

Quantum computation and information is a new, rapidly developing interdisciplinary field. Therefore, it is not easy to understand its fundamental concepts and central results without facing numerous technical details.

We refer here not only to problems of interest for physics and mathematics, but also to a much wider class of problems in different fields such as chemistry, biology, economics, medicine, engineering, social sciences, meteorology, population dynamics and so on. From the viewpoint of computational complexity, the following question naturally arises: More precisely, given a generic dynamical system, is it possible to find its solution at time t efficiently? That is, since the number of bits required to specify the time t is $\log t$, can we solve the problem in a number of operations polynomial in $\log t$? We shall see in this section that this is not the case for a generic dynamical system, whose evolution is typically described by non-linear equations. Let us briefly explain the meaning of the wording "deterministic chaos". A system is said to be deterministic when its future, as well as its past, are determined by its present state. On the other hand, the motion of the system can be so complex as to be indistinguishable in practice from purely chaotic motion. This property allows us to reconcile the determinism of physical laws and the apparent chaoticity of natural phenomena, such as turbulence, which we observe in everyday life. Hence, the term "deterministic chaos" is not self-contradictory, since a phenomenon can be both deterministic and chaotic: Let us try to clarify this statement. We first consider the harmonic oscillator, namely, the simplest example of a classical solvable or so-called integrable system. In this way, we obtain a sequence of integers, which provides a coarse-grained description of the orbit. For a chaotic system, no regularity appears. Therefore, for chaotic orbits, knowledge of the coarse-grained past is not sufficient to determine the coarse-grained future. In contrast, this is possible in nonchaotic systems, since the coarse-grained orbit exhibits regularities. Note that no restrictions on the size of the partition have been made. That is, a sequence of finite precision measurements is unable to predict the future of a chaotic system, independently of their finite precision. Let us illustrate the concept of deterministic chaos by means of an example. We consider the logistic map, one of the best known models for studying the transition to chaos. The behaviour of the logistic map is very complicated and exhibits regions of regular or chaotic motion when the parameter a is varied. In particular, the map is fully chaotic for $a \geq 4$. It has the following simple analytic solution: Therefore, one bit of information is erased at each map step. It is now easy to show that the solution of the deterministic equation 1. In our example the unit interval $[0,1]$ plays the role of the energy surface the orbit resides in this interval. From the binary representation 1. Since the decimal point moves one digit to the right at each map step, the coarse-grained orbit corresponds to the binary representation 1. Indeed, if we know the first t digits of the binary expansion of y_0 , we cannot determine the subsequent digits. As time goes on, the solution will depend on ever diminishing details of the initial condition. In other words, when we fix y_0 we supply the system with infinite complexity which arises owing to the chaotic nature of the motion. How random is the solution of Eq. Let us assume that someone who knows the precise solution of 1. Say that 0 corresponds to heads, 1 to tails. The answer is no. Indeed, we can easily convince ourselves that the set of all possible initial conditions y_0 is in one-to-one correspondence with the set of all possible coin-tossing sequences. Therefore, the orbit itself is also random. Each binary digit carries one bit of information. Therefore, an n -bit binary sequence can carry n bits of information. However, if there are correlations between digits, the information contained in this n -bit string can be expressed by a shorter sequence.

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Chapter 2 : Principles Of Quantum Computation And Information Vol. 1: Basic Concepts

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VIII Principles of Quantum Computation and Information General approach Quantum computation and information is a new and rapidly developing field. It is therefore not easy to grasp the fundamental concepts and cenÅ-.

Advanced Search Abstract The behavior of individual microscopic particles, such as an atom or a photon, predicted using quantum mechanics, is dramatically different from the behavior of classical particles, such as a planet, determined using classical mechanics. How can the counter-intuitive behavior of the microscopic particle be verified and manipulated experimentally? David Wineland and Serge Haroche, who were awarded the Nobel Prize in physics in 2012, developed a set of methods to isolate the ions and photons from their environment to create a genuine quantum system. Furthermore, they also developed methods to measure and manipulate these quantum systems, which open a path not only to explore the fundamental principles of quantum mechanics, but also to develop a much faster computer: Their achievements involve individual or a few atoms and photons, which are the fundamental particles in quantum physics. Wineland worked on the ion trap system that traps the ions in an electromagnetic potential. He and his group developed methods in particular, the sideband cooling method to cool the ions to their ground state without phonons, by interacting with laser fields. Using these technologies, the ion trap is an ideal system to test the fundamental principles of quantum mechanics, to demonstrate the feasibility of the quantum computation and to improve the accuracy of the clock standard. A Rydberg atom is used to interact with the field in the cavity. The interaction should be significantly strong because of the high Q, making it a good detector for monitoring the field. With the aid of a quantum non-demolition measurement, this system could be a very good platform to test quantum information theory and fundamental problems in quantum mechanics, especially the decoherence processes. Their achievements are not only very important for fundamental quantum mechanics, but they also paved the way for quantum technologies, such as quantum computation. In the following, we introduce their experimental methods and their applications. Quantum mechanics provide the basic principles for the microscopic world, and general relativity describes the large-scale universe. Quantum mechanics has been successfully used to understand experiments at the atomic scale. Unlike general relativity, which is based on very simple assumptions, quantum mechanics is based on more complex explanations. According to the Copenhagen interpretation, quantum theory includes three basic parts: The state of a quantum system is represented by a vector: Based on the structure of the Hilbert space, the quantum state could be a linear superposed state on various bases, which is known as the superposition principle of quantum states: $H(t)$ is a time-dependent Hamiltonian of the system controlling the evolution. Therefore, the manipulation of a quantum system can be described by some ordered unitary operators and is exactly determined by the Hamiltonian $H(t)$. The evolution of a quantum state is well defined; however, the results of the measurements are random. A measurement is a subtle process in quantum mechanics and fills the gap between the quantum world and our classical world. A measurement plays a central role in the fundamentals of quantum mechanics. A general measurement must have the following characteristics according to the Copenhagen interpretation as described in [3]: When immediately repeating the same measurement on a quantum system, the same outcome should result. Each outcome of a measurement should be one of the eigenvalues of the measured variable, and the final state of the measured system should be one of the eigenstates. This process is called collapse processing. This result means that all of the particles are strongly correlated. This type of correlation between different particles extends beyond classical correlation and is called quantum correlation. One of the most important quantum correlations is described by quantum entanglement. Quantum entanglement plays a critical role in quantum information and quantum computation. The power of quantum technologies originates mainly from the entanglement of the quantum system. The Copenhagen interpretation of the measurement process is partly phenomenological, and the collapse interpretation is not well satisfied. A more elegant interpretation of the measurement should unify the measurement process and the evolution. Much research has been devoted to this

problem [3]. Introducing decoherence into the measurement process is a promising approach to filling the gap between the classical and quantum world. Generally, a quantum system is not isolated and interacts with its environment. When considering the measurement process, its environment must be included. Because the environment has a large number of degrees of freedom, it should be Markovian, and the coherent information between the observed system and measurement instrument is completely lost for the non-Markovian environment [4] the coherence will revive after some time when we trace out the environment. Finally, the observed system will collapse to a classical ensemble system. Therefore, the decoherence process is one of the fundamental problems in quantum mechanics. Therefore, to maintain the coherence superposition character of the quantum system, the system must be isolated enough to avoid interaction with the environment, according to decoherence theory. One of the remarkable applications of the superposition of the quantum state is that it can be used to design certain quantum algorithms with parallelism and can significantly speed up the computation. This algorithm is used to factorize a large number into two prime numbers. Before this algorithm, the most efficient classical algorithm for this problem grew exponentially with the length of the number. The efficiency of the new algorithm will destroy the security of the widely used Rivest, Shamir and Adleman algorithm. However, it is not easy to build a system to realize the powerful quantum algorithm in a physical system. The quantum system must satisfy special conditions, which are called the DiVincenzo criteria [6]: There are well-defined local qubits, which are isolated two-level systems. The entire system can implement a few local quantum gates forming a universal set, generally including single-qubit unitary operations and a two-qubit controlled-NOT CNOT gate or a controlled phase gate. A universal quantum computer can be realized using these gates. There is an efficient qubit measurement method to read out the results. The system is a scalable system that allows us to coherently manipulate many qubits. Wineland and his co-workers performed many experiments to demonstrate that the ion trap is an ideal system to realize quantum computation. In addition, if we are more ambitious in building a quantum network, then the system has additional requirements to connect the quantum computers located at different nodes. Generally, the information transmits between different nodes using flying qubits photons. Therefore, the state of a stationary qubit computation qubit needs to be efficiently converted into a flying qubit. The most popular individual quantum system is an atom or a photon. Generally, an atom or a photon moves in a vacuum and is difficult to manipulate and measure. Therefore, it is important to be able to confine it. The ion, which is a charged atom, can be trapped in a specific electromagnetic potential using the technique developed by Paul and Dehmelt [7 , 8], who were awarded the Nobel Prize in Physics. In general, it is impossible to trap a charged atom in a stationary electromagnetic field because of the analytic character of the field. The entire instant electromagnetic potential is a trap potential with a saddle point [7 , 8]. The time-dependent field will make the potential rotation and trap the ion at the saddle point see Fig. One simple experimental setup is presented in Fig. View large Download slide The potential of the ion trap, which is set up as in Fig. A saddle point exists in the instantaneous potential where the ion is not stable. However, the time-dependent field will cause the potential to rotate; from the time average view, the potential will have a minimal point, and the ion will be confined. The setup of a typical ion trap. There are five poles in total, two of which are connected to a radio-frequency RF current and the others to a direct current. The scheme of sideband cooling details are provided in the text. Redrawn from figure in [18]. View large Download slide The scheme of sideband cooling details are provided in the text. Generally, the depth of the trap potential is of several volts, and the kinetic energy of the ions is approximately of the same magnitude. To reach the quantum region quantized oscillation , the ion should be cooled down after the trapping. The Doppler cooling of the ions is the first important step to trap the ions, which Wineland and Dehmelt proposed in [9]. The laser frequency in the Doppler cooling processes should be tuned to a slightly lower frequency than the transition frequency of the atoms charged or neutral. After some time, the photon will then be emitted spontaneously. The spontaneous emission is random in all directions, and the average momentum for different atoms or the average over a long time for a single atom will be zero. Generally, the velocity of the atom will be reduced. If we set up two opposite lasers and

scan the detuning slowly, the velocity of the atoms along the direction of the light will be reduced. If six lasers are set along the x, y and z directions, the momentum in all of the directions will be reduced, and the temperature of the atoms will be lower. There is a Doppler cooling limit, which is caused by the recoil energy of the ion when it emits a photon. However, for many applications, such as precise spectroscopic measurements and quantum computation, the ions should be further cooled to a lower temperature such as the ground state of the system. In precise measurements, an extremely low temperature, which corresponds to the low velocity of the ions, is required to eliminate the Doppler effect. These requirements call for new cooling techniques. After Doppler cooling, the temperature of this system was low enough to quantize the oscillation of the trapped ions. Therefore, two sets of quantized levels were present in this system: The coupling between these two sets of levels will play an important role in further cooling and quantum computation. The coupling between the internal level of an ion and the quantized harmonic oscillator in a trap can be induced by a laser. The interaction can then be described by a simple Hamiltonian under the Raman-Dicke approximation, a rotating wave approximation and setting of the detuning between the laser frequency and the atom frequency to be the trap frequency [15]: This Hamiltonian will play a key role in the further cooling process, i. The sideband cooling technique was developed by Wineland and his colleagues [16 , 17]. This technique can be used to cool the ion to the lowest energy level by reducing the oscillator of the system to zero. The excited ion will then decay to the lower state with fewer oscillators. If the processes continue, the ion will eventually be stable at the state without an oscillator. The entire process is similar to the optical pumping processes [19]. Wineland and his colleagues [20-22] used well-cooled single ions as optical clocks, which was based on the transition within the optical domain, and dramatically improved the precision of the optical clock see Fig.

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Chapter 4 : Principles of Quantum Computation and Information Vol. 1: Basic Concepts - PDF Free Download

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