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Ising machines offer an optimized solution

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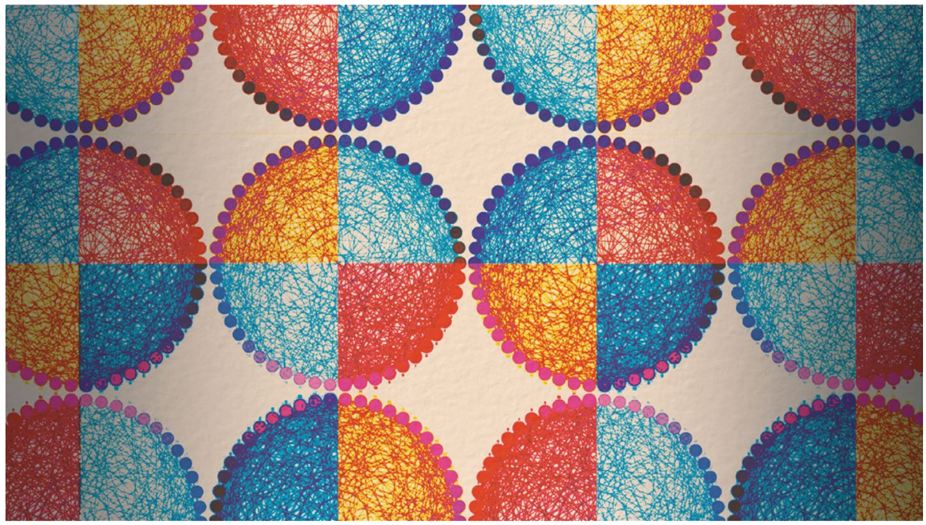
Computing hardware that can find the ground states of the Ising model could provide a powerful route to solving difficult combinatorial optimization problems.



Combinatorial optimization problems are ubiquitous, emerging in applications ranging from resource allocation and quantitative finance to artificial intelligence and circuit design. The problems often belong to the non-deterministic polynomial-time (NP)-hard or NP-complete complexity class — and the computational resources required to solve such problems can scale exponentially with problem size. Many NP-hard problems can though be related to one another, and thus solving one allows others to also be solved (with a polynomial overhead). And here the Ising problem is particularly helpful.

The Ising problem was first developed in the 1920s by Wilhelm Lenz and Ernst Ising, and was originally proposed as a simplified model for ferromagnetism. It involves finding the ground-state arrangement of interacting up and down spins. The problem belongs to the NP-hard complexity class, and it can be mapped to other NP-hard and NP-complete problems. Thus, if there is an effective route to solving the Ising problem, it can be used to solve other combinatorial optimization problems as well.

The problem is conventionally solved with digital hardware and heuristic algorithms. But in efforts to develop efficient methods to solve difficult combinatorial optimization problems, novel forms of computing hardware are also being explored that take inspiration from the physics of interacting spins and aim to find the ground states of the Ising model. Such Ising machines have been developed using a variety of physical systems, including optical states, trapped ions, superconducting circuits and complementary metal–oxide–semiconductor (CMOS)-based devices. But one approach that has been of increasing interest in recent years is the oscillator-based Ising machine[1].

An oscillator can be made to function like an Ising spin, with the up and down spins represented by the phase of the oscillator. Networks of coupled oscillators can then synchronize into low-energy states and can be used to physically implement an Ising machine. Relying on the nonlinear dynamics of oscillators[2], the systems can be built from almost any type of oscillator.

Back in July 2021, for example, Suman Datta and colleagues at the University of Notre Dame, Georgia Institute of Technology and Cornell University reported an Ising machine based on a network of electrically coupled phase transition nano-oscillators[3]. And then in May 2022, Chris Kim and colleagues at the University of Minnesota reported an Ising machine based on a coupled ring oscillator circuit fabricated with 65-nm CMOS technology[4]. Now, in an Article in this issue of *Nature Electronics*, Kim and colleagues take this approach further and report an Ising machine that is based on coupled ring oscillators and offers an all-to-all connected array architecture. The machine allows optimization problem graphs with up to 48 nodes to be directly mapped to the hardware.

As Tianshi Wang at HiSilicon Technologies in Shanghai explores in a News & Views article elsewhere in this issue, challenges remain before such oscillator-based Ising machines can offer a practical technology. The hardware implementations need to go beyond proof-of-concept demonstrations for a start, which will require fundamental studies that connect the performance and shortcomings of the hardware to the underlying mechanisms. The field also now needs to develop "a suite of benchmark problems derived from practical applications", Wang argues. These could then help identify suitable architectures for Ising machines.

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