The joy of simulation

The Oxford English Dictionary offers a definition of 'simulate' as "to give a computer model of a process". But this way of thinking is a little narrow. Simulation means exploring the workings of one thing by studying something else, whether it involves computation or not. We only need confidence that the two things are somehow similar, with one being simpler, perhaps, or at least easier to control.

So, we can simulate the formation of crystalline solids with plastic microspheres suspended in liquid, or the creation of cosmic strings as defects in samples of liquid helium. Computation is useful, of course, but, for any specific phenomenon, other methods may be faster and more accurate — or just more instructive and compelling. Take, for example, the surging interest in ultracold atoms, cooled, trapped and manipulated by lasers, as a way to mimic the rich dynamics of condensed-matter systems.

A decade ago, when researchers first achieved Bose–Einstein condensation in a gas of ultracold rubidium atoms, one could wonder whether confirming an uncontroversial prediction was really worth it. But the experimental techniques involved were perhaps more interesting than the result, and reflected a tremendous advance, especially in experimental atomic physics and quantum optics, that is now producing a practical means for building physical models more or less from scratch. In an optical lattice, researchers can now put atoms together, design their interactions, and then watch what happens — a recipe for simulations that are sometimes better than either computation or even real condensed-matter experiments.

Sometimes the results confirm the expected, but with a pleasing elegance. For example, three lasers propagating at right angles can create a periodic potential with a three-dimensional array of trapping centres. Atoms introduced into this field act something like electrons in an ionic lattice, except that here there are no lattice vibrations to complicate matters, and both the temperature of the atoms and the strength of the potential can be easily tuned. In this setting, a number of experiments have documented a beautiful transition from a superfluid to a Mott-insulating phase, having precisely one atom per centre.

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But the real hope is to probe physics that we cannot currently either produce or measure in real-world systems. For example, ultracold atoms confined in two dimensions by laser fields show tantalizing evidence for the break-up of paired vortices in a phase transition with increasing atomic temperature — as predicted by the Berezinskii–Kosterlitz–Thouless theory. Experiments in liquid helium confirmed the basic picture long ago, yet this new experiment comes closer than anything yet to confirming the supposed mechanism (Z. Hadzibabic *et al. Nature* **441,** 1118–1121; 2006).

These are early examples of what is likely to be a long line of such simulations probing otherwise elusive phenomena, ranging from quantum fluctuations in one dimension to disorder-induced localization, and from exotic quantum phases relevant to high-temperature superconductivity to lattice gauge theory. And it is all the rather surprising result of the seemingly mundane — the development of better ways to trap and hold atoms and of optical means for controlling their interactions.

Mark Buchanan

Universal effect

Neutrinos have always been my favourite elementary particles. In spite of, or perhaps because of, their elusive nature, they were key to unravelling the nature of both the strong and weak interactions. Astrophysical neutrinos provided — through the observation of oscillations between different neutrino species, which require neutrinos to have mass — the first definitive evidence for new physics beyond the standard model of elementary particles.

But oscillations are not an unambiguous pointer to the source or energy scale of the new physics. Moreover, they do not pin down the mass of the neutrinos, but only the scale of the mass differences between neutrino types. As a result, we do not even know whether the electron neutrino is heavier than the muon neutrino, or vice versa.

All this may change in the near future. New terrestrial experiments and, in particular, new astrophysical observations, might be directly sensitive to neutrino masses: I find it remarkable that an observation of minute gravitational effects associated with the clustering of galaxies in the Universe might be sensitive to neutrino masses, over ten million times smaller than the mass of the electron.

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For example, the South Pole Telescope will measure small temperature and polarization anisotropies in the cosmic microwave background radiation, caused by the radiation's traversal of clumps of matter, such as galaxies and clusters, over the past 14 billion years. Untangling these effects can, in principle, enable precise three-dimensional 'tomography' of the distribution of matter on a wide range of cosmological scales. If neutrinos have masses in the range suggested by oscillation experiments, then cosmological neutrinos left over from the Big Bang should leave an imprint on the clustering of matter that may be detectable by the end of this decade.

It would be another triumph for the power of cosmological observations, and for neutrinos as an empirical guidepost, constraining the otherwise vivid imaginations of particle theorists.

Lawrence M. Krauss