Natural or not? A single-channel meandering form provides the template for many river engineering and restoration projects, but as Walter and Merritts show in this issue, it may not reflect forms that predated anthropogenic modifications.

multithread channels to meandering single-thread channels occurred in all three regions. This observation suggests that a common transformation accompanied human development of temperate forest rivers.

Walter and Merritts also help to resolve a long-standing geographical conundrum. Recent studies have confirmed the long-articulated idea that modern agriculture greatly accelerated rates of soil erosion (*7–9*), but at the same time, sediment delivery to oceans declined by half (*10*). Where is all the dirt thought to have been stripped from upland farms? Walter and Merritts show that tremendous amounts of floodplain sediment previously thought to date back thousands of years actually represents material impounded behind mill dams. Here may lie much of New England's precolonial topsoil.

The study by Walter and Merritts also has substantial implications for river restoration. The implicit mantra of such restoration programs—enough studying, let's just fix it—has been based on the idea of reengineering an archetypal meandering channel form. Given the compelling demonstrations of extensive human alteration of the fundamental morphology of river systems in New England (*1*), Europe (*4*), and the Pacific Northwest (*5*, *6*), the first step in a river-restoration program should instead be to develop a solid understanding of what the targeted rivers were actually like before the changes that restorationists seek to undo or mitigate.

Over recent decades, substantial progress has been made in deepening the understanding of how rivers work and addressing how different environmental contexts in different regions left their own mark on rivers. The report by Walter and Merritts shows that it pays to do the painstaking work of historical sleuthing—even in areas thought to define benchmarks in understanding.

References

1. R. C. Walter, D. J. Merritts, *Science* **319**, 299 (2008).
2. L. B. Leopold, M. G. Wolman, J. P. Miller, *Fluvial Processes in Geomorphology* (Freeman, San Francisco, 1964).
3. D. Rosgen, *Applied River Morphology* (Wildland Hydrology, Pagosa Springs, CO, 1996).
4. K. Harwood, A. G. Brown, *Earth Surf. Process. Landforms* **18**, 741 (1993).
5. B. D. Collins, D. R. Montgomery, *Restor. Ecol.* **10**, 237 (2002).
6. D. R. Montgomery, *King of Fish: The Thousand-Year Run of Salmon* (Westview, Boulder, CO, 2003).
7. D. R. Montgomery, *Dirt: The Erosion of Civilizations* (Univ. of California Press, Berkeley, 2007).
8. D. R. Montgomery, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 13268 (2007).
9. B. H. Wilkinson, B. J. McElroy, *Geol. Soc. Am. Bull.* **119**, 140 (2007).
10. J. P. M. Syvitski, C. J. Vörösmarty, A. J. Kettner, P. Green, *Science* **308**, 376 (2005).

10.1126/science.1153480

PHYSICS

Probing Quantum Magnetism with Cold Atoms

The interactions of atoms held in an optical trap reveal fundamental mechanisms of magnetism.

Maciej Lewenstein and Anna Sanpera

In 1995, ultracold atoms were experimentally locked together in a single quantum state known as a Bose-Einstein condensate (*1*). Since then, researchers keep broadening the scope of research with ultracold atoms. On page 295 of this issue, Trotzky *et al.* (*2*) report measurement of interactions between atoms trapped in an optical lattice that are analogous to the interactions between atomic spins in magnetic materials, a phenomenon called "superexchange." This is an essential step toward experimental realization of models for studying arrangements of quantum spins. These relatively simple models will help us study and understand the most fundamental physics associated with quantum magnetic ordering, quantum phase transitions, and a large zoo of exotic quantum phases.

The authors are at the Institució Catalana de Recerca i Estudis Avançats, E-08010, Barcelona, Spain. M. Lewenstein is also at the Institut de Ciències Fotòniques, E-08860, Castelldefels, Spain. A. Sanpera is also in the Grup de Física Teòrica, Universitat Autònoma de Barcelona, E-08193, Bellaterra, Spain. E-mail: maciej.lewenstein@icfo.es

Although spin models have been traditionally constructed as ideal approximations of real magnetic materials, many theorists have pointed out that ultracold atoms in optical lattices allow for an almost perfect realization of these systems [see review (*3*) and references therein]. An optical lattice is a spatially ordered array of potential wells or traps produced by the interference pattern of counterpropagating laser beams. In simpler terms, the optical lattice looks effectively like an egg carton, where the atoms, like eggs, can be arranged one per well to form crystals of quantum matter.

These quantum crystals can be controlled and manipulated by modifying the frequency, intensity, or polarization of the lasers forming the lattice. One can also superimpose a secondary optical lattice (or "superlattice") on top of the primary one to further modify the potential in which the atoms are trapped.

Moreover, one can use internal atomic properties, such as the magnetic moment of atoms (the spins), to design strongly correlated quantum spin models with a variety of exotic properties. In condensed matter, interactions between spins arise from the overlapping of different electronic orbitals. In optical lattices, however, where there is only one atom in each potential well, the overlap between the electronic orbitals is very small. Nevertheless, interactions between spins can be induced through virtual hopping of atoms between adjacent lattice wells. In other words, quantum mechanics allows the atoms to tunnel through the barrier so the spins can interact. These are called superexchange interactions and were discovered by Kramers (*4*) and Anderson (*5*).

The experiment of Trotzky *et al*. uses a superlattice to examine the dynamical evolution of the simplest matter crystal consisting of a pair of wells, where each well is loaded with an individual rubidium atom (see the figure). The two atoms are initially prepared in different spin states. Although the average number of atoms in each potential well does not change in time, the atoms are allowed to interact by virtual tunneling. Passing through a virtual state of double occupancy, the energy of the system can increase as a result of collisions inside a single potential well, giving in this way a clear signature of superexchange interactions.

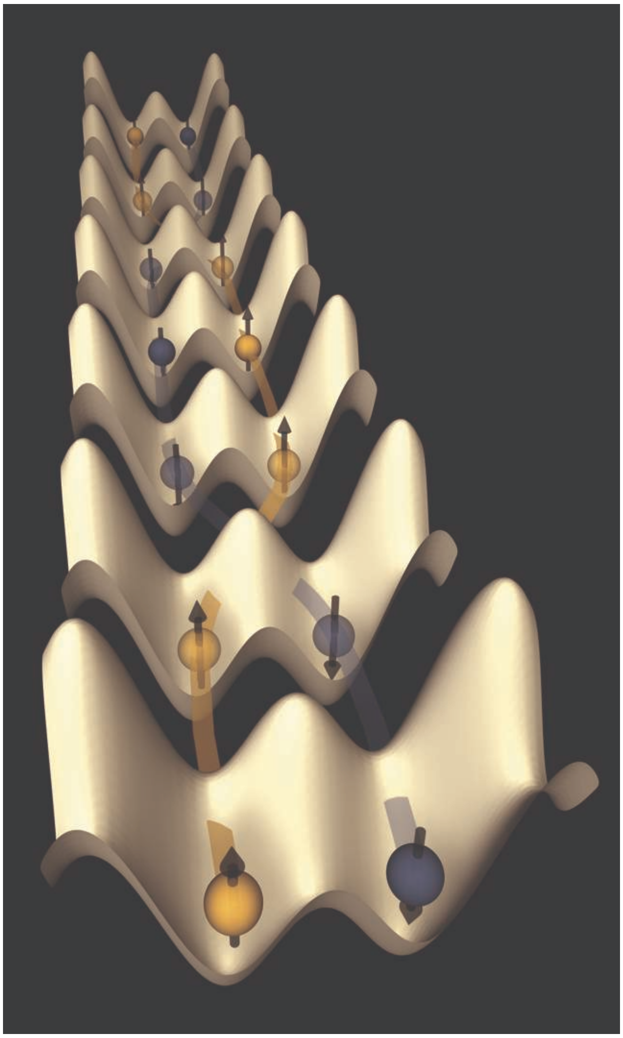
By imposing an additional magnetic field to mismatch the potential energies of the two wells, it is possible to tune the hopping (that is, the hopping increases from a shallower well) while keeping the collision energy unchanged. This allows the researchers to test the accuracy of the underlying theoretical spin model (in this case, the so-called Bose-Hubbard model) and even to control the sign of the interactions. Depending on the value of the applied field, the superexchange interactions can either be antiferromagnetic or ferromagnetic, where at zero temperature the spins orient in antiparallel or aligned fashion, respectively.

The experiment of Trotzky *et al*., although dealing with an ensemble of nearly noninteracting pairs of atoms, opens a direct path toward realization of low-temperature quantum magnets and a variety of many-body spin models with ultracold atoms. Studies of this kind focus on both the equilibrium state and the dynamics of such systems. Trotzky *et al.* discuss some particular spin models in lattices of various geometries and anisotropic interactions. Even more fascinating is the possibility of studying polymerized lattices that consist of regular arrays of plaquettes (i.e., complexes of a few close sites, forming dimers, trimers, etc.). Such systems could be used to mimic some theoretical models of particle physics, such as lattice gauge theories that occur in quark physics.

The three-dimensional lattice of double wells, used in the present experiment, is an example of a dimerized cubic lattice. A trimerized kagome lattice (i.e., a triangular lattice of smaller triangles) was originally introduced by Mila (*6*) to study resonating valence-bond (RVB) states that are superpositions of states in which random pairs of neighboring atoms attain zero total spin, and are examples of a so-called quantum spin liquid. The RVB state is important for, among other reasons, the possibility that it may be the basis for high-temperature superconductivity. The possibility of realizing trimerized kagome and other polymerized lattices, such as a quadruply polymerized square lattice of square plaquettes, using cold atoms and superlattices was suggested by one of us (*7*). A very simple proposal for a quadruply polymerized square lattice was recently formulated by Paredes and Bloch (*8*) and is expected to be investigated by several experimental groups for novel quantum information processing applications.

One of the most challenging questions concerns not only how to experimentally create "exotic" quantum magnetic phases but also how to detect them. Recent prominent examples of detection schemes include interferometry that seeks correlations in noisy signals (*9*), methods involving cavity quantum electrodynamics (*10*), or quantum spin polarization spectroscopy, formulated by us (*11*) as a quantum nondemolition method (i.e., where the quantum state is examined but not destroyed) particularly suited for studying unusual quantum magnetic phases.

Since the first Bose-Einstein condensates were created, researchers have started to unify atomic, molecular, and quantum optics with condensed matter physics and quantum information. Now recent developments (*2*, *3*, *8*, *10*) show that experiments with ultracold gases can address quantum magnetism and might even allow us to make progress on some unsolved problems of high-energy physics in benchtop experiments.



Atomic hopping. An array of double well potentials, where each well contains a single atom. Adjacent atoms interact through superexchange spin-spin coupling in which atoms quantum-mechanically tunnel from one well to the adjacent well and back, as studied by Trotzky *et al*.

CREDIT: I. BLOCH/UNIVERSITY OF MAINE

References

1. M. H. Anderson *et al*., *Science* **269**, 198 (1995).
2. S. Trotzky *et al*., *Science* **319**, 295 (2008); published online 20 December 2007 (10.1126/science.1150841).
3. M. Lewenstein *et al*., *Adv. Phys*. **56**, 243 (2007).
4. H. A. Kramers, *Physica* **1**, 182 (1934).
5. P. W. Anderson, *Phys. Rev*. **79**, 350 (1950).
6. F. W. Mila, *Phys. Rev. Lett*. **81**, 2356 (1998).
7. B. Damski *et al*., *Phys. Rev. A* **72**, 052612 (2005).
8. B. Paredes, I. Bloch, http://arxiv.org/abs /0711.3796.
9. E. Altman, E. Demler, M. D. Lukin, *Phys. Rev. A* **70**, 013603 (2004).
10. L. Jiang *et al*., http://arxiv.org/abs/0711.1365.
11. K. Eckert *et al*., *Nature Phys*., 10.1038/nphys776 (2007).

10.1126/science.1153723