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## QUANTUM SIMULATORS

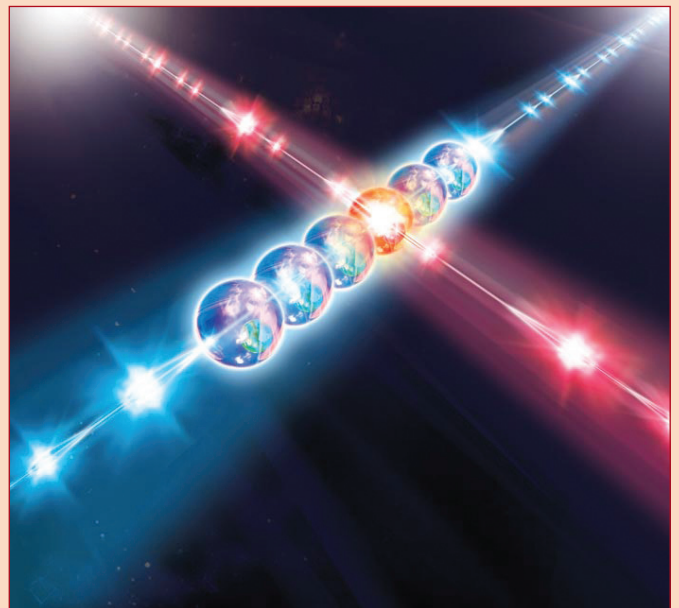
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### An introduction to quantum simulators

The universal quantum computer will revolutionize our technology in the future. Unfortunately, this future does not seem to be very close at hand. However, quantum computers with a special purpose, i.e. quantum simulators, already exist.

Various quantum phenomena such as high- $T_c$  superconductivity or quark confinement are still awaiting universally accepted explanations because of the computational complexity of solving the simplified theoretical models designed to capture the relevant physics. Richard Feynman, in 1982, suggested solving such models by 'quantum simulation'. He pointed out that it might be possible sometimes to find a simpler, and experimentally more accessible, system to mimic the quantum system of interest. Feynman's idea was motivated by the complexity of classical simulations of quantum systems. Suppose we want to study a system of  $N$  spins  $\frac{1}{2}$ ; then the dimension of the Hilbert space is  $2^N$ , and the number of coefficients we need to describe the wave function of the system may be in principle just as large. As  $N$  grows, this number quickly becomes larger than the number of atoms in the universe, so classical simulations are evidently impossible. Of course, in practice this number may be very much reduced by using clever representations of the wave functions, but in general there are many quantum systems which are very hard to simulate classically.

The modern concept of quantum simulators is not exactly the same as that of Feynman. Since condensed matter systems are typically very complex, theorists therefore construct simplified models. In this simplification, symmetries of the original problem are kept intact, and the concept of universality is used: different Hamiltonians with similar symmetry properties belong to the same universality classes, i.e. they exhibit the same phase transitions and have the same critical exponents. Unfortunately, even these simplified models are often difficult to understand. A paradigmatic example of such a situation concerns high- $T_c$  superconductivity of cuprates, where it is believed that the basic physics is captured by an array of weakly coupled 2D Hubbard models for electrons, i.e. spin- $\frac{1}{2}$  fermions. Even this simple model reduced to one 2D plane does not allow for accurate treatment, and there is much controversy concerning, for instance, the phase diagram or the character of the transitions. The role of quantum simulators, as proposed in many quantum information projects, will be to simulate simple models, such as 2D Hubbard models, and obtain a better understanding of them, rather than try to simulate the full complexity of the condensed matter.



*Artist's impression of laser pulses controlling a six-ion digital quantum simulator. (Courtesy: Harald Ritsch)*



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### A 'working' definition of a quantum simulator could be as follows<sup>1</sup>:

- A quantum simulator is an experimental system that mimics a simple model, or a family of simple models, of condensed matter (or high-energy physics, or quantum chemistry...).
- The simulated models have to be of some relevance for applications and/or our understanding of the challenges of the above-mentioned areas of physics.
- The simulated models should be computationally intractable for classical computers. Note that this statement may have two meanings: i) an efficient (scalable to large system size) algorithm to simulate the model might not exist, or might not be known; ii) the efficient scalable algorithm may be known, but the size of the simulated model is too large to be simulated under reasonable time and memory restrictions. The latter situation, in fact, occurs with classical simulations of the Bose or Fermi Hubbard models as compared to their experimental quantum simulators. There might also be exceptions to the general rule. For instance, it is desirable to realize quantum simulators to simulate and to observe novel, hitherto only theoretically predicted phenomena, even though it might be possible to simulate these phenomena efficiently with present-day computers. Simulating and observing is more than just simulating.
- A quantum simulator should allow for broad control of the parameters of the simulated model, and for control of the preparation, manipulation and detection of the states of the system. In particular, it is important to be able to set the parameters in such a way that the model becomes tractable using classical simulations. This provides the possibility of validating the quantum simulator.

There exist many proposals for quantum simulators employing ultracold atoms in optical lattices, ultracold trapped ions, atoms in arrays of cavities, atoms/ions in arrays of traps, quantum dots, or superconducting circuits. The EPL compilation constitutes an excellent selection of papers that have been published in the journal on this subject.

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<sup>1</sup> Lewenstein M, Sanpera A and Ahufinger V 2012 *Ultracold Atoms in Optical Lattices: Mimicking Quantum Many-Body Systems* (Oxford: Oxford University Press) in press (to appear January 2012)