The Quantum Computing Company™

Phase transitions in a programmable quantum spin-glass simulator

SYNOPSIS

Summary

In *Science*, July 13, 2018, researchers from D-Wave Systems Inc. report upon using a 2048-qubit quantum processing unit to experimentally study a computationally difficult problem known within the field of quantum magnetism as the transverse field Ising model. The researchers programmed 3-dimensional cubic lattices containing up to 512 quantum spins into their processor and studied the magnetic properties as a function of energy scales and intentionally induced disorder. The predicted phase transitions between paramagnetic and ordered antiferromagnetic phases for low concentrations of disorder, and between paramagnetic and spin-glass phases for high concentrations of disorder, were demonstrated as a function of the quantum mechanical energy scale.

What is a phase transition?

Physical systems composed of large numbers of particles can be described by aggregate bulk properties that define a so-called *phase*. For example, water can be in either a solid, liquid, or gas phase depending on external conditions such as temperature and pressure. Slowly tuning the external conditions can reveal a critical point at which a material makes a discrete *phase transition*. The solid-to-liquid phase transition of water at 0 °C and standard atmospheric pressure is a familiar example.

Magnetic systems also exhibit phase transitions. For example, bar magnets are composed of a large number of electronic magnetic moments that are aligned parallel to one another, thus giving rise to a macroscopic magnetic field. This is referred to as the *ferromagnetic* phase. However, if a bar magnet is slowly heated, then one will observe a critical temperature at which the ferromagnetic phase disappears because the moments become randomly oriented. In this so-called *paramagnetic* phase, the net magnetic field created by the sum over all individual moments is zero.

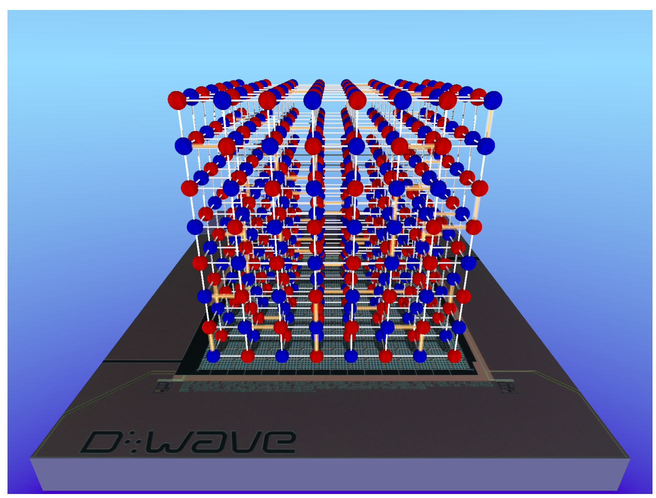

Figure 1: An illustration of one particular $8 \times 8 \times 8$ cubic lattice instance studied in *Science*, July 13, 2018. Red and blue spheres represent the two possible states of the magnetic moments. Silver bars represent antiferromagnetic interactions that favor alternating (red-blue) ordering of the moments. Gold bars represent randomly added ferromagnetic interactions that favor uniform (blue-blue or red-red) ordering. These latter interactions serve to disorder the otherwise antiferromagnetic (alternating) ordering of the moments.

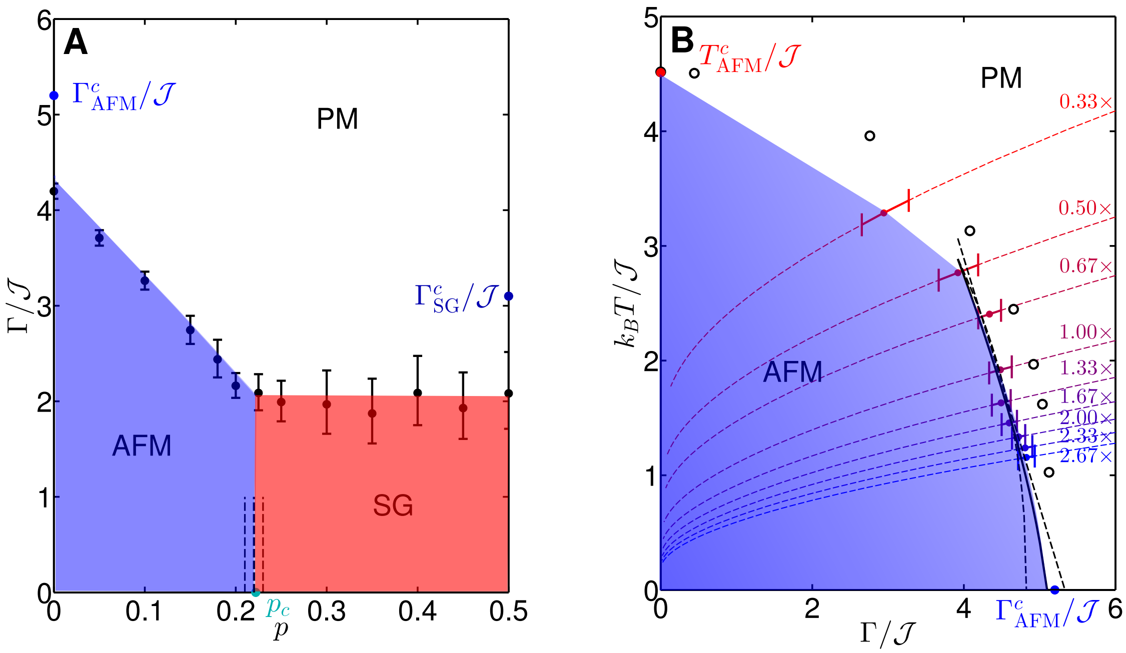

Figure 2: Experimentally determined phase diagrams for the TFIM on a cubic lattice. In **A**, phases are shown as a function of ferromagnetic interaction concentration, or disorder, p and dimensionless quantum mechanical energy scale $\Gamma/\mathcal{J}$ on the horizontal and vertical axes, respectively. The three magnetic phases are identified as paramagnetic (PM), antiferromagnetic (AFM), and spin glass (SG). In **B**, phases are shown as a function of $\Gamma/\mathcal{J}$ and dimensionless temperature $k_BT/\mathcal{J}$ on the horizontal and vertical axes, respectively, for no disorder $p = 0$. Figure reproduced from *Science*, July 13, 2018.

What was accomplished?

One of the *quantum processing unit* (QPU) technologies being developed by D-Wave realizes a particular quantum magnetic system known as the *transverse field Ising model* (TFIM). The premise is that a QPU based on the TFIM can harness the physics of phase transitions for performing computation. In this case, it is the tuning of a quantum mechanical energy scale, via a process referred to as *quantum annealing*, that drives phase transitions. Since the interactions between magnetic moments are programmable within the QPU, a single processor can be used to represent a wide variety of magnetic instances within the TFIM.

In *Science*, July 13, 2018, researchers report on using a 2048-qubit QPU to study 3-dimensional simple cubic lattices up to dimensions $8 \times 8 \times 8$ (512 quantum spins) as a function of quantum mechanical energy scale, interaction energy scale, and disorder among the programmable interactions. Of note, the structure of the magnetic system studied was vastly different from the physical layout of qubits within the QPU. The magnetic phases and, most importantly, the phase transitions were correctly identified within the 3-dimensional space defined by the aforementioned energy scales and disorder.

Why is this interesting?

A *quantum simulator* is an engineered quantum system that can be programmed to simulate other quantum systems. It has been proposed that a large-scale quantum simulator could perform computational tasks in many branches of science and engineering that may be otherwise intractable using classical digital computing technologies. The results presented in *Science*, July 13, 2018 represent some of the most advanced steps to date toward realizing Richard Feynman's original vision of a quantum simulator.

