature, does not appear to encounter any substantial difficulties in dealing with millions of qubits. Various noise

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\* *Concatenation* in this context means spreading the information of one qubit onto a certain state of several qubits, so that the *logical* qubit gets encoded by several *physical* qubits. The idea of quantum error correction by concatenation was first proposed by Peter Shor.

models are being considered, and it has been proved (under certain assumptions) that errors generated by "local" noise can be corrected by carefully designed and very ingenious methods, involving, among other tricks, *massive parallelism*: many thousands of gates should be applied simultaneously to different pairs of qubits and many thousands of measurements should be done simultaneously too.

The ARDA Experts Panel also claimed: "It has been established, under certain assumptions, that if a threshold precision per gate operation could be achieved, quantum error correction would allow a quantum computer to compute indefinitely". Here, the key words are "*under certain assumptions*", however the distinguished experts did not address the crucial point of whether these assumptions can be realized in the physical world.

I argue that they can't. In the physical world, continuous quantities (be they voltages or the parameters defining quantum-mechanical wave functions) can neither be measured nor manipulated *exactly*. That is, no continuously variable quantity can be made to have an exact value, including zero. To a mathematician, this might sound absurd, but this is the unquestionable reality of the world we live in, as any engineer knows.

Sure, discrete quantities, like the number of students in a classroom or the number of transistors in the "on" state, *can* be known exactly. Not so for quantities that vary continuously. And this fact accounts for the great difference between a conventional digital computer and the hypothetical quantum computer.

Indeed, all of the assumptions that theorists make about the preparation of qubits into a given state, the operation of the quantum gates, the reliability of the measurements, and so forth, cannot be fulfilled *exactly*. They can only be approached with some limited precision. So, the real question is: *What precision is required?* With what exactitude must, say, the  $\sqrt{2}$  (an irrational number that enters into many of the relevant quantum operations) be experimentally realized? Can it be approximated as 1.41 or as 1.41421356237? Or is even more precision needed? There are no clear answers to these and many similar crucial questions.

An important issue is related to the *energies* of the  $\uparrow$  and  $\downarrow$  states. While the notion of *energy* is of primordial importance in all domains of physics, both classical and quantum, it is not in the vocabulary of QC theorists. They implicitly assume that the energies of all  $2^N$  states of an ensemble of qubits *are exactly equal*. Otherwise, the existence of an energy difference  $\Delta E$  leads to oscillations of the quantum amplitudes with a frequency  $\Omega = \Delta E/\hbar$ , where  $\hbar$  is the Planck constant, and this is a basic fact of quantum mechanics. (For example, one of the popular candidates for a qubit, the electron spin, will make a precession around the direction of the Earth's magnetic field with a frequency  $\sim 1$  MHz). Should the Earth's magnetic field be screened, and if yes, with what precision?

Whatever is the nature of qubits, some energy differences will necessarily exist because of stray fields, various interactions, *etc.* resulting in a chaotic dynamics of the whole system, which will completely disorganize the performance of the quantum machine. I am not aware of any studies of this very general problem.

The problem of the accuracy required arises already at the first step, the preparation of the initial state of the quantum computer, which should be ( $\uparrow\uparrow\uparrow\uparrow\dots$ ), or in conventional notation  $|00000\dots\rangle$ , *e.g.* we start with all spins aligned in the  $z$ -direction, which will be the first task for the *future quantum engineer*. However, where is the  $z$ -direction? Certainly, it can be defined arbitrarily, but only *within a certain precision* (like any continuous parameter). Aligning spins along this direction can also be done only approximately. So, instead of the desired  $|00000\dots\rangle$  state, inevitably we will have an admixture of *all other states*, hopefully with small amplitudes.

The same question (again, without any answers) concerns *quantum gates*, that is our *manipulations* with the qubits required to perform a meaningful quantum calculation. For example, the theorist proposes us to flip the qubit, *i.e.* perform the operation  $|0\rangle \rightarrow |1\rangle$ . Obviously, this again cannot be done exactly (especially, since the initial state  $|0\rangle$  cannot be exact either), but the needed precision has not been established so far.

**Quantum annealing.** A completely different approach, initially started by the D-Wave company and now followed and developed by IBM, Google, Microsoft, and others, is based on using as qubits superconducting Josephson junctions at ultra-low dilution fridge temperatures. Depending on some parameters of the system, Josephson junctions can operate either as classical two-state bits (and classical computers using Josephson logic have been demonstrated), or as quantum bits.

This is *not* going to be the quantum computer everyone was talking about for the past 20 years, as it will *not* be able to factor large numbers by Shor's algorithm or to efficiently search databases by Grover's quantum algorithm. Rather, it is supposed to perform "*quantum annealing*". After initial preparation, any system, whether classical or quantum, at low temperature will relax to its ground state. Calculating the ground state of more or less complex quantum systems, either analytically or numerically, is usually impossible – this is what originally inspired Feynman's idea of quantum computing.

Hence comes the idea of *simulating* a system of interacting qubits by an equivalent system of superconducting quantum circuits based on Josephson junctions. One does *not* do any quantum calculations by applying quantum gates, and quantum error correction is not needed either. One has just to measure the state of the system after annealing, more precisely, one can measure *some* of its  $2^N$  parameters.

Such an approach is perfectly reasonable. However, Google claims that the 72-qubit

superconducting chip in a 10-millikelvin dilution refrigerator (note that such a system is described by  $2^{72} \sim 5 \times 10^{21}$  quantum amplitudes) will prove that quantum computers can beat classical machines, and thus demonstrate "quantum supremacy".

This claim appears to be somewhat exaggerated. The chip in question is not going to be a *quantum computer*, it will be only a specific quantum system (which might be quite interesting on its own) defined by the way the Josephson junctions are interconnected. It is not entirely clear what will be the possible practical use of such systems. However, such modelling might provide some additional knowledge on the behavior of large and complicated quantum systems. Recently, a remarkable simulation of the Kosterlitz–Thouless phase transition was demonstrated in a network of Josephson superconducting rings arranged in a frustrated lattice [4].

**Conclusions.** The hypothetical quantum computer is a system with an unimaginable number of continuous degrees of freedom – the values of the  $2^N$  quantum amplitudes with  $N \sim 10^3$ – $10^5$ . These values cannot be arbitrary, they should be under our control with a high precision (which has yet to be defined).

In riding a bike, after some training, we learn to successfully control 3 degrees of freedom: the velocity, the direction, and the angle that our body makes with respect to the pavement. A circus artist manages to ride a one-wheel bike with 4 degrees of freedom. Now, imagine a bike having 1000 (or  $2^{1000}$ !) joints that allow free rotations of their parts with respect to each other. Will anybody be capable of riding this machine?

Thus, the answer to the question in title is: As soon as physicists and engineers learn to control this number of degrees of freedom, which means – *never!*

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