The peculiar principles of quantum theory mean that, in a quantum state, a many-particle system can exhibit behaviour that would be inconceivable within classical physics. Superfluids, such as liquid helium at very low temperatures, can flow with no viscosity; superconductors can carry electricity with absolutely zero resistance.

These systems fall into states with so-called quantum coherence — unusually strong correlations of behaviour among many particles, which can only be interpreted with quantum mechanics. Quantum coherence underlies many of the most exciting phenomena of modern physics, including high-temperature superconductivity and the quantum Hall state, in which several fundamental particles collectively form a composite particle with a fraction of the elementary charge.

Historically, most of these phenomena were discovered by accident; however, scientists have made enormous progress in learning to control electronic behaviour in solids, and to create genuine many-body phenomena with cold atoms. Further progress in techniques for this nascent field of quantum engineering over the next decade will advance both fundamental physics and new technologies.

STATUS OF THE FIELD

Control of quantum coherence in solids has progressed fastest in semiconductors, in which modern fabrication techniques make it possible to grow nearly perfect crystalline materials and to confine electrons in constricted spaces of zero, one or two dimensions, creating respectively quantum dots, wires or wells. Such precise confinement has allowed scientists to probe fundamentally new physics. A quantum dot, for example, is akin to an artificial atom in which the force binding the electrons, and the atom’s energy levels, can be carefully tuned. Consequently, quantum dots have been used to create powerful devices in electronics and laser optics.

Going further, researchers have recently learned to create quantum dots, wires and wells that interact with one another — or with other nanostructures such as carbon nanotubes — in a controlled way. This capability has revolutionized understanding of fundamental many-particle phenomena, including the decades-old mystery of the Kondo effect, which describes an increase in electrical resistance at low temperatures in the presence of magnetic ion impurities in non-magnetic crystals. Progress in fabricating more precise semiconductor structures will create further opportunities to probe similar quantum-coherent phenomena with unprecedented precision.

BOSE-EINSTEIN CONDENSATION

Similar dramatic progress has been made in atomic physics. Fifteen years ago, after long effort, physicists finally observed the Bose-Einstein condensation — an archetypal example of quantum coherence in which all the atoms in an extremely cold gas behave identically. This landmark advance kick-started a new era of many-body physics and researchers have since learned to control the strength of atomic interactions in these gases over a wide range. By imposing periodic laser fields on dilute gases, to influence atomic motion in a similar way to how internal fields influence electrons in crystalline solids, researchers have also been able to probe many-particle phenomena previously seen only in solid matter.

Such experiments illustrate how solid materials and systems of cold atoms provide complementary opportunities for exploring novel quantum many-body physics. The diversity of atomic elements offers a virtually unlimited variety of solid compounds for the possible discovery of many-body states, and atomically precise nanostructures can be built out of increasingly complex compounds. Physicists using cold-atom systems can tune how strongly the atoms interact and the shape of the optical-defined energy landscapes in which they reside. This flexibility presents opportunities for testing some of the most basic models of solid-state theory in ways not possible with real solids.

FUTURE DIRECTIONS

The cold-atom approach has been demonstrated for bosonic systems — comprising particles with integer values for spin (Fig. 1). A major challenge is to extend this approach to fermionic systems — containing particles, such as electrons, of half-integer spin. These systems have physical properties that are notoriously difficult to compute. This is especially significant as the dynamics of fermionic systems might hold the key to some of the most fascinating phenomena in solid-state physics. For example, fermionic cold-atom systems can potentially be used as ‘quantum simulators’ — capable of accurately simulating the physics of strongly interacting fermions, especially in frustrated networks with an ordered structure that forbids a minimal energy state and for which there is so far no solution (see Highlight Box, below left).

Analogous approaches exist in solid-state physics, where techniques used to build nanostructures one atom at a time might offer a clear path to controlling the...
spin–spin interactions of a macroscopic number of electrons. The realization of model spin systems in complex metal oxide structures (Fig. 2) could offer clues for controlling and stabilizing quantum phenomena such as superconductivity at room temperature$^{3,4}$.

**TOWARDS QUANTUM COMPUTING**

Another long-term vision of quantum many-body physics research is the quantum computer, which would exploit the phenomenon of quantum coherence to solve problems that are currently intractable. Such a device would use individual elements — quantum bits or ‘qubits’ — that can now be realized either in the form of atoms, molecules or ions confined to optical traps or implanted in solids, or as solid-state microstructures or nanostructures.

It is unlikely that bona fide quantum computers will be developed before 2020, but even limited devices will find applications in quantum communication and cryptography$^5$; they might also yield insights into quantum information theory, which might in turn stimulate the development of novel computational methods for many-body problems$^6$.

Another research field studies the topological properties of many-body wave functions, with the aim of avoiding unwanted disruption by the environment$^7$. This ‘decoherence’ issue is one of the key obstacles to quantum computation specifically, and to many-body physics in general.

Realizing the tremendous potential of quantum coherence in systems of many particles will require a significant investment in research infrastructure. New experimental methods need to be developed to cool gases of fermionic atoms or molecules, for example, or to create hybrid devices bringing together solid-state nanostructures and cold-atom systems. Nonetheless, advances in this new field of quantum engineering promise an exciting and surprising future for fundamental and applied research.

More precise control over quantum phenomena will help realize advances in fundamental physics and a range of new technologies.

Being able to build solid structures with extreme resolution at the nanoscale will be crucial.

There will be closer synergy between atomic and solid-state physics as complementary means for probing quantum many-particle systems.

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**Fig. 1** | Single-atom resolved snapshot of density distributions.

The Bose-Einstein condensate (left) shows large density fluctuations, whereas these are suppressed in the Mott insulators (middle and right).

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**Fig. 2** | Valence electron wavefunctions of a superconductor and an artificial superlattice.

Doped La$_2$CuO$_4$ (left) is a high-temperature superconductor. Its electronic structure is copied in an artificial superlattice (right) consisting of the metal PrNiO$_3$ and the insulator PrScO$_3$. The behaviour of electrons in these systems makes them candidates to exhibit engineered high-temperature superconductivity$^{8,9}$.